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The limnic ecosystems at Forsmark and Laxemar-Simpevarp

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Update notice

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

Updated 2011-10

Location	Original text		Corrected text	
Page 384, Table 11-3	Mean	122.7	Mean	126
	Max	150	Max	220
	Min	71.7	Min	72
	n	9	n	8
Page 387, Table 11-10	Mean	166,7	Mean	138
	Max	256,3	Max	256
	Min	71,7	Min	72
	Std	38,2	Std	38
	n	35	n	12
Page 388, Table 11-12	Mean	0.94	Mean	0.93
	Min	0.92	Min	0.90
	Std	0.07	Std	0.02
	n	14	n	7
Page 388, Table 11-13	Mean	662.0	Mean	663
	Max	662	Max	664
	Min	662.0	Min	662
	n	7	n	3
Page 388, Table 11-14	Mean	0.96	Mean	0.64
	n	14	n	10
Page 389, Table 11-16	Mean	2,110	Mean	2,132
	Max	2,300	Max	2,200
	Min	1,900	Min	1,980
	Std	110	Std	87
	N	18	n	5
Page 389, Table 11-17	Mean	0.25	Mean	0.21
	Max	0.42	Max	0.27
	Min	0.075	Min	0.18
	Std	0,05	Std	0.04
	n	15	n	4

Updated 2013-01

Location	Original text	Corrected text
Page 432, reference Avila and Pröhl 2008	Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of 14C doses.	Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of 14C doses. SKB R-08-16, Svensk Kärnbränslehantering AB.
Page 440, reference Larsson-McCann et al. 2002	SKB R-02-03	SKB TR-02-03
Page 440, reference Lundin et al. 2004	SKB R-08-04	SKB R-04-08

Updated 2013-08

Location	Original text	Corrected text
Page 385, heading above the last paragraph	...Aqu_z_regoMid_PG (m)	...Aqu_z_rego_pg (m)
Page 385, last paragraph, line 1	…of glacial clay.	…of glacial clay below the identified biosphere objects when they are in the lake/terrestrial stage.
Page 385, last paragraph, line 5	...Aqu_z_regoMid_GL.	...Aqu_z_rego_pg.
Page 386, Table 11-8, caption	Mean, minimum and maximum depth, in m, of the lower regolith (Aqu_z_regoMid_GL) in the Forsmark objects.	Mean, minimum and maximum depth (m) of glacial clay (Aqu_z_regoMid_gl_lake) below the identified biosphere objects when they are in the lake/terrestrial stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified lake basins. The biosphere objects 121_02 and 121_03 do not have a lake stage and the glacial clay layers are assumed to be similar to the glacial clay layers of the sea basins.
Page 386, Table 11-8	Wrong data in table	Table updated with correct data
Page 573, second last line, column 1	Aqu_z_regoMid_pg	Aqu_z_rego_pg
Page 573, second last line, column 2	Depth of postglacial clay in aquatic middle regolith layer…	Depth of aquatic postglacial sediments…

Summary

The overall objective of this report is to describe the limnic ecosystems at Forsmark and Laxemar-Simpevarp, identify important processes in a radionuclide perspective and provide a description of the radionuclide model for the biosphere used in SR-Site.

The report includes a thorough description of the lakes and streams in Forsmark and Laxemar-Simpevarp and covers the following areas: catchment area characteristics, hydrology, climate, sediment characteristics, physical characteristics of streams, habitat distribution in lakes, biotic components (biomass as well as production), water chemistry, and comparison with other lakes and streams in the region, and a historical description. Ecosystem models for carbon and mass balances for a number of elements have been calculated to further improve the understanding of the lake ecosystems. Important processes for the safety assessment are described and evaluated in the report. A separate chapter is included to specifically describe how and where these processes are included in the radionuclide model. The radionuclide model is described and parameterisation and guidance to parameter calculation is provided. The last chapter of the report provides a summary of the knowledge of the limnic systems at the two areas.

The Forsmark regional model area contains more than 25 permanent lakes and pools. All lakes are small and shallow, and are characterized as oligotrophic hardwater lakes. Calcareous soils in the area give rise to high calcium concentrations in the surface water, which in turn leads to high pH and low nutrient concentrations in water as phosphorus often co-precipitates with calcium. The shallow depths and moderate water colour permit photosynthesis in the entire benthic habitat of the lakes, and the bottoms are covered by dense stands of the macroalgae *Chara sp*. Moreover, many of the lakes also have a thick microbial mat (>10 cm), consisting of cyanobacteria and diatoms, in the benthic habitat. Fish in the lakes are dominated by species resistant to low oxygen concentrations, mainly due to poor oxygen conditions during the winter. The streams in Forsmark are all very small, and long stretches of the streams are dry during summer. The downstream parts of some of the streams may function as passages for migrating fish, and extensive spawning migration between the sea and a lake has been observed. Human activities in the area have affected the limnic ecosystem, and large parts of the streams in the Forsmark area consist of man-made ditches. Moreover, one of the lakes has been lowered and one has been divided into two basins.

The ecosystem carbon models for the Forsmark area show that the lakes that contain a microbial mat have larger primary production than respiration, and thus show a positive net ecosystem production (NEP). In lakes that lack a microbial mat, respiration is similar in magnitude as primary production and net ecosystem production is close to zero. Carbon mass balance models for the Forsmark lakes indicate, in accordance with the ecosystem models, that the larger lakes (with a microbial mat) in the area have a positive NEP. However, in contrast to the ecosystem models, the mass balance models indicate that the smaller lakes in the area have negative NEP, regardless of the occurrence of a microbial mat. A low proportion (7–10%) of the carbon incorporated into primary producers in the lake is transported upwards in the food web, and instead most carbon is consumed by bacteria in the form of DOC and POC. The mass balances for a number of elements in Forsmark lakes show that the proportions of different fluxes to and from the lakes are dependent on lake size and position in the catchment, but also on the specific properties of the different elements.

A total of 6 lakes are situated partly or entirely within the regional model area of Laxemar-Simpevarp. The Laxemar-Simpevarp lakes are small and all but one are characterized as brown-water lakes. The lakes have moderate phosphorus concentrations, whereas the concentrations of nitrogen and dissolved organic carbon tend to be high. Because of the brownish water, light penetration is poor and the depth of the photic zone is generally small. In accordance, macrophyte coverage in the lakes is small and biota is dominated by heterotrophic organisms, particularly bacteria. Perch is the predominant fish species in numbers, as well as in weight, in the lakes in the area. Most of the streams in the Laxemar-Simpevarp area are small with mostly calm or slowly flowing water and many of the streams have dry sections in the summer. Most lakes in the Laxemar-Simpevarp area are affected by human activities; the water level in most lakes has been lowered, and one lake, Söråmagasinet, was originally a sea bay but was dammed in order to ensure freshwater reserves to

the nuclear power plant. Water is pumped from Laxemarån to Söråmagasinet in order to maintain the available water storage in the lake.

Both the carbon ecosystem model and the mass balance for Lake Frisksjön in Laxemar-Simpevarp indicate a negative NEP, i.e. higher respiration than primary production. The carbon mass balance show that the lake receives large inputs of organic matter and that these inputs are to a large extent mineralized to CO_2 and emitted to the atmosphere. A large part of the carbon influx also contributes to sediment accumulation in the lake. The annual amount of carbon transported to the lake via inflow is of the same magnitude as the internal processes of primary production and consumption, and there is a large probability that carbon entering the lake will be incorporated into the lake food web. A relatively large part of the primary produced carbon (34%) is transported upwards in the food web. Mass balances for a number of elements indicate that, in general, the most important influx of different elements to the lake is via surface water and the most important outflux is via sediment accumulation.

Interactions between different components of ecosystems have been listed in an interaction matrix. In total, 51 processes are listed in the interaction of which 34 were identified as important to consider in the safety analysis SR-Site. Accordingly, these processes are considered in the radionuclide model. A description of the radionuclide model for the biosphere is provided together with a description of parameters used in the model. Calculations of limnic parameters are thoroughly described and references are given to the reports where calculations of other parameters are described.

In conclusion, this report covers a description of the limnic ecosystems at Forsmark and Laxemar-Simpevarp that has been applied on the SR-Site safety assessment but that also may be applied on future safety analysis. In addition, important processes to consider in radionuclide modelling of the biosphere are identified and the radionuclide model for the biosphere used in SR-Site is described.

Contents

1 Introduction

This report is a compilation data aimed at describing the limnic ecosystems at Forsmark and Laxemar-Simpevarp, identification of important processes in a radionuclide perspective and description of the radionuclide model for the biosphere (including limnic parameters) used in SR-Site. This report was published in an earlier version /Nordén et al. 2008/ covering the site description, which now has been updated and extended with description of the radionuclide model and parameterisation of the radionuclide model (Chapters 10 and 11). In addition, the chapter describing important processes (Chapter 9) has been updated and covers the handling of processes in the radionuclide model. The chapter covering historical development (Chapter 8) have been extended and now includes a description of future development. Several authors have provided the original texts for this report and or contributed to the work presented in the report (see Table 1-1).

1.1 Background

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

Between 2002 and 2007, SKB performed site investigations with the intention on finding a suitable location for a repository. Investigations were focused on two different sites along the eastern coast of southern Sweden; Forsmark in the municipality of Östhammar and Laxemar-Simpevarp in the municipality of Oskarshamn. Data from the site investigations have been used to produce comprehensive, multi-disciplinary site descriptions for each of the sites. The resulting site descriptions were reported in /SKB 2008/ (Forsmark) and /SKB 2009/ (Laxemar-Simpevarp). The locations of Forsmark and Laxemar-Simpevarp are shown in Figure 1-1. Based on available knowledge from the site descriptions and from preliminary safety assessments of the planned repository, SKB decided in June 2009 to select Forsmark as the site for the repository. An application for the construction of a geological repository for spent nuclear fuel at Forsmark is planned to be filed in 2011.

According to the regulations from the Swedish Radiation Safety Authority, SSM, a safety assessment of the planned repository has to be performed before the construction of the repository starts (SSMFS 2008:21 /SSM 2008/). The assessment should focus on potential developments that may lead to the release of radionuclides. SKB launched the project SR-Site to conduct the safety assessment, which is summarised in the **SR-Site main report**.

The safety assessment SR-Site focuses on three major fields of investigation: performance of the repository, the geosphere and the biosphere. The biosphere part of SR-Site, SR-Site Biosphere, provides estimates for human exposure given a unit release, expressed as *Landscape Dose Conversion Factors (LDFs)*. Multiplying these factors with modelled release rates from the geosphere results in estimates of the annual doses used to assess compliance with the regulatory risk criterion. The effects on the environment of a potential release from the repository are also assessed in SR-Site Biosphere. The complete work of SR-Site Biosphere project are synthesised in the **Biosphere synthesis report**.

This report is produced within SR-Site Biosphere and summarises the knowledge of the limnic ecosystems at the sites and presents the radionuclide model for the biosphere. Although produced within SR-Site, the intention is that the description of limnic systems presented in this report will be used also for future safety assessments. The present report covers the methodology and input data related to the site description of the present, historical and predicted future limnic ecosystems in the Forsmark and Laxemar-Simpevarp area. The radionuclide model used to calculate LDFs are presented together with a description of parameter calculations for limnic parameters used to populate the model. In addition, an interaction matrix is used to illustrate how important processes for radionuclide transport and accumulation in ecosystems are considered in the radionuclide model.

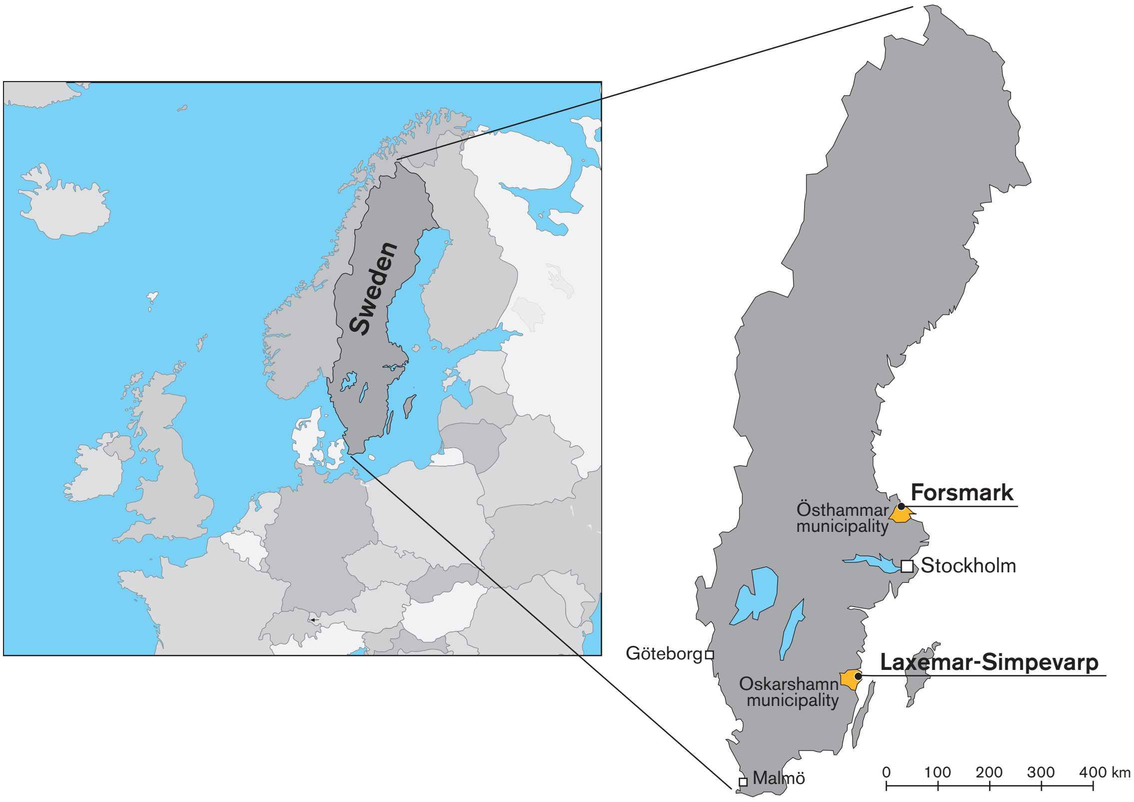

Figure 1-1. Location of the Forsmark and Laxemar-Simpevarp sites.

The work with the biosphere demands interaction over several disciplines and thus everyone involved in SR-Site Biosphere has contributed to the work presented in this report. The major part of the group has been involved from the beginning of the site investigation, via the site characterization and modelling tasks, and in this final synthesis for the safety assessment SR-Site (see Table 1-1).

Table 1-1. Contributors to this report in alphabetic order, their affiliation and role in SR-Site are listed below. This report has been produced within the SR-Site project and thus all members of the project have contributed to the development of this report since all disciplines interact in the development of the radionuclide model. Listing of chapters refers to contribution to the writing of chapters. [a] Project members in SR-Site, [b] project leader in SR-Site biosphere [c] External reviewers.

Eva Andersson[ab], Studsvik Nuclear AB	process descriptions and limnic ecosystems, editor of this report, Chapters 1–11
Karin Aquilonius[a], Studsvik Nuclear AB	marine ecosystems, Chapters 8, 9,10, 11
Rodolfo Avila[a], Facilia	radionuclide modelling and dose assessment, Chapter 10
Sten Berglund[a], SKB	geohydrology and near surface radionuclide transport
Emma Bosson[a], SKB	surface and near surface hydrology, Chapter 11
Anna Brunberg[c]	reviewer of earlier version of this report (Chapters 1–8)
Lars Brydsten[a], Umeå University	regolith dynamics and lake development
Anders Clarhäll[a], SKB	editorial work
Per-Anders Ekström[a], Facilia	numerical modelling
Anders Engqvist[a], KTH	physical oceanographical modelling
Sara Grolander[a], Facilia	site specific chemical data, Chapter 10
Anna Hedenström[a], SGU	Quaternary geology
Ulrik Kautsky[ab], SKB	overall biosphere assessment project leader
Tobias Lindborg[b], SKB	site modelling and landscape development
Regina Lindborg[c]	reviewer of earlier version of this report (whole report)
Angelica Lorentzon af Ekenstam[a], SKB	project administration, process description

Anders Löfgren[a], Eco Analytica	terrestrial ecosystem and synthesis, Chapters 8, 9,10, 11
Sara Nordén[a], SKB	radionuclides and element specific properties, Chapters 3–8
Peter Saetre[a], SKB	synthesis, data evaluation and review of results
Mona Sassner[a], DHI	surface hydrology, Chapter 11
Gustav Sohlenius[a], SGU	Quaternary geology, land use, regolith chemistry, Chapter 11
Mårten Strömgren[a], Umeå University	GIS analysis, landscape development
Björn Söderbäck[a], SKB	historical descriptions, Chapters 3–8
Mike Thorne[c]	reviewer of earlier version of this report (whole report)
Jesper Torudd[a], Facilia	non-human biota assessment
Mats Tröjbom[a], MTK AB	biogeochemistry and mass balances, Chapters 3 and 7
Per-Gustav Åstrand[a], Facilia	numerical modelling

1.2 Aims

The overall objective of this report is to describe the limnic ecosystem at the two sites Forsmark and Laxemar-Simpevarp. The report summarizes the site investigations that are presented in more detail in separate reports and also presents descriptions and estimates of data not presented elsewhere. The intention is firstly to give the initiated reader a coherent description of the limnic ecosystems at the sites. Secondly, the data are used, along with other information, to provide rough descriptions of pools and fluxes of organic matter, water and other elements in the ecosystems. Moreover, historical descriptions of successional trajectories, discussion on boundaries to important ecosystem properties adds further information to the present day data. This information will also be the base for the derivation of the parameter values that are used in the radionuclide modelling in the biosphere assessment. The radionuclide model for the biosphere is presented in this report and an interaction matrix is used to illustrate how important processes in limnic ecosystems are considered in the radionuclide model.

The major outputs can be summarized as:

- A compilation and overview of the studies of different aspects of the limnic systems that have been conducted during the site investigations.
- A general description of the limnic ecosystems at the two sites and factors of importance for the characteristics of the present limnic ecosystems.
- Descriptive ecosystem models that describe pools and fluxes of carbon on a detailed ecosystem level, as well as more generalized carbon mass balance models.
- Ecosystem models that describe pools and fluxes of a wide range of elements.
- Description of historical and predicted future development of the limnic ecosystems both in general terms and for the two sites specifically
- Description of the radionuclide model and how ecosystem knowledge are incorporated in the development of the model
- Description of how different ecosystem process interaction are handled within the radionuclide model using an interaction matrix
- Presentation of data and calculations used for limnic parameter values used in the radionuclide model.

2 This report

This chapter puts the report in a wider context, i.e. in comparison to the overall SR-Site project. The objective of this chapter is also to guide the reader through the different chapters and definitions of the model area and explain some commonly used terms in the report.

2.1 This report in a broader context

This report is the produced within the SR-Site Safety assessment (see **SR-Site main report** for a through description of the assessment). The landscape is in most cases the link between radionuclides occurring in the biosphere and the exposure of these to humans and biota. The landscape may be divided into three ecosystems: the limnic, marine and terrestrial ecosystems. The connection with other reports in the project is illustrated in Figure 2-1.

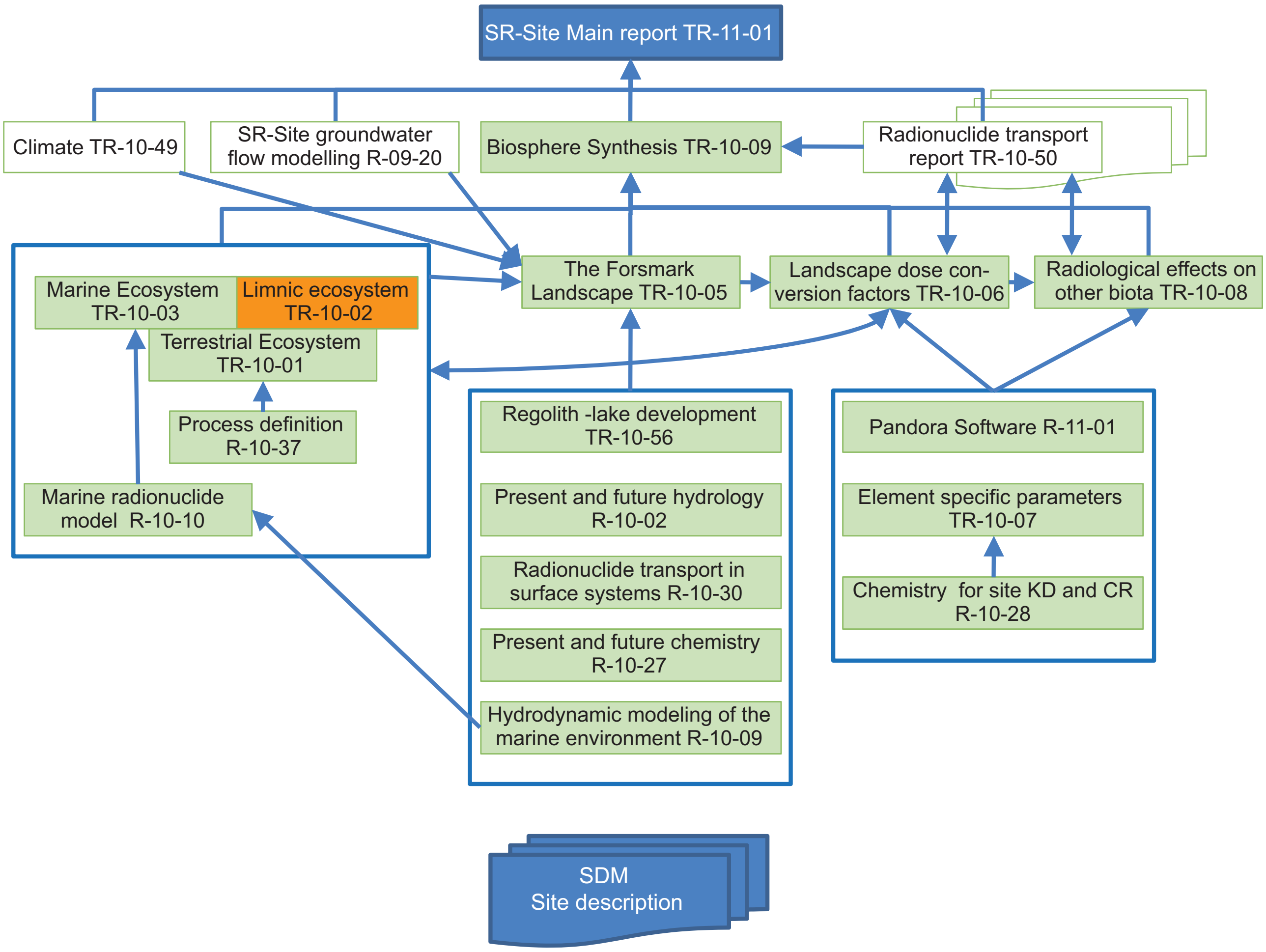

Figure 2-1. The hierarchy of reports produced in the SR-Site Biosphere project. This report (market red) and its connection with other reports produced within SR-Site Biosphere. Arrows indicates major interactions during project work flow of analysis and results, but interactions have been substantial among most parts of the project throughout the process.

2.2 Report content

The extent to which elements are transported and accumulated in the biosphere depends on the properties of the element and the context to which it is exposed. The approach used in this report is to examine a number of different aspects concerning pools and fluxes of elements in the landscape of today, but also consider historical and future aspects that are deemed important for modelling of radionuclide transfer and accumulation in an evolving surface system. Below is a brief summary of the content of the different chapters.

The characteristics of the limnic systems in the two investigated areas are described in **Chapter 3,** *Description of lakes and streams in the Forsmark area,* and in **Chapter 4,** *Description of lakes and streams in the Laxemar-Simpevarp area*. Biotic data concerning species composition, biomasses and habitat distributions are presented along with abiotic data on the morphometry, hydrology and chemistry of the systems, as well as the character of the catchments and the thickness and composition of sediments. Climatic conditions are also described, as well as human impact and human use of the systems. Each chapter concludes with a general description of the lakes and streams in each region in order to put the local conditions in a regional perspective.

Based on the descriptions in Chapter 3 and 4, conceptual models for carbon dynamics in lakes in the two areas are constructed. These models are presented in **Chapter 5,** *The lake ecosystem – conceptual and quantitative carbon models.* Models for streams are described in **Chapter 6,** *The stream ecosystem – conceptual model and model assumptions for carbon*. Two model approaches are presented for lakes: ecosystem carbon budgets and carbon mass balances. The different habitats and functional groups in the ecosystem are defined, the distributions of these groups are described, and their connections are shown in a food web. A summary of the data used in the models is presented. This section also refers back to where in the earlier descriptive chapters these data are presented. Results of the carbon budgets and mass balances are presented for five selected lakes, four lakes in Forsmark and one lake in the Laxemar-Simpevarp area. Confidence and uncertainties in model assumptions are described and discussed.

Pools and fluxes of a number of elements are presented in **Chapter 7,** *Pools and fluxes of different elements in, out and within lakes.* In this chapter, mass balances for a number of elements are described for 5 lakes in Forsmark and 1 lake in Laxemar-Simpevarp. To calculate ecosystem models for other elements than carbon demands more data than available for the lakes in the Forsmark and Laxemar-Simpevarp area. Instead, as a complement to the mass balances, pools of elements are described.

Chapter 8, *Long term development of lakes and streams* describes how the limnic systems have evolved at the sites and make predictions for the future lake development. Successional processes influencing landscape development are described and effects of climate are discussed.

Chapter 9, *The radionuclide model for the biosphere* includes a description of the radionuclide model and how the ecosystem understanding achieved in previous chapters is incorporated into the model.

Chapter 10 *parameterisation of the radionuclide model* includes description of parameters used for the radionuclide model with focus on the calculation of limnic parameters.

The interaction matrix is a tool to describe how important processes for the Safety assessment are considered in the radionuclide model. **Chapter 11,** *Couplings to the process interaction matrix,* describes which processes are included in the radionuclide model.

Chapter 12, *Concluding description of the limnic ecosystems in Forsmark and Laxemar-Simpevarp and comparison between the two areas,* presents a concluding synthesis. A description of the limnic ecosystem, (including e.g. major pools, fluxes and human impact) is presented with comparison between the two areas. In addition, the radionuclide model is discussed in relation to the ecosystem understanding and important processes.

2.3 Definitions

2.3.1 Model area

Both Forsmark and Laxemar-Simpevarp are located on the Swedish east coast. When the two sites are referred to in a general sense in an SDM-Site context, and without reference to clearly defined outer boundaries, they are called the **Forsmark area** and the **Laxemar-Simpevarp area**. At the start of the site investigations in 2002, regional model areas with clearly defined outer boundaries were defined for each site for the purpose of regional scale modelling (see Appendix 1 and 2). These areas were denominated **the Forsmark regional model area** and **the Simpevarp regional model area**. Furthermore, two smaller areas within the Simpevarp regional model area, the Simpevarp subarea and the Laxemar subarea, were defined, and preliminary site descriptions were produced for both subareas. Since the two subareas are included in the same regional model area, the former Simpevarp regional area is designated the **Laxemar-Simpevarp regional model area** in an SDM-Site context, for clarity and to avoid confusion.

2.3.2 Delimitations of the ecosystems and common terms

The site descriptions of the surface system divide the landscape into three ecosystems: limnic, marine and terrestrial. The principal difference between the terrestrial and aquatic ecosystems is the position of the water table, which has implications for a number of ecosystem characteristics and ecosystem processes, such as life form, plant water availability and decomposition. The interface between the two systems often shows high primary production and accumulation of organic material, for example a reed belt in a lake. Some interface areas show high production but no accumulation, e.g. exposed sea shores with input of marine residues. The interface between aquatic and terrestrial environments is in some cases easy to distinguish, such as a rock outcrop/water interface. However, in other cases the boundary between land and water may not be so clear and easy to identify. In most cases, the interface on a freshwater shore is clearly distinguishable along a transect of a few metres (the littoral of a lake), whereas a sea shore, with larger fluctuations in water level, might be distinguished along a transect of tens of metres. In both Forsmark and Laxemar, zones of high production and accumulation have been identified around lakes and in sheltered bays. In the ecosystem models, these zones are classified as wetlands and treated as part of the terrestrial ecosystem in order to treat all kinds of wetlands in a similar way. The interface zones have to be considered as a transient stage in the succession of sea basins/lakes to land.

Some important terms and concepts used in this report are presented and defined in Table 2-1 below whereas the three crucial definitions for limnic ecosystems are defined in the text below, i.e. lakes, streams and catchments

Table 2-1. Definitions of important terms and concepts used in the report. Definitions are in accordance with /Chapin et al. 2002/ and /Begon et al. 1996/.

Concept/term	Definition
Abiotic	Non-living physical or chemical component or process.
Autotroph	Organism that utilises photosynthesis or chemosynthesis to build up organic carbon. The term can also be used for ecosystems and shows then a positive Net Ecosystem Production (NEP).
Basin	In the SR-Site terminology, a basin is the drainage area of a biosphere object (e.g. lake), minus the drainage area of any upstream object. When the basin is below sea level, the basin equals the biosphere object.
Biosphere	That part of the environment normally inhabited by living organisms.
Biosphere object	An area in the landscape that potentially will receive radionuclides released from a future repository.
Biotic	Living ecosystem component or process involving living organisms.
Climate cases	A climatically determined environment with a specific set of characteristic processes of importance for repository safety.
Climate domain	A climatically determined environment in which a set of characteristic processes of importance for repository function and for site development appear. Three climate domains have been identified as important for SR-Site; temperate-, periglacial- and glacial climate domains. For a full definition of the concept of climate domains, (see the **Climate report**).
Conceptual model	A qualitative description of important components and their interactions in a model.

Concept/term	Definition
DEM (digital elevation model)	The DEM describes topography and bathymetry of a certain area. The DEM is a central data source for the site characterisation, and is used as input to most of the descriptions and models produced for the surface system.
Descriptive model	A quantitative description of the components in a considered ecosystem. Can be static or dynamic (see below).
Discharge point/area	The area where deep groundwater reaches the ground surface.
Drainage area	The area generating runoff through a given point in the landscape, equivalent to catchment area.
Dynamic model	A dynamic model describes the behaviour of a distributed parameter system in terms of how one qualitative state can turn into another.
Ecosystem	The combined biotic and abiotic components of an environment.
Ecosystem model	Conceptual or numerical representation of an ecosystem, divided into compartments, and its included processes.
Flux	Flow of energy or material from one pool to another.
Food web	A series of related food chains displaying the movement of energy and matter through an ecosystem.
Functional group	A group of organisms with a common function in the ecosystem, e.g. primary producers, filter feeders etc.
Geosphere	Those parts of the lithosphere not considered to be part of the biosphere. In safety assessment, usually used to distinguish the subsoil and rock (below the depth affected by normal human activities, in particular agriculture) from the soil that is part of the biosphere.
Glacial cycle	A period of c. 120,000 years that includes both a glacial (e.g. the Weichselian) and an interglacial.
Gross Primary Production (GPP)	Total fixation of carbon by photosynthesis, including respiration (cf. Net Primary Production, NPP).
Heterotroph	Organism that uses organic compounds produced by autotrophs. The term can also be used for ecosystems, which then shows a negative Net Ecosystem Production (NEP).
Infilling	The sum of processes that turns a lake into a terrestrial area.
Interglacial	A warm period between two glacials. In SR-Site an interglacial is defined as the time from when the ice sheet retreats from the area (time of deglaciation) to the time for the first occurrence of permafrost.
Interstadial	A warm period during a glacial, sometimes with ice-free conditions.
Landscape development model	A model at landscape level that describes the long-term development of a landscape. The model is used to describe time-dependent properties of the biosphere objects that are input parameters to the Radionuclide model.
Landscape model	In SR-Site, the landscape model is a description of where biosphere objects are situated in the landscape and how they are hydrologically interconnected.
LDF (landscape dose conversion factor)	The LDF is a radionuclide-specific dose conversion factor, expressed in Sv/y per Bq/y. The LDF represents the mean annual effective dose to a representative individual from the most exposed group, resulting from a unit constant release rate, or alternatively per unit released in a single pulse to the biosphere of a specific radionuclide. The LDF relates a unit release rate to dose.
Mass balance	The mass balance model calculates the total sum of major sources and sinks for individual chemical elements in the landscape.
Net ecosystem production (NEP)	The balance between gross primary production and ecosystem respiration.
Net primary production (NPP)	The balance between gross primary production and plant respiration (cf. Gross Primary Production, GPP).
Pandora	The Matlab/Simulink toolbox used for implementation of the SR-Site Radionuclide model.
Radionuclide model	Model used to calculate radionuclide inventories in different compartments of the biosphere, radionuclide fluxes between the compartments and radionuclide concentrations in environmental media (soil, water, air and biota). Exposure calculations for humans to estimate LDF's are included in the radionuclide model, whereas exposure of non-human biota is calculated separately.
Regolith	All matter overlying the bedrock is collectively denominated regolith. This includes both minerogenic and organogenic deposits as well as antropogenic landfills.
Respiration	A biochemical process that converts carbohydrates into CO_2 and water, releasing energy that can be used for growth and maintenance. Heterotrophic respiration is animal respiration plus microbial respiration. Ecosystem respiration is heterotrophic plus autotrophic respiration.
Sub-catchment	The drainage area of a biosphere object minus the drainage area of the inlet(s) to the object.
Terrestrialisation	The transfer of an aquatic ecosystem (marine or limnic) to a terrestrial ecosystem.
Watershed	The drainage area of a future Biosphere object, equivalent to catchment and drainage area above.

Lakes

The definition of what qualifies as a lake differs in the literature, but parameters that are often included are lake size and water retention time /Wetzel 2001/. Most of the world's lakes are freshwater systems, although brackish and salt water systems may also be defined as lakes. A pond is defined as a body of water smaller than a lake. The difference between lakes and ponds is, however, subjective and what some define as a lake others may define as a pond. Most lakes are open and have distinct flow into, through, and out of their basins. These throughflows determine the water retention time (the time required to replace all the water in the lake), and the retention time can be used to distinguish between lake and streams, with lakes having longer retention times than streams. All the lakes in Forsmark and Laxemar-Simpevarp have relatively long retention times. Lakes are distinguished from ponds based on size. The definition of lakes used in this report is "a body of freshwater with a minimum size of 0.5 ha surrounded entirely by land".

The borderline between a lake and the surrounding terrestrial environment may be set differently depending on the aim. In the two site investigation areas, the extents of lakes have been mapped by applying the highest high water level to delimit the lake from terrestrial areas /Brunberg et al. 2004a, b/. Using this definition, wetland areas in direct contact with the lake are also included, as well as the "artificial" wetland areas in some lakes where the water level has been lowered due to anthropogenic activities. Hence, in addition to the aquatic plants, wetland plants and even bushes and small trees may occasionally be included in this zone, especially if the area is tufty. In the ecosystem models and radionuclide model (presented in Chapter 5 and 10, respectively), we have chosen to treat all areas defined as Littoral I (reed belts and in Frisksjön also wetland plants, trees and bushes) by /Brunberg et al. 2004a, b/ as wetland areas. The main reason for this is to treat all kinds of wetlands within the areas in the same way. The interface zones have to be considered as a transient stage in the succession of lakes becoming land. In the safety assessment of a repository for spent nuclear fuel, fluxes of elements are of interest on a landscape level, and the models for the three ecosystem types (terrestrial, limnic and marine) will be linked together to model the overall fluxes. At this point it is not of particular importance how these areas are defined, but that they are included somewhere. Data from littoral I (reed belts) are presented in Chapter 3 and 4. Neither the reed biomass nor ecosystem processes in the reed belt are explicitly included in the lake ecosystem model, but the resulting transport of elements is indirectly included in the lake budget as import from adjacent terrestrial areas. The biological processes within the reed belt are further described in the account of the terrestrial ecosystems /Löfgren 2010/.

Streams

One definition of streams is "*mass of freshwater moving through the landscape driven by gravity*". This definition also includes water flowing in man-made ditches. As large stretches of the watercourses within the areas at Forsmark and Laxemar-Simpevarp are ditches, we use this definition in this report. For most of the running waters in the two areas the furrow is distinct, which makes the delimitation between the stream and the surrounding terrestrial ecosystem easy. In some parts, the surrounding areas are temporarily flooded during periods of high water flow. This occurs during very short periods and the flooded areas are not considered as part of the limnic ecosystem but are treated as terrestrial areas in /Löfgren 2010/. Areas that are flooded have been defined through field examinations (see Sections 3.3.5 and 4.3.4).

In large river systems the character of the stream changes along the stretch from the source(s) to the final outlet in the sea. To consider this character change, streams are often divided into stream orders /Strahler 1957/. The stretch from the source is given stream order 1 until it meets another furrow of the same order. From here the stream order is 2 until the furrow meets another with an equal or higher stream order. The stream order system has been used in this report.

Catchments

Terrestrial and aquatic ecosystems are linked by movements of water and materials. There is a continual downstream movement of surface waters in streams and lakes towards the sea. A catchment can be defined as the area draining to a defined point /Wetzel 2001/. For example, the catchment of a lake is defined as all area draining to the outlet point of the lake and thus includes all the area draining to the lake as well as the lake itself. The catchment for a lake may contain several lakes in upstream areas, in which case it is common to define sub-catchments for the separate lakes.

3 Description of lakes and streams in the Forsmark area

The Forsmark area includes 8 small catchments, 25 lakes and a number of small streams (Figure 3-1 and 3-2). Site data for description of the limnic systems have been collected during the site investigations. The following text describes these investigations with a focus on the limnic ecosystems. The sampling methods used are only briefly described here. For further details the reader is directed to the investigation reports.

3.1 General description of the lakes and streams

The lakes in the Forsmark area are characterized as oligotrophic hardwater lakes. The bedrock in the area is dominated by granite and gneisses, covered by calcareous glacial till and small areas with postglacial clay. Chemical weathering of the calcareous till gives rise to very high calcium concentrations in the surface water and the shallow groundwater. High concentrations of calcium ions [Ca^{2+}] lead to precipitation of $CaCO_3$, especially in the summer when the pH is high due to high primary production. Nutrients (P, Mn, Fe) often co-precipitate with calcium, leading to oligotrophic conditions; hence the definition oligotrophic hardwater lakes.

The Forsmark lakes are generally small and shallow with small volumes. The water level in the lakes varies over the year, with the highest water levels in March–April following snowmelt and the lowest water levels in July–September. Most of the lakes in the Forsmark area are surrounded by mires and it is not always apparent how to draw the borderline between lake and mire.

The water chemistry in lakes in Forsmark is characterized by high pH, high concentrations of major ions and high electrical conductivity. The phosphorus concentrations are generally low, whereas nitrogen concentrations tend to be high. The water has high concentrations of dissolved organic carbon, which in combination with the moderate water colour is unusual.

Due to the shallow water depth and clear water, the biota in the lakes is strongly concentrated in the benthic habitat, which is covered by the macroalgae *Chara* and a thick microbial mat consisting of microphytobenthos and benthic bacteria. The microbial mat is unusually thick, and chlorophyll *a*, which indicates photosynthesising organisms, has been found down to depths of 10–15 cm. In the pelagic habitat, on the other hand, the biomass of microbiota is low. Similar to biomass, primary production is also concentrated in the benthic habitat. The fish populations in the lakes were compared with other Swedish lakes and classified according to Swedish fish index (FIX). The fish populations varied between lakes and there were populations with no deviation from a normal lake but also populations with significant deviation from a normal lake. The lakes which deviated from normal lakes had a high share of biomass from species resistant to low oxygen levels and/or a low biomass share of piscivore percids. Species tolerant to low oxygen conditions, e.g. Crucian carp, dominate in many of the lakes /Borgiel 2004b/.

There are no large streams in the Forsmark regional model area but a number of small streams draining the area (Figure 3-2). The mean specific discharge for the largest investigated catchment was 4.88 $L\ s^{-1}\ km^{-2}$, which can be considered low. Large parts of the streams are dry for part of the year and all of the automatic discharge gauging stations (n=4) had zero discharge for relatively long periods in late summers and early autumns. Most of the streams have been excavated.

Similar to the lakes, the water chemistry of the streams is characterized by high pH, high alkalinity, and high nitrogen concentrations. The concentration of dissolved organic carbon is very high and shows large temporal variation. The phosphorus concentration varies considerably due to differences in rainfall and water velocity, but is generally low. The coverage of vegetation in the streams varies, but vegetation is often very dense in the uppermost parts of the streams. The most common species of higher vegetation is the common reed.

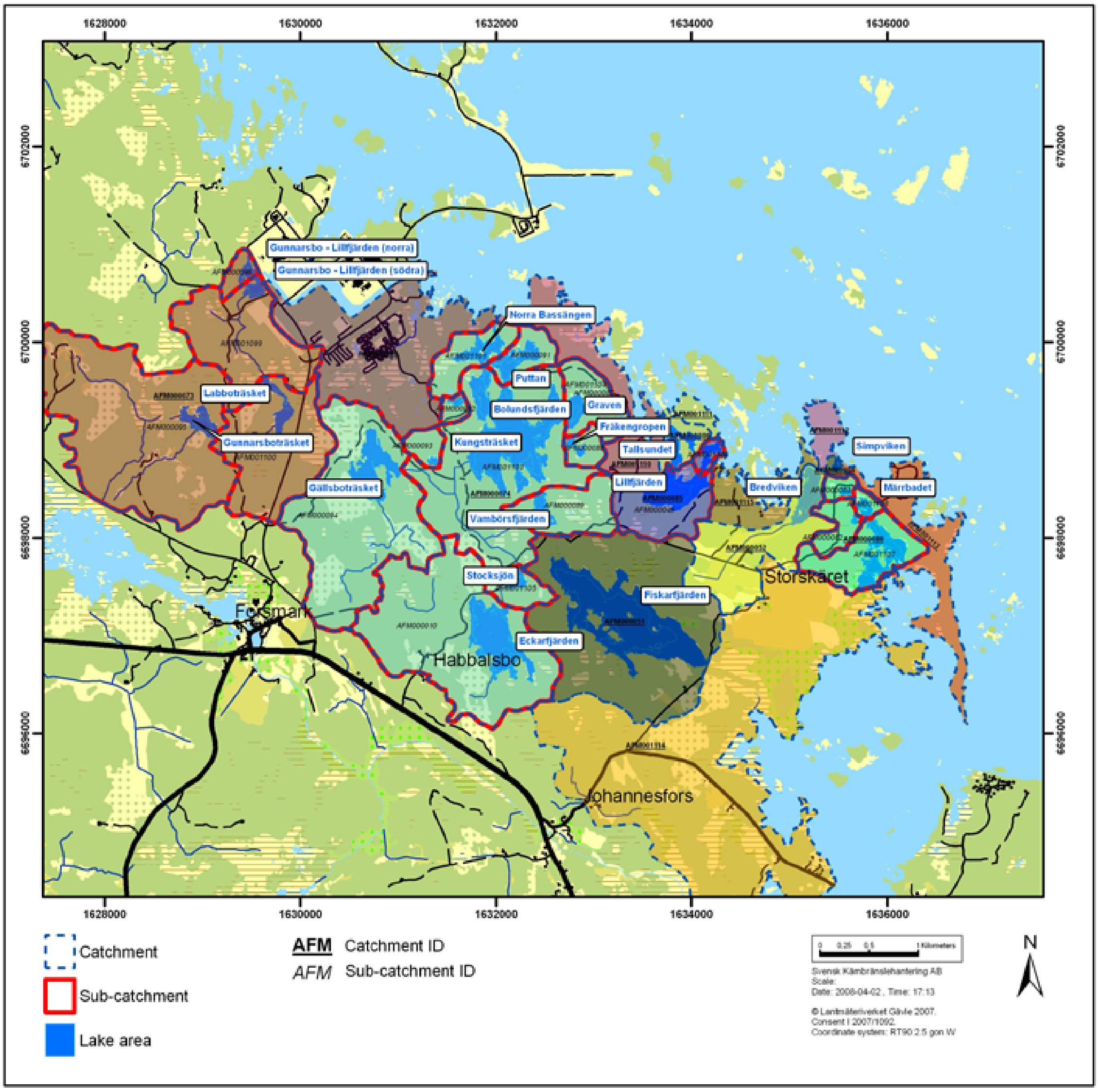

Figure 3-1. Delineated catchments and location of 20 of the 25 lakes in the Forsmark area. Some of the smallest lakes have been omitted from the map for clarity.

3.2 Catchment characteristics

The catchment is the land area (including lakes) from which the water is drained to the same stream. The area is delimited by the topography, and all precipitation falling within the catchment less evapotranspiration will eventually reach the sea through the same stream channel.

The catchment clearly determines the characteristics of lakes and streams within it /Wetzel 2001/. The geomorphology of the land determines the ionic composition and slope of the soil, and, in combination with the climate, also the vegetation of the area. The vegetation and soil composition influence the amount of runoff as well as the composition and quantity of organic matter that enters streams and lakes.

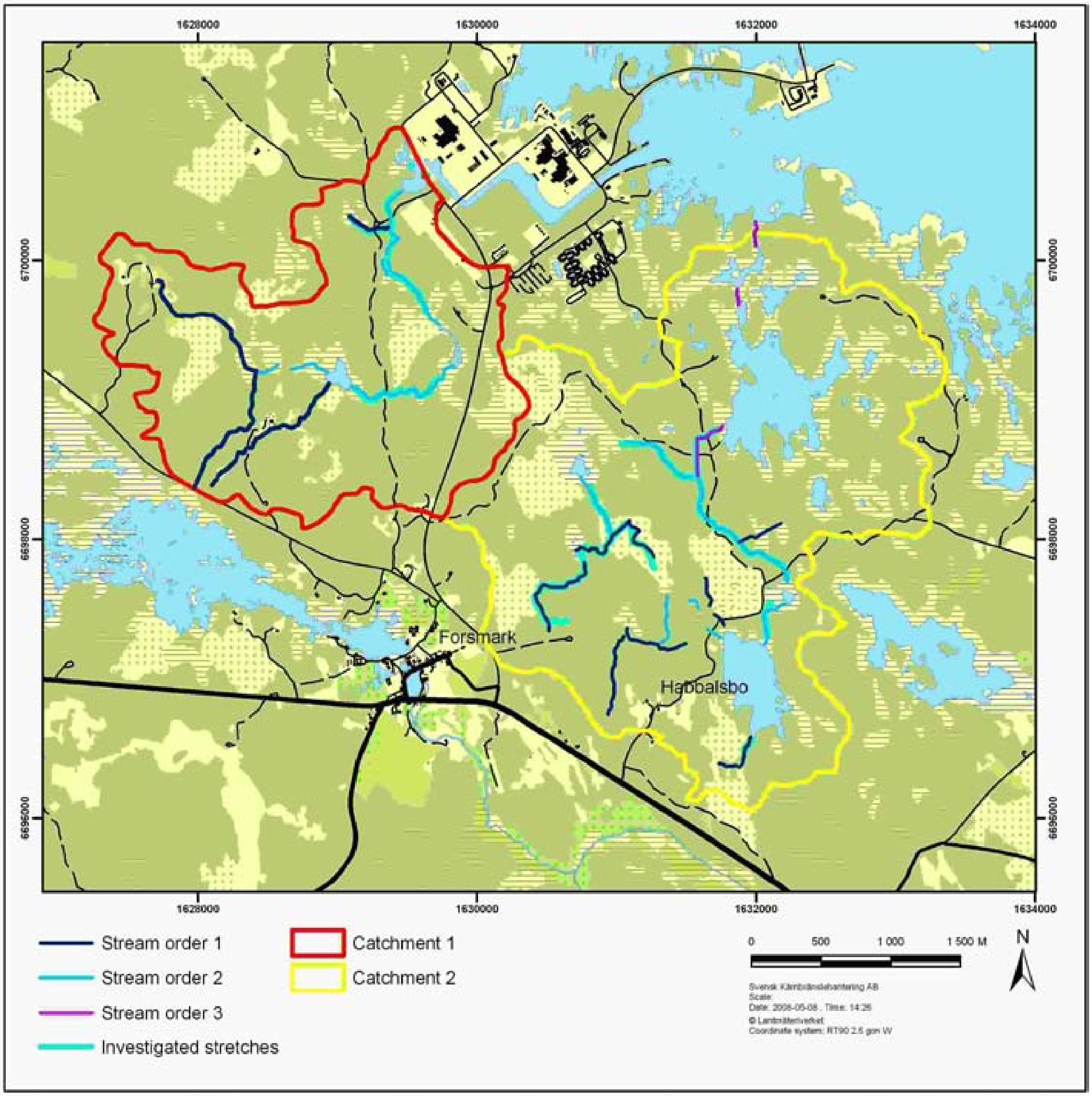

Figure 3-2. *Streams in the Forsmark area. Stream orders and investigated stretches are indicated by different colours.*

Morphological parameters as well as land use, soil composition and vegetation types of the different catchments in the Forsmark area were examined by /Brunberg et al. 2004a/. The maximum elevations above sea level in the different catchments vary between 5 and 27 m, whereas the minimum levels vary between –1 and 5 m (Table 3-1). The number of residents is very low, and only one of the main catchments has a permanent population: 5 people live in catchment 1.

Forest is the most common land type, comprising on average 60% of the catchments (Table 3-2). The second most common use type for most catchments is wetland. Agriculture accounts for little land use in all catchments except one, Bredviken.

Table 3-1. Morphological parameters of the catchments in Forsmark. From /Brunberg et al. 2004a/. The model area in Forsmark is divided into 8 catchments. Several of these contain more than one lake and sub-catchments for the separate lakes may be calculated. Sub-catchment is the area draining directly to the lake, i.e. excluding the catchment area of upstream lake(s) but including water area in the catchment.

ID code	Catchment number	Name	Area (km^2)	Maximum level (m.a.s.l.)	Minimum level (m.a.s.l.)	Population (number)
	1	**Forsmark 1**				
AFM000073	1:1–4	Gunnarsbo-Lillfjärden (south)	5.120	27	1	5
AFM001099	01:01	Subcatchment: Gunnarsbo-Lillfjärden (south)	1.089	12	1	0
AFM000096	01:02	Gunnarsbo-Lillfjärden (north)	0.104	8	1	0
AFM000048	1:3–4	Labboträsket	3.928	27	3	5
AFM001100	01:03	Subcatchment Labboträsket	1.193	23	3	0
AFM000095	01:04	Gunnarsboträsket	2.734	27	5	0
	2	**Forsmark 2**				
AFM000074	2:1–10	Norra Bassängen	8.668	20	0	0
AFM001101	02:01	Subcatchment: Norra bassängen	0.350	8	0	0
AFM000092	02:02	Lake 2:2	0.071	7	1	0
AFM000050	2:3–10	Bolundsfjärden	8.003	20	0	0
AFM001103	02:03	Subcatchment: Bolundsfjärden	2.244	13	–1	0
AFM000087	2:4–5	Graven	0.531	7	0	0
AFM001104	02:04	Subcatchment: Graven	0.392	6	0	0
AFM000088	02:05	Fräkengropen	0.139	7	1	0
AFM000089	02:06	Vambörsfjärden	0.484	8	0	0
AFM000093	02:07	Kungsträsket	0.126	9	2	0
AFM000094	02:08	Gällsboträsket	2.141	20	1	0
AFM000090	2:9–10	Stocksjön	2.477	20	2	0
AFM001105	02:09	Subcatchment: Stocksjön	0.210	12	2	0
AFM000010	02:10	Eckarfjärden	2.267	20	3	0
AFM000091	02:11	Puttan	0.244	9	1	0
	3	**Forsmark 3**				
AFM000086	03:01	Tallsundet	0.215	6	0	0
	4	**Forsmark 4**				
AFM000085	4:1–2	Lake 4:1	0.689	11	0	0
AFM001106	04:01	Subcatchment: Lake 4:1	0.069	7	0	0
AFM000049	04:02	Lillfjärden	0.621	11	0	0
	5	**Forsmark 5**				
AFM000052	05:01	Bredviken	0.944	10	0	0
	6	**Forsmark 6**				
AFM000084	06:01	Simpviken	0.035	6	0	0
	7	**Forsmark 7**				
AFM000080	7:1–4	Lake 7:1	0.895	8	0	0
AFM001107	07:01	Subcatchment: Lake 7:1	0.558	8	0	0
AFM000081	7:2–4	Märrbadet	0.337	8	0	0
AFM001108	07:02	Subcatchment: Märrbadet	0.068	7	0	0
AFM000082	07:03	Lake 7:2	0.192	8	0	0
AFM000083	07:04	Lake 7:3	0.077	5	0	0
	8	**Forsmark 8**				
AFM000051	08:01	Fiskarfjärden	2.926	13	0	0
Mean of the 8 main catchments			2.4	12.6	0.1	0.6
Median of the 8 main catchments			0.9	10.5	0	0
Min of the 8 main catchments			0.04	6	0	0
Max of the 8 main catchments			8.7	27	1	5

Table 3-2. Example of the relative distributions (%) of some vegetation types, and catchment area (excluding water area) for some of the modelled Forsmark catchments based on the vegetation map in /Löfgren 2010/.

Catchment	Basin nr	Area (km²)	Forest	Forested wetland	Wetland	Arable land	Pasture	Clear-cut
Bolundsfjärden	136	1.84	69.6	2.2	17.9	0.0	0.0	10.3
Eckarfjärden	149	2.08	64.4	0.0	7.7	0.5	4.8	22.6
Fräkengropen	133	0.14	78.6	0.0	21.4	0.0	0.0	0.0
Gällsboträsk	142	2.13	40.8	0.5	11.3	0.0	0.5	46.9
Graven	127	0.38	63.2	0.8	26.3	0.0	0.0	7.9
Kungsträsket	131	0.12	58.3	0.0	5.0	0.0	0.0	33.3
Lake 2:2	128	0.07	71.4	0.0	7.1	0.0	0.0	28.6
Norra Bassängen	125	0.32	68.8	1.9	28.1	0.0	0.0	0.3
Puttan	124	0.22	59.1	0.0	36.4	0.0	0.0	2.3
Stocksjön	147	0.21	76.2	0.0	19.0	0.0	1.4	1.4
Varmbörsfjärden	141	0.46	78.3	2.2	19.6	0.0	0.0	2.2
Total		8.0	60.6	0.9	14.7	0.1	1.4	22.2

The dominant rock type in the north-eastern part of the Forsmark regional model area is a medium-grained metagranite. Rock domains with strongly deformed and in some cases banded and inhomogeneous rocks occur in the area. The bedrock has a high silica content and, in contrast to the overlaying deposits, a low buffering capacity. The most common soil type is glacial till. Three different kinds of till are represented in the Forsmark area: a sandy till with medium boulder frequency (dominant), a clayey till with low boulder frequency (Storskäret) and a clayey till with high boulder frequency (Börstilåsen) /Hedenström and Sohlenius 2008/.

3.3 Hydrology

The hydrology of the Forsmark area is generally characterized by a shallow groundwater table with many small catchments. No major water courses flow through the catchments, and small brooks connect the lakes with the sea.

3.3.1 Discharge

There are no large streams within the Forsmark regional model area. However, a number of small streams drain the area. Some of these carry water most of the year, while many are dry for long periods (Figure 3-3). Four permanent automatic discharge gauging stations have been installed in the largest streams as a basis for water balance calculations and for calculation of mass transport of different elements (Figure 3-4). Monitoring of water levels, electrical conductivities, temperatures and discharges has been performed at the stations. Measurements have been performed at one station since April 2004 and at the other stations since December 2004 /Johansson and Juston 2007/. This time period is relatively short, so the mean discharge values presented in Table 3-3 should be used with caution.

The mean specific discharge for the largest catchment in Forsmark during the monitored period was 4.88 L s^{-1} km^{-2} (Table 3-3). In comparison, the specific discharge at Vattholma, a station with a considerably larger catchment, situated further inland c. 50 km SW of Forsmark, is approximately 6.5 L s^{-1} km^{-2} /SGU 1983/.

Due to the small catchment areas, the discharge rates at all gauging stations in Forsmark are very low (Figure 3-5). The mean discharge for the largest catchment was 27 L s^{-1} (Table 3-3). In comparison, the mean discharge in the Forsmarksån River (located just outside the Forsmark area) is 2,800 L s^{-1} /Brunberg and Blomqvist 1998/ and the mean discharge in the Dalälven River is 353,000 L s^{-1} at the outlet to the Baltic Sea (average for the time period 1976–2000 according to www.dalalvensvvf.se/omdal.htm**,** accessed 16 April 2008). The highest recorded discharge in the largest catchment in Forsmark (gauging station PFM005764) was 212 L s^{-1} and in the smallest catchment 75.9 L s^{-1} (gauging station PFM002668) (Figure 3-5). All stations had zero discharge for relatively long periods in late summer and early autumn. For a specific station, the variation in specific discharge between selected time periods (hydrological years) was 30–35%, while the variation between stations for a selected time period was 10–17% /Johansson and Juston 2007/.

The surface discharge in the streams is dominated by water of groundwater origin /Johansson et al. 2008/. Overland flow contributes to the discharge mainly during long periods of wet conditions during autumn and winter and in direct connection to snow melt in spring.

Figure 3-3. *Photos showing (left) one of the largest streams in the Forsmark candidate area, taken at the inlet to Bolundsfjärden in May 2007 (later than the highest flow during snowmelt), and (right) a stream section that is dry in the summer, a common sight in the Forsmark area.*

Figure 3-4. *Location of the four discharge gauging stations and the electrical conductivity monitoring station (PFM002292) in Forsmark.*

Table 3-3. Discharge characteristics for the four gauging stations for various time periods (total available time series) in Forsmark. From /Johansson and Juston 2007/.

	PFM005764	PFM002667	PFM002668	PFM002669
Time interval	**Apr 2004–Mar 2007**	**Dec 2004–Mar 2007**	**Dec 2004–Mar 2007**	**Dec 2004–Mar 2007**
Mean discharge (L s^{-1})	27.2	15.4	11.55	15.9
Min. discharge (L s^{-1})	0.00	0.00	0.00	0.00
Max. discharge (L s^{-1})	212	131	75.9	183
Specific discharge (L s^{-1} km^{-2})	4.88	5.13	5.07	5.61
Specific discharge (mm yr^{-1})	154	162	160	177
Catchment area (km^2)	5.59	3.01	2.28	2.83

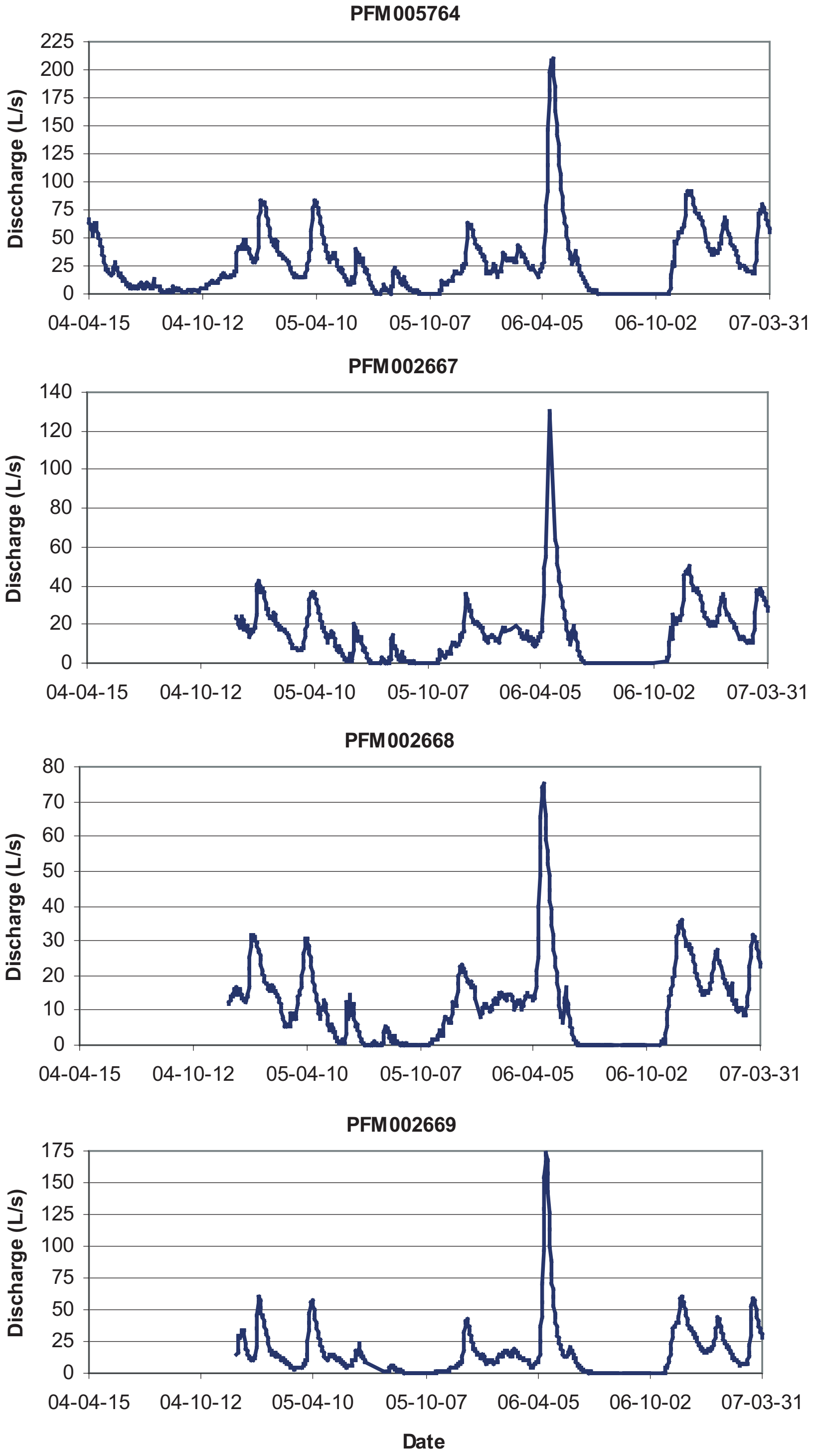

Figure 3-5. *Surface discharge at the four gauging stations in the Forsmark area (daily means). Note the different scale of the discharge axes. Data from /Johansson et al. 2008/.*

3.3.2 Water levels in lakes

The water level has been measured in 6 lakes in the Forsmark area. The measuring period varies between three and four years. The same pattern is seen for all lakes, i.e. maximum water levels in March–April, during snowmelt, followed by a decline to a minimum level during the period July–September. In late October the levels rise again up to a new maximum level in November–December (Figure 3-6). The mean, minimum and maximum water levels in lakes measured during the site investigations are presented in Table 3-4.

3.3.3 Groundwater discharge/recharge

Groundwater levels have been measured in the till below lakes and related to surface water levels measured at the same site in five lakes in the area /Juston et al. 2007/. The gradients were variable and typically small, often within uncertainties of the measurements. All lakes showed changing conditions between upward and downward gradients, indicating that they function as both recharge and discharge areas for groundwater. In some lakes (Eckarfjärden and Bolundsfjärden), there was a higher downward gradient in the late summer and early autumn in 2003 and 2005. Comparison with groundwater measurements in the area surrounding the lakes shows that at least two of the lakes in the area (Bolundsfjärden and Eckarfjärden) seem to act as sources of groundwater recharge to the surrounding (local) areas during some periods and as discharge areas during other periods /Juston et al. 2007, Johansson et al. 2008/. One reason for the observed downward gradient from the lake to the surrounding areas is groundwater abstraction by evapotranspiration. Due to the low permeability of the bottom sediments, the resulting water fluxes can be assumed to be small /Johansson 2008/. The chemistry of the water below the lakes Bolundsfjärden, Fiskarfjärden and Gällsboträsket indicates a very limited flow, since relict marine water is found /Johansson et al. 2008/. The hydrogeological and hydrochemical interpretations indicate that shallow groundwater flow systems involving only Quaternary deposits have discharge areas around the lake and in the near-shore parts of the lake, while deeper systems are drained into the Baltic sea by the highly transmissive shallow bedrock /Johansson et al. 2008/.

Table 3-4. Water levels in six lakes in the Forsmark area (m.a.s.l. RHB 70) (data from SICADA[1], March 2008). "N" denotes the number of registrations for each lake (daily measurements).

	Norra Bassängen	Bolundsfjärden	Eckarfjärden	Fiskarfjärden	Gällsboträsket	Lillfjärden
Mean	0.36	0.37	5.28	0.55	1.80	0.09
Min.	0.07	0.11	5.09	0.30	1.51	–0.17
Max.	0.87	0.76	5.54	0.74	2.30	0.71
No. of obs	1,424	1,414	1,251	978	1,066	887

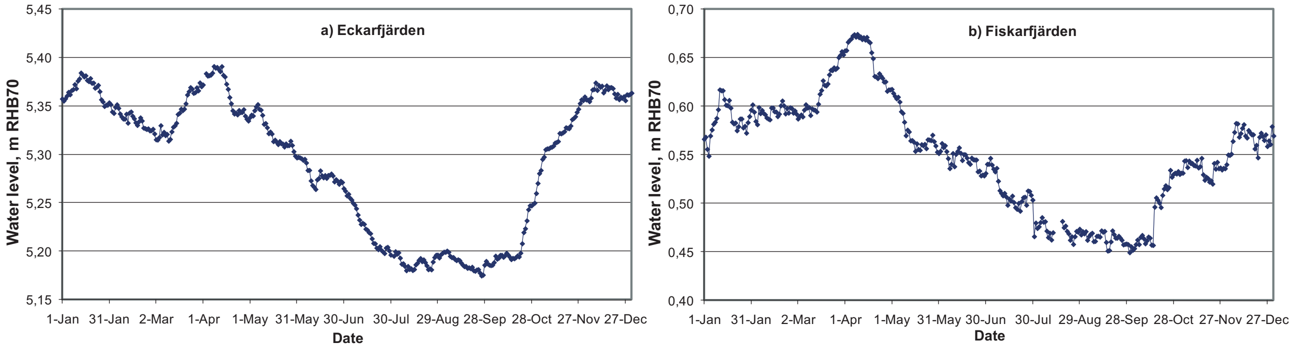

Figure 3-6. *Examples of annual variation in water levels as daily mean values, a) Eckarfjärden and b) Fiskarfjärden (m.a.s.l. RHB 70). From /Johansson and Juston 2007/.*

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[1] SKBs database SICADA, access might be given on request.

3.3.4 Inflow of marine water to lakes

Several of the lakes in the Forsmark area are very young and some of them still have occasional contact with the Baltic Sea. Two of these lakes are Norra Bassängen and Bolundsfjärden, for which inflow of saline water has been observed occasionally during the site investigation /Johansson et al. 2008/. The measured lake and sea water levels in these two lakes and the Baltic Sea are shown in Figure 3-7.

A station for monitoring of water electrical conductivity is located at the outlet of Bolundsfjärden. It was installed in December 2004, when the measurements also started. The electrical conductivity of the water leaving Bolundsfjärden was for most of the observation period between 70 and 100 mS m^{-1}. However, during events of extremely high sea water levels (Figure 3-8), brackish water flowed into the lake and the electrical conductivity increased up to 900 mS m^{-1} (Figure 3-8). Such events appeared during December 2004–January 2005 and November 2006–January 2007. The two extreme events correspond to the two storms "Gudrun" and "Per". The inflow of water is relatively large, approximately 180,000 m^3 during 10 hours in which the water level rised from 0.53 to 0.8 m.a.s.l.

There is a distinct conductivity profile in Bolundsfjärden following saltwater intrusion (Figure 3-9). Approximately 3 weeks after the seawater intrusions (January 31, 2005) the saline water had settled at the lake bottom. Two months later (March 29, 2005), the conductivity profile was virtually identical. At that time the lake was still covered by ice, preventing wind-driven water mixing. However, in the late summer the profiles indicate well-mixed conditions.

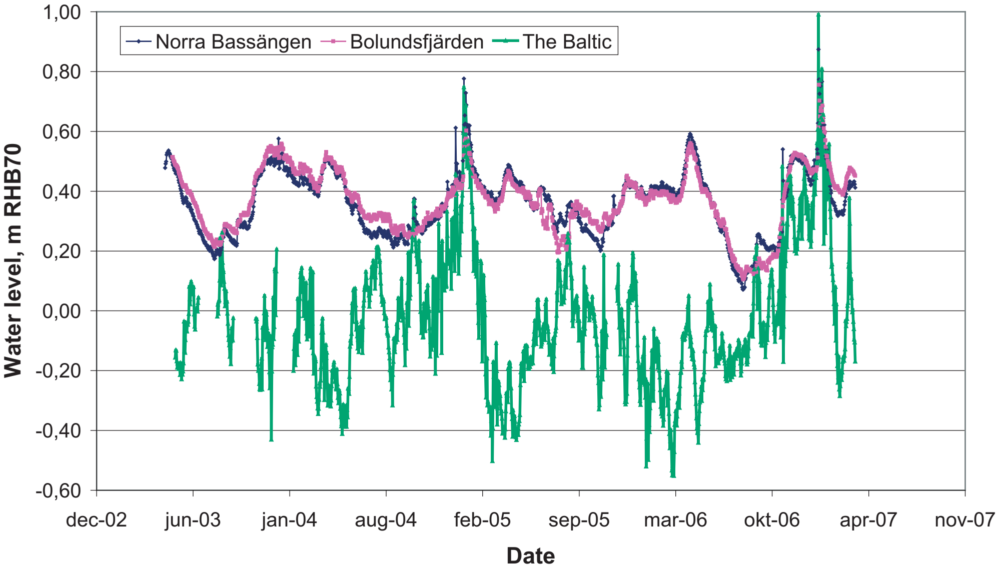

***Figure 3-7.** Water levels in the Baltic Sea and in the lakes Norra Bassängen and Bolundsfjärden measured during the site investigation in Forsmark. From /Johansson 2008/.*

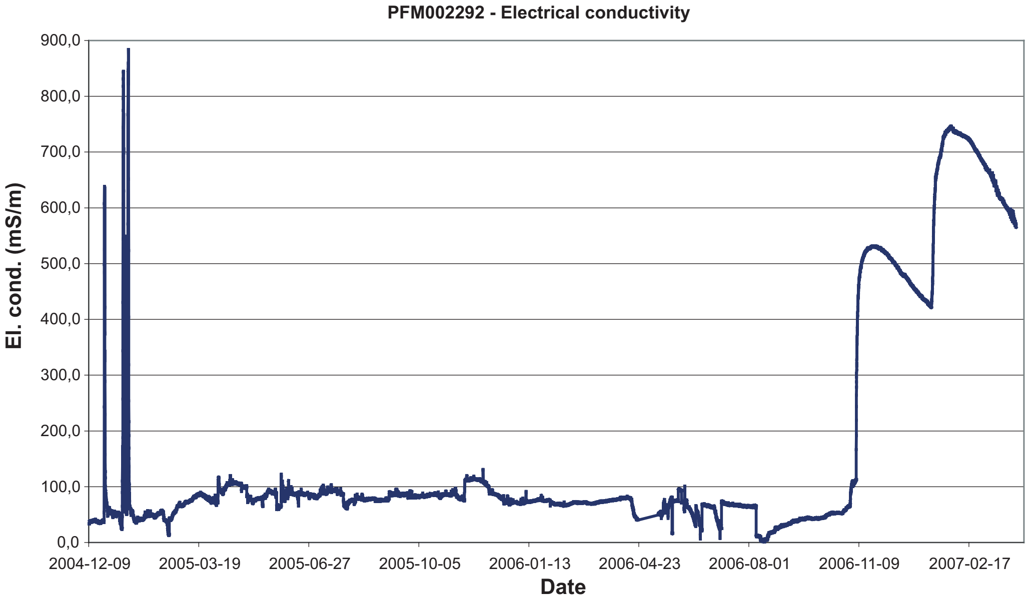

***Figure 3-8.** Electrical conductivity at the monitoring station at the outlet of Bolundsfjärden (PFM002292). The two peaks correspond to occasions with salt water intrusion into Bolundsfjärden. From /Johansson and Juston 2007/.*

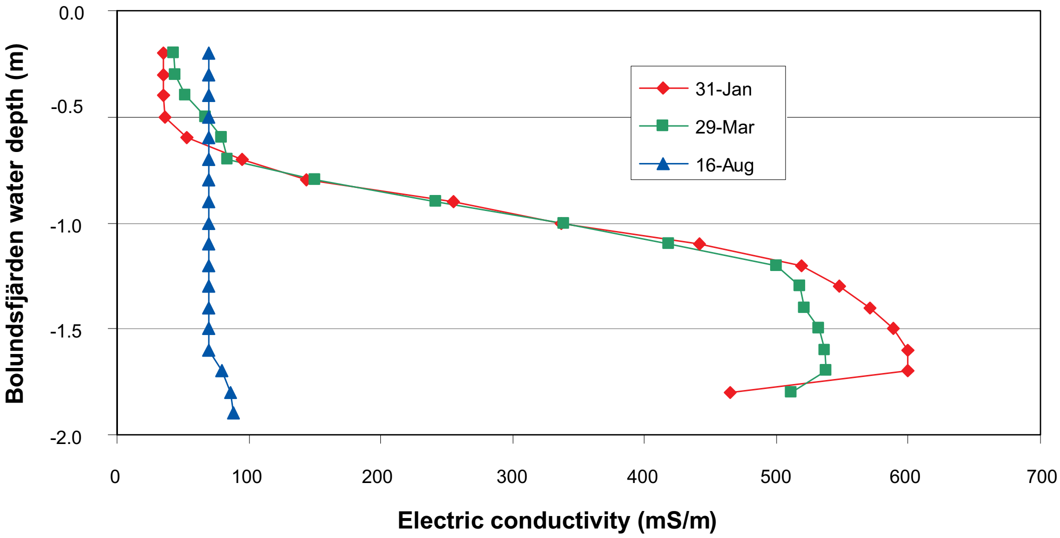

***Figure 3-9.** Electrical conductivity profiles in Bolundsfjärden measured during winter, early spring, and summer, 2005. From /Juston et al. 2007/.*

3.3.5 Flooded areas

The Forsmark area is very flat with small elevation gradients. During periods of high water flow, some areas surrounding the streams are flooded (Figure 3-10). The extent of these areas has been investigated in two catchments (Figure 3-11) /Carlsson et al. 2005b/. The sizes of the flooded areas are shown in Table 3-5. The stream in catchment 8 is extremely short (30 m) and the entire length of the stream can be considered to be a periodically flooded area. In catchment 2, 30% of the stream stretch was periodically flooded (Figure 3-11). Altogether, 0.313 km^2 of flooded area was investigated. The flooded areas are classified as (terrestrial) wetland areas and are further described in /Löfgren 2010/.

Table 3-5. The investigated flooded areas of the streams in the Forsmark area (data from /Carlsson et al. 2005b/).

Catchment	Length of investigated stream stretch (m)	Flooded area (km^2)	Flooded area per stream length (km^2/km)	Share of stream stretch with flooded areas[2] (%)
Forsmark 2	4,760	0.134	0.03[1]	c. 30
Forsmark 8	860[3]	0.179	0.21	c. 100
Total	5,620	0.313	0.06	c. 40

[1] investigated stream length including tributaries (N.B. not the total stream length),
[2] rough estimate from GIS map,
[3] including the wetland area with no visible channel.

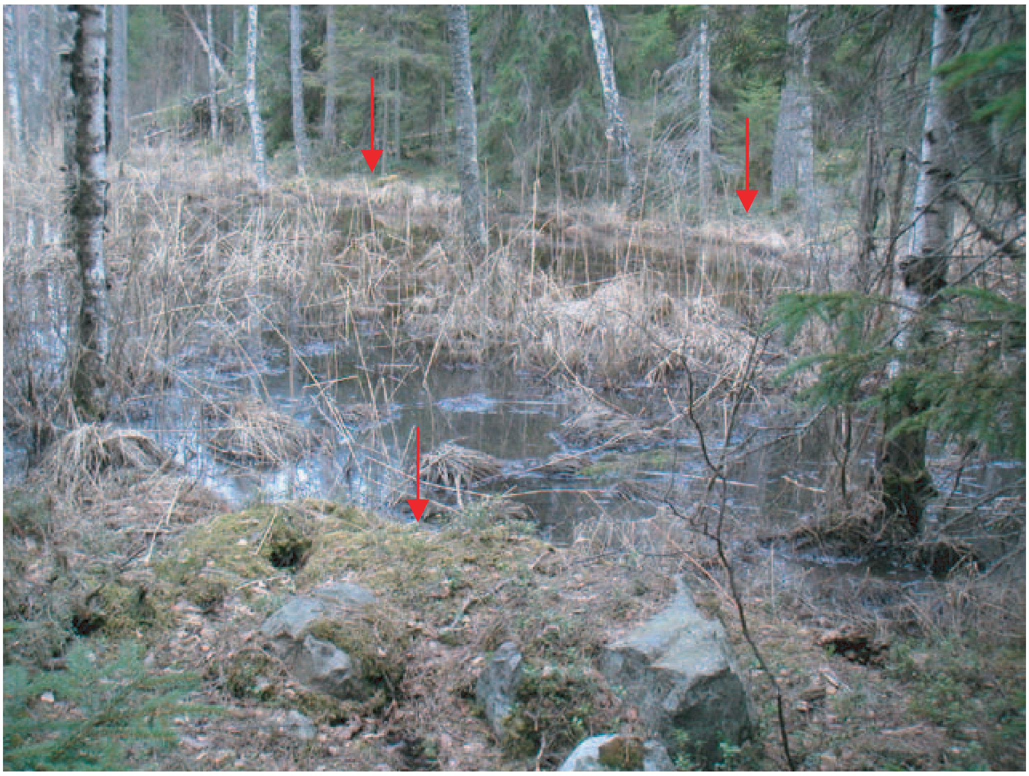

Figure 3-10. A flooded area in the catchment Forsmark 2 in April 2004. Red arrows indicate the limits of the flooded area. From /Carlsson et al. 2005b/.

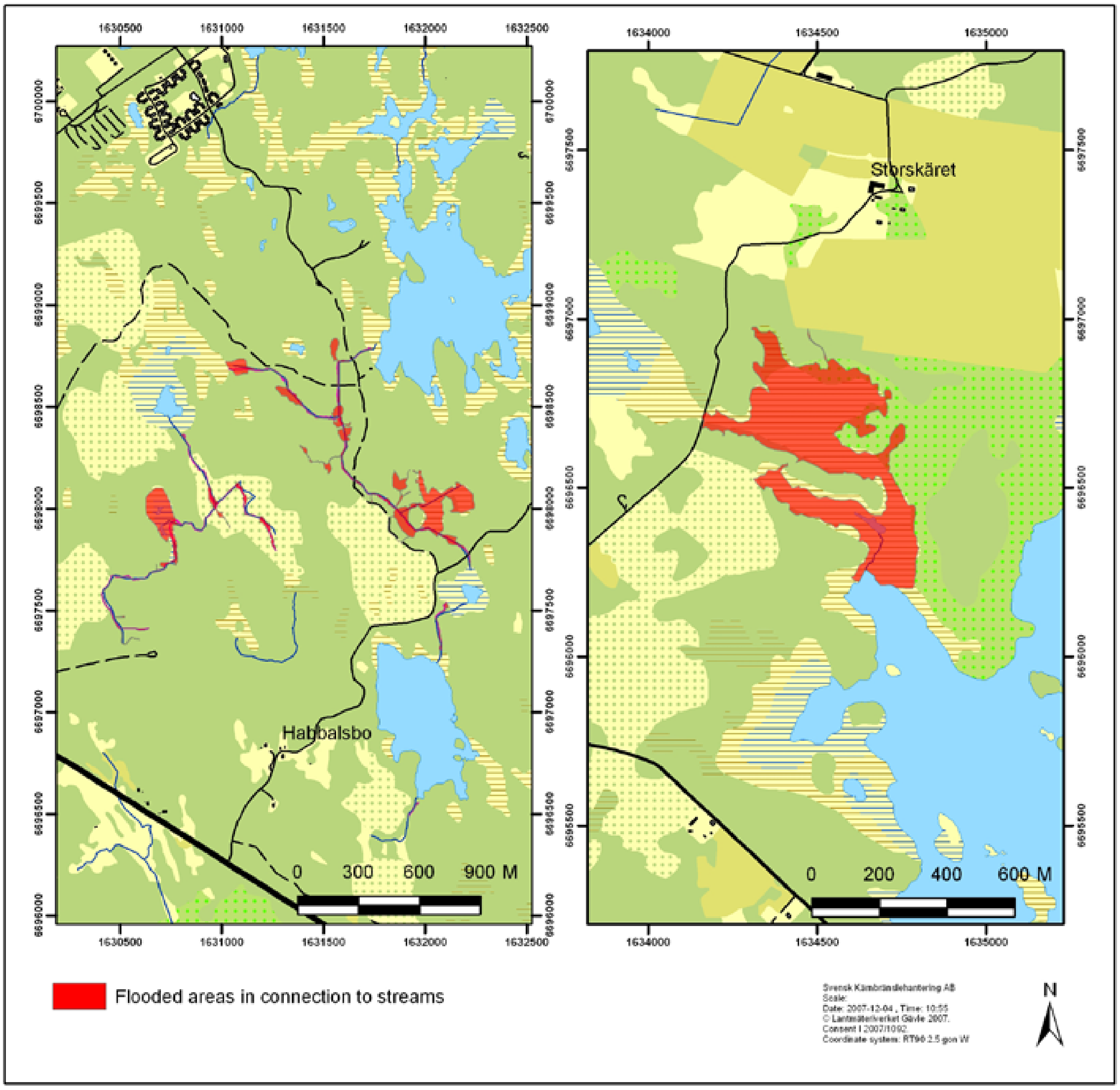

Figure 3-11. *Periodically flooded areas in catchment 2 (left) and 8 (right) in the Forsmark area.*

3.4 Climate

3.4.1 Air temperature

The air temperature at Forsmark has been measured continuously during the site investigations /Johansson and Öhman 2008/. The investigation period (3 years) is short and the measurements are therefore compared with data from two other climate stations in northern Uppland: Örskär and Film. The first is located on the island of Gräsö north of the Forsmark area, while Film is an inland location. The winters are slightly milder on the coast than inland. The mean annual temperatures at Örskär and Film were 5.5 and 5.0°C, respectively, for the period 1961–1990 (Figure 3-12). The temperatures in the Forsmark area are somewhere in between the temperatures at these two locations. During 2004–2006, the mean annual temperatures were higher than the long-term means: 7.1, 6.9 and 6.1°C at Örskär, Forsmark and Film, respectively (Figure 3-13).

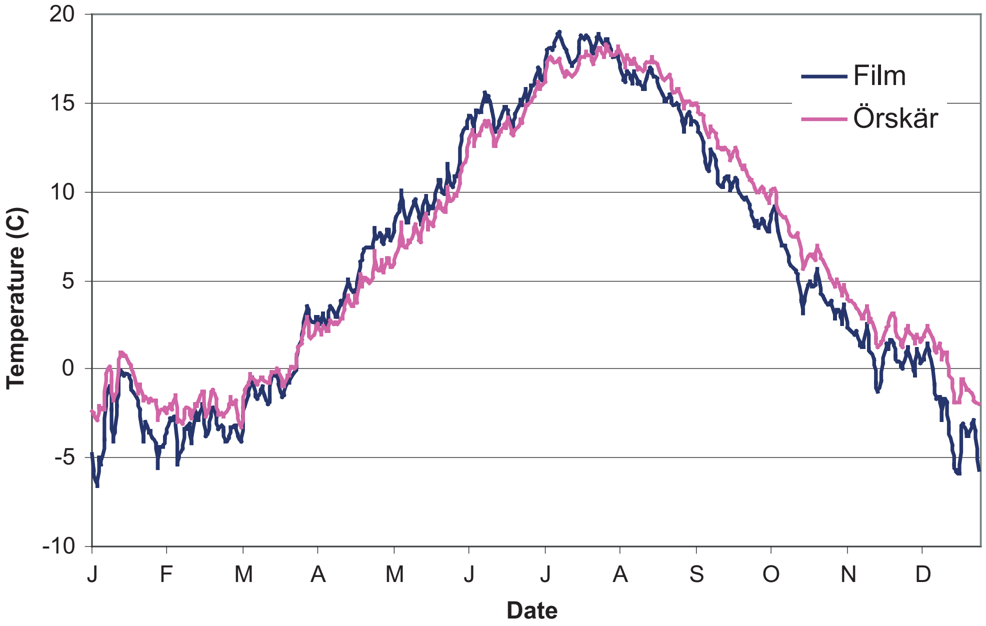

Figure 3-12. *Long-term (1994–2006) daily mean temperature over the year in Film and Örskär. From /Johansson and Öhman 2008/.*

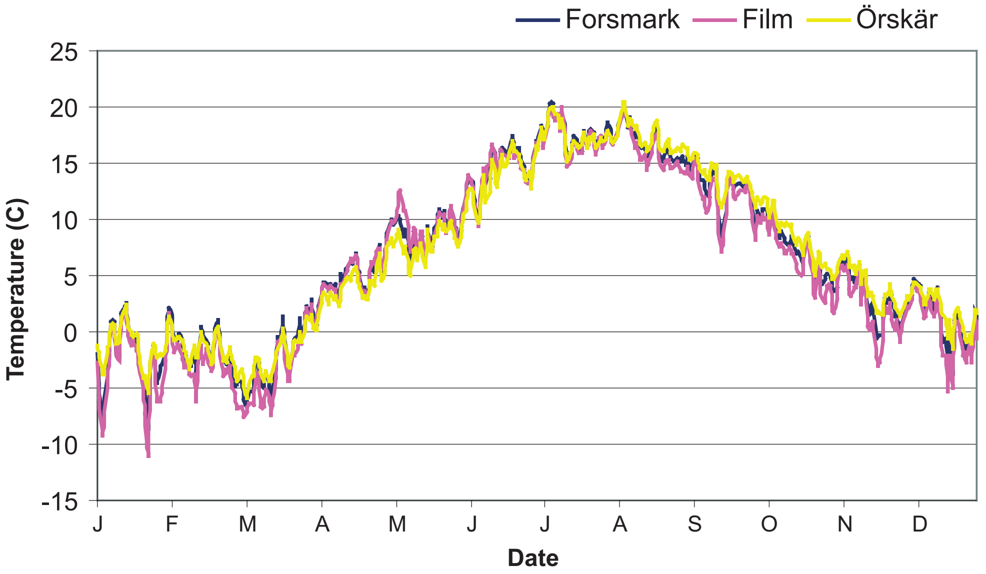

Figure 3-13. *Daily mean temperature over the year in Forsmark, Film and Örskär (mean for the period 2004–2006). From /Johansson and Öhman 2008/.*

3.4.2 Precipitation

The regional mean annual precipitation in the Forsmark area has been estimated to be 559 mm for the period 1961–1990 /Johansson 2008/. Circa 25–30% of the annual precipitation falls in the form of snow. The highest monthly precipitation for the period June 2003–May 2007 was in August, followed by October (Figure 3-14). The lowest precipitation during the same period occurred in April.

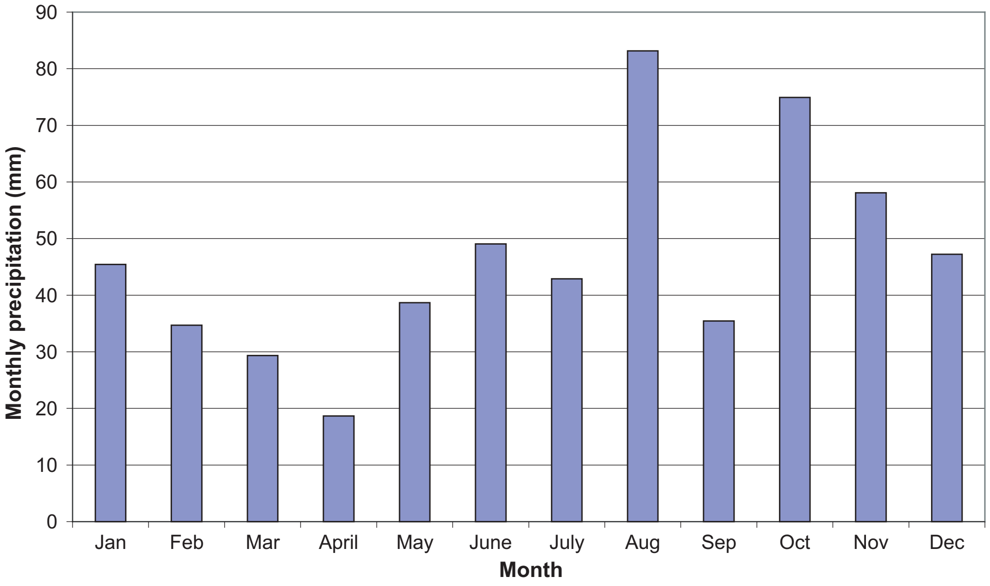

Figure 3-14. *Monthly precipitation in Forsmark, June 2003–May 2007. Mean from the two stations Högmasten and Storskär. From /Johansson 2008/.*

3.4.3 Snow cover

Snow cover has been measured weekly during five seasons, 2002/03–2006/07, at two sites: in forest land and in open land /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/. During this period there was an average snow cover of 105 days per season on forest land and 80 days on open land (Table 3-6). In general there was a snow cover from the end of November/beginning of December until the end of March/beginning of April. However, during some of the seasons there were periods when the snow cover disappeared. The maximum recorded snow depth was 48 cm on forest land and 25 cm on open land, and the maximum snow water content was 144 and 64 mm, respectively (Table 3-6).

Table 3-6. Summary of snow measurements at Forsmark 2002/03–2006/07, data from /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.

Year	No. of days with snow cover	Maximum snow depth (cm)	Maximum snow water content (mm)
Open land (AFM000071)			
2002/03	85	20	–
2003/04	75	19	37
2004/05	85	21	53
2005/06	120	25	64
2006/07	40	17	30
Average 2002/03–2006/07	81	25	64
Forest land (AFM000072 and AFM001172)			
2002/03	125	–	–
2003/04	105	31	65
2004/05	110	25	61
2005/06	133	38	101
2006/07	65	24	34
Average 2002/03–2006/07	108	38	101

3.4.4 Ice cover

The ice cover recordings were made at Eckarfjärden, which was considered to be representative for the lakes of the area /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/. Eckarfjärden was usually covered with ice from the middle of November/December until the beginning of April. On average Eckarfjärden was covered with ice 128 days per season. The ice cover data are summarized in Table 3-7.

3.4.5 Global radiation

Global radiation at Forsmark has been measured continuously during the site investigations. The investigation period is short and the measurements are therefore compared with data from another climate station in northern Uppland, Örskär, which is located on the island Gräsö north of the Forsmark area. At Forsmark, the mean global radiation was 949 kWh m^{-2} during 2004–2006. Based on the observations at Örskär, the mean annual global radiation was calculated to 930 kWh m^{-2} for the period 1961–1990 /Johansson et al. 2008/. Global radiation was highest in June, followed by July (Figure 3-15).

Table 3-7. Periods of ice cover on Lake Eckarfjärden at Forsmark 2002/03–2006/07, from /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.

Year	Date for ice freeze-up	Date for ice break-up	Period of ice cover (days)
2002/03	2002-11-12	2003-04-02	141
2003/04	2003-12-12	2004-04-06	117
2004/05	2004-11-18	2005-04-09	143
2005/06	2005-11-21 2005-12-12	2005-12-01 2006-04-24	143
2006/07	2006-12-18	2007-03-26	98
Average 2002/03–2006/07			128

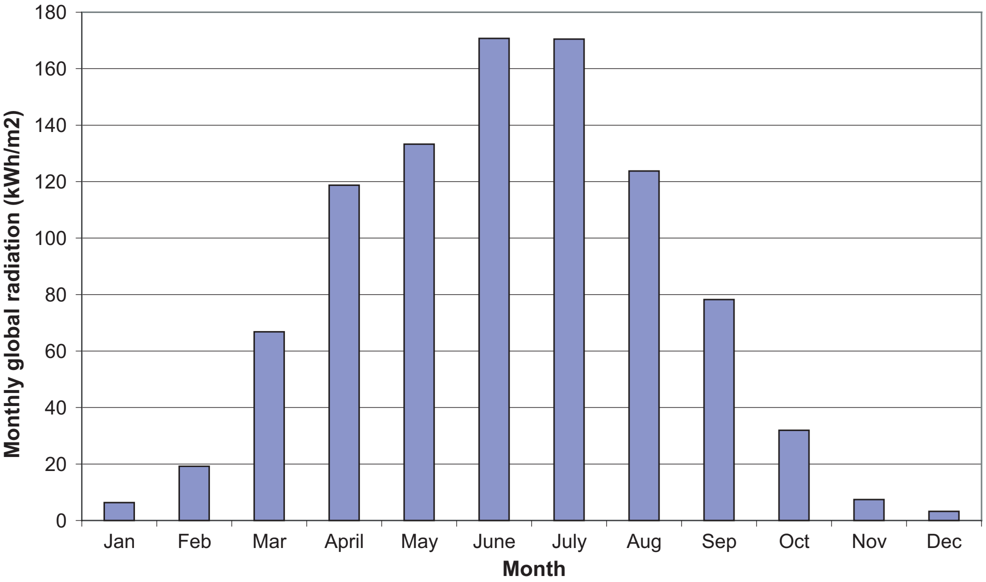

Figure 3-15. Global radiation (monthly mean 2004–2006) at Högmasten in Forsmark (kWh m^{-2}). Data from /Johansson and Öhman 2008/.

3.5 Lake bathymetry

All lake basins in Forsmark are very shallow (maximum depths range between 0.4 and 2.2 m) and – with the exceptions of Bolundsfjärden, Eckarfjärden and Fiskarfjärden – the basins are also very small. The median lake of the area has a mean depth of 0.7 m and a maximum depth of 1.0 m. The retention times of the lakes in Forsmark range from a few days to almost a year. In Table 3-8 some morphometric parameters are presented for the lakes in the Forsmark area. Bathymetric maps for four of the lakes in the Forsmark area is shown in Figure 3-16. These are chosen as examples, and maps for all investigated lakes in the area are presented in /Brunberg et al. 2004a/.

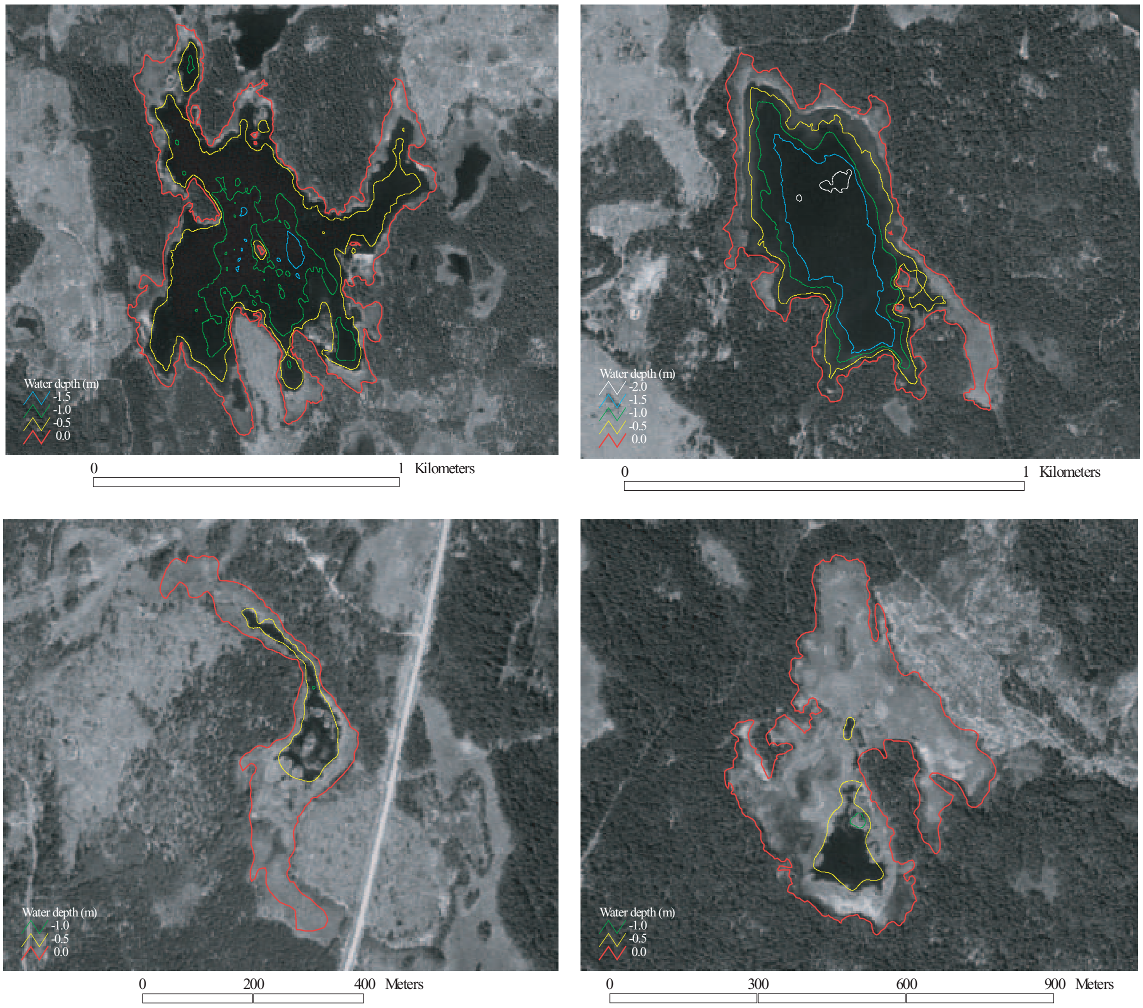

Figure 3-16. *Bathymetric maps for four lakes in the Forsmark area; Bolundsfjärden (upper left), Eckarfjärden (upper right), Labboträsket (lower left) and Gällsboträsket (lower right). From /Brunberg et al. 2004a/.*

Table 3-8. Morphometry parameters for the lakes in the Forsmark area (data from [1]/Brunberg et al. 2004a/, [2]/Brydsten and Strömgren, 2005/ and [3]calculated from SKB's GIS database).

ID Code	Catchment number	Name	Threshold elevation[2] [m.a.s.l. RHB70]	Area[1] [km^2]	Max. depth[1] [m]	Mean depth (Littoral I included)[1] [m]	Mean depth (Littoral I excluded)[3] [m]	Volume (Littoral I included)[1] [Mm^3]	Volume (Littoral I excluded)[3] [Mm^3]	Shore length[1] [m]	Mean discharge[1] [m^3/s]	Retention[1] time [Days]	Fetch[1, A] [m]	Width[1, B] [m]
AFM000073	**1:1–4**	**Gunnarsbo-Lillfj. (south)**	**1.92**	**0.03**	**2.2**	**0.7**	**1.0**	**0.023**	**0.018**	**1,034**	**0.036**	**7**	**198**	**171**
AFM000096	01:02	Gunnarsbo-Lillfj. (north)	1.07	0.02	0.9	0.3	0.5	0.007	0,003	1,041	0.001	110	122	61
AFM000048	1:3–4	Labboträsket	2.65	0.06	1.1	0.3	0.8	0.016	0.002	2,185	0.028	7	62	18
AFM000095	01:04	Gunnarsboträsket	5.68	0.07	1.3	0.5	0.9	0.034	0.017	1,848	0.019	21	204	188
AFM000074	**2:1–11**	**Norra Bassängen**	**0.19**	**0.08**	**0.9**	**0.3**	**0.5**	**0.024**	**0.016**	**2,553**	**0.059**	**5**	**293**	**177**
AFM000092	02:02	Lake 2:2	1.77	0.01	0.6	0.3	0.4	0.003	0.002	518	0.001	66	129	55
AFM000050	2:3–10	Bolundsfjärden	0.28	0.61	1.8	0.6	0.8	0.374	0.324	9,140	0.056	77	1,059	878
AFM000087	2:4–5	Graven	0.44	0.05	0.4	0.1	0.25	0.006	0.002	1,190	0.003	25	153	75
AFM000088	02:05	Fräkengropen	1.34	0.02	0.8	0.2	0.6	0.004	0.002	909	0.001	44	88	44
AFM000089	02:06	Vambörsfjärden	1.02	0.05	1	0.4	0.7	0.021	0.014	1,193	0.003	70	250	132
AFM000093	02:07	Kungsträsket	2.31	0.01	0.5	0.2	0.3	0.002	0.001	466	0.001	20	85	50
AFM000094	02:08	Gällsboträsket	1.47	0.19	1.5	0.2	0.7	0.032	0.006	4,059	0.02	18	138	90
AFM000090	2:9–10	Stocksjön	2.70	0.04	0.8	0.2	0.7	0.008	0.004	890	0.013	9	108	82
AFM000010	02:10	Eckarfjärden	5.15	0.28	2.1	0.9	1.2	0.257	0.226	4,405	0.009	328	755	393
AFM000091	02:11	Puttan	0.48	0.08	1.3	0.4	0.8	0.033	0,021	2,390	0.061	6	255	168
AFM000086	**03:01**	**Tallsundet**	**–0.23**	**0.08**	**0.8**	**0.2**	**0.6**	**0.018**	**0.006**	**2,624**	**0.002**	**141**	**154**	**78**
AFM000085	4:1–2	Lake 4:1	–0.34	0.04	1.5	0.4	0.8	0.013	0.006	1,520	0.005	32	188	66
AFM000049	04:02	Lillfjärden	–0.35	0.16	0.9	0.3	0.6	0.047	0.025	2,947	0.004	125	367	279
AFM000052	**05:01**	**Bredviken**	**–0.26**	**0.1**	**1.7**	**0.7**	**1.1**	**0.072**	**0.057**	**2,049**	**0.004**	**191**	**518**	**67**
AFM000084	**06:01**	**Simpviken**	**–0.32**	**0.01**	**1.8**	**0.5**	**0.8**	**0.005**	**0.002**	**517**	**0**	**232**	**61**	**36**
AFM000080	**7:1–4**	**Lake 7:1**	**–0.47**	**0.16**	**1.1**	**0.3**	**0.5**	**0.053**	**0.037**	**4,818**	**0.006**	**97**	**489**	**192**
AFM000081	07:02	Märrbadet	–0.29	0.02	1	0.4	0.8	0.009	0.003	768	0.002	42	117	71
AFM000082	07:03	Lake 7:3	0.17	0.01	0.7	0.3	0.5	0.002	0.001	421	0.001	14	66	35
AFM000083	07:04	Lake 7:4	0.36	0.01	0.8	0.2	0.6	0.002	0.001	434	0.001	49	47	29
AFM000051	08:01	Fiskarfjärden	0.28	0.75	1.9	0.4	0.5	0.274	0.190	7,584	0.02	155	1,370	555
Mean			**1.08**	**0.12**	**1.2**	**0.4**	**0.7**	**0.053**	**0.039**	**2,300**	**0.014**	**76**	**291**	**160**
Median			**0.44**	**0.05**	**1.0**	**0.3**	**0.7**	**0.018**	**0.006**	**1,520**	**0.004**	**44**	**154**	**78**
Min			–0.47	0.01	0.4	0.1	0.3	0.002	0.001	421	0.000	5	47	18
Max			5.68	0.75	2.2	0.9	1.2	0.374	0.324	9,140	0.061	328	1,370	878

[A] Fetch maximum length (m), the longest straight line over the water.

[B] Width maximum width (m), the longest straight line perpendicular to the length line.

3.6 Lake sediments

The sediments of the majority of the lakes and small ponds in the area have been investigated in different studies /Bergström 2001, Hedenström and Risberg 2003, Hedenström 2003, 2004, Borgiel 2004a, Strömgren and Brunberg 2006, Hannu and Karlsson 2006, Nordén 2007, Roos et al. 2007, Engdahl et al. 2008/. These studies include stratigraphy, carbon content and chemical composition of the sediment, as well as depth of the redox zone and sediment accumulation rate. Overview of chemical sediment data and sampling locations are found in /Tröjbom and Nordén 2010/.

3.6.1 Stratigraphy

A lake in the Forsmark area is a temporary stage of a basin in the transition between a marine environment into a terrestrial area (further described in Chapter 8). Accumulation of sediment starts already during the marine phase, so the deeper sediments present in a lake are often older than the lake itself. The distribution of sediments in lakes is relatively uniform and a general stratigraphy for the Forsmark area has been presented (Table 3-9, from /Hedenström 2004/). Gyttja is deposited during the lake stage, whereas clay gyttja and clay are deposited in the Baltic and during the lagoon stage.

The different layers including the upper biological layer of microphytobenthos are described below:

1. Microphytobenthos: the uppermost layer containing benthic algae and bacteria, often seen as a distinct green layer in the sediment cores from the lakes. Sometimes this layer is whitish due to calcite precipitates

2 and 3. Gyttja: organic rich sediment layer deposited during the lake stage of the basin. Limnologists often divide this sediment layer into "gyttja" and "dy" according to the origin of the organic matter (produced by the surrounding terrestrial environment or produced within the lake basin). In Forsmark, a typical feature is calcareous gyttja, formed as a result of the high lime content in the surrounding deposits.

4. Clay gyttja: organic rich sediment layer deposited during the marine phase of the basin. This layer contains more clay than the gyttja layer and also has a lower content of water and organic matter.

5. Sand and gravel: coarse-grained minerogenic deposits with high hydraulic conductivity.

6 and 7. Clay: dense and often thin layer with low content of water and organic carbon. Deposited during the melting of the glacial ice.

8. Till: coarse-grained inorganic layer, located on top of bedrock.

Since the upper layers of the sediment: gyttja and clay gyttja contain most of the organic matter in the regolith we have chosen to concentrate on these regolith layers in this report. In some sections, such as Chapter 7, the clay layer is also considered.

Table 3-9. Generalized stratigraphy of the sediment in the Forsmark area and the environment in the water column at the formation of the units (from /Hedenström 2004/).

Layer	Environment during sedimentation	Lithology
1	Freshwater lake	Microphytobenthos
2	Freshwater lake	Calcareous gyttja
3	Freshwater lake and coastal lagoons	Algal gyttja
4	Postglacial Baltic basin	Clay gyttja
5	Shallow coast	Sand and gravel
6	Postglacial Baltic basin	Postglacial clay
7	Late glacial Baltic basin	Glacial clay
8	Weichselian glaciation	Till

A compilation of sediment characteristics in the lakes in the Forsmark area is shown in Table 3-10. Stratigraphical data for all lakes presented in the table are based on data from /Hedenström 2004/. The stratum thicknesses shown are the average thickness for each sediment layer in each lake. This data do not include the upper part of the gyttja layer or the microphytobenthos layer since these are not captured with the sampling technique used in that study. The depth of the missing layer should not be more than 0.5 m (Hedenström, personal communication). The stratum thickness varies between lakes mirroring different lake ages and also different sedimentation conditions during the marine lagoon stadium of the lakes (see Chapter 8). The spatial distribution of different Quaternary deposits (at 0.5 m sediment depth) in two of the lakes in the Forsmark area (Bolundsfjärden and Eckarfjärden) is shown in Figure 3-17.

3.6.2 Redox zone

The upper part of the sediment layer in the Forsmark lakes is very loose and the boundary between the water phase and the sediment is often hard to distinguish; it consists of a continuous transition towards more compacted sediment with gradually less water content. As in most lake sediments the carbon content decreases downwards in the sediment profile. The reducing conditions in the deeper part of the sediment restrict the habitat for biota, resulting in a bioactive upper sediment layer. A somewhat different characteristic compared to most other lakes is that the very upper part of the sediment in most Forsmark lakes contains a very thick layer of microphytobenthos, i.e. benthic algae and bacteria. In the Forsmark lakes this layer can be several centimetres and in some cases even decimetres thick whereas in most lakes this layer is constrained to millimeters in thickness. This combined with shallow water depth result in sediments easily disturbed by wind, leading to a mixing of the upper sediment. Therefore the thickness of the redox zone is relatively thick in lakes with microbial mat compared to lakes lacking a microbial mat. In lakes lacking a microbial mat, the redox zone is estimated from literature to be 1 cm /Wetzel 2001/. In lakes with microbial mat, redox zone is estimated to equal the depth of the microbial mat. The thicknesses of the layer vary within the same lake, between lakes and over the year (see Section 3.10 for more details). A mean depth of the redox zone was calculated from site data in 9 lakes to be 5.3 cm (149 subsamples including both summer and winter values).

The zone where the redox potential changes from positive (aerobic conditions) to negative (anaerobic environment) is often present within this layer of microphytobenthos. This zone can sometimes be seen in cores as a thin red layer which consists of purple sulphur bacteria. These bacteria migrate vertically and follow the border between aerobic and anaerobic environments. This zone is of importance both chemically and biologically. Due to the change in redox potential some elements change chemical state leading to a change in mobility (e.g. iron and manganese).

3.6.3 Carbon content

The carbon content has been estimated for the three layers (gyttja, clay gyttja and clay) in three lakes: Eckarfjärden /Hedenström and Risberg 2003/, Fiskarfjärden and Puttan /Hedenström 2004/ (Table 3-10). In addition, carbon content was analyzed in sediments from Eckarfjärden and Stocksjön by /Hannu and Karlsson 2006/ and /Strömgren and Brunberg 2006/. The water content has been estimated for the gyttja layer in Eckarfjärden, Bolundsfjärden and Puttan /Nordén 2007/. In that study no separation of gyttja and clay gyttja was performed. An examination of the values from one of the cores (PFM007372) shows that the water content is almost constant down to the clay layer and we therefore assume that no clay gyttja was present in this sediment core. The same is true also for the other lakes, which means that no site-specific data on water content from the clay gyttja layer in lakes are available. Data for this sediment type are, however, available from two marine bays in the area Kallrigafjärden and Tixelfjärden /Sternbeck et al. 2006/, and an average value from these two bays is presented in Table 3-10. A comparison with data on water content in clay gyttja from Lake Frisksjön in the Laxemar-Simpevarp area shows good agreement (14% dry weight in Frisksjön, 15% in Tixelfjärden and 16% in Kallrigafjärden). Water content data from the clay layer is available from Eckarfjärden /Nordén 2007/.

The amount of carbon per area (g C m^{-2}) has been calculated using the site-specific water and carbon contents and an assumption of a density for mineral particles of 2,650 kg m^{-3}. As site specific data for (most) parameters are available only for Eckarfjärden, the value is only shown for this lake in the table. The total carbon content in the lake sediment was calculated using the lake area (excluding reed belts).

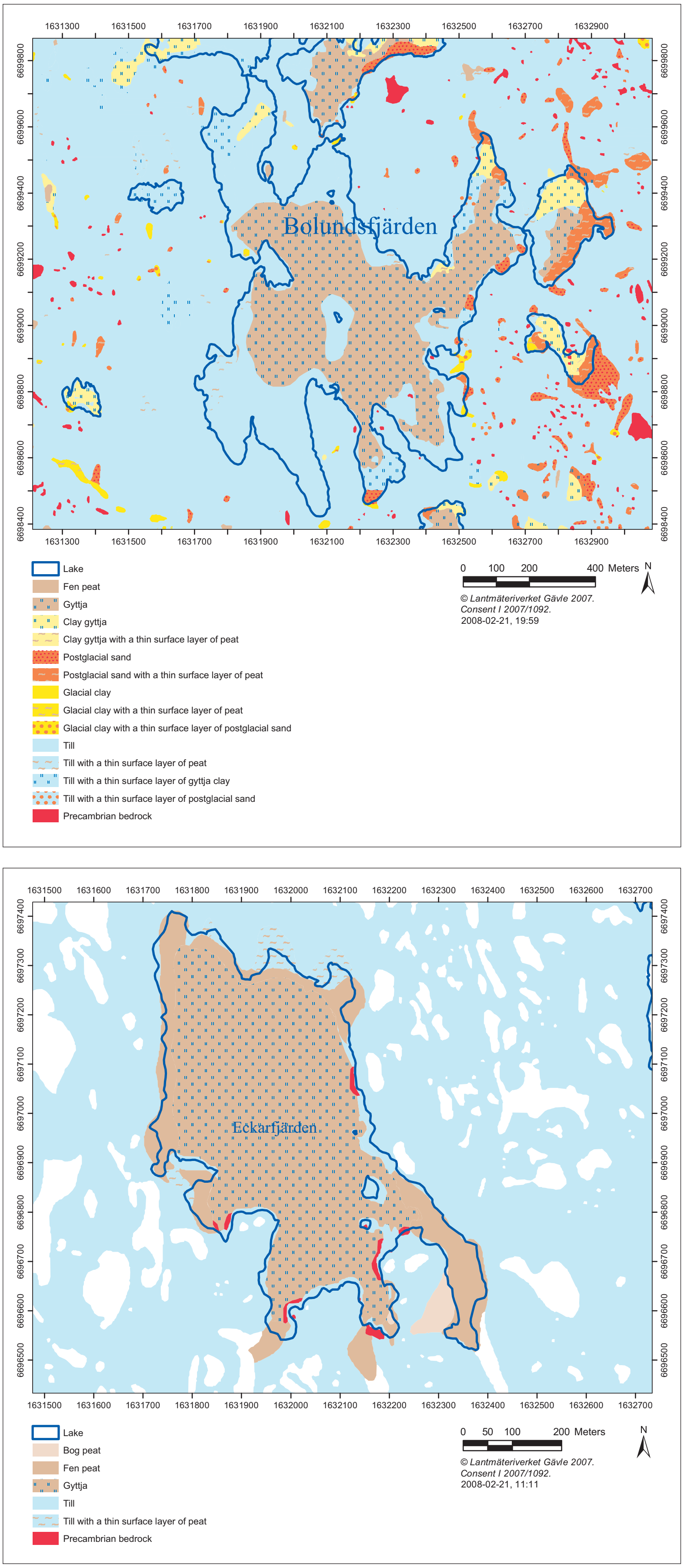

Figure 3-17. *Spatial distribution of Quaternary deposits at 0.5 m sediment depth in the lakes Bolundsfjärden (above) and Eckarfjärden (below).*

Table 3-10. Characteristics of lake sediments in the Forsmark area. Only data measured in the area are presented with one exception. Data from /Hedenström and Risberg 2003, Hedenström 2004, Nordén 2007/.

	Stratum thickness (m)	Carbon content (g C/g dw)	Water content (–)	Carbon content (g C/m^3)	Total carbon content (g C)	Acc. rate (m/y)	Acc. rate (g C/m^2 y)	Acc. rate (g C/y)
Eckarfjärden	1.75			3.8E+04	4.6E+10			
Gyttja	0.96	0.27	0.93	1.9E+04	3.5E+09	0.001	19.4	3.7E+06
Clay gyttja	0.11	0.08	0.845[1)]	1.2E+04	2.5E+08			
Clay	0.68	0.01	0.53	6.6E+03	8.5E+08			
Fiskarfjärden	3.52							
Gyttja	1.00	0.17						
Clay gyttja	0.61	0.05						
Clay	1.91	0.01						
Stocksjön	0.49							
Gyttja	0.4							
Clay gyttja	0.03							
Clay	0.06							
Gällsboträsket	1.41							
Gyttja	0.34							
Clay gyttja	0.37							
Clay	0.7							
Bolundsfjärden	0.6							
Gyttja	0.48		0.90					
Clay gyttja	0.07							
Clay	0.05							
Puttan	0.82							
Gyttja	0.8	0.20	0.89					
Clay gyttja	0.02	0.09						
Clay	0							
Norra Bassängen	0.16							
Gyttja	0.15							
Clay gyttja	0.01							
Clay	0							

[1)] mean value from the marine bays Kallrigafjärden and Tixelfjärden /Sternbeck et al. 2006/.

3.6.4 Sedimentation, resuspension and long term accumulation

Particles that sedimentate are commonly resuspended many times before permanently accumulated. In a review by /Weyhenmeyer 1998/ it was shown that about 70% of settling particles in lakes was made up by resuspended particles and the upper millimeters of the sediment can be assumed to be subjected to resuspension. The bottom of lakes can be divided into accumulation bottoms, transport bottoms and erosion bottoms depending on the accumulation pattern of sediments. Accumulation bottoms are located at the deepest parts of the lakes where sediment accumulates for long periods of times. In transport bottoms, sediment may accumulate but only for shorter periods of times and at storm events the sediments are resuspended and further transported towards accumulation bottoms. Erosion bottoms are located where wave action prevent accumulation of sediments and there hard substrates are the only bottom substrate. In the shallow lakes of Forsmark, all lakes are shallow and the entire lake bottoms can be considered to be accumulation bottoms, i.e. there are no deep locations towards which sediment are concentrated but the sediments can be assumed to be evenly distributed onto the lake floor.

In Forsmark, long-term accumulation of matter has been estimated in sediment cores from Eckarfjärden /Hedenström and Risberg 2003/. The estimated average accumulation rate during the last 1,200 years was 1 mm year^{-1}. The accumulation rate of carbon within the lake sediment has been estimated using this accumulation rate, combined with the average carbon content of the gyttja layer in Eckarfjärden (27% of dry weight) /Hedenström and Risberg 2003/, the average water content of that sediment layer (93%) /Nordén 2007/, and assuming that the density of minerals is 2,650 kg m^{-3} and that the amount of organic matter can be calculated by multiplying the carbon content by 1.7 /Hedenström et al. 2008/. As mentioned before, the gyttja was deposited during the lake stage, whereas the clay gyttja and clay were deposited in the Baltic and during the lagoon stage. Therefore, the estimate of the carbon accumulation rate of the lake stage has only been based on accumulation of the gyttja layer. The resulting accumulation rate of 19 g C m^{-2} year^{-1} is of the same order of magnitude as carbon accumulation rates estimated in one of the sea bays outside the Forsmark area (14 g C m^{-2} year^{-1} in Kallrigafjärden) /Sternbeck et al. 2006/, but is lower than the accumulation rates estimated in Lake Frisksjön in the Laxemar-Simpevarp area (74 g C m^{-2} year^{-1}) /Sternbeck et al. 2006/.

3.6.5 Chemical composition

Chemical characterization of sediments from Forsmark lakes has been performed by /Hannu and Karlsson 2006, Strömgren and Brunberg 2006, Roos et al. 2007, Engdahl et al. 2008/. In /Hannu and Karlsson 2006/, one sediment sequence from Eckarfjärden was analyzed for 64 elements, while /Strömgren and Brunberg 2006/ contains data for 54 elements in a sediment sequence from the smaller lake Stocksjön. /Roos et al. 2007/ analysed sediment for several artificial and natural occurring radioisotopes. /Engdahl et al. 2008/ analysed 75 elements in order to deremine distribution coefficients between suspended material and water phase. In addition, data on contents of carbon, nitrogen, sulphur and $CaCO_3$ in some Forsmark lakes are presented in /Hedenström 2004/. Similar for all sediment analysis is that hydrogen and oxygen are not included in the analyses. Hydrogen and oxygen are abundant in organic compounds and oxygen in oxidized form of elements. Therefore analysed elements only contributes around 50% of dry weight of the sediment. The chemical composition of sediments are thoroughly discussed in /Tröjbom and Nordén 2010/ whereas a short description is given below.

The relative amounts of different elements differ between sediment layers (Figure 3-18). However, the ten most common elements are present in virtually the same amounts in all layers. Carbon is the most common element in the gyttja layer (4,700 tonnes, 63% of investigated elements), followed by silicon (1,100 tonnes) and calcium (850 tonnes). The carbon content decreases downwards in the sediments: the share is 24% of investigated elements in the clay gyttja layer and only 2% of investigated elements in the clay layer. The most common element in the clay gyttja and clay layers is silicon, which constitutes 43 and 48% of the weight of investigated elements in those layers, respectively. Aluminium is an important component, as is iron. In the gyttja layer, on the other hand, aluminium and iron contribute less to the total weight of the elements (Figure 3-18).

Compared with the gyttja layer in Frisksjön in the Laxemar area (Section 4.6) the sediments in the Forsmark lakes have a higher carbon content and lower content of silicon and aluminium. The share of calcium is much higher in the Forsmark gyttja, 11% compared with less than 2% in Frisksjön. The sediment from Frisksjön more closely resembles the clay gyttja layer of the Forsmark lakes. Both are dominated by silicon followed by carbon, aluminium and iron. The carbon content is somewhat higher in Frisksjön while the aluminium content is somewhat lower. The chemical composition of sediments as well as other parts of the limnic ecosystems in the Forsmark area is further discussed in Chapter 7.

Large amounts of gas have been found in the sediments of lakes and shallow coastal bays during the site investigations /Borgiel 2004a/. No estimations have been made of the quantities, but the chemical composition of this gas was examined in one gas sample from Puttan /Karlsson and Nilsson 2007/. The sample contained 56% (by volume) of methane. The origin of this gas is most probably from the decomposition of organic matter within the sediments.

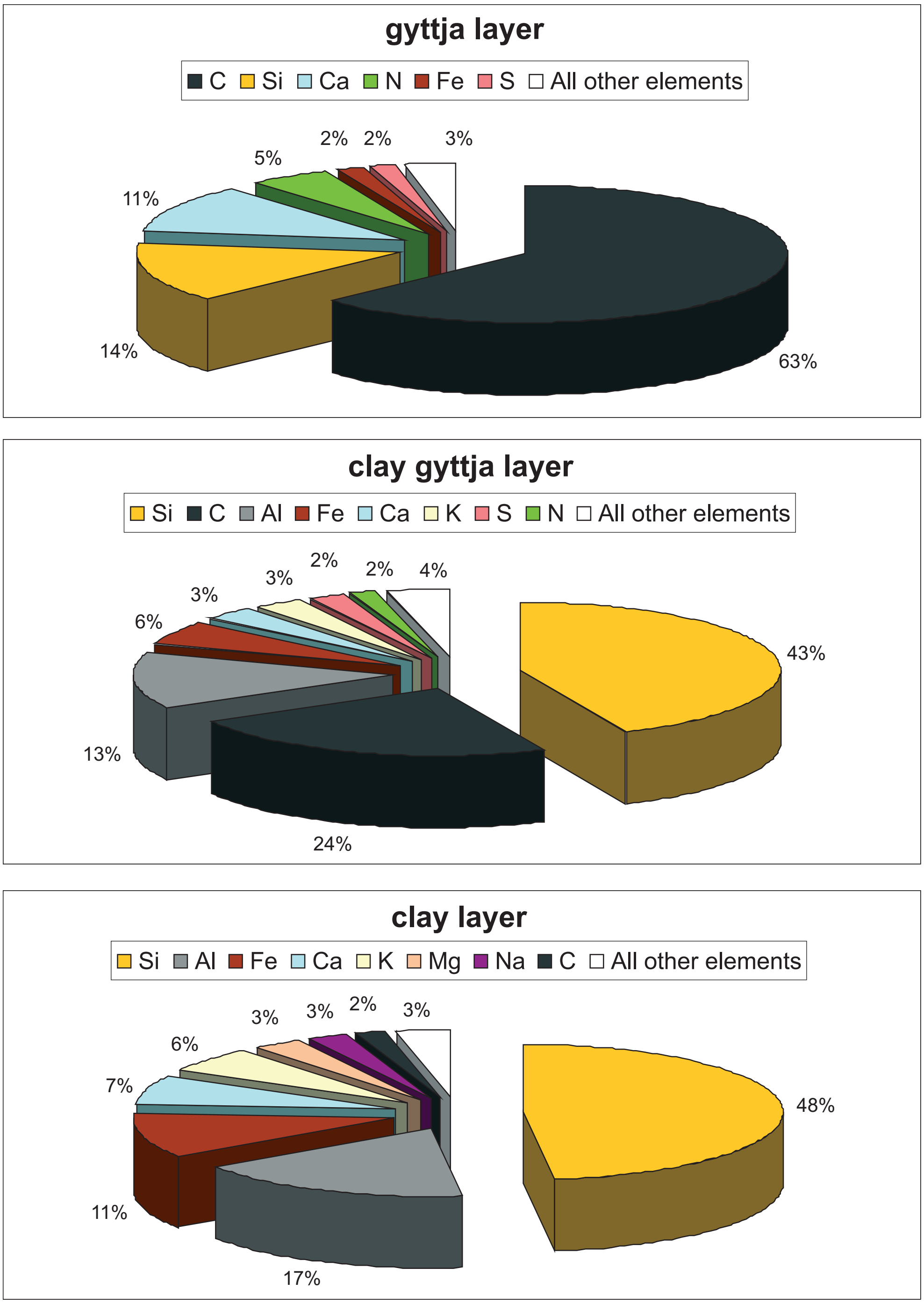

Figure 3-18. *Relative amounts of different elements (%) in the three upper sediment layers of Eckarfjärden. Note that the figure shows percentage of dry weight of analyzed elements and that hydrogen and oxygen are not analyzed. In addition to water hydrogen and oxygen are included in dry weight when elements occurs in oxidized form and also in organic compounds. Therefore the percentage in this figure does not show percentage of dry weight but percentage of analysed elements.*

3.7 Habitat distribution in the lakes

Lakes may be divided into five different habitats: Littoral I, II, and III, Pelagic and Profundal /Brunberg et al. 2004a, b/. The areal distribution of each habitat in the Forsmark lakes has been investigated by /Brunberg et al. 2004a/ are defined as follows:

- Littoral I, with emergent and free-floating macrophytes, is developed in shallow wind-sheltered areas with soft substrate. The upper limit of this zone, which distinguishes it from the surrounding terrestrial area, was set by the high water level. Wetland areas in direct contact with the lake are also included, as are "artificial" wetland areas in some lakes where the water level has been lowered due to anthropogenic activities. Hence, in addition to aquatic plants, wetland plants and even bushes and small trees may occasionally be included in this zone.
- Littoral II has a hard substrate and develops in wind-exposed areas. The photosynthetic organisms in this area consist of species that are able to attach to the hard substrate, e.g. periphytic algae.
- Littoral III is found in the deeper areas of the lake where there is enough light to sustain photosynthetic primary production by submerged vegetation.
- The profundal habitat is the benthic habitat where light penetration is less than needed to sustain a permanent vegetation of primary producers. The profundal organisms are dependent on carbon supplies imported from other habitats of the lake or from allochthonous sources.
- The pelagic habitat includes the open water and a pelagic food web with planktonic organisms. Depending on the light availability, the plankton is dominated either by photosynthetic production (by autotrophic phytoplankton) or, if the water is strongly coloured or turbid, by heterotrophic carbon processing (e.g. by heterotrophic bacterioplankton and mixotrophic phytoplankton). The pelagic habitat covers the same area as the sum of Littoral II, Littoral III and the profundal habitat.

Since the lakes in the Forsmark area are small and shallow, only three habitats were found, Littoral I, Littoral III, and the pelagic habitat /Brunberg et al. 2004a/. Littoral I with emergent macrophytes was the dominant habitat in the lakes, on average comprising 69% of the lake area (range 34–96%). In general, Littoral I constitutes a larger share of total lake area in the smaller lakes than in the larger ones. The distribution of different habitats in the lakes is presented in Table 3-11. The habitat distributions in two of the larger lakes, Bolundsfjärden and Eckarfjärden, and in the small Labboträsket are illustrated in Figures 3-19a, b and c.

The borderline between a lake and surrounding terrestrial environment may be set differently depending on focus of a study. /Brunberg et al. 2004a, b/ used the highest high water level to delimit the lake (Littoral I) from terrestrial areas. Using this definition, wetland areas in direct contact with the lake are also included, as well as the "artificial" wetland areas in some lakes where the water level has been lowered due to anthropogenic activities. Hence, in addition to the aquatic plants, wetland plants and even bushes and small trees may occasionally be included in this zone, especially if the area is tufty. In the lake models presented in Chapter 5 and 7, we have chosen to treat all areas defined as Littoral I (reed belts and in Frisksjön also wetland plants, trees and bushes) by /Brunberg et al. 2004a, b/ as wetland areas. Thus, lake areas used in Chapter 5 and 7 are smaller than presented by Table 3-11.

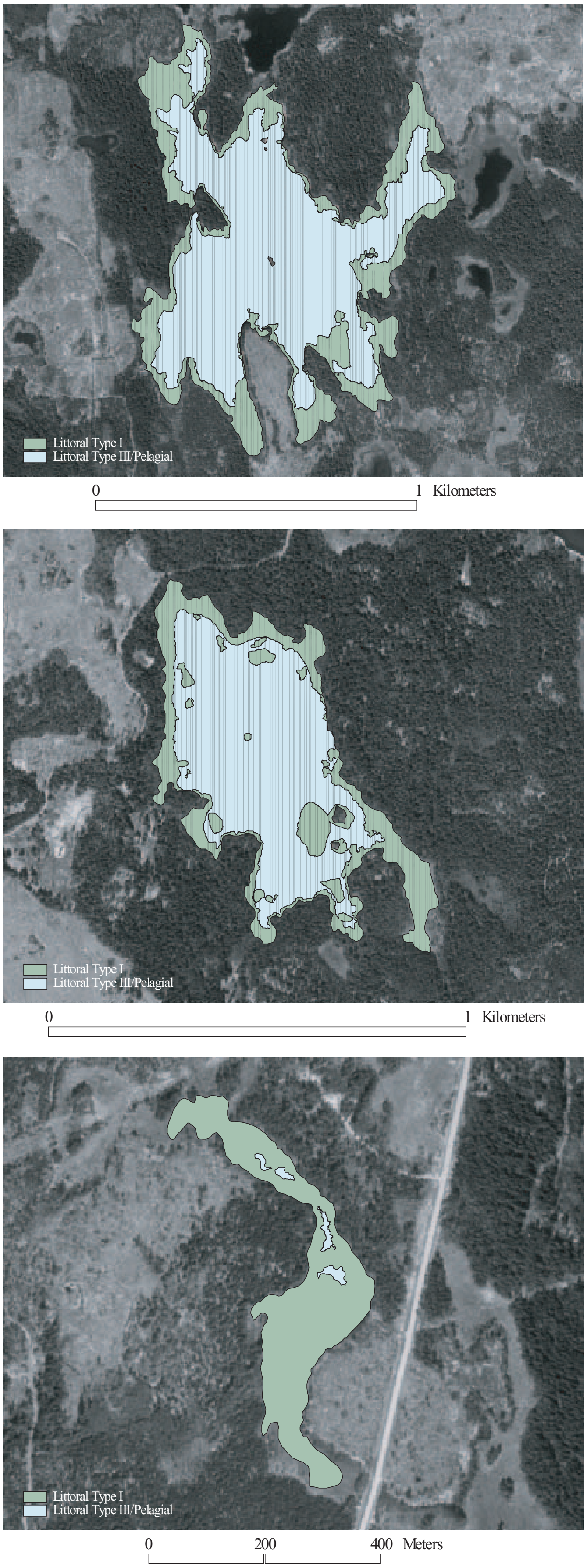

Figure 3-19. *Distribution of major habitats in a) Bolundsfjärden, b) Eckarfjärden and c) Labboträsket (from /Brunberg et al. 2004a/).*

Table 3-11. Distribution of habitats and total lake area for the lakes in Forsmark. The pelagic habitat covers the same area as Littoral III.

Catchment	Lake	Littoral I m²	% of total lake area	Littoral III m²	% of total lake area	Total lake area m²
Forsmark 1	Gunnarsbo-Lillfjärden S basin	15,177	46	17,930	54	33,107
	Gunnarsbo-Lillfjärden N basin	17,998	78	5,150	22	23,148
	Labboträsket	57,843	96	2,199	4	60,042
	Gunnarsboträsket	49,649	74	17,804	26	67,453
Forsmark 2	2:1 N. Bassängen	44,395	58	31,675	42	76,070
	Lake no 16	4,954	50	4,975	50	9,929
	2:3 Bolundsfjärden	206,719	34	404,593	66	611,312
	2:4 Graven	42,185	84	7,902	16	50,087
	2:5 Fräkengropen	16,913	87	2,510	13	19,423
	2:6 Vambörsfjärden	29,781	60	19,796	40	49,577
	2:7 Kungsträsket	4,755	62	2,978	39	7,733
	2:8 Gällsboträsket	178,344	95	8,704	5	187,048
	2:9 Stocksjön	31,012	85	5,468	15	36,480
	2:10 Eckarfjärden	95,318	34	188,532	66	283, 850
	2:11 Puttan	56,230	68	26,511	32	82,741
Forsmark 3	Tallsundet	68,944	87	10,470	13	79,414
Forsmark 4	Lake no 8	27,455	78	7,603	22	35,058
	Lillfjärden	118,167	73	43,102	27	161,269
Forsmark 5	Bredviken	44,369	45	53,295	55	97,664
Forsmark 6	Simpviken	7,045	77	2,074	23	9,119
Forsmark 7	Lake no 1	89,723	55	73,329	45	163,052
	Märrbadet	19,359	82	4,252	18	23,611
	Lake no 4	5,030	79	1,362	21	6,393
	Lake no 5	8,475	91	837	9	9,312
Forsmark 8	Fiskarfjärden	373,541	50	380,762	50	754,303
Average		**64,535**	**69**	**52,953**	**31**	**117,488**
Standard deviation		**82,792**	**19**	**109,423**	**19**	**184,033**
Median		**42,185**	**74**	**8,704**	**26**	**50,087**
Min.		**4,755**	**34**	**837**	**4**	**6,393**
Max.		**373,541**	**96**	**404,593**	**66**	**754,303**

3.8 Physical characteristics of streams

The streams in the catchments Forsmark 1, 2 and 8 were investigated in 2004 and 2005 /Carlsson et al. 2005b, Brydsten and Strömgren 2005/. Bottom substrate, morphometry (x, y and z coordinates), water velocity, bottom vegetation, shading from terrestrial vegetation and technical encroachments were recorded. Bottom substrate, morphometry and shading from terrestrial vegetation are described below. Water velocity is described in Section 3.3.1 and vegetation is described in Section 3.10.

Bottoms substrate and shading is important for settlement and production of primary producers in streams. The bottom substrate and shading from terrestrial vegetation, was investigated by walking along the streams and making observations every 10 m. The same stretches were investigated in the early summer (June) and during the drier late summer (August). For the morphometry investigation, the deepest part in the watercourse was determined every 20 metres. If the gradient was large, shorter distances were used. Every 100 m along the watercourses the cross-sections were measured: one measurement was made at the deepest part of the section, at two points on each shoreline, and at two points in the middle.

In a drainage network tributary streams may by different methods be ordered according to location in the network, of which and the Horton-Strahler method is one of the most widely used /Strahler 1957, Wetzel 2001/. I this method the smallest permanent streams are named stream order 1. When two first order streams are joined stream order 2 is formed. The order of streams is not altered by the addition of a stream with lower order but only when two tributaries of equal orders are joined, the stream order increase. In the model area of Forsmark, streams order 1, 2 and 3 are present. The total length of the stream stretches in the two catchments estimated from maps is c. 15 kilometres. Stream order 1 is the most abundant stream order covering 7.8 km (52% of the total stream length). Stream order 2 is the next most common stream order (6.1 km and 42% of the total stream length) and stream order 3 is the least common stream order (0.8 km and 5% of the total stream length (Figure 3-2). The stream orders were investigated approximately in proportion to their abundance in the two catchments; 62% of the total investigated length was of stream order 1, 32% of stream order 2 and 6% of stream order 3. Altogether, c. 7 kilometres of the streams were investigated in the field.

3.8.1 Bottom substrate

Fine organic matter dominates as the bottom substrate in stretches with stream order 1, whereas clay is more common and dominates in stretches with stream order 2 and 3 (Table 3-12).

3.8.2 Morphometry

Catchment 1

The morphometry of the stream is clearly defined all the way from the start of the investigated stretch upstream Labboträsket down to the lake, except for a section at the outlet from Gunnarsboträsket and a section approximately 500 m from the outlet where the water overflows the banks of the streams. The gradient is very low at first, but about 300 m downstream of Labboträsket the upper part of the stream has a well-defined geometry. At some locations the bank is several metres high. Further downstream the stream flows into a swampy area where a distinct channel is hardly distinguishable. The slope is mostly very gentle except for the last 200 m where it is steeper. The total gradient in this catchment is about 4.5 m height in 2.5 km length.

Catchment 2

In the section from Eckarfjärden to Stocksjön the morphometry of the stream is clearly defined. The gradient is low in the beginning and increases after c. 250 m downstream Eckarfjärden. The gradient is about 2 m in c. 300 m. The stream is clearly defined also in the section between Stocksjön and Bolundsfjärden. In some parts, however, the water overflows the banks and the channel is difficult to distinguish. The stream has its largest gradient in the beginning. The gradient is about 2.5 m in c. 1.6 km. Between Bolundsfjärden and Norra Bassängen the water flows through a wide area with reed vegetation and stony bottom and without any clear channel. The gradient is negligible. The part of the stream between Norra Bassängen and the outlet to the sea does not have a clearly defined channel. The gradient is about 0.5 m over a distance of a few metres.

Table 3-12. Distribution of different bottom substrates (%) in the investigated stream stretches in the Forsmark area (data from /Carlsson et al. 2005b/).

Catchment	1			2				1 and 2			
Stream order	1	2	total	1	2	3	total	1	2	3	total
Fine organic detritus	84	40	47	82	13	–	38	82	25	0	41
Coarse organic detritus	16	3	5	10	3	–	5	10	3	0	5
Clay	–	46	39	5	75	86	50	4	62	86	46
Sand	–	1	1	–	3	5	2	0	2	5	2
Gravel	–	–	–	–	1	–	0.4	0	0	0	0
Cobble	–	10	8	3	5	9	5	3	7	9	6
Boulder	–	–	–	–	0.4	–	0.2	0	0	0	0

Upstream of Gällsboträsket the stream has a clearly defined channel along the entire stretch. The gradient varies: it is steep in the beginning, than flat and c. 200 m upstream of Gällsboträsket the gradient is steep again. In the easterly channel, the stream was investigated from Gällsboträsket and approximately 150 m upstream until the stream dried up. This channel is not as clearly defined as the westerly channel, appearing more like a ditch with stationary water.

The total gradient in the measured stretches upstream of Gällsboträsket is about 5 m in c. 450 m. The channel of the stream between Gällsboträsket and the junction with the stream from Eckarfjärden is clearly defined down to approximately 30 m from the junction, where the stream discharges its waters into a marsh. The gradient is about 1 m in c. 800 m.

Catchment 8

The outflow from Fiskarfjärden is mostly diffuse with large areas flooded and it is not until the last 50 m from the outlet that the channel is clearly defined. The gradient is about 0.8 m in c. 800 m.

3.8.3 Shading

With the exception of some areas with cut forest, the investigation by /Carlsson et al. 2005b/ showed that the streams in catchment 1 and 2 were most often densely shaded (see Figure 3-20). In catchment 8 the section closest to Fiskarfjärden was moderately shaded (5–50%) by the surrounding terrestrial vegetation whereas downstream, close to the sea, the channel was not shaded at all, since the surrounding wetland lacked trees and bushes. Due to the small sizes of the streams they ought to be shaded to a high degree unless the forest was recently cut.

Figure 3-20. *Many streams in the Forsmark area are, like this small stream, densely shaded.*

3.9 Hydrochemical characteristics of lakes, streams and shallow groundwater

Six lakes and 8 stream stations located in 4 sub-catchments were monitored during the site investigations predominantly on a monthly basis (Figure 3-21). In addition, groundwater in 46 soil tubes and wells were sampled up to four times per year. The description of water chemistry in lakes and streams includes data from March 2002 to March 2005 /Sonesten 2005/ and the description of groundwater chemistry includes data from July 2002 to February 2005 /Tröjbom and Söderbäck 2006b/. The surface water chemistry was compared with regional and national data from the national survey of lakes and watercourses (cf. /Wilander et al. 2003/). The groundwater chemistry was compared with a database from the Geological Survey of Sweden, containing data from private wells[2]. The data were also compared with Swedish Environmental Quality Criteria (EQC) /Naturvårdsverket 1999b/ (groundwater), /Naturvårdsverket 2000/ (lakes and streams). Some of the comparison of the chemical composition in the lakes and streams with regional and national reference data is presented in box plots (Figure 3-22). In addition, to the monitoring during site investigations some extra sampling occasions has been performed. In /Tröjbom and Nordén 2010/ an overview of sampling occasions and data are presented, sampling of water chemistry Integrated evaluations of the hydrochemistry in the surface system is found in /Tröjbom et al. 2007/ and evaluations of mass transports and pools of elements in /Tröjbom and Grolander 2010/.

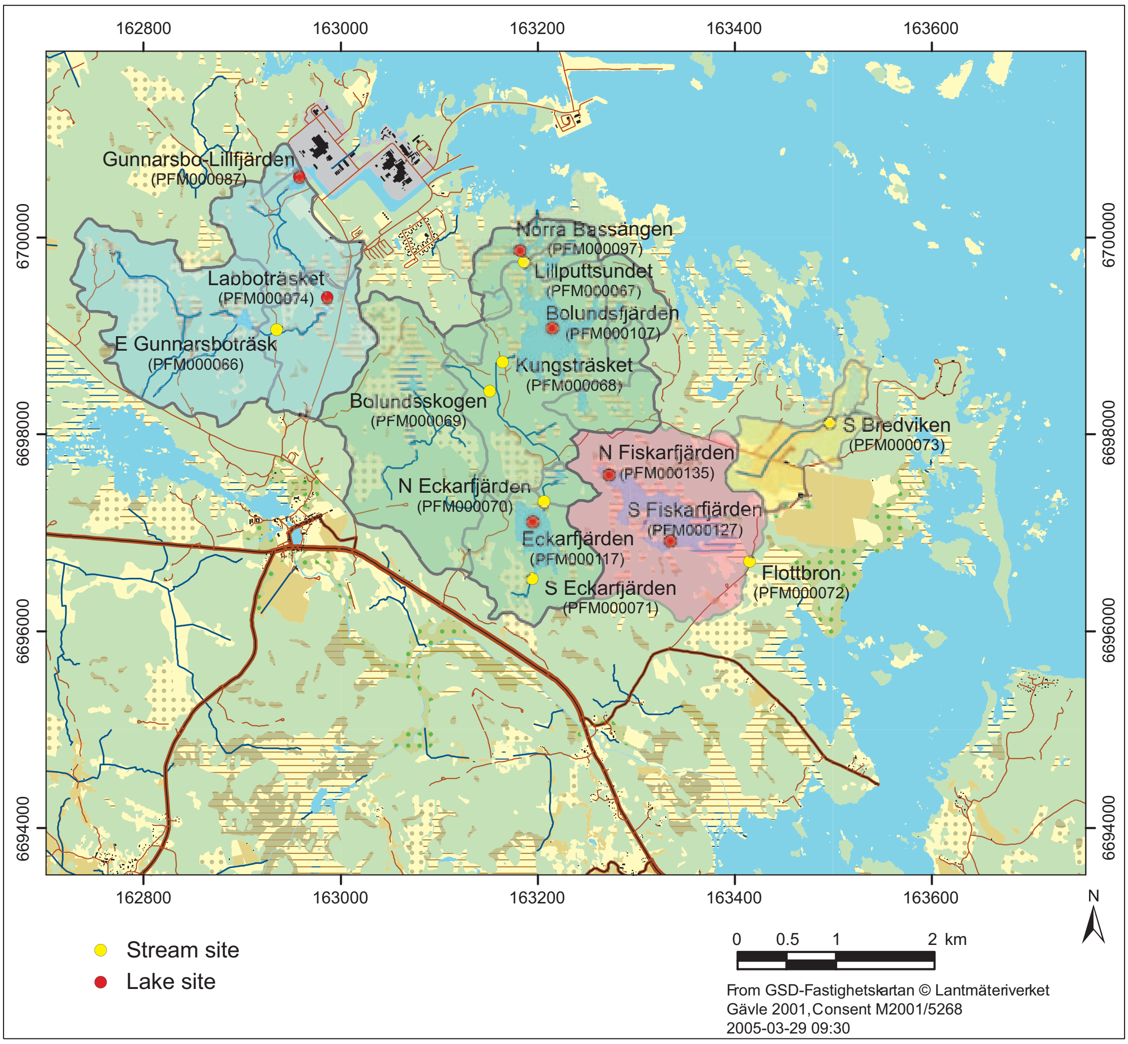

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Figure 3-21. *Monitored lakes (red) and stream sites (yellow) in the Forsmark area. The SKB ID code for each sampling site is given in brackets. The water divides between the different catchments are also shown.*

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[2] Accessed from web 2005-07-15 at www.sgu.se\sgu\sv\service\kart-tjanst_start.htm#brunn.

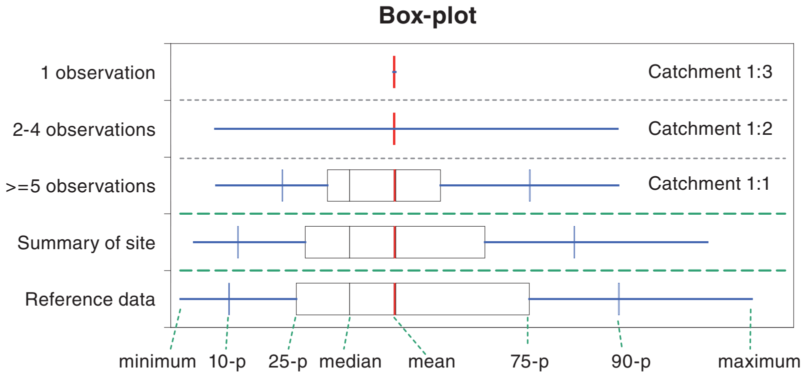

Figure 3-22. The structure of box plots, showing statistical distributions of parameter values for individual sampling sites or soil tubes, and for different categories (summary of site). The corresponding distributions for local, regional and national reference data are included under "Reference data". 10-p denotes the 10th percentile etcetera. When applicable, the colour scale of the Swedish Environmental Quality Criteria is included in the box plots. The meaning of the different colours differs depending on the parameter and usually ranges from low (blue) to high (red). The scale often refers to statistical distributions and is not necessarily coupled to "good" or "bad" conditions.

Concentrations of major elements and major ions, pH, temperature, oxygen concentrations and water colour, in lakes, streams and groundwater are presented below and in Appendices 7 and 8. Water chemistry for trace elements is presented in Appendices 6 and 7 and in /Tröjbom and Söderbäck 2006b/.

3.9.1 Water chemistry in lakes

The lakes in Forsmark are characterized by high pH, high concentrations of major ions and high electrical conductivity. Phosphorus concentrations are generally low while nitrogen concentrations tend to be high /Sonesten 2005, Tröjbom and Söderbäck 2006b/. The water has a high content of dissolved organic carbon, which is unusual in combination with the moderate water colour in the lakes /Brunberg et al. 2002/. Due to the shallowness of the lakes, the concentration of dissolved oxygen can reach very low levels during winter, and in some lakes anoxia occurs. Generally, the chemical conditions in freshwaters in the Forsmark area are relatively unaffected by anthropogenic influence.

Acidity and alkalinity

The pH values are high, with a median pH of 7.9 in the Forsmark lakes (Table 3-13). Occasionally the pH values are very high exceeding 9 in Bolundsfjärden, Norra Bassängen and Fiskarfjärden. These events generally occur in late summer or early autumn and coincide with high primary production. Alkalinity is also very high in the Forsmark lakes compared with the majority of Swedish lakes due to the high concentrations of bicarbonate. Accordingly, the buffering capacity against acidification is high.

Nutrients

Phosphorus is often considered to be a limiting factor for the growth of microbiota in lakes /Vollenweider 1976, Elser et al. 1995, Vadeboncoeur et al. 2003/. This may be the case in the Forsmark lakes, as phosphorus concentrations are low according to EQC (Table 3-13, Figure 3-23). The concentration of total phosphorus is at the same level as in the majority of Swedish lakes but is, with exception of Fiskarfjärden, lower than what is typical for lakes in the region /Sonesten 2005/. Fiskarfjärden show higher concentrations of all phosphorus fractions than the rest of the lakes in Forsmark. Moreover, a gradient with increasing phosphorus concentrations downstream is evident among the lakes in the Norra Bassängen catchment. This is what can be expected considering the greater influence of the catchment downstream in a system.

Table 3-13. Mean water chemistry (March 2002–March 2005) for major elements in surface water (0.5 m depth) in the investigated lakes in the Forsmark area. Percentiles, mean, minimum and maximum values have been calculated from all measurements in all the monitored lakes. pH and conductivity have been measured in the field, while the other parameters are from laboratory analyses.

Element	Count	Min.	25-p	Median	75-p	Max.	Mean	SD
pH	245	6.31	7.30	7.92	8.52	9.52	7.94	0.73
Conductivity (mS m^{-1})	246	17	30	35	42	450	45	40
Tot-P (mg L^{-1})	250	0.0044	0.0084	0.010	0.014	0.039	0.012	0.005
POP (mg L^{-1})	253	0.0010	0.0036	0.0047	0.0065	0.036	0.0057	0.004
PO4-P (mg L^{-1})	255	<0.001	<0.001	0.0010	0.0018	0.0052	0.0013	0.0009
Tot-N (mg L^{-1})	250	0.33	0.82	0.99	1.2	3.7	1.1	0.4
NH_4-N (mg L^{-1})	255	<0.01	<0.01	<0.01	0.033	1.4	0.069	0.2
NO_2+NO_3-N (mg L^{-1})	255	<0.01	<0.01	<0.01	0.010	0.26	0.011	0.03
PON (mg L^{-1})	249	0.0078	0.035	0.050	0.069	0.74	0.065	0.07
TOC (mg L^{-1})	254	5.5	16	17	19	35	17	4
DOC (mg L^{-1})	255	4.2	15	17	19	33	17	4
POC (mg L^{-1})	248	0.046	0.25	0.37	0.53	6.3	0.50	0.6
SO_4-S (mg L^{-1})	247	0.43	2.7	4.9	6.5	25	5.2	3
Si (mg/l)	247	<0.03	0.76	2.3	4.2	11	2.8	2
Fe (mg L^{-1})	70	0.0069	0.036	0.056	0.11	0.67	0.094	0.1
Mn (mg L^{-1})	70	<0.003	0.0041	0.0088	0.027	0.64	0.034	0.08
Cations								
Ca (mg L^{-1})	247	13	37	46	61	130	49	20
Mg (mg L^{-1})	247	0.70	3.3	4.7	6.2	26	5.4	3
Na (mg L^{-1})	247	1.4	7.0	12	28	210	23	30
K (mg L^{-1})	247	0.73	2.0	2.5	3.3	9.6	2.8	1
Anions								
Cl (mg/l)	246	0.90	7.6	15	43	430	38	60
HCO_3 (mg L^{-1})	244	46	120	140	190	370	160	50
F (mg L^{-1})	223	<0.2	<0.2	0.24	0.29	3.1	0.27	0.3
Br (mg L^{-1})	245	<0.2	<0.2	<0.2	<0.2	12	<0.2	0.8
I (mg L^{-1})	200	<0.001	0.0050	0.0060	0.0090	0.026	0.0073	0.004

Besides phosphorus, primary producers in lakes can also be limited by ***nitrogen*** /Blomqvist et al. 1993, Jansson et al. 1996, Camacho et al. 2003/. In the Forsmark lakes, nitrogen seems to be in rich supply as the concentrations are high or very high according to EQC (Table 3-13, Figure 3-24). However, in the summer, inorganic nitrogen concentrations decrease and there are indications that the benthic primary production in the microbial mat is stimulated by nitrogen influxes, indicating nitrogen limitation /Andersson and Brunberg 2006b/. The concentrations of total nitrogen are approximately at the same level as in the lakes in the region, except for in Fiskarfjärden and Eckarfjärden, where concentrations are higher. Most of the nitrogen in the lakes is associated with organic substances. However, occasionally during episodes of decomposition, the inorganic fractions (NH_4, NO_3, and NO_2) increase in importance. This is indicated by a relatively narrow distribution but with a few observations with very high inorganic nitrogen concentrations (Figure 3-24).

Iron and ***manganese*** are micronutrients that can be limiting nutrients for primary production at some occasions /Hyenstrand et al. 2001/. The iron level in the Forsmark lakes is generally lower than in many other lakes in the region and also compared with Swedish lakes as a whole. On the contrary, iron concentrations in the streams are at the same level or higher than in most regional streams (Section 3.8.2), indicating that there is an uptake of iron in the lakes. Thus, iron could potentially limit primary production in the Forsmark lakes. A study in Lake Eckarfjärden with nutrient additions to mesocosms suggests that there is no iron limitation of either phytoplankton or bacterioplankton /Andersson 2005/. However, iron limitation may occur in the benthic habitat. The manganese concentrations are slightly lower than in the lakes in the region, but agree well with the concentration distribution in Swedish lakes. There are a few exceptions with very high concentrations of manganese in Labboträsket, Lillfjärden and Fiskarfjärden.

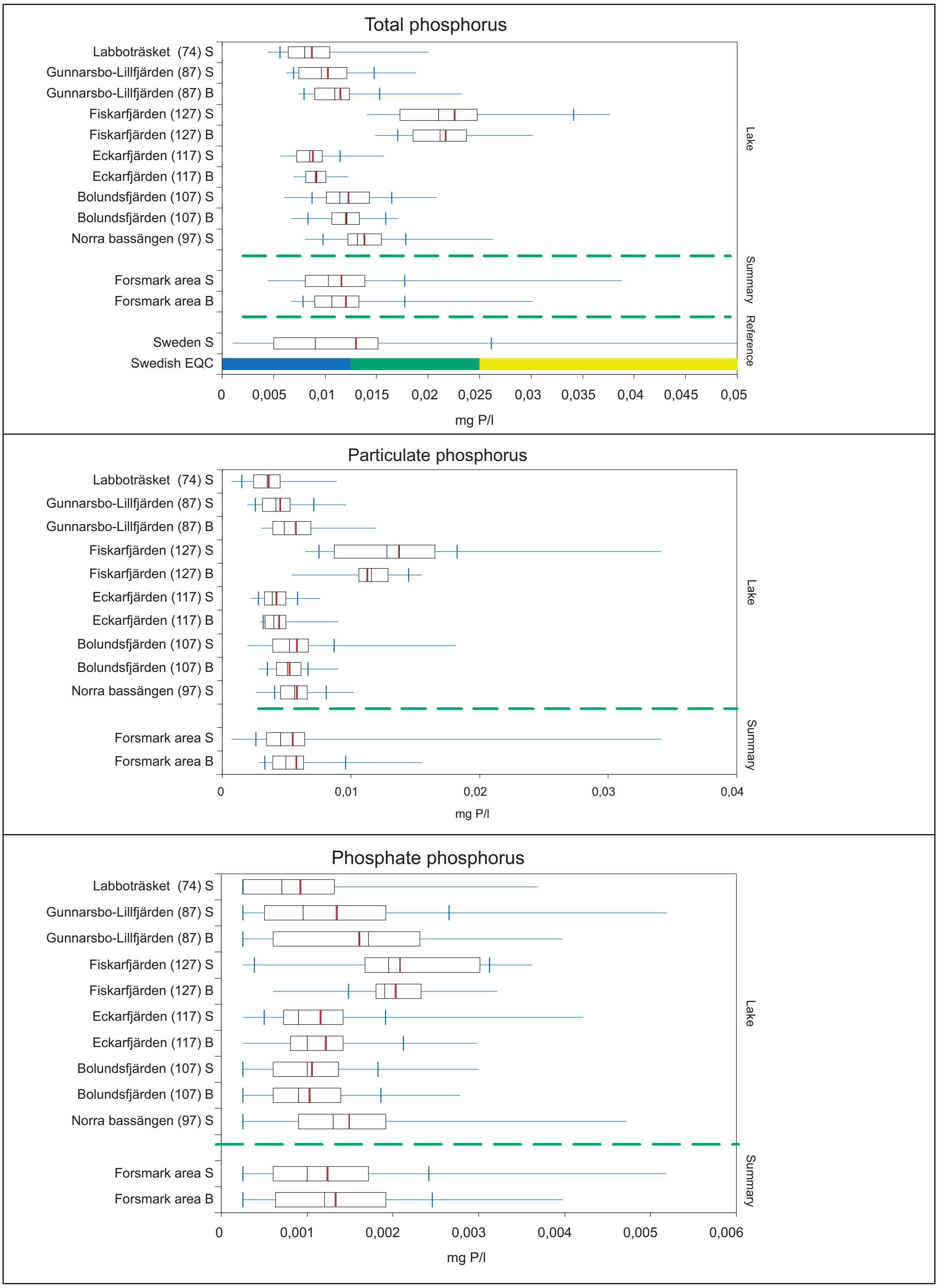

***Figure 3-23.** Concentrations of total, phosphate and particulate phosphorus species in surface (S) and bottom (B) water in lakes in the Forsmark area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.*

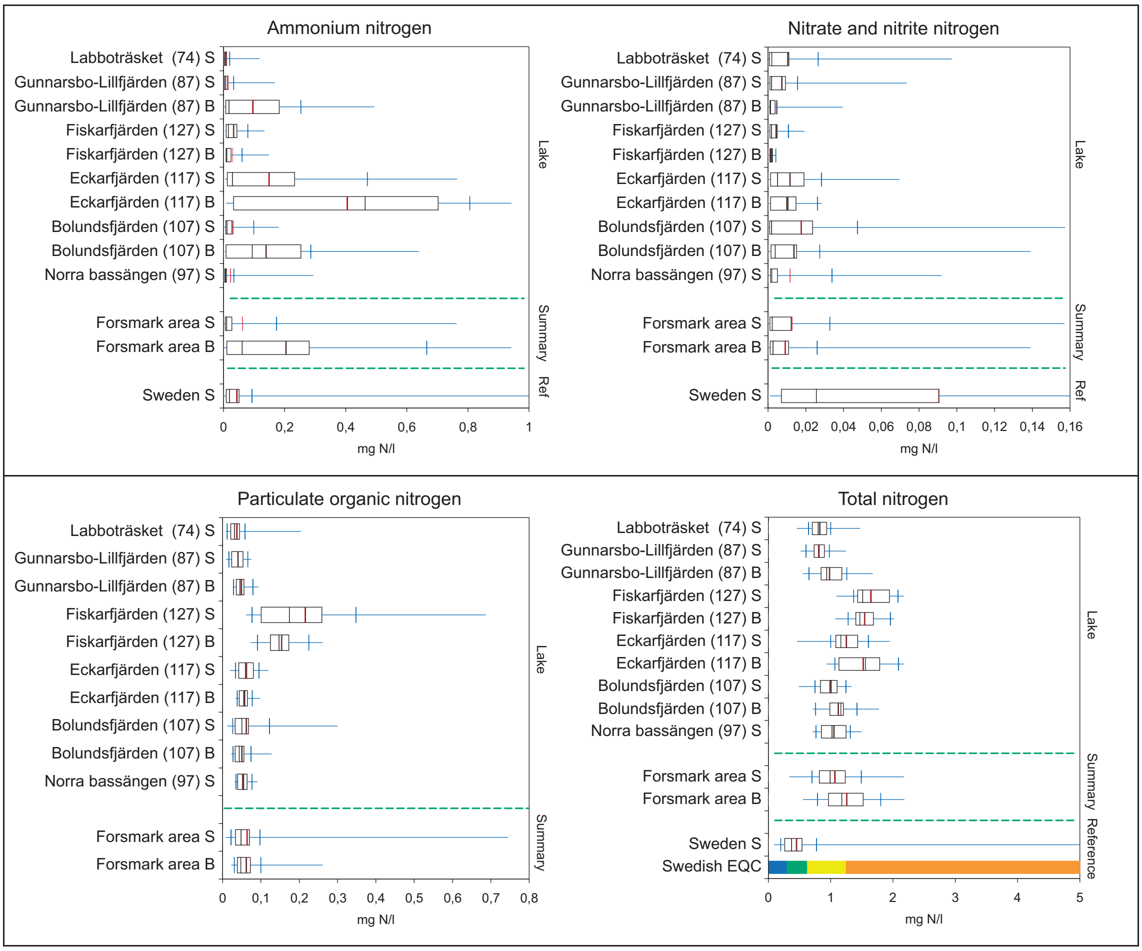

Figure 3-24. Concentrations of total, nitrate and nitrite, ammonium and particulate nitrogen in surface (S) and bottom (B) water in lakes in the Forsmark area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.

Concentrations of total organic ***carbon*** (TOC) are very high according to EQC (Figure 3-25). Although the TOC concentrations are lower than in many lakes in the region, they are on average in the 75th–90th percentiles compared with national lakes. The dissolved organic carbon (DOC) concentrations are very high, especially in combination with the moderate watercolour of the lakes (water colour see below) /Brunberg et al. 2002/. This suggests that much of the DOC could be of autochtonous origin, i.e. produced by primary producers within the lakes in contrast to coloured DOC, which often consists of humic compounds originating from the catchment. Both DOC and TOC concentrations vary over the year within the lakes. Particulate organic carbon (POC) concentrations are generally highest in Fiskarfjärden (Figure 3-25). Dissolved inorganic carbon (DIC) concentrations (Figure 3-25) are very high compared with Swedish lakes as a whole.

The ***sulphate*** concentrations in the Forsmark lakes are, as in many other lakes in the region, higher than in the majority of Swedish lakes. The exception is Eckarfjärden, which shows comparably low sulphate concentrations /Sonesten 2005/. The high sulphate concentrations can in most lakes be attributed to leaching from the catchments, as the atmospheric deposition in the region is similar to many other parts of the country (cf. /Tröjbom et al. 2007/).

Silicon originates from weathering, and the concentrations are comparable to those in other Swedish lakes. Only Lillfjärden deviates with higher concentrations. Silicon is characterized by its utilization by diatoms, hence a marked seasonality can be seen in the concentrations, with lower summer concentrations and higher winter concentrations. In Eckarfjärden where phytoplankton and microphytobenthos have been investigated, phytoplankton diatom biomass is low but diatoms are

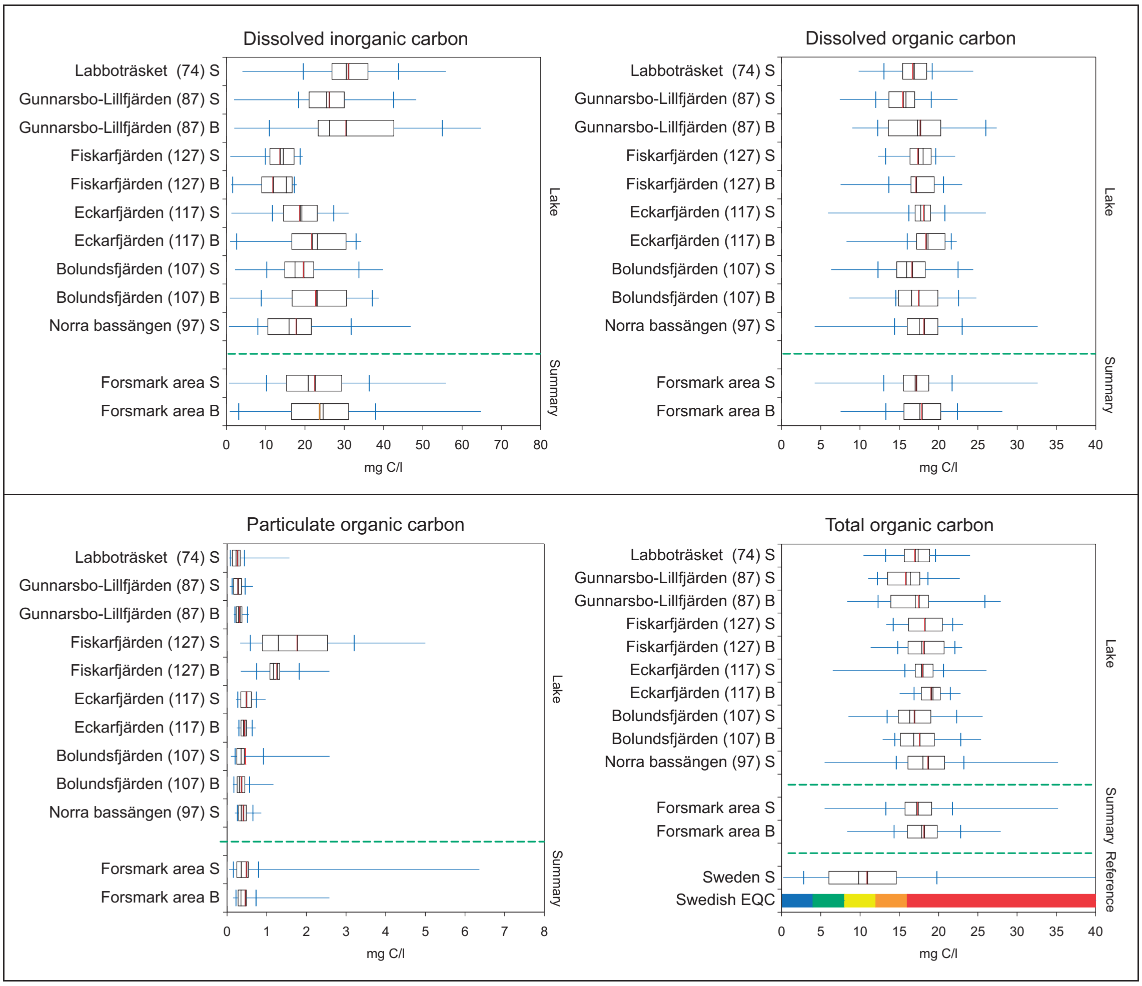

Figure 3-25. *Concentrations of total, dissolved and particulate organic carbon, as well as contents of dissolved inorganic carbon, in surface (S) and bottom (B) water in lakes in the Forsmark area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.*

present in high biomass in the benthic microbial mat. There is a substantial retention of silicon in the lakes. According to mass balances, as much as 50% of the silicon supplied is precipitated in Lake Eckarfjärden /Tröjbom et al. 2007/.

Dissolved ions and conductivity

The total amount of dissolved ions, measured as the electrical ***conductivity***, is markedly higher in the Forsmark lakes and the lakes in the region compared with the majority of Swedish lakes. The elevated amounts of dissolved ions are caused by the calcareous till in the catchments and by the recent emergence of the catchments from the sea. There is an increase in conductivity from the upper parts to the lower parts of the Norra Bassängen catchment.

All lakes in the Forsmark area show high levels of ***cations***. The levels of calcium, magnesium and potassium in particular are higher than in the majority of Swedish lakes, as well as in most other lakes in the region. Sodium concentrations are also comparatively high in Bolundsfjärden, Norra Bassängen and Fiskarfjärden, whereas the other lakes show sodium levels more common to the majority of Swedish lakes. There is a high seasonal variation in ***calcium*** levels in all lakes. This is due to precipitation of calcium carbonate into a solid state during periods of high primary production and high pH. In connection with degradation and lower pH, the process is reversed and calcium carbonate concentrations rise again. Mass balances indicate that there is a substantial retention of Ca in the lakes and as much as 30% of the total input is retained /Tröjbom et al. 2007/.

The levels of ***magnesium, sodium and potassium*** are highest in Bolundsfjärden and Norra Bassängen. These lakes also have the highest variation in the concentrations of the ions, which is probably caused by intrusion of brackish water from the Baltic Sea (further discussed in Section 3.3). There is also some evidence for brackish water intrusion into Fiskarfjärden.

In accordance with the high concentrations of cations, the amounts of ***anions*** in the Forsmark lakes are also high. The concentrations of ***chloride*** are generally higher than in most other regional and Swedish lakes. The highest levels of chloride are recorded in Bolundsfjärden and Norra Bassängen, followed by Fiskarfjärden. This corresponds well with the expected occasional intrusion of brackish water to these lakes. During 2004 to 2006, as much as 66% of the total input of Cl to Lake Bolundsfjärden could be explained by these intrusions /Tröjbom et al. 2007/. The most abundant ion in the fresh surface waters is the bicarbonate ion, which is released via chemical weathering of the calcite rich till. Mass balances show that there is a substantial retention of bicarbonate in the lakes du to calcite precipitation.

Dissolved oxygen

The concentration of dissolved oxygen is dependent on mixing of the water column, temperature, inflow of oxygen-rich water, inflow of oxygen-depleted groundwater, and on the balance between primary production and decomposition of organic matter. In connection with primary production, dissolved oxygen is released to the water and the concentrations increase. In connection with decomposition, oxygen is consumed and concentrations decrease. The concentrations of dissolved oxygen are highest in the spring and autumn circulation (Figure 3-26). In the summer, oxygen concentrations show strong diurnal variation and generally lower values than in the spring and autumn. This is probably due to the lower solubility of oxygen at elevated temperatures. Other possible reasons for the decreased oxygen concentrations in the summer can be increased decomposition and also a higher proportion of groundwater inflow compared with stream inflow during summer. Groundwater generally contains low amounts of dissolved oxygen. However, studies in Eckarfjärden have shown over-saturation of oxygen concentrations during large parts of the open water season, indicating that the lower concentrations are mainly caused by temperature-dependent solubility /Brunberg et al. 2002/. In winter, there is only limited primary production, but decomposition of organic matter consumes oxygen and anoxic conditions prevail in some of the lakes. Because of the shallow water depth, the whole water body is well mixed for most of the year. Only when the lake is covered with ice does stratification occur, resulting in an oxygen deficit in the bottom waters (Figure 3-27).

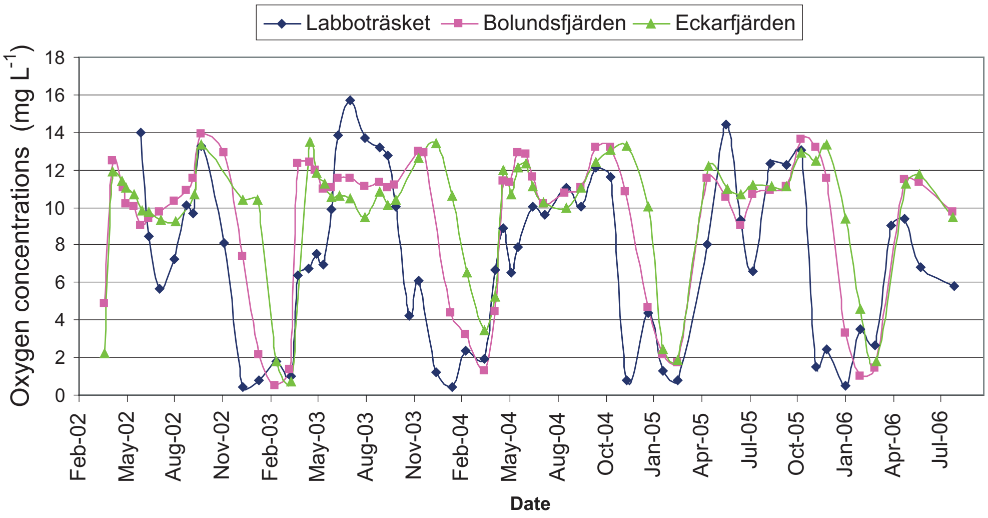

Figure 3-26. *Concentrations of dissolved oxygen in surface waters of three Forsmark lakes during the period April 2002–August 2006.*

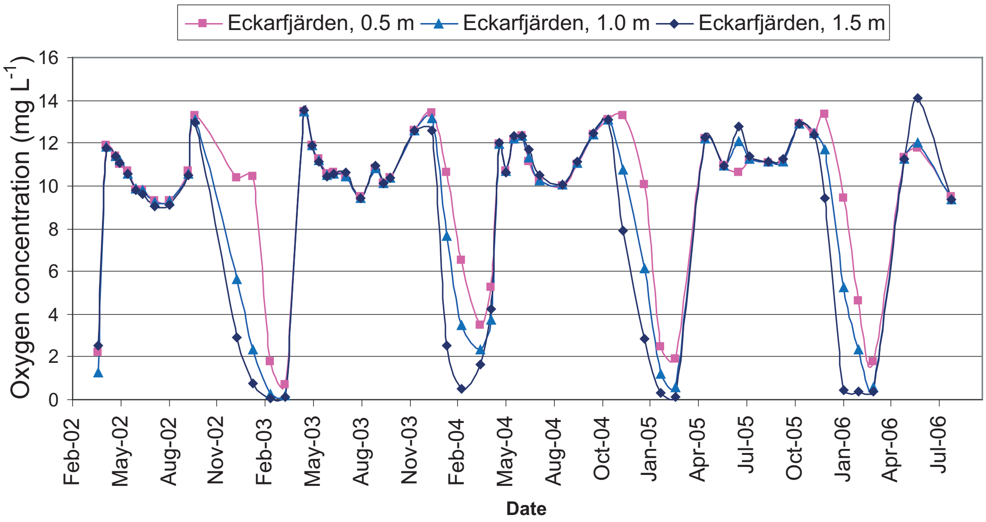

Figure 3-27. *Concentrations of dissolved oxygen at different water depths in Eckarfjärden.*

Temperature

Water temperature has been measured in several of the Forsmark lakes. Data for four lakes are presented in Figure 3-28 (data from SICADA[3], October 2006). The water temperatures varied between a few tenths of a degree above zero in the winter up to above 20°C in the summer. The same pattern is seen for all four lakes.

Water colour

The water colour of the Forsmark lakes is moderate. The annual mean water colour measured as absorbance at 420 nm is 0.149 (n=15) for Eckarfjärden /Brunberg et al. 2002/. Unfortunately, no reliable data on water colour are available from the site investigations but there are no reasons to suggest any substantial differences between the lakes in the area.

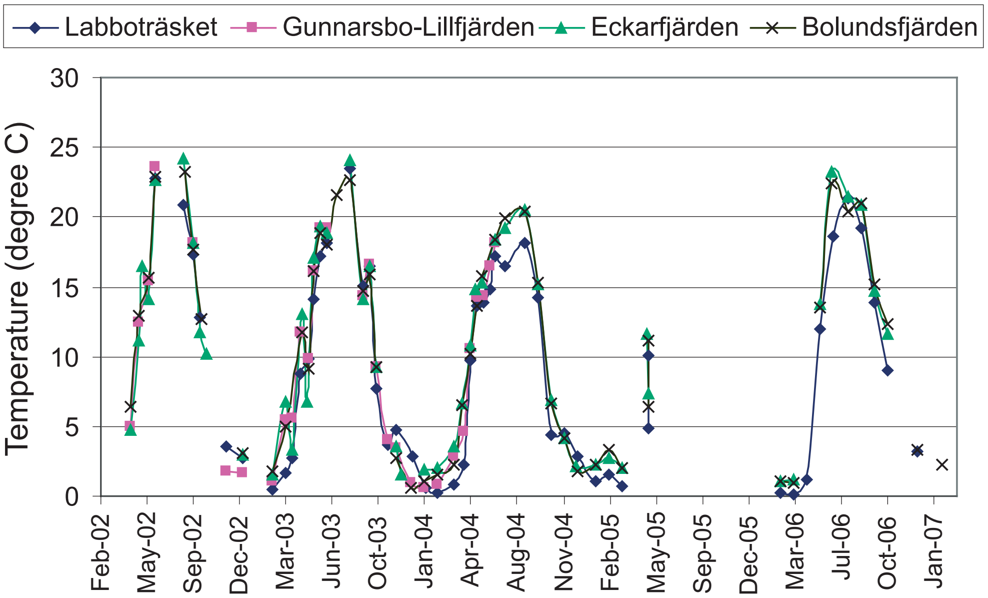

Figure 3-28. *Water temperature in the surface waters of four Forsmark lakes. (Data from SICADA[4], October 2006).*

[3,4] SKBs database SICADA, access might be given on request.

3.9.2 Water chemistry in streams

The water chemistry of the streams in Forsmark is similar to the water chemistry in lakes with high pH, alkalinity, carbon and nitrogen concentrations, but relatively low phosphorus concentrations.

Acidity and alkalinity

The pH values in the streams are, like those in the lakes, generally high and are seldom below 7 (Table 3-14). Even though the pH is high in the streams, it is not as high as in the lakes; nor does it deviate as much from other Swedish watercourses as the pH in lakes does. The difference is probably due to a very high primary production in the lakes generating a higher pH. The measurements of alkalinity in the Forsmark streams are all considerably higher than the 90th percentile of alkalinity in streams in the national survey.

Major elements

The variation in ***phosphorus*** concentrations is high, which is expected since levels in watercourses may vary considerably due to differences in rainfall and water velocity. The total phosphorus concentrations in the streams in the Forsmark area, as in the majority of Swedish streams and rivers, are in most cases low or moderately low according to EQC (Figure 3-29, Table 3-14). However, the levels in the inlet to Eckarfjärden and Bredviken, as well as in the outlet from Fiskarfjärden, are somewhat higher, corresponding to high or very high levels (but on the same levels as many streams and rivers in the county). The levels of phosphate and particulate phosphorus are also elevated at these locations.

Table 3-14. Mean water chemistry (March 2002–March 2005) for major elements in the investigated streams in the Forsmark area. Percentiles, mean, minimum and maximum values have been calculated from all measurements in all the monitored streams. pH and conductivity have been measured in the field, while the other parameters are from laboratory analyses.

Element	Count	Min.	25-p	Median	75-p	Max.	Mean	SD
pH	309	6.40	7.06	7.27	7.47	8.66	7.31	0.37
Conductivity (mS m^{-1})	309	9.4	31	37	42	100	39	10
Tot-P (mg L^{-1})	320	0.0043	0.0098	0.014	0.021	0.25	0.024	0.03
POP (mg L^{-1})	312	0.0012	0.0039	0.0053	0.0082	0.14	0.0086	0.01
PO4-P (mg L^{-1})	323	<0.001	<0.001	0.0017	0.0048	0.15	0.0070	0.02
Tot-N (mg L^{-1})	320	0.48	0.78	0.95	1.2	8.0	1.1	0.7
NH_4-N (mg L^{-1})	323	<0.0005	0.0069	0.016	0.041	1.3	0.053	0.1
NO_2+NO_3-N (mg L^{-1})	323	0.00030	0.0044	0.014	0.047	5.5	0.15	0.6
PON (mg L^{-1}))	311	0.0030	0.025	0.037	0.056	0.28	0.049	0.04
TOC (mg L^{-1})	320	2.5	14	17	20	27	17	4
DOC (mg L^{-1})	319	2.9	13	17	19	28	16	5
POC (mg L^{-1})	311	0.058	0.18	0.26	0.41	2.2	0.36	0.3
SO_4-S (mg L^{-1})	317	0.55	2.9	4.7	7.1	31	6.3	5
Si (mg L^{-1})	317	0.080	1.9	3.5	4.5	8.7	3.3	2
Fe (mg L^{-1})	89	0.024	0.068	0.11	0.22	1.5	0.18	0.2
Mn (mg L^{-1})	89	<0.003	0.0080	0.014	0.039	0.65	0.034	0.07
Cations								
Ca (mg L^{-1}))	317	10	45	55	66	150	59	20
Mg (mg L^{-1})	317	0.70	3.2	4.5	6.4	17	5.5	3
Na (mg L^{-1})	317	1.9	5.6	12	22	100	17	20
K (mg L^{-1})	317	<0.4	1.9	2.3	3.1	12	2.9	2
Anions								
Cl (mg L^{-1})	313	1.5	4.7	15	36	210	26	30
HCO_3 (mg L^{-1})	315	30	140	170	200	540	180	70
F (mg L^{-1})	270	<0.2	<0.2	0.24	0.31	1.1	0.25	0.1
Br (mg L^{-1})	316	<0.2	<0.2	<0.2	<0.2	0.87	<0.2	0.1
I (mg L^{-1})	229	<0.001	0.0040	0.0050	0.0080	0.023	0.0061	0.004

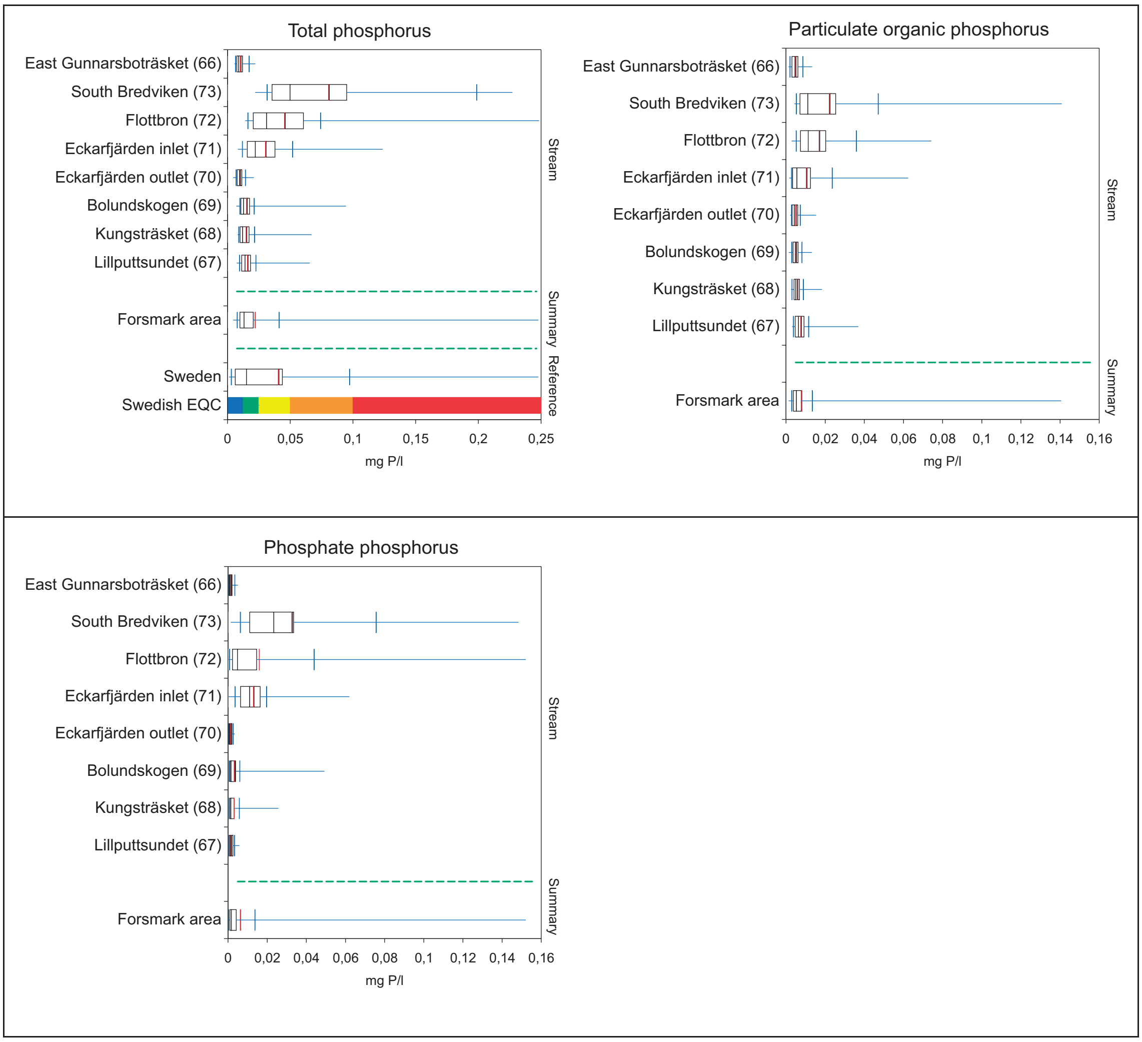

Figure 3-29. *Concentrations of total, phosphate and particulate phosphorus species in streams in the Forsmark area. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.*

The total ***nitrogen*** levels in streams are high or very high according to EQC, but with the exception of the inlet to Bredviken, the levels are significantly lower than for many other streams in the county (Figure 3-30, Table 3-14). In contrast to the other locations where ammonium is the dominant nitrogen species, the dominant nitrogen species in the inlet to Bredviken are nitrate and nitrite. The origin of the nitrate is probably the agricultural activities in the catchment Bredviken. The ammonium nitrogen levels in the Forsmark streams are generally in the same range as the concentrations in streams from the national survey, while the particulate organic nitrogen level in the outlets to the Baltic Sea in the area seems to be higher. There are no obvious explanations for this tendency.

Like the carbon levels in the lakes, the level of total organic ***carbon*** in the Forsmark streams is high or very high according to EQC (Figure 3-31, Table 3-14). There are two exceptions: the inlet to Eckarfjärden, which has a significantly lower TOC content than in lake water or in water from the outlet, and the inlet to Bredviken, which exhibits the lowest TOC levels of all the investigated streams and lakes in the Forsmark area. Dissolved organic carbon constitutes most of the total organic carbon pool in streams. The content of dissolved organic carbon is, like in the lakes, very high and exhibits considerable in-site variation. The temporal variation in concentrations of DOC and TOC follows the same pattern. The levels of particulate carbon (POC) in streams are similar to those in most of the Forsmark lakes, but the streams generally show higher temporal variation of POC than lakes. The DIC content is very high and exhibits considerable in-site variation. There seems to be a certain loss of DIC in Eckarfjärden as the concentrations in the inlet are significantly higher than in the lake and in the outlet.

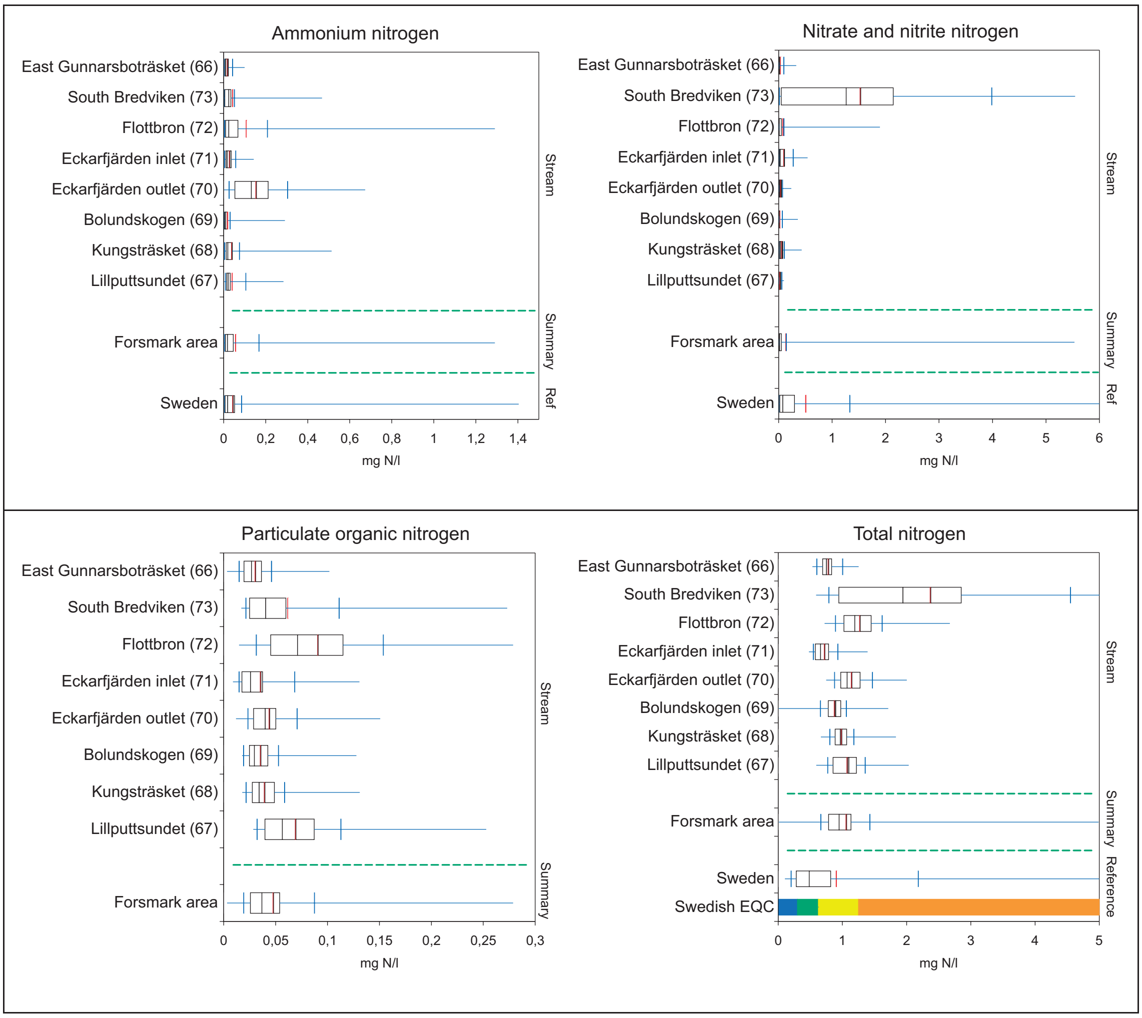

__Figure 3-30.__ Concentrations of total, nitrate and nitrite, ammonium and particulate nitrogen in streams in the Forsmark area. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.

The ***sulphate*** levels in the Forsmark streams are within the normal range of Swedish watercourses in the national survey. However, the level is considerably lower than in other streams in the county.

The ***silicate*** levels in the Forsmark streams are generally within the range of most Swedish streams and rivers. An exception is the outlet from Bolundsfjärden to Norra Bassängen, which has lower values. This may be an effect of brackish water intrusions from the Baltic Sea (further discussed in Section 3.3.4). Si mainly originates from weathering of minerals in the regolith and bedrock. There is a tendency of slightly lower area specific transports of Si in the Forsmark region, which could be an indication of reduced weathering of Si bearing minerals due to the competition from calcite dissolution /Tröjbom and Grolander 2010/.

Dissolved ions

The total amount of dissolved ions is considerably higher in the streams in Forsmark than in most watercourses in Sweden. In contrast to the lakes in the area, the streams have a somewhat lower ***conductivity*** than the majority of streams in the county.

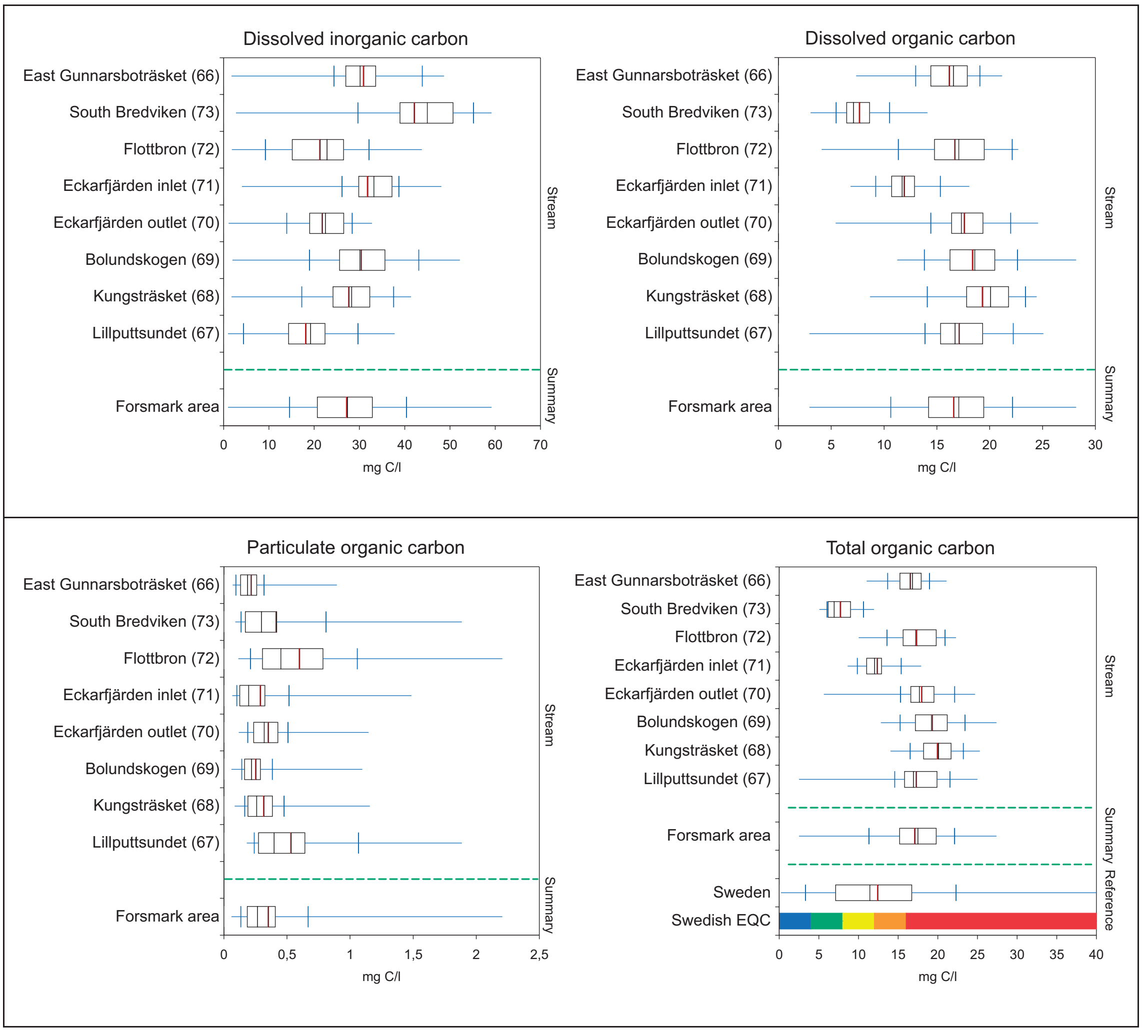

Figure 3-31. *Concentrations of total, dissolved and particulate organic carbon, as well as contents of dissolved inorganic carbon, in streams in the Forsmark area. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from Appendix 1 in /Tröjbom and Söderbäck 2006b/.*

Generally, the highest levels and greatest variation of ***cations*** in the Norra Bassängen catchment are found in the lower part. These higher levels are an effect of that these areas recently have been submerged below the sea and therefore contain high concentrations of marine ions. The large variations are an effect of brackish water intrusion from the Baltic Sea. A major exception from this pattern is the ***calcium*** levels in the streams, as the water from the Bolundsskogen sub-catchment contains very high amounts of calcium. The ***sodium*** level is higher in the outlet from Fiskarfjärden than in the other streams (except the outlet from Bolundsfjärden) indicating that brackish water may enter the lake at high water levels in the Baltic Sea. The highest levels of ***magnesium*** and ***potassium*** are found in the inlet to Bredviken. The reason for this is not clear, but the agricultural activities within the catchment may be one explanation.

The levels of ***chloride*** and ***fluoride*** in the Forsmark streams are higher than the median Swedish watercourse in the national survey. Compared with watercourses in the county as a whole, the fluoride levels are within the normal range. The ***bromide*** levels and their variation are roughly the same as for chloride, with the highest levels and the greatest variation at the outlets from Bolundsfjärden and Fiskarfjärden and intermediate levels at Bolundsskogen and Kungsträsket. The ***iodine*** level is somewhat higher in the outlet from Fiskarfjärden and in the lower parts of the Norra Bassängen catchment.

Both the ***iron*** and ***manganese*** levels in the Forsmark streams are on the same level or slightly higher than those in other streams in the county. Compared with the Laxemar-Simpevarp streams, on the other hand, concentrations are low. Area specific transports of iron are lower in the streams of the Forsmark area compared to the larger catchment of Forsmarksån /Tröjbom and Grolander 2010/.

Dissolved oxygen

Oxygen concentrations in streams vary over the year (Figure 3-32). The oxygen concentration in streams is affected by inflowing surface water, inflowing groundwater and by decomposition and production in parts of the streams with slowly flowing or standing water. The investigated streams are shallow and the water flow is generally low, especially during the summer and/or winter. The net water amounts entering the streams in the summer are limited due to high evapotranspiration. The situation is the same in the winter since most of the surface water is kept in a frozen state, preventing inflow to the streams. This suggests that the influence of groundwater is comparatively greater during these episodes of low water flow. Groundwater generally contains very low amounts of dissolved oxygen. This means that during periods with a high proportion of groundwater in the water entering a stream, the dissolved oxygen content will be low, at least in the area close to the groundwater discharge.

The oxygen concentrations at the four measuring stations show relatively strong co-variation during most of the measurement period, but a discrepancy can be seen between the autumn of 2003 and the spring of 2004. During this period the oxygen concentrations in the outlet from Eckarfjärden (PFM000070) show high values, while minimum values are recorded in the other three locations. We have no explanation for this pattern.

Temperature

Water temperature has been measured continuously (every 10 minutes) at the four permanent automatic discharge stations in the largest streams in the Forsmark area since March/December 2004. The water temperature varied between a few tenths of a degree below zero in the winter up to well above 20°C on hot summer days with low discharge (Figure 3-33) /Johansson and Juston 2007/.

Water colour

No reliable data on water colour are available from the site investigations in the streams, but there is nothing to suggest any substantial differences between the lakes in the area. Thus, the stream can be assumed to possess moderate water colour.

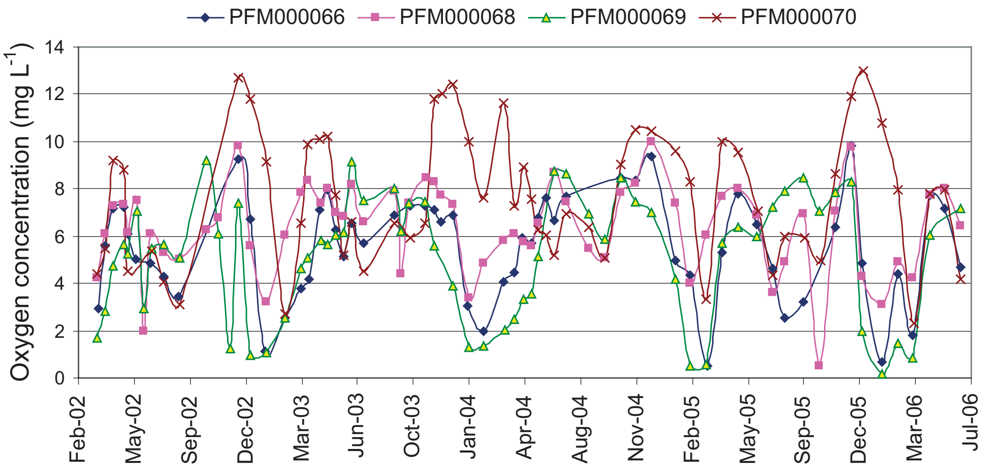

Figure 3-32. *Concentrations of dissolved oxygen in some of the streams in the Forsmark area in the period from March 2002 to June 2006. For location of the measuring stations, see Figure 3-21.*

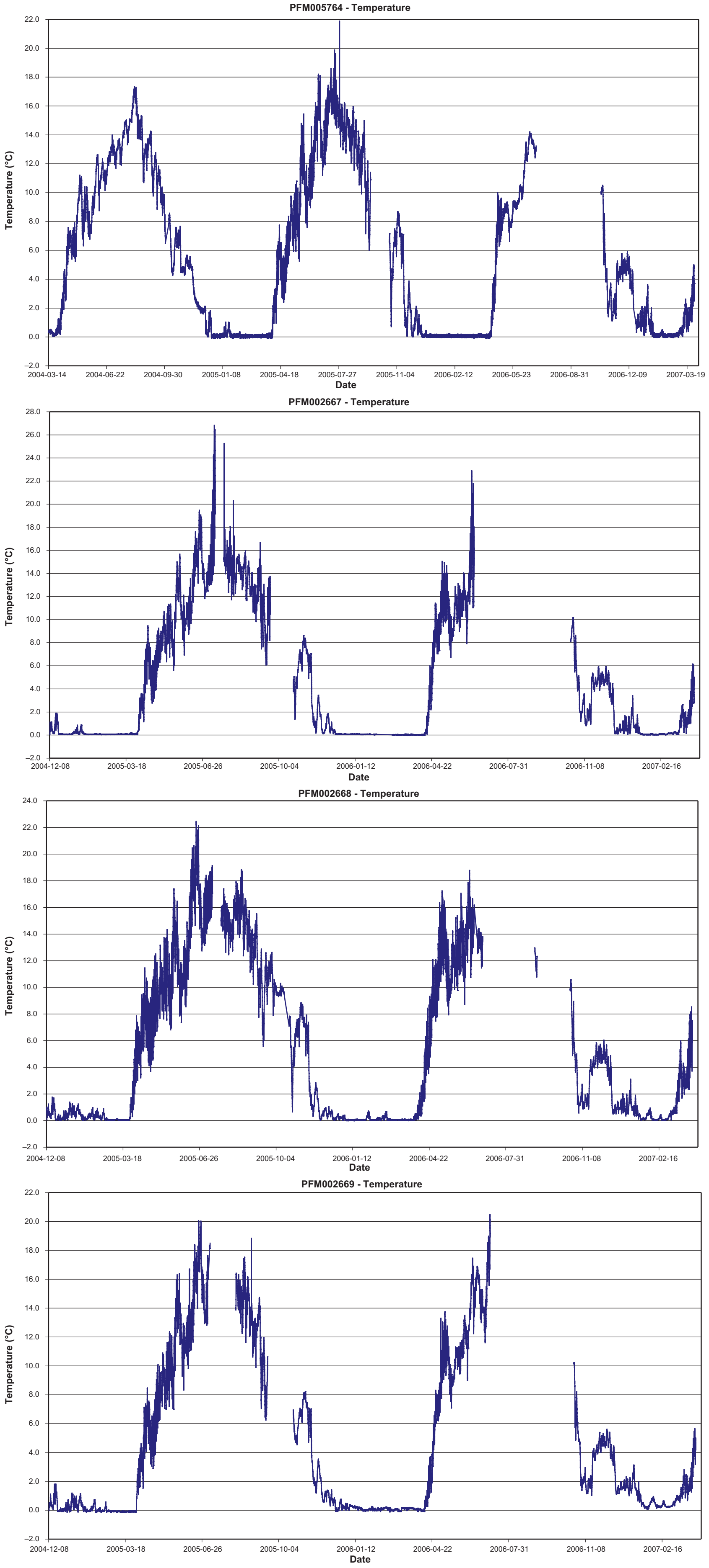

Figure 3-33. *Water temperature measured in the Forsmark streams during the period from December 2004 to March 2007. From /Johansson and Juston 2007/. For the location of the measuring stations, see Figure 3-21.*

3.9.3 Chemistry in groundwater

The shallow groundwater in the Forsmark area is characterized by high pH-values and a high content of major constituents, especially calcium and bicarbonate. “Lower” situated localities, in presumed discharge areas, are strongly influenced by marine relicts, resulting in a high content of e.g. chloride, bromide, sodium and manganese. Higher situated localities, presumably in recharge areas, show clear influences of the calcite-rich overburden, resulting in very high levels of calcium, bicarbonate and strontium. Several parameters show large discrepancies compared with national reference data. Calcium, bicarbonate and manganese median concentrations correspond to the 90th percentile of national reference data for Swedish wells, indicating very high values.

Acidity and alkalinity

The pH values are neutral or slightly basic (Table 3-15). All measurements of alkalinity are classified as very high according to EQC. The pH is generally lower in shallow groundwater compared with stream, lake and sea water. A typical pH value in shallow groundwater in Forsmark is 7.2.

Major elements (C, N, P)

Total organic ***carbon*** (TOC) concentrations are almost entirely composed of dissolved organic carbon (DOC) (Figure 3-34, Table 3-15). The concentrations of TOC and DOC decrease with increasing sampling depth in shallow groundwater /Tröjbom et al. 2007/.

Table 3-15. Mean water chemistry (July 2002–February 2005) for major elements in the shallow groundwater in the Forsmark area. Percentiles, mean, minimum and maximum values have been calculated from all measurements in all the locations (soil tubes). Parameters have been measured by laboratory analyses.

Element	Count	Min.	25-p	Median	75-p	Max.	Mean	SD
pH	178	6.38	7.08	7.22	7.39	8.04	7.25	0.27
Conductivity (mS m^{-1})	171	36	68	86	200	1,200	210	300
Tot-P (mg L^{-1})	108	0.0029	0.0096	0.015	0.043	3.0	0.076	0.3
POP (mg L^{-1})	10	0.0048	0.019	0.031	0.052	7.7	0.90	2
PO4-P (mg L^{-1})	128	<0.0005	0.0019	0.0050	0.012	0.20	0.012	0.02
Tot-N (mg L^{-1})	111	0.26	0.51	0.72	1.3	8.7	1.3	2
NH_4-N (mg L^{-1})	128	<0.0005	0.032	0.092	0.47	8.6	0.86	2
NO_2+NO_3-N (mg L^{-1})	126	<0.0002	0.00033	0.0016	0.011	0.85	0.048	0.1
PON (mg L^{-1})	10	0.0042	0.0083	0.032	0.037	0.055	0.026	0.02
TOC (mg L^{-1})	128	1.6	6.1	10	16	36	11	7
DOC (mg L^{-1})	127	2.1	6.6	11	16	37	12	7
POC (mg L^{-1})	10	0.15	0.42	0.55	0.82	0.97	0.57	0.3
DIC (mg L^{-1})	124	8.1	49	62	72	140	62	30
SO_4-S (mg L^{-1})	199	0.25	8.4	16	43	120	30	30
Si (mg L^{-1})	199	1.0	5.0	6.3	7.8	14	6.4	2
Fe ((mg L^{-1})	135	<0.02	0.16	1.3	2.3	510	6.3	40
Mn (mg L^{-1})	139	0.0027	0.11	0.17	0.24	1.4	0.23	0.2
Cations								
Ca (mg L^{-1})	197	29	91	110	140	680	150	100
Mg (mg L^{-1})	199	4.2	8.5	13	35	180	32	40
Na (mg L^{-1})	197	2.2	17	37	260	1,600	240	400
K (mg L^{-1})	197	1.7	5.0	7.8	18	70	14	10
Anions								
Cl (mg L^{-1})	196	4.2	18	56	340	3,800	460	900
HCO_3 (mg L^{-1})	199	72	320	360	420	770	370	100
F (mg L^{-1})	195	<0.2	0.34	0.55	0.66	2.3	0.53	0.3
Br (mg L^{-1})	199	<0.2	<0.2	0.23	1.3	20	2.0	4
I (mg L^{-1})	157	<0.001	0.0050	0.0070	0.021	0.11	0.016	0.02

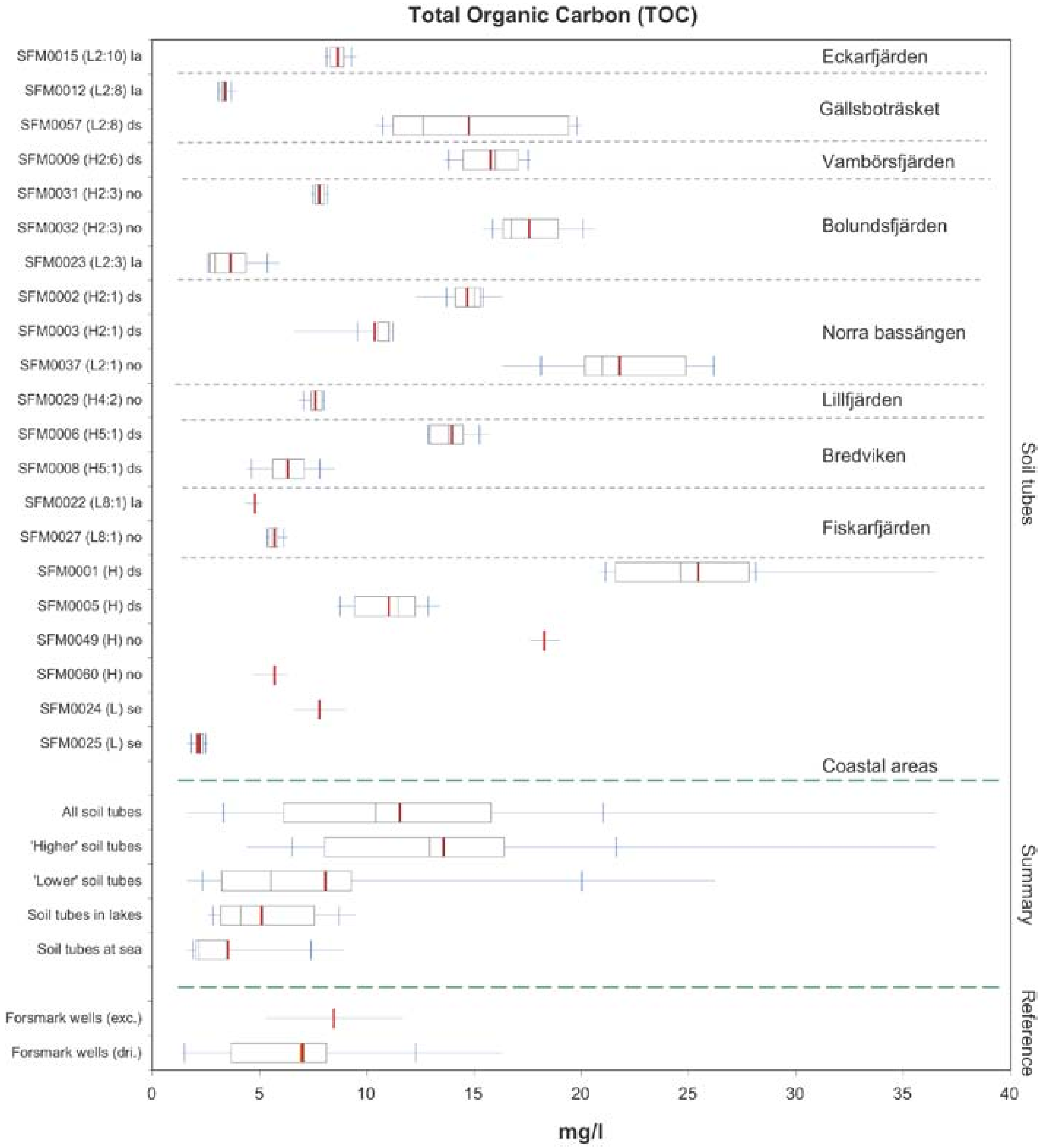

Figure 3-34. *Total organic carbon in shallow groundwater in the Forsmark area. The annotation within brackets denotes the position of the sampled soil tubes ('higher' (H) or 'lower' (L) location according to /Tröjbom and Söderbäck 2006b/, the sub-catchment number, and finally the supplementary information as to whether the soil tube is located at a drill site (ds), in till below lake sediments (la) or sea sediments (se). The rest of the soil tubes are marked 'no'.*

Total ***nitrogen*** concentrations (tot-N) are highest in low situated soil tubes, while higher situated soil tubes usually show lower concentrations (Figure 3-35, Table 3-15). In soil tubes at lower levels, most of the total nitrogen usually occurs as ammonium, implicating reducing redox conditions. Concentrations of nitrate are often low in groundwater, depending on nitrate used as an electron acceptor by microorganisms and as nitrogen source for plants and microorganisms, cf. /Hallbeck 2008/

The concentration of total ***phosphorus*** (tot-P) differs from nitrogen in displaying higher variability and the fact that the differences between high and low situated soil tubes are less accentuated (Figure 3-35, Table 3-15). Most of the phosphorus occurs as particulate phosphorus, and in general only a small fraction of the total phosphorus consists of phosphate.

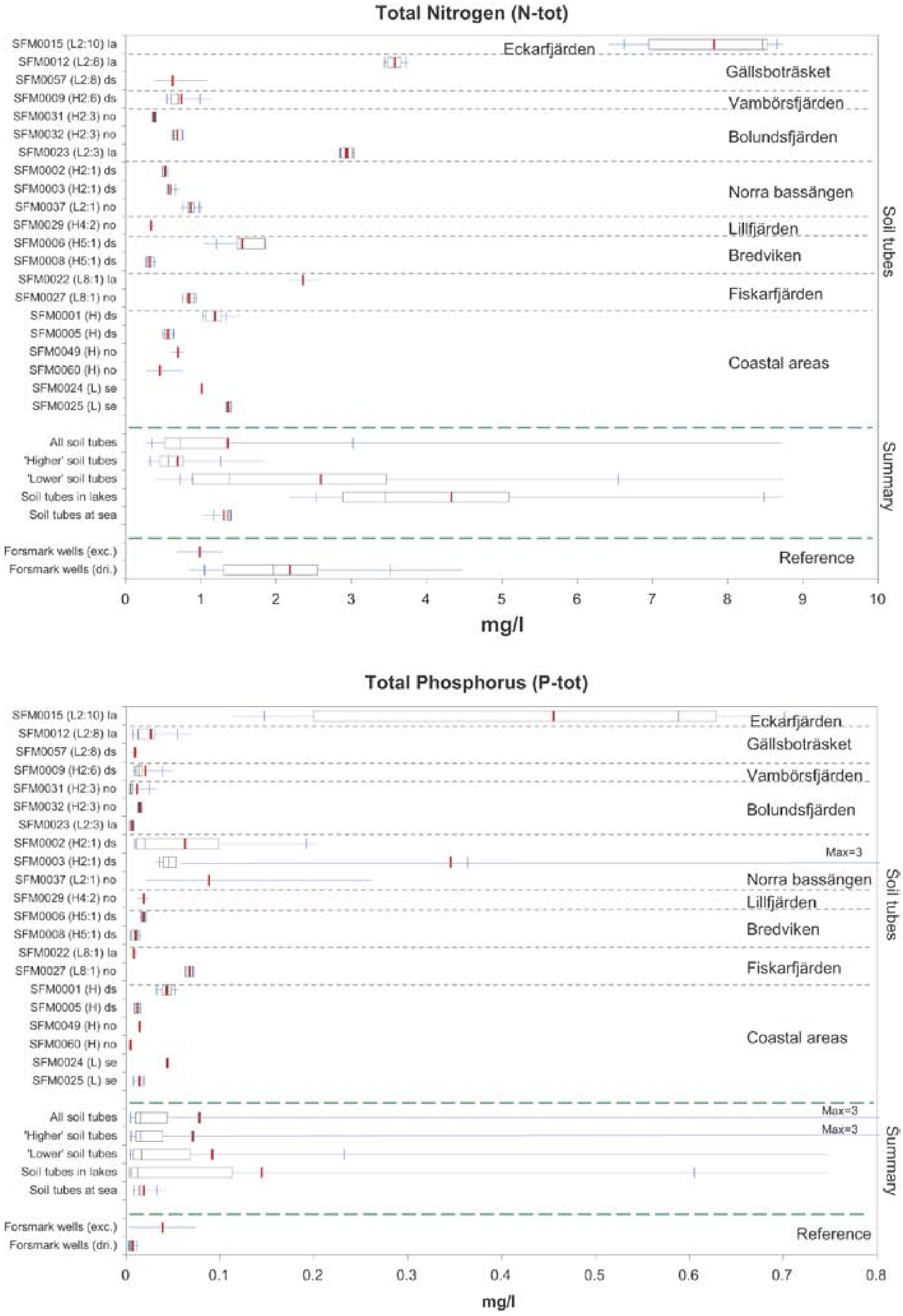

Figure 3-35. *Concentration of total nitrogen and total phosphorus in shallow groundwater in the Forsmark area. The annotation within brackets denotes the position of the sampled soil tubes ('higher' (H) or 'lower' (L) location according to /Tröjbom and Söderbäck 2006b/, the sub-catchment number, and finally the supplementary information as to whether the soil tube is located at a drill site (ds), in till below lake sediments (la) or sea sediments (se). The rest of the soil tubes are marked 'no'.*

Major constituents

Major constituents of the groundwater are generally calcium, chloride, magnesium, silica, sodium, sulphate and bicarbonate. The shallow groundwater in the Forsmark area can be divided into two main water types with respect to content of major constituents: the Ca-HCO_3 type that is found in higher situated soil tubes (presumably recharge areas) and the Na-CHO_3 or Na-Cl types that are found in most lower situated soil tubes (presumably discharge areas). The major constituents of sea water – e.g. chloride, sodium, magnesium and sulphate – occur in elevated levels in many of the soil tubes due to the influence of relict marine water. Cf. /Tröjbom et al. 2007/.

Calcium concentrations are considerably elevated in the Forsmark area compared with both regional and national wells. Especially high calcium concentrations are found in soil tubes located below lakes or at sea. There are relatively small differences between calcium concentrations in low and high situated soil tubes. Calcium concentrations are generally higher in shallow groundwater compared with stream, lake and sea water.

Magnesium concentrations are slightly elevated compared with regional and national wells. The magnesium concentrations in shallow groundwater are generally higher than in stream and lake water but of the same magnitude or lower than in sea water.

Sodium concentrations in higher situated soil tubes are on the same level as concentrations in most Swedish wells. Sodium concentrations in lower situated soil tubes show considerably elevated concentrations, however. The lowest concentrations are found at topographical heights, indicating that marine relict is the major factor behind the sodium pattern. The sodium concentrations are generally higher in shallow groundwater than in stream and lake water but on the same magnitude as in sea water.

The concentrations of ***silica*** range from 1–10 mg L^{-1} with a typical concentration of 5 mg L^{-1}. This is about half the concentration measured in soil tubes in the Laxemar-Simpevarp area.

Chloride concentrations differ between low and high situated soil tubes. Concentrations in high situated soil tubes are only slightly elevated compared with Swedish wells, while concentrations in low situated soil tubes are considerably elevated. Chloride concentrations in lower situated soil tubes are generally higher compared with stream and lake water. Soil tubes at higher levels show concentrations at lower or the same levels as in stream and lake water. This pattern reflects the sea water influence via atmospheric deposition and flushing of relict marine remnants in this coastal region.

Sulphate concentrations are elevated 3–6 times compared with concentrations in most Swedish wells. The lowest sulphate concentrations are found at topographical heights. The sulphate concentrations are generally higher in shallow groundwater than in stream and lake water, but lower or of the same magnitude as in sea water. In general, approximately one third of the sulphate in the surface water, not directly influenced from sea water intrusions, seems to originate from atmospheric deposition, whereas the remaining two thirds originate from e.g. sulphide minerals in the sediments /Tröjbom et al. 2007/.

Bicarbonate concentrations are elevated ten times compared with concentrations in most Swedish wells. Bicarbonate concentrations are generally higher in shallow groundwater than in stream, lake and sea water due to the dissolution of calcite in the regolith. Except for very high concentrations in the soil tube in Eckarfjärden and very low concentrations in the soil tube in Bolundsfjärden, the bicarbonate concentrations are rather uniformly distributed in the area.

Redox potential

No calculations based on redox pairs have been performed to evaluate the redox potential. However, a simplified classification based on iron, manganese and sulphate is presented /Tröjbom and Söderbäck 2006b/. The redox potential in most soil tubes is low according to EQC and there are only two exceptions with a high redox potential. In soil tubes with a low redox potential, concentrations of hydrogen sulphide are usually elevated and the fraction of Fe^{2+} of total iron is usually substantial. In soil tubes with a high redox potential, on the other hand, the fraction of Fe^{2+} is lower than 50% of total iron. Cf. evaluation of shallow groundwater data from a microbiological perspective /Hallbeck 2008/.

Iron and ***manganese*** concentrations in Forsmark wells are higher compared with Swedish wells, indicating elevated levels in shallow groundwater in the area. The iron and manganese concentrations are generally higher in shallow groundwater compared with stream, lake and sea water due to lower redox conditions in this environment.

3.10 Biota

3.10.1 Biota in lakes

In Forsmark, the biomass in lakes is strongly concentrated to the benthic habitat where the macroalgae C*hara sp.* is very abundant and where there is a thick microbial mat consisting of heterotrophic bacteria and microphytobenthos. The biomass of pelagic microbiota (phytoplankton, bacterioplankton) is low as well as zooplankton biomass. The fish biomass varies between investigated lakes and is close to the regional average in some lakes, but only half of the regional average in others.

The biomass of biota in the lakes has been thoroughly investigated and primary production measurements have been performed for some organisms. Annual averages of both biomass and primary production have been calculated from monthly means. All species found in the site investigations are listed in Appendix 4.

Biomass of primary producers

The ***phytoplankton*** biomasses in the Forsmark lakes are low. The annual mean biomass in Eckarfjärden, estimated by microscopic counts, was 41 mg C m^{-3} (n=3 years based on a total of 36 samples, SD = 17 mg C m^{-3}, min. annual mean 22 mg C m^{-3}, max. annual mean 57 mg C m^{-3}) with a seasonal variation showing maximum values in summer and minimum in winter (Figure 3-36) /Blomqvist et al. 2002, Andersson et al. 2003/. The highest recorded biomass was 184 mg C m^{-3} and occurred in June 2000. The phytoplankton biomasses are in agreement with literature values: according to /Wetzel 2001/ the phytoplankton biomass in oligotrophic lakes ranges between 20–100 mg C m^{-3}. Phytoplankton in Eckarfjärden is dominated by mixotrophic species (mainly chrysophytes), that is, species that are able to consume bacteria as energy source in addition to photosynthesis. This is often an indication of nutrient or light limitation. Light conditions in Eckarfjärden are good, but the dominance of mixotrophic species corresponds well to the relatively low inorganic phosphorus concentrations measured in the lake. The measured phytoplankton biomass in Bolundsfjärden was in the same order of magnitude as the phytoplankton biomass in Eckarfjärden (n=6 samples) /Franzén 2002/. However, the species composition differed and the community was instead dominated by truly autotrophic cyanobacteria. Chl *a* concentrations, which is another estimate of the phytoplankton biomass, were low to moderate in 6 studied lakes (Table 3-16) /Tröjbom and Söderbäck 2006b, Naturvårdsverket 2000/. The only lake that deviates some from the rest is Fiskarfjärden, showing somewhat higher chl *a* concentrations. Fiskarfjärden is the lake with the highest nutrient concentrations in the area.

Table 3-16. Chl *a* concentrations (*µg* L^{-1}) in lakes in the Forsmark area (surface samples). Fiskarfjärden are represented twice, reflecting two different sampling sites within the lake (data from /Tröjbom and Söderbäck 2006b/).

Lake	Count	Min	Max	Median	Mean	SD
Labboträsket	43	<0.5	5.6	1.0	1.2	1.13
Gunnarsbo-Lillfjärden	41	<0.5	6.6	1.3	1.6	1.46
Eckarfjärden	48	<0.5	3.7	1.7	1.8	0.98
Bolundsfjärden	48	<0.5	6.6	1.5	1.9	1.63
Norra bassängen	36	<0.5	6.1	1.2	1.4	1.19
Fiskarfjärden NW	14	1.1	16	5.1	7.0	5.13
Fiskarfjärden SE	19	<0.5	18	1.8	3.3	4.62

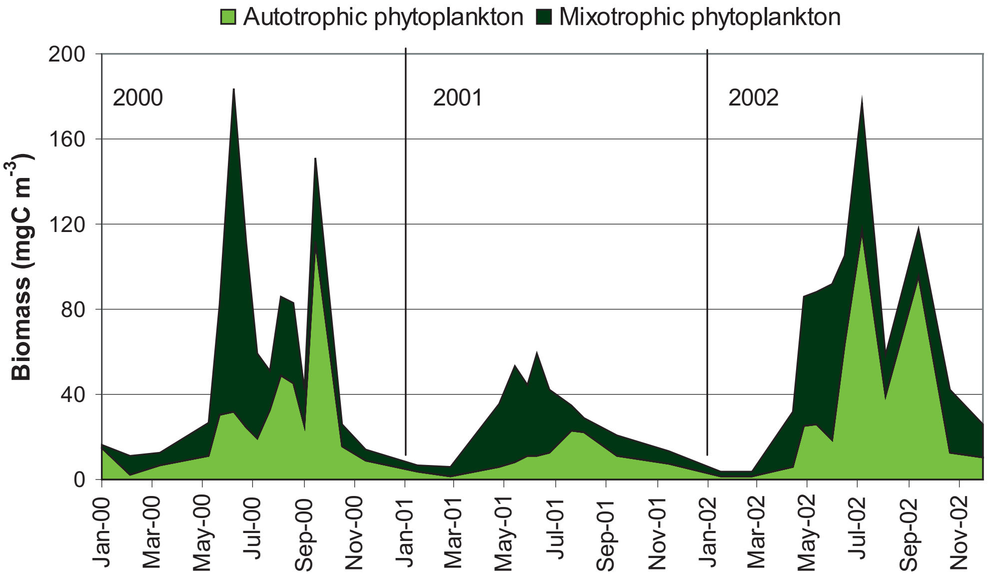

Figure 3-36. *Phytoplankton biomass (mg C m^{-3}) in Eckarfjärden during 2000 to 2002. A large part of the phytoplankton community is made up of mixotrophic species. Data from /Blomqvist et al. 2002, Andersson et al. 2003/.*

The biomass of the ***microphytobenthos*** in the Forsmark lakes is extremely high. An unusually thick microbial mat is found in the benthic habitat of Eckarfjärden with chlorophyll down to a depth of 10–15 cm (Figure 3-37) /Andersson et al. 2003/. The mean annual biomass of the microphytobenthos measured in the top 5 cm of the microbial mat was 3.8 g C m^{-2} (n=3 years based on 39 samples, standard deviation 1.7, min. annual mean = 2.8 g C m^{-2}, max. annual mean = 5.8 g C m^{-2}). There is a seasonal fluctuation with a summer maximum, but the seasonality is less pronounced than for phytoplankton (Figure 3-38). The highest recorded biomass of the microphytobenthos in the top 5 cm of the microbial mat was as high as 13 g m^{-2}. The microbial mat is dominated by non-nitrogen fixing cyanobacteria and purple sulphur bacteria. Some pennate diatoms and a few green algae are also present. Some species of cyanobacteria are known to produce toxins that may inhibit other organisms. Toxins was not found in analysis of microphytobenthos in Eckarfjärden (Andersson E, unpublished) indicating that the microbial mat is composed of non-toxic species. The purple sulphur bacteria thrive at the boundary between oxic and anoxic conditions, and in the winter a distinct purple layer could often be seen at varying depth in the microbial mat. The biomass of the microphytobenthos in Bolundsfjärden (n=5) was in the same magnitude as in Eckarfjärden.

The thickness of the microbial mat has been investigated in five lakes in the winter and in eight lakes in the summer (Table 3-17). Overall, the microbial mat in the Forsmark area is remarkably thick compared with that in other lakes. The microphytobenthos reaches several centimetres and sometimes even decimetres in thickness, whereas in most lakes the microbial mat is usually only a few millimetres thick (e.g. /Hargrave 1969, Wiltshire 2000/). In the winter investigations, a microbial mat was found in all 5 investigated lakes: Eckarfjärden, Bolundsfjärden, Fiskarfjärden, Gunnarsbo-Lillfjärden and Labboträsket (Table 3-17). In the latter, however, only one centimetre of algal mat was found in one of 16 samples. In the summer study, a substantial microbial mat was also observed in Stocksjön, Vambörsfjärden and Fräkengropen, whereas one other lake in the area (Lillfjärden) was found to have a very thin algal layer (Andersson and Brunberg, unpublished). No microbial mat was found in Labboträsket in seven replicates in the summer investigation, and this, along with the fact that only one out of 16 samples in the winter contained a microbial mat, shows that the microbial mat in Labboträsket is practically absent.

Occasions with pieces of microbial mat being detached from the benthic habitat in the spring have been reported in Eckarfjärden and could potentially exist in the other lakes as well (Figure 3-39) /Andersson 2005/. The reason for this has not been investigated, but it can be speculated that strong winds in the spring and bad conditions of the microbial mat immediately after ice break-up are responsible.

Figure 3-37. *Sediment sample from Eckarfjärden showing the microbial mat in the top 10 cm.*

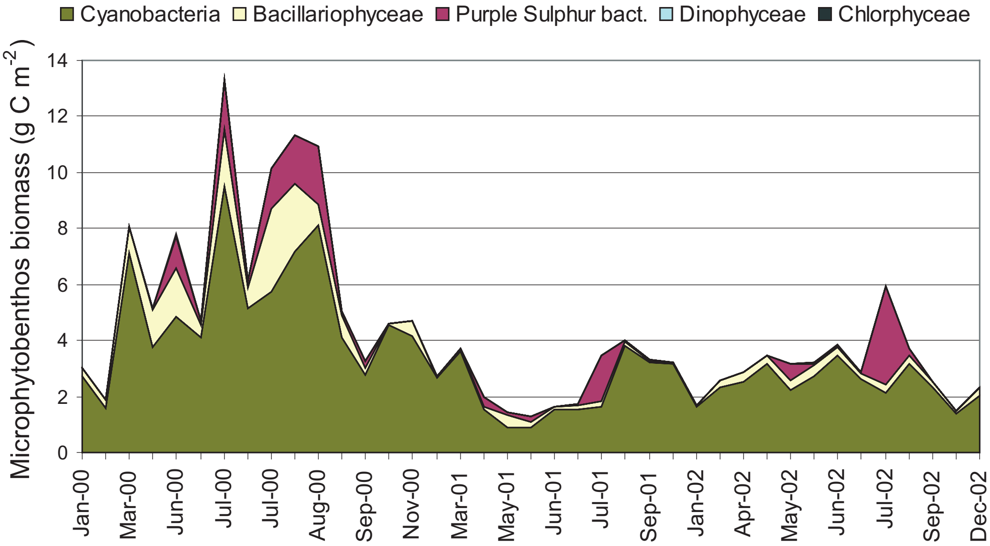

Figure 3-38. *Biomass of the microphytobenthos in the top 5 cm of the microbial mat in Eckarfjärden during the period January 2000 to December 2002. Note that the biomasses of Dinophyceae and Chlorophyceae are too small in comparison with the cyanobacteria to be visible in the graph.* ***.*** *Data from /Blomqvist et al. 2002, Andersson et al. 2003/.*

Table 3-17. Thickness of the microbial mat (cm) in lakes in the Forsmark area in the winter (w) /Borgiel 2004a/ and summer (s) (Andersson and Brunberg, unpublished).

Lake	Number of samples	Depth interval	Mean	Median	Min	Max	SD
Eckarfjärden (w)	17		1.9	2.5	0	5	2.0
Bolundsfjärden (w)	17		3.0	3.8	0	7	2.8
Fiskarfjärden (w)	17		1.7	0.5	0	7	2.3
Gunnarsbo-Lillfjärden (w)	16		4.6	5.0	1	8	2.4
Labboträsket (w)	16		0.1	0.0	0	1	0.3
Eckarfjärden (s)	15	0.1–2.0	6	6	1	12	2.7
Bolundsfjärden (s)	9	0.5–1.5	1	1	0	2	0.8
Labboträsket (s)	7	0.05–1.0	0	0	0	0	0.0
Lillfjärden (s)	3	0.2–0.3	0	0	0	0.01	0.0
Stocksjön (s)	6	0.15–0.5	20	20	8	30	11.4
Vambörsfjärden (s)	9	0.1–0.85	6	6	3	14	0.5
Fräkengropen (s)	7	0.1–0.27	4	4	4	5	3.3
Fiskarfjärden (s)	10	0.25–2.0	8	8	0	11	3.2

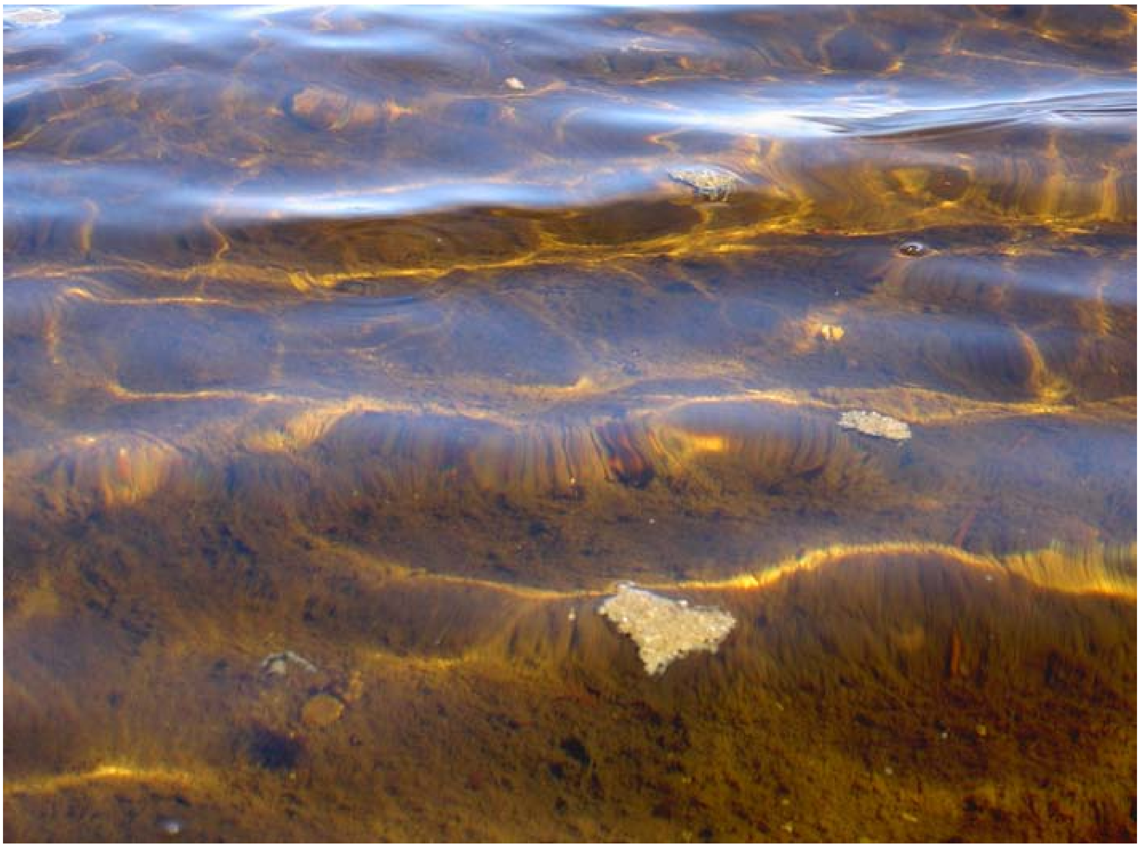

Figure 3-39. *Occasionally in the spring, parts of the microbial mat detach from the benthic habitat and floats to the surface.*

Four species of ***emergent macrophytes*** were noted in a quantitative investigation of macrophytes in Eckarfjärden /Andersson et al. 2003/: common reed (*Phragmites australis*), bulrush (*Typha sp.*), common club-rush (*Schoenoplectus lacustris*), and water horsetail (*Equisetum fluviatile*). The by far most common species were *P. australis* and *Typha sp.* (Table 3-18). The average biomass of emergent macrophytes within Littoral I was 458 g dry weight m^{-2} which corresponds to a biomass of 181 g C m^{-2} assuming a conversion factor of 0.395 g C g dw^{-1} (from /Kautsky 1995/). Although the reed stands are dense, the biomass is rather low compared with the reed biomass in Frisksjön in the Laxemar-Simpevarp area (287 g C m^{-2}) and only 1/3 of the biomass in a lake in northern Germany (687 g C m^{-2}) /Gessner et al. 1996/. Still, the biomass is within the same order of magnitude as in the studies above, and the number of reed straws (49 m^{-2}) is similar to what is reported from a lake in the Netherlands (53 m^{-2}) /Meulemanns 1988/. The biomass can therefore be considered to be within reported values in literature.

The biomass of ***submerged vegetation*** investigated in Fiskarfjärden /Huononen 2005/ and Bolundsfjärden /Huononen 2005, Karlsson and Andersson 2006/ is generally high, and dense mats of the macroalgae *Chara spp.* are found in the benthic habitat (Figure 3-40, Table 3-19). The biomass of submerged vegetation exhibits great spatial variation within the lakes. In Bolundsfjärden, the biomass ranged between 0 and 475 g C m^{-2} and the median biomass was 22 g C m^{-2} (83 g dw m^{-2}, n=60) /Karlsson and Andersson 2006/. There was a clear seasonal distribution in Bolundsfjärden with the highest biomass at midsummer and lower at the beginning and end of the growing season (Table 3-19). The median biomass of submerged vegetation (22 g C m^{-2}) from Bolundsfjärden is within the range of *Chara* biomass reported in the literature (42–500 g dw m^{-2}, which using the same conversion factor as in this study corresponds to 11–134 g C m^{-2}) /Kufel and Kufel 2002/.

Three species of submerged vegetation were identified in Bolundsfjärden and Fiskarfjärden: *Chara baltica*, *C. tomentosa* and *C. intermedia*. The latter was found in Fiskarfjärden and is classified as "Near threatened" according to www.artdata.slu.se/rodlista, accessed 2008-04-17. The abundance and biomass of other submerged macrophytes was low, and only two species were noted in the quantitative investigations: *Potamogeton pectinatus* and *Najas marina* /Huononen 2005, Karlsson and Andersson 2006/. In addition, the species *Potamogeton filiformus* and *P. natans* were noted although not quantified in Eckarfjärden /Brunberg et al. 2004a/.

Table 3-18. Biomass (mean ± SD) of emergent macrophytes in areas containing that macrophyte species, and coverage (m^2) of lake area in Eckarfjärden /Andersson et al. 2003/. Note that *Typha sp.* and *Schoenoplectus lacustris* are growing within the stand of *Phragmites* and therefore the total area of macrophytes is smaller than the sum of areas of separate macrophyte species.

Species	Biomass g dw m^{-2}	Coverage in Eckarfjärden (m^2)	Carbon biomas g C m^{-2}
Phragmites australis	296 (316)	82,287	74
Typha sp.	184 (246)	3,511	13
Schoenoplectus lacustris	54 (11)	88,424	117
Equisetum fluviatile	34 (27)	7,267	21
Total macrophytes		**91,935**	**181**

Table 3-19. Biomass of the submerged vegetation (mainly *Chara spp.*) in Bolundsfjärden and Fiskarfjärden.

	Median value (g dw m^{-2})	Minimum value (g dw m^{-2})	Maximum value (g dw m^{-2})	Number of samples
Bolundsfjärden /Karlsson and Andersson 2006/				
June–September 2006	83	0	1,774	60
June 2006	81	0	1,060	20
July 2006	209	0	1,239	20
September 2006	51	0	1,774	20
Bolundsfjärden /Huononen 2005/				
September 2004	99	0	2,005	10
Fiskarfjärden /Huononen 2005/				
September 2004	43	0	934	10

Figure 3-40. *Dense stands of the macroalgae Chara spp. are often found in the benthic habitat of the lakes in Forsmark.*

Primary production

The net primary production (NPP) of ***phytoplankton*** in Eckarfjärden was measured by ^{14}C incorporation during a two-year period (2001–2002, n=18) (Figure 3-41) /Blomqvist et al. 2002, Andersson et al. 2003/. The mean annual NPP was 24 g C m^{-2} y^{-1} (n=2 years, min. 23.2 g C m^{-2} y^{-1}, max. 25.5 C m^{-2} y^{-1}) and thereby relatively low compared with the median NPP (100 g C m^{-2} y^{-1}) in 35 clear-water lakes reviewed by /Nürnberg and Shaw 1999/. However, the range of NPP in clear-water lakes is large and the NPP in Eckarfjärden is well within the reported range (1–1,403 g C m^{-2} y^{-1}) /Nürnberg and Shaw 1999/. There was a clear summer maximum and winter minimum in the production (Figure 3-41). The maximum phytoplankton production observed in the summer was 24 mg C m^{-2} h^{-1}.

The annual ***microphytobenthos*** production in Eckarfjärden was twice the phytoplankton production on an areal basis, 56 g C m^{-2} y^{-1} (Figure 3-41) (based on 16 samplings during 2001 and 2002, n=2 years, min. 34 g C m^{-2} y^{-1}, max. 77 g C m^{-2} y^{-1}) /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/. There was a clear summer maximum and winter minimum in production. The maximum recorded production was 144 mg C m^{-2} h^{-1} (July 2001). The production at a depth of 1.5 m was assumed to be the average microphytobenthos production in the entire lake area. Values of primary production from literature are not always easily compared since they are estimated by different methods and therefore presented in different units. Moreover, few studies cover entire years but more often present productions for separate dates. However, a few whole-year studies of microphytobenthos production in lakes in the literature suggest that primary production in Eckarfjärden is within reported values although in the higher range /Hargrave 1969, Gruendling 1971, Björk-Ramberg 1981, Björk-Ramberg and Ånell 1985, Heat 1988/. This is expected considering the very high abundance of microphytobenthos in the Forsmark lakes compared with other lakes (see above).

The production of ***emergent macrophytes*** in Eckarfjärden, estimated as the maximum standing stock in Littoral I in August, was on average 458 g dw m^{-2} y^{-1} (which is equivalent to 181 g C m^{-2} y^{-1}) /Andersson et al. 2003/. This biomass and thereby the production is rather low compared with the reed biomass in Lake Frisksjön in Laxemar-Simpevarp area and compared with a lake in northern Germany (687 g C m^{-2})

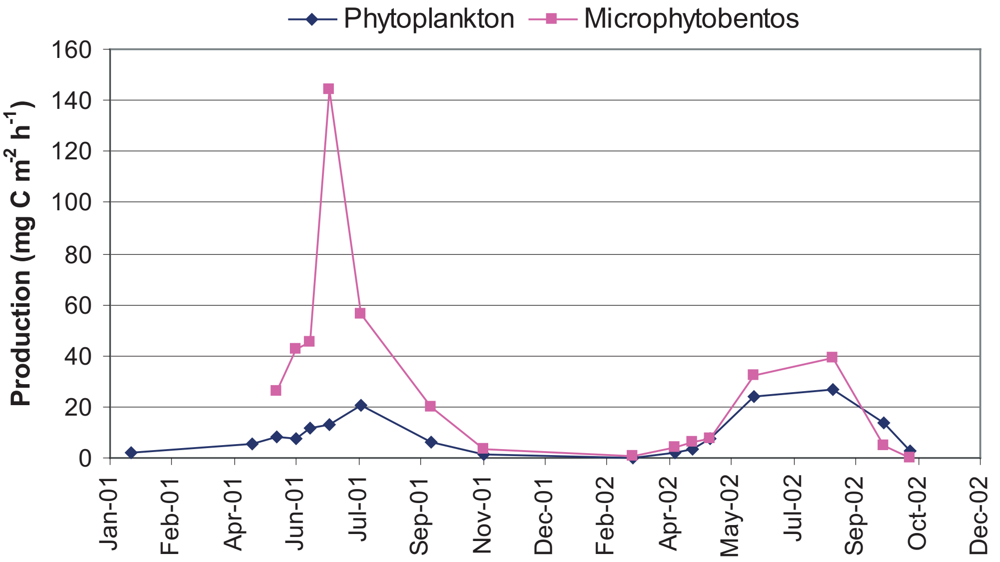

***Figure 3-41.** Primary production of phytoplankton and microphytobenthos in Eckarfjärden during the period 2001–2002. Data from /Blomqvist et al. 2002, Andersson et al. 2003/.*

The net primary production of the ***macroalgae Chara sp.*** in Bolundsfjärden varied seasonally, with highest production in July (118 mg C m^{-2} h^{-1}), intermediate production in June (34 mg C m^{-2} h^{-1}) and low production in September (11 mg C m^{-2} h^{-1}) /Karlsson and Andersson 2006/. The estimated yearly net primary production of macroalgae in Bolundsfjärden was high, approximately 87 g C m^{-2} y^{-1} (n=1 year based on 5 replicates at 3 occasions net primary production during day: 108 g C m^{-2} y^{-1}, night respiration: 21 g C m^{-2} y^{-1}). Annual net primary production of submerged vegetation was calculated assuming a direct linear response between net primary production and light, and by subtracting night respiration which was calculated by assuming the same respiration at night as measured in dark bottles during the day. The respiration varied from 3 mg C m^{-2} h^{-1} (in September) to 35 mg C m^{-2} h^{-1} (in July). As the annual production is based on measurements from only three occasions, the value is somewhat uncertain. However, the estimate should provide a realistic picture of the magnitude of production of submerged vegetation, and the primary production is within reported values from the literature. The production is similar to that reported for a lake in Northern Poland /Pereyra-Ramos 1981/ but small compared with reported *Chara* production in Oakland, USA /Hough and Putt 1988/.

Some of the carbon fixed through photosynthesis may be released as exudates. The amounts of carbon released as DOC can vary and in literature microphytobenthos has been shown to release between 30 and 73% of fixed carbon /Goto et al. 1999, Smith and Underwood 2000/, whereas macroalgae Cara may release c. 10% of fixed carbon /Sorell et al. 2001/. The DOC released from primary producers within the lake are assumed to be of high quality for bacteria /Wetzel 1995/ whereas allochtonous carbon are assumed to be of worse quality and only c. 10% of allochtonous carbon are assumed to be available for bacterial growth /Tranvik 1988/. Correlation between primary production and heterotrophic bacteria in combination with result from nutrient experiments in the Forsmark lakes, indicates that bacteria in the Forsmark lakes are dependent on carbon exudates from the primary producers /Andersson and Brunberg 2006 a, b/.

Biomass of consumers

Heterotrophic bacteria make up a substantial part of the microbial mat in the lakes /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/. The annual mean biomass of ***benthic bacteria*** in Eckarfjärden was 3.7 g C m^{-2} (n=3 years and 36 samplings, SD = 0.58, min. annual mean 3.0 g C m^{-2}, max. annual mean 4.2 g C m^{-2}), which was almost the same as that of the microphytobenthos (mean 3.8 g C m^{-2}, SD = 0.026). The seasonal fluctuation of benthic bacteria was high and the biomass varied between 1,021 and 8,212 mg C m^{-2} (Figure 3-41). The number of sediment bacteria can vary within a wide span, but typically ranges between 10^8 and 10^{10} cells per ml sediment /Schallenberg et al. 1989/. The benthic bacterial number in Eckarfjärden is 10^9 cells per ml sediment and thus within the reported range.

The annual mean biomass of ***bacterioplankton*** in Eckarfjärden was 54 mg C m^{-3} (n=3 years and 27 samples) and much lower than biomass of benthic bacteria (about 2% of the benthic bacterial biomass on an areal basis in a water column with the mean depth 1.2 m). As for benthic bacteria, the seasonal fluctuation of the bacterioplankton biomass was high, between 11 and 164 µg C L^{-1}. The estimated bacterioplankton biomass 0.05 g C m^{-3} is within reported values from the literature, although the bacterial number (1.1×10^{6} cells ml^{-1}) is somewhat low compared with the median cell number (3.3×10^{6} cells ml^{-1}) for 91 clear-water lakes /Nürnberg and Shaw 1999, Wetzel 2001/.

The annual mean meta-***zooplankton*** biomass in Eckarfjärden was low, 0.057 g C m^{-3} (based on 8 sampling occasions in 2002) (data from /Blomqvist et al. 2002, Andersson et al. 2003/). In addition there were on average 0.007 g C m^{-3} ciliates (annual average, n=2 year and 26 samples, min. 0.003 g C m^{-3}, max. 0.012 g C m^{-3}) and 0.0016 g C m^{-3} heterotrophic flagellates (annual average, n=3 year and 38 samples, min. 0.009 g C m^{-3}, max. 0.029 g C m^{-3}). /Gyllström et al. 2005/ showed that the zooplankton biomass in 81 shallow European lakes was correlated to phosphorus concentrations, and the observed zooplankton biomass together with the phosphorus concentration in Eckarfjärden fit well into their correlation graph. Thus, although the zooplankton biomass (0.07 g C m^{-3}) was at the lower end of the 81 shallow European lakes (0.0047–5.151 g dw m^{-3}, equivalent to 0.02–2.3 g C m^{-3} /Gyllström et al. 2005/), it is a realistic estimate due to the low phosphorus concentrations in the Forsmark lakes. The metazooplankton community was dominated by copepods in winter and rotifers (mainly *Polyarthra*) in summer. The metazooplankton biomass in Eckarfjärden showed an opposite seasonal trend compared with most other Swedish lakes, with a summer minimum and winter maximum (Figure 3-42). One explanation for this seemingly inverse seasonal trend could be that the copepods are mainly benthic, but are 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.

The biomass of ***benthic fauna*** in Eckarfjärden, Bolundsfjärden, and Fiskarfjärden is generally relatively low /Andersson et al. 2003, Huononen 2005/. Different sampling techniques gave different results in terms of biomass and dominant species (Table 3-20). The estimated biomass of benthic fauna in Eckarfjärden, based on sampling with an Ekman grabber, was 0.47 g dw m^{-2}, which is in the same order of magnitude as the corresponding estimates for biomass in Bolundsfjärden and Fiskarfjärden (0.57 g dw m^{-2} in both lakes). The estimated biomass of benthic fauna in Bolundsfjärden based on sampling with a frame (2.03 g dw m^{-2}) was considerably higher than the biomass sampled with an Ekman grabber /Huononen 2005/. In Fiskarfjärden as well, the biomass was higher when sampled with a frame, but the difference was less pronounced. In general, carnivores (e.g. *Tanypodinae*) constituted a major part of benthic fauna, but omnivores, detrivores and herbivores also made significant contributions to the biomass. Benthic fauna have been shown to correlate

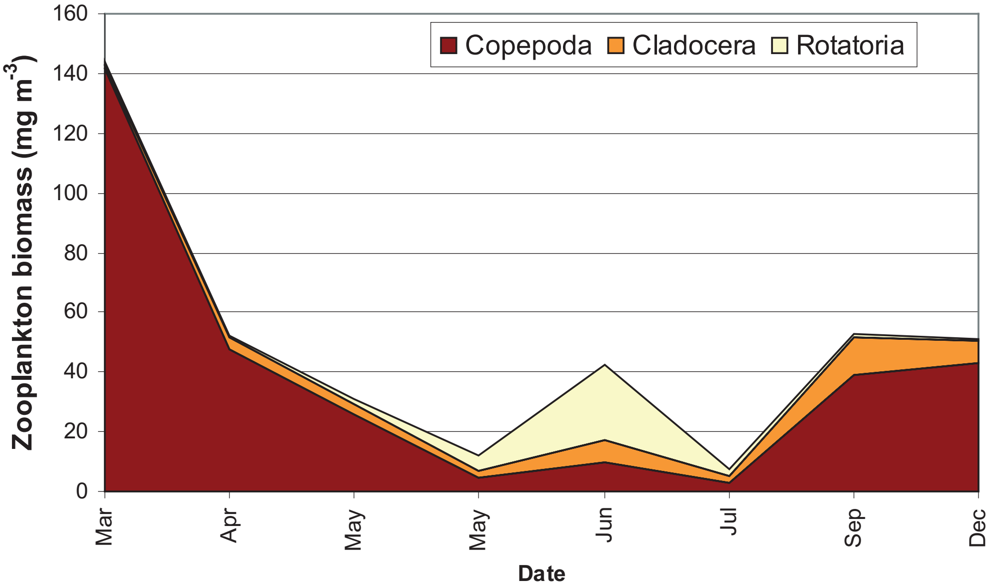

Figure 3-42. *Metazooplankton biomass in Eckarfjärden during the period March 2002 to December 2002.*

Table 3-20. Biomass (g dw m^{-2}) of benthic fauna in Eckarfjärden, Bolundsfjärden and Fiskarfjärden sampled using different methods /[1]Andersson et al. 2003, [2]Huononen 2005/. The value in parenthesis represents the biomass including one large *Anodonta*. The biomass of one large *Anodonta* was excluded when calculating the mean value. Mussels are quite common in the lake, but have a scattered distribution. Considering the small number of bottom fauna samples in the study, including the biomass of one single *Anodonta* will lead to an unrealistically high mean biomass value.

Biomass	Eckarfjärden[1] Ekman grabber	Bolundsfjärden[2] Ekman grabber	Bolundsfjärden[2] Frame	Fiskarfjärden[2] Ekman grabber	Fiskarfjärden[2] Frame
Filter feeders	0.11	0.06 (25.5)	0.14	0.01	0.18
Herbivores	0.23	0.02	0.39	0.00	0.12
Carnivores	0.05	0.16	0.94	0.46	0.28
Omnivores	–	0.22	0.23	0.03	0.03
Detrivores	0.08	0.12	0.33	0.06	0.14
Sum	0.47	0.57	2.03	0.57	0.74

with macrophyte coverage /van den Berg et al. 1997/, so the different sampling techniques could explain the different biomass estimates from the same lake as the frame was used in areas with dense macrophytes. The benthic fauna biomass in Bolundsfjärden and Fiskarfjärden was low (2.0 and 0.74 g dw m^{-2}, respectively in frame samples) compared with the benthic fauna biomass in *Chara* habitats in Krankesjön in southern Sweden (almost 15 g dw m^{-2}) /Hargeby et al. 1994/. However, the biomass was higher than in vegetation-free habitats and of the same size as the benthic fauna biomass in the *Potamogeton* habitats in the study by /Hargeby et al. 1994/. Thus, considering the small sample size in our data we may have underestimated the benthic fauna biomass, but there may also be a true difference between lakes. Nevertheless, the estimate can be considered to be of a realistic magnitude.

In total, 8 ***fish*** species were caught in a fish survey conducted in 2003, in 4 of the Forsmark lakes /Borgiel 2004b/. Most species were found in Bolundsfjärden (8), followed by Fiskarfjärden (6), Eckarfjärden (5) and Gunnarsbo-Lillfjärden (3). The fish survey was conducted using benthic multi-mesh gillnets according to standardized methods /Fiskeriverket 2001, Naturvårdsverket 2000, Naturvårdsverket 1999a/. The species, length and weight of all fish were determined. The catch per unit effort (CPUE = kg fish per net) was similar in Eckarfjärden, Bolundsfjärden and Gunnarsbo-Lillfjärden, whereas Fiskarfjärden had almost twice the CPUE (Table 3-21). In all lakes, roach (*Rutilus rutilus,* sw. *mört*) and perch (*Perca fluviatilis*, sw. *abborre*) dominated in terms of number of individuals. In terms of biomass, however, tench (*Tinca tinca*, sw. *sutare*) dominated in Eckarfjärden and Bolundsfjärden, and Crucian carp (*Carassius carassius*, sw. *ruda*) dominated in Fiskarfjärden. In a study in 2007, Crucian carp was the only fish found in Labboträsk (Nordén, unpublished). Crucian carp is tolerant of low oxygen conditions, and the oxygen concentrations in Labboträsket are very low in the winter, which could explain why only one species is found there. The fish biomass in Labboträsket was also low; one gillnet gave a catch of 7 small Crucian carps (mean weight 11.5 g ww, median = 13.4 g ww, min. = 0.4, max. = 2.2, SD = 0.4). Length and weight distribution diagrams for different species in the different lakes are presented in Appendix 5.

Fish were classified into the functional groups zooplanktivore fish (Z-fish), benthivore fish (B-fish) and piscivore fish (P-fish), based on the weight of individual fish according to /Holmgren and Appelberg 2000/. In the case of Crucian carp (*Carassius carassius*), no information about feeding preferences for individuals smaller than 64 g is available. Here we have assumed that individuals smaller than 8 g feed on zooplankton, whereas larger individuals mainly feed on benthic fauna. All lakes were dominated by fish feeding on benthic fauna (B-fish).

To calculate the total fish biomass in the Forsmark lakes, a conversion factor of 33 kg fish ha^{-1} CPUE^{-1} was used (i.e. 1 kg fish in the net represents 33 kg fish ha^{-1} in the lake) (as proposed by Per Nyberg at Fiskeriverket Örebro, personal communication

Table 3-21. Catch per unit effort (kg ww), weight per hectare (kg ww ha^{-1}) and total fish biomass (kg ww) in Eckarfjärden, Bolundsfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden.

Functional group	**Species**	**Eckarfjärden**	**Bolundsfjärden**	**Fiskarfjärden**	**Gunnarsbo-Lillfjärden**
		CPUE	**CPUE**	**CPUE**	**CPUE**
Zooplanktivore fish		**0.10**	**0.003**	**0.037**	**0.007**
	Crucian carp			**0.005**	
	Perch	0.014	0.0003	0.018	0.007
	Roach	0.081	0.0025	0.014	
	Rudd		0.0004		
Benthivore fish		**2.47**	**2.09**	**4.12**	**2.39**
	Crucian carp		0.234	2.640	2.048
	Perch	0.282	0.353	0.138	0.327
	Roach	0.712	0.470	0.457	0.010
	Rudd		0.003		
	Ruffe	0.005	0.019	0.005	
	Tench	1.470	1.005	0.879	
	White bream		0.002		
Piscivore fish		**1.08**	**0.36**	**0.475**	**0.80**
	Perch	0.625	0.320	0.434	0.802
	Pike	0.451	0.044	0.041	
Total CPUE		**3.65**	**2.45**	**6.63**	**3.195**
Total biomass per hectare (kg ww ha^{-1})		**120.1**	**80.9**	**152.8**	**105.4**
Total biomass in the lake (kg ww)		**2,264**	**3,273**	**5,919**	**189**

The results of the gillnet fishing in Forsmark /Borgiel 2004b/ were compared with other data according to the Swedish fish index (FIX) /Naturvårdsverket 2000/ which gave the following classification of the lakes: Eckarfjärden is classified as a "normal lake", whereas Gunnarsbo-Lillfjärden and Bolundsfjärden deviate slightly, mainly due to their large proportion of fish species resistant to low oxygen conditions. Fiskarfjärden deviates significantly from a "normal lake" because of the large share of the species resistant to low oxygen levels and low proportion of percids. The fish biomass was also investigated in two earlier investigations in Eckarfjärden (1991) /Nyberg 1999/ and Bolundsfjärden (2001) /Franzén 2002/. The fish survey performed in Eckarfjärden 1991 gave almost identical CPUE (3.87) as the study in 2003 (3.65). The species composition, however, had changed between the years. In 1991, the biomass of pike and roach was half of that in 2003, whereas the perch biomass was almost twice the biomass in 2003. The fish survey in Bolundsfjärden 2001 deviated from the survey 2003 and showed more than twice the CPUE (4.8 compared to 2.5). However, in the fish survey in 2001 only 4 gillnets were used compared with 16 in 2004. Since the catch is measured per effort (i.e. per gillnet) similar results could be expected between the studies but since 4 gillnets is a relatively small number of nets it is likely that the CPUE in 2001 gives an overestimation of the actual fish population.

The test fishing in different lakes in Forsmark suggest that there is no correlation between lake area and occurrence of fish in the Forsmark lakes today whereas there seem to be a correlation between maximum depth and occurrence of fish (Figure 11-6). Some lakes, such as Labboträsk, can be assumed to have insignificant amounts of fish, i.e. 0.1 kg per unit effort compared with about 3 kg per unit effort in larger Forsmark lakes. Other smaller lakes (such as Gunnarsbo-Lillfjärden) do contain fish. However, it seems as if catches decrease with decreasing maximum depth of the lake and approach zero at a maximum depth of 1 m (Figure 3-43). This is expected since oxygen depletions will be severe in lakes with lower depths.

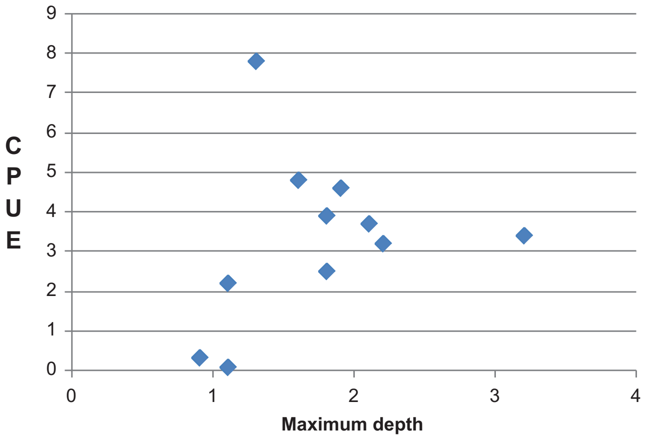

Figure 3-43. *Catch per unit effort (kg ww) in relation a) lake area, and b) maximum depths in lakes in Forsmark. Data from Table 3-32.*

3.10.2 Biota in streams

Biomass of primary producers

Chlorophyll *a* (chl *a*), which can be used as an indirect measure of the ***phytoplankton*** biomass, was measured in 8 different streams in the Forsmark area (n=108) /Tröjbom and Söderbäck 2006b/. The chl *a* concentrations is generally low with a median for all streams of 0.67 µg chl *a* L^{-1}. This is about half of the median chl *a* concentration found in the lakes in the area. The low chl *a* concentration is expected, as the phytoplankton biomass is generally low in small streams /Wetzel 2001/. The plankton in the water from the upstream lakes will settle to the bottom in the calm water of the small streams. No identification of species was done, but it seems reasonable that the phytoplankton composition in streams is similar to what is found in the upstream lakes.

Streams in catchments nos. 1, 2, and 8 were investigated for vegetation in 2004 /Carlsson et al. 2005b/. In total, 56 species of ***macrophytes*** were noted in the streams. The common reed was the most abundant species in all catchments, but otherwise species composition differed between catchments. The coverage of the stream section by macrophytes was classified in five classes:

1. Vegetation lacking
2. Single plants (covering < 5% of the area)
3. Moderate growth (covering 5–50% of the area)
4. Substantial growth (covering 50–75% of the area)
5. Intense growth (covering > 75% of the area)

The aquatic vegetation was very dense in stretches of the lowest stream order (i.e. in upstream parts), but was less dense in downstream parts. In stream order 3 (only found in catchment 2), more than half of the stretches lacked vegetation (Table 3-22).

Table 3-22. Total abundance of vegetation (%) growing in each section of the investigated stream stretches in the Forsmark area. – indicates vegetation class not encountered for a specific stream order and catchment.

Catchment	1			2				1 and 2			
Stream order	1	2	total	1	2	3	total	1	2	3	total
Vegetation lacking	–	2	2	6	11	66	16	5	8	67	13
Single plants (<5% cov.)	–	12	11	1	7	23	7	1	8	23	8
Moderate growth (5–50% cov.)	–	23	20	4	22	7	16	3	22	7	17
Substantial growth (50–75% cov.)	6	30	26	11	36	2	26	10	34	2	26
Intense growth (75–100% cov.)	94	33	41	78	24	–	34	81	27	0	36

The coverage of vegetation differed between catchments, and the dominant species and coverage of the stream sections for the three catchments are described below:

In catchment no 1, dominating species besides Common reed (*Phragmites australis*) were spiked water-milfoil (*Myriophyllum spicatum*) and water horsetail (*Equisetum fluviatile*). The vegetation was denser in the upstream compared to the downstream parts in August and September (Figure 3-44).

In catchment no. 2, the vegetation was dominated by common reed (*Phragmites australis*), water moss (*Fontinalis sp.*), unbranched bur-reed (*Sparganium sp.*), tufted loosestrife (*Lysimachia thyrsiflora*) and corn mint (*Mentha arvensis*). The abundance of vegetation varied along the stream. A large part of the channel close to the inlet to Bolundsfjärden lacked vegetation, whereas the areas upstream of Gällsboträsket were dominated by intense growth (75–100%) (Figure 3-45).

In catchment no. 8, the vegetation was dominated by common reed (*Phragmites australis*) and yellow iris (*Iris pseudacorus*). The yellow iris is a characteristic plant for eutrophic conditions. In contrast to catchment no. 1, the vegetation was denser in the downstream part (5–50%) than in the upstream part (single plants <5%) (Figure 3-46).

Biomass of primary producers in streams was not investigated but was estimated from the abundance. Data for each 10 meters from /Carlsson et al. 2005b/ was used to estimate biomass. First percentage coverage was estimated from the groups above to 0, 2.5, 27.5, 62.5 and 87.5% coverage. For each location the dominating species was assumed to be the only species in that 10 meter section. The biomass of dominating species was taken from investigations in the Forsmark lakes or from literature according to Table 3-23. The biomass in each 10 m section was then calculated as the percentage coverage multiplied with the biomass of that species (at 100% coverage).The mean biomass of all 10 meter sections was assumed to be the mean biomass of primary producers in streams was calculated to be 35 g C m^{-2} (median 12 g C m^{-2}) the Forsmark streams. This of course is a very rough estimate but gives an idea of order of magnitude.

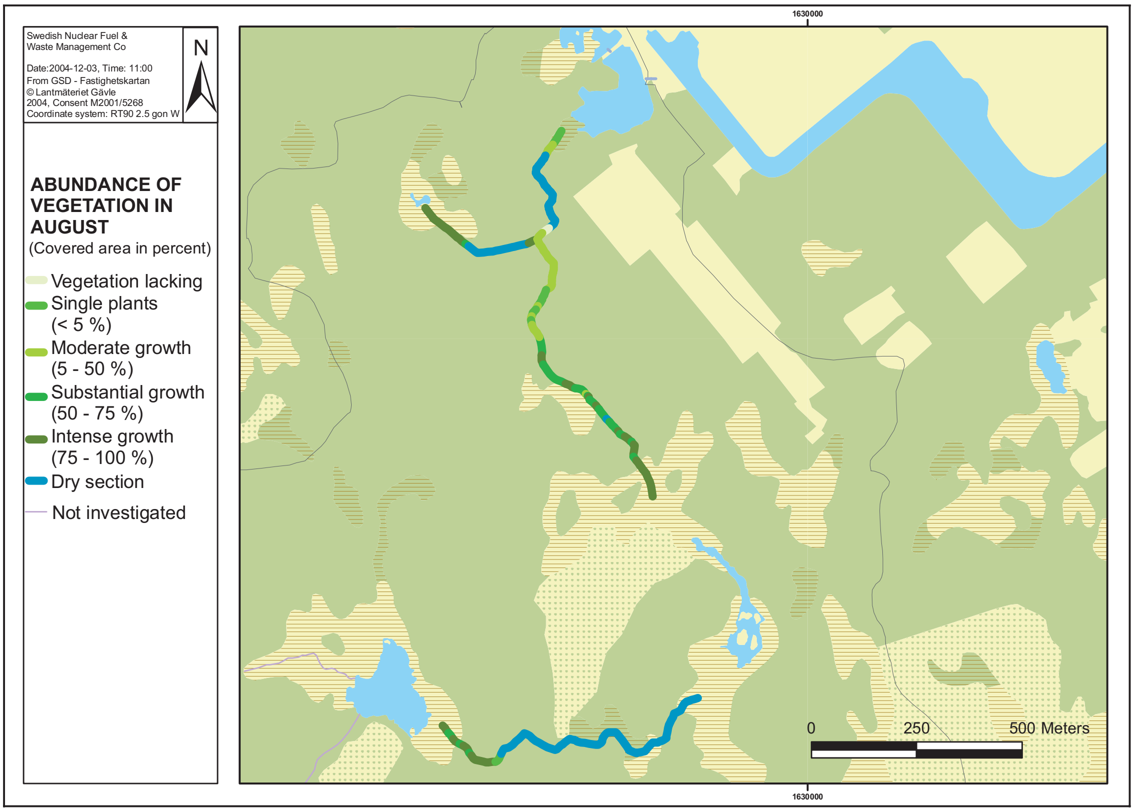

***Figure 3-44.** Vegetation abundance in the stream of catchment Forsmark 1 in late summer.*

Table 3-23. Biomass estimates of different macrophytes present in the Forsmark streams.

Species	Biomass (g dw m^{-2})	Comment	Reference
Alisma planatago-aquatica	54	Assuming the same biomass as *Schoenoplectus lacustris*	Andersson et al. 2003
Carex sp.	40	Assuming a straw density of 100 straws m^{-2}. Within reported values from literature (see e.g. /Bernard and Solsky 1977, Solander 1983/ reporting values between 11–45 g dw m^{-2})	Aquilonius 2005
Equisetum fluviatile	34	From Lake Eckarfjärden in Forsmark	Andersson et al. 2003
Fontinalis antipyretica	245	Assuming a density of 100 individual m^{-2}.	Aquilonius 2005
Galium palustre	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Glyceria fluitans	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Hottonia palustris	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Hydrocharis morsus-ranae	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Iris pseudacorus	54	Assuming the same biomass as *Schoenoplectus lacustris*	Andersson et al. 2003
Juncus sp.	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Lemna minor	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Lycopus europaeus	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Lysimachia thyrsiflora	39	Assuming a straw density of 100 straws m^{-2}.	Aquilonius 2005
Mentha arvensis	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Myosotis laxa	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Peusedanum palustre	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Phalaris arundinacea	40	Assuming the same biomass as *Carex sp.*	Aquilonius 2005
Phragmites australis	481	Assuming a density of 67 straws m^{-2}, i.e. the sum of phragmites and typha in the reed belts around Lake Eckarfjärden in Forsmark	Andersson et al. 2003
Potamogeton polygonifolius	380		Owens and Edwards 1961
Ranunculus aquatilis var. Diffusus	250	Mean of the range presented by the reference	Owens and Edwards 1961
Schoenoplectus lacustris	54	From Lake Eckarfjärden in Forsmark	Andersson et al. 2003
Sparganium sp.	54	Assuming the same biomass as *Schoenoplectus lacustris*	Andersson et al. 2003
Typha sp.	840	Assuming a density of 67 straws m^{-2}, i.e. the sum of phragmites and typha in the reed belts around Lake Eckarfjärden in Forsmark	Andersson et al. 2003

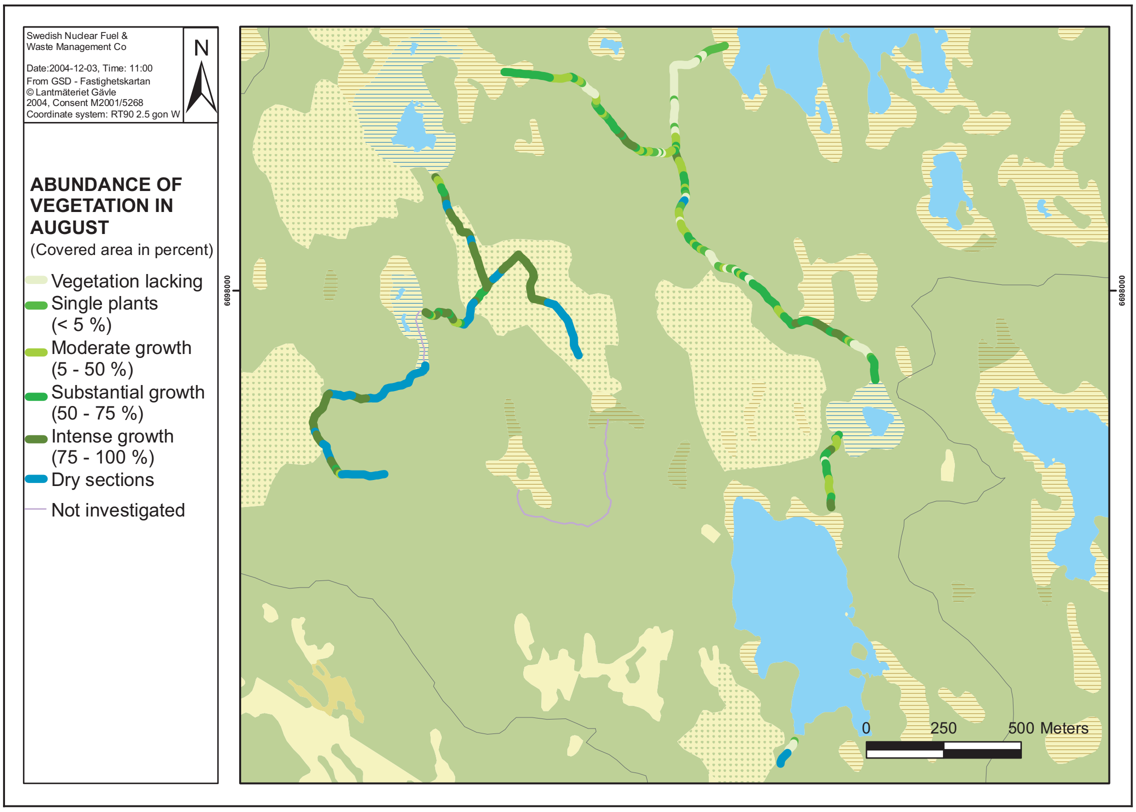

***Figure 3‑45.** Vegetation abundance in the stream of catchment Forsmark 2 in late summer.*

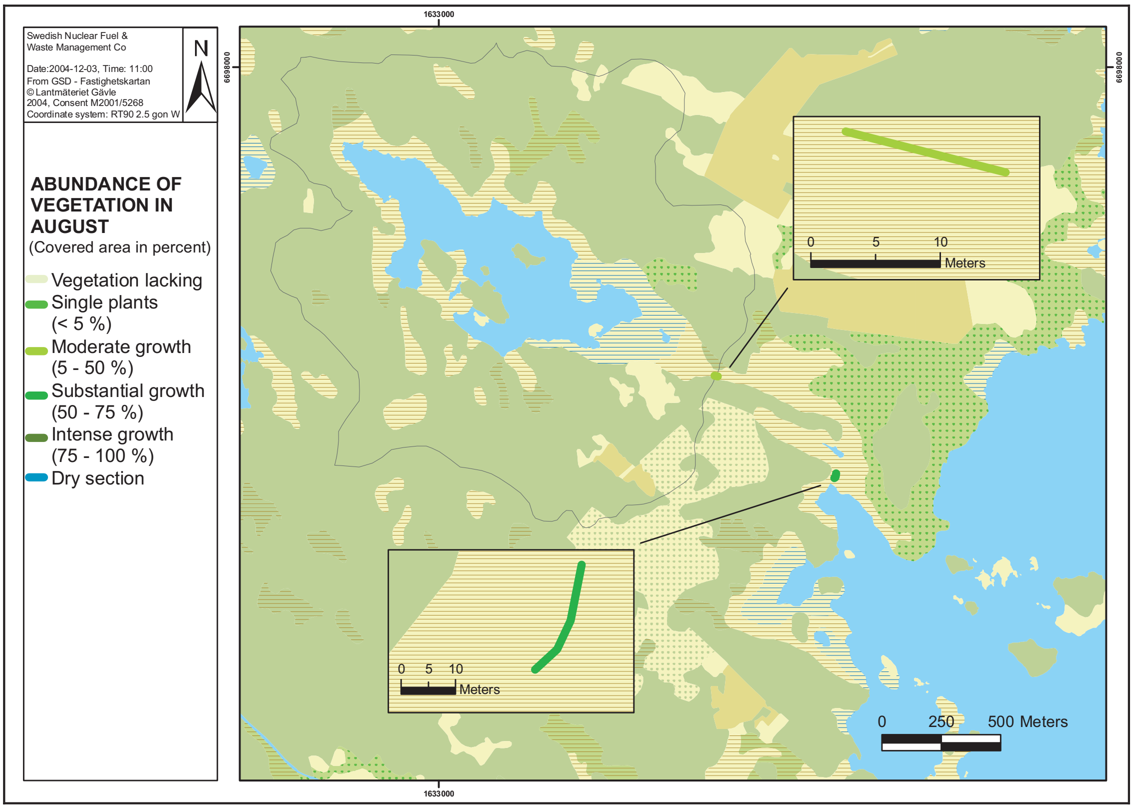

***Figure 3‑46.** Vegetation abundance in the channel downstream of catchment Forsmark 8 in late summer.*

Biomass of consumers

The small and sometimes dry streams of the Forsmark area cannot sustain a stationary ***fish*** population. Instead, the streams may function as feeding areas and/or channels for migration of fish during times of the year when there is enough water. Fish migration was quantified during the period from the 4th of April to 12th of May 2004 in the outlet stream from Norra bassängen and in one of the inlet streams to Bolundsfjärden (main inlet) /Loreth 2005/. Fish were caught with a fyke-net that catches all fish moving upward in the stream. There was a large migration of sexually mature fish from the Baltic Sea to Norra Bassängen in the spring. Altogether 18,567 fishes were caught migrating from the coast (Asphällsfjärden) to Norra Bassängen. Four species were caught: ruffe (*Gymnocephalus cernua*), roach (*Rutilus rutilus*), perch (*Perca fluviatilis*) and pike (*Esox lucius*). In number of individuals, ruffe clearly dominated the migration (12,394), followed by roach (4,704), perch (1,257) and pike (212). A small number of fish (129) were caught in the inlet to Bolundsfjärden and many of these were sexually immature. Thus, there was no significant spawning migration to areas upstream of Bolundsfjärden, indicating that spawning of migratory fish takes place predominantly in Norra Bassängen and Bolundsfjärden.

The outlet from Fiskarfjärden is a short stretch, more like a reed wetland than a stream. A small bridge crosses the stretch and under this a small pond of water is created when the area dries out. Observations of fish in this pond indicate that there are fish in the stream stretch and that migration may occur during wetter periods, i.e. when the small pond is in contact with the sea and Fiskarfjärden.

The biomasses of ***bacteria***, ***zooplankton*** and ***benthic fauna*** in the streams in Forsmark were not investigated. The bacterial biomass in streams can be high, especially in small streams that receive high inputs of allochthonous carbon sources /Wetzel 2001/. The zooplankton biomass in small streams is generally lower than in rivers, which in turn tend to have a lower zooplankton biomass than lakes /Wetzel 2001/. Moreover, the zooplankton biomass tends to be positively correlated to the phytoplankton chl *a* biomass. Thus, the low chl *a* concentrations in the streams in the area indicate that the zooplankton biomass was also low. Macroinvertebrates larger than 0.5 mm, particularly insects, can be important components of streams /Wetzel 2001/. However, benthic fauna may differ considerably between different streams depending on stream size, substrate, temperature, oxygen etc, and it is therefore difficult to estimate the biomass from literature studies. The fact that many of the streams are dry for long periods of the year indicates that the biomass of benthic fauna should be low.

Primary production

No estimations of primary production have been performed in the Forsmark streams. Instead, production of macrophytes can be assumed to equal the maximum biomass estimated from abundance above.

3.10.3 Threatened species in lakes and streams

Three species listed on the Swedish red list 2010 have been found in the limnic ecosystems in Forsmark; pool frog (*Rana lessonae*), common otter (*lutra lutra*) and Northern crested newt (*Triturus cristatus*). Pool frogs are present in some of the smaller ponds in the Forsmark area but do not occur in the lakes that contain fish since they cannot coexist with fish. Common otter has been seen close to SFR and Northern crested newt has been found in rock pools in the area. Some species found in Forsmark that was classified as threatened in the Swedish red list 2005 are now, in the red list 2010, classified as having robust populations. These species are: *Chara intermedia* (mellansträfse), *Hirudo medicinalis* (blodigel), *Leptocerus tineiformis* (en art av trollsländor), *Oecetis furva* (en art av trollsländor) och *Aplexa hypnorum* (Stor blåssnäcka).

3.10.4 Edible biota in lakes and streams

It is of importance for the safety assessment to estimate the production of edible biota. Today, the use of lake biota is assumed to be negligible as fishing is assumed to take place predominantly in the coastal marine areas. Nevertheless, the production of food that can be sustainably produced by the limnic ecosystem has been estimated to provide input data for the models of the safety assessment, since the future usage of the lakes as food source may be higher than today.

Food production is categorized as food normally consumed and edible products /SKB 2006a/. Food normally consumed for a lake includes fish, while edible products are everything that has some potential to be consumed by humans. Edible products could be worms, larvae, molluscs as well as fish etc above a certain practical size. Production is estimated as the weight of organic carbon (m^{-2} $year^{-1}$). This partly compensates for the energetic quality of food as structural components such as bones, shells etc which normally are not eaten also contain a low fraction of organic carbon.

In SR-Can, production was estimated for species or taxa where biomass was quantified in the site investigations. Production for most species was estimated by means of production per biomass ratios (P/B) from the literature. Some estimates (for e.g. fish) were based on calculations of the mass balance from metabolic demands and consumption using literature values /Kautsky 1995, Lindborg 2005/. The results in SR-Can was that the production of normally eaten products (here fish) was 4 g C m^{-2} $year^{-1}$ /SKB 2006c/. This estimate was used as the food production in the SR-Can safety assessment.

However, when this value was compared with the estimates of yields of fish as food from lakes, it was unrealistically high since yield in other studies are about 0.03 to 0.17 g C m^{-2} $year^{-1}$ (calculated from /Degerman et al. 1998/). This value was considerable lower than in SR-Can and cannot be attributed to the fact that SR-Can considers all fish while the estimated yields consider only fish normally fished for food. The fish production figures were reviewed and production was estimated using P/B ratios instead.

The P/B ratios are dependent on fish size (weight and length), and an allometric relationship has been established from studies of 79 freshwater species in Canada /Randall and Minns 2000/ Several of the fish species are similar to the Scandinavian species, and as this paper and other papers show, the P/B ratio is well correlated to size for most animals /Banse and Mosher 1980, Downing and Plante 1993, Randall and Minns 2000/.

Biomass of fish was estimated from catch of unit effort (see Section 3.10.1) and using conversion from wet weight to dry weight (0.2 from site investigations and literature /Hannu and Karlsson 2006, Kautsky 1995/) from dry weigh to carbon (0.44 using site data /Hannu and Karlsson 2006/). The maximum lengths of the fish species caught in the surveying gillnets were taken from the site study at Forsmark /Borgiel 2004b/. These ranges were compared with the data from /Randall and Minns 2000/ and for each species a mean P/B was estimated for this range (Table 3-24). This P/B ratio was multiplied by the estimated biomass per m^2 to obtain the area-specific fish production for each tabulated species in each of the studied lakes: Eckarfjärden, Fiskarfjärden, Bolundsfjärden and Gunnarsbo-Lillfjärden. The total sum of fish production for each lake was used to obtain an average fish production estimate for the area, which is 0.5 g C m^{-2} $year^{-1}$. This estimate is one order of magnitude lower than the estimate in SR-Can and considerably higher than the maximum generic estimates by /Degerman et al. 1998/. Some of the differences can be explained as our data also includes fish that are not popular food species, which is evident from Table 3-24. Moreover, the sustainable yield from a lake must be less than the production, to compensate for natural mortality. Different sources suggest that between 10 and 75% of the fish production can be sustainably harvested /Alanärä and Näslund 1995, Degerman et al. 1998, Näslund et al. 2000, Waters 1992/. However, it seems that the higher figure 75% is only valid an overestimate since severe effect on fish populations has been noted at much lower catches and /Näslund et al. 2000/ and /Waters 1992/ states that 50% is the highest possible sustainable yield for a long time sustainable fish population. Since over-fishing leads to reduced catches for long time afterwards we have chosen chosen a 50% cath of fish population to illustrate maximum annual yield. This corresponds to 0.27 g C m^{-2} y^{-1} and is assumed to be the maximum sustainable yield of fish from the Forsmark lakes.

Table 3-24. Biomass, B (g C m^{-2} $year^{-1}$), and production, P (g C m^{-2} $year^{-1}$), of different fish species in Forsmark area, based on average P/B ratios (1/y) of size range from /Randall and Minns 2000/. Biomass and size estimates from /Lindborg 2005/ and /Borgiel 2004b/, respectively.

Species	Size length (mm)	P/B	Eckarfjärden		Fiskarfjärden		Bolundsfjärden		Gunnarsbo-Lillfjärden		Mean
			B	P	B	P	B	P	B	P	P
Roach *Rutilus rutilus*	200–300	1.0	0.23	0.23	0.14	0.13	0.14	0.13	0.00	0.00	0.12
Tench *Tinca tinca*	500–600	0.3	0.42	0.14	0.25	0.08	0.29	0.09	0.00	0.00	0.08
Perch *Perca fluviatilis*	300–400	0.5	0.26	0.14	0.17	0.09	0.19	0.10	0.33	0.17	0.12
Pike *Esox lucius*	700–1,300	0.2	0.13	0.03	0.01	0.00	0.01	0.00	0.00	0.00	0.01
Ruffe *Gymnocephalus cernuus*	100–200	1.5	0.001	0.002	0.00	0.00	0.01	0.01	0.00	0.00	0.01
Crucian carp *Carassius carassius*	250–500	0.5	–	–	0.76	0.41	0.07	0.04	0.59	0.32	0.19
Total			1.04	0.53	1.33	0.72	0.70	0.38	0.92	0.49	0.53

Additionally a future potential food item in this area could be crayfish. There are no crayfish in the lakes studied today at the sites, but future lakes could contain them. The generic yield of a good crayfish lake is about 50 kg ha^{-1} /Fiskeriverket 2003/, which corresponds to a production of 0.4 g C m^{-2} $year^{-1}$. Thus, a maximum total food production (i.e. both crayfish and fish) from a Forsmark lake is less than 0.7 g C m^{-2} $year^{-1}$.

If the range is extended to other theoretical food items, molluscs and insect larvae could be eaten. There is no evidence that insect larvae from aquatic habitats are eaten on a regular basis, while molluscs are at least utilized in marine environments. Freshwater mussels of the family Unionidae (e.g. *Anodonta anatina*, duck mussel, sw. *allmän dammmussla*) are abundant in the lakes, although there are no biomass estimates for the lakes in Forsmark. Comparing with production in the River Thames, a theoretical upper estimate of production is 132 g fw ha^{-1} y^{-1} /Negus 1966/. The abundance of mussels in the Thames is about 100 times higher compared with semi-quantitative estimates from Lake Mälaren in Sweden /Lundberg and Proschwitz 2007/. Thus, probably a very high estimate of the production of large molluscs is 0.3 g C m^{-2} $year^{-1}$. However, it is not likely that freshwater mussels will be eaten. Firstly, it does not taste good, and secondly, the effort required to collect the mussels is considered greater than that required to collect mussels from the nearby coastal areas. Even in other parts of the world where other species of freshwater mussels have been consumed, in the past, the contribution of freshwater mussels to total diet has been small due to low energy input from the mussels /Parmalee and Klippel 1974/.

Combining the production of fish and crayfish, which seem to be the only realistically utilised food products from limnic ecosystems, the maximum production of food from lakes similar to the present and future lakes in the Forsmark area and is estimated to less than 0.9 g C m^{-2} $year^{-1}$.

3.10.5 Chemical characteristics of biota

The chemical composition of biota in the Forsmark lakes has been investigated /Hannu and Karlsson 2006/. In total, 23 samples from limnic environments were analyzed (Table 3-25). In addition to the content of macronutrients (carbon, nitrogen and phosphorus), the concentrations of 61 other elements in biota were also determined.

Since all the lakes in the area are oligotrophic hardwater lakes with similar characteristics, and as the number of analyzed samples is restricted, data is presented here per functional group, irrespectively of from which lake the samples were collected. The concentrations of carbon, nitrogen, phosphorus, iodine and uranium are presented in Table 3-26. The compiled data for all analyzed elements are

Table 3-25. Description of biological samples analyzed for elemental composition /Hannu and Karlsson 2006/. "repl." denotes number of replicate samples.

	Sampling site/ ID code	Number and description of samples	Sample state before analysis
Fish	Bolundsfjärden AFM000050	Benthivorous fish: ruffe 1 repl.[1] tench 3 repl. Piscivorous fish: pike 1 repl.	Frozen
	Eckarfjärden AFM000010	Planktivorous fish: small roach 1 repl.[2] Benthivorous fish: tench 3 repl. Piscivorous fish: pike 2 repl.	
	Fiskarfjärden AFM000051	Planktivorous fish: small roach 1 repl.[3] Benthivorous fish: tench 3 repl. Piscivorous fish: pike 1 repl.[4]	
Macroalgae	Bolundsfjärden AFM000050	3 repl. (*Chara tomentosa*)	Dried
	Fiskarfjärden AFM000051	1 repl. (*Chara tomentosa*)	
Microalgae	Eckarfjärden PFM002502	Algal mat 1 repl.	Freeze-dried
Benthic fauna (mussel)	Bolundsfjärden AFM000050	3 repl. (*Anodonta sp.*)[5]	Frozen

[1] 6 individuals
[2] 18 individuals
[3] 16 individuals
[4] 5 individuals
[5] 2 individuals, muscle only.

presented in Appendix 10, while primary data are provided in /Hannu and Karlsson 2006/. For many of the trace elements (and sometimes also for other elements), the results of the analyses were below the detection limit. In these cases, a value equal to half of the detection limit was used in the calculation of mean concentrations. The number of samples varied from one to at most 15.

The carbon content expressed as g C gdw^{-1} was relatively constant among different functional groups and varied only by a factor of two. The carbon content was lowest in macroalgae (*Chara sp.*) and highest in fish.

Nitrogen and phosphorus concentrations were also lowest in macroalgae and highest in fish. High concentrations of phosphorus were also noted in benthic fauna (mussels). Differences in concentrations between functional groups were greater for nitrogen than for carbon, and these differences were even more pronounced for phosphorus. The reported concentrations of nitrogen and phosphorus in the macroalgae *Chara sp.* agrees well with values reported by /Pereyra-Ramos 1981/.

Two elements which are not main constituents of biota are included in Table 3-26: iodine and uranium. For both of these elements, the concentrations show an opposite distribution to C/N/P, with the highest concentrations in producers, somewhat lower concentrations in benthic biota and the lowest concentrations in fish. The concentration of uranium is very high in microalgae. However, this group is represented by only two samples with high variation, and the figure should therefore be used with caution. However, both these values are much higher than those recorded for any of the other groups. As uranium is toxic to biota, one possible explanation for the lower concentrations in higher biota such as fish could be an active avoidance of this element, either through blocking of uptake and/or through effective excretion. It should be noted that all but one iodine concentration reported for fish were below the reported detection limit. Two of the concentrations of uranium in fish were below the detection limit (see footnotes in Table 3-26). A comparison between these data and corresponding data for the Laxemar-Simpevarp area is made in Section 4.10.4.

Table 3-26. Concentrations of a number of selected elements in biological samples from the Forsmark lakes. Samples from different lakes have been pooled in order to present the results for functional groups. Data from /Hannu and Karlsson 2006/ and /Strömgren and Brunberg 2006/.

Element	Sample type	N	Mean	Median	Min.	Max.	SD
Total carbon (g/kg dw)	Microbial mat	1	380	380			
	Macroalgae	4	268	250	240	330	41.9
	Total producers	*5*	*290*	*250*	*240*	*380*	*62.0*
	Benthic fauna	3	340	340	340	340	0
	Planktivorous fish	4	440	440	440	440	0
	Benthivorous fish	12	445	450	430	460	12.4
	Piscivorous fish	6	432	430	420	450	9.83
	Total consumers	*25*	*428*	*440*	*340*	*460*	*35.1*
Total nitrogen (g/kg dw)	Microbial mat	1	37.3	37.3			
	Macroalgae	4	6.83	6.75	6.20	7.60	0.591
	Total producers	5	12.9	6.90	6.20	37.3	13.6
	Benthic fauna	3	73.7	73.0	71.0	77.0	3.06
	Planktivorous fish	4	158	140	140	213	36.3
	Benthivorous fish	12	116	133	64.1	148	30.3
	Piscivorous fish	6	142	144	130	150	6.73
	Total consumers	*25*	*124*	*140*	*64.1*	*213*	*34.9*
Total phosphorus (g/kg dw)	Microbial mat	2	0.847	0.847	0.546	1.15	0.847
	Macroalgae	4	0.525	0.496	0.479	0.629	0.525
	Total producers	*6*	*0.632*	*0.523*	*0.479*	*1.15*	*0.632*
	Benthic fauna	3	28.4	27.5	19.6	38.2	28.4
	Planktivorous fish	2	10.3	10.3	10.0	10.6	10.3
	Benthivorous fish	10	10.8	10.6	9.39	12.3	10.8
	Piscivorous fish	4	13.3	13.6	12.0	14.1	13.3
	Total consumers	*19*	*14.1*	*11.9*	*9.39*	*38.2*	*14.1*
Iodine (mg/kg dw)	Microbial mat	1	6.04	6.04			
	Macroalgae	4	7.29	6.15	5.58	11.3	2.69
	Total producers	*5*	*7.04*	*6.04*	*5.58*	*11.3*	*2.40*
	Benthic fauna	3	4.4	4.7	3.8	4.7	0.49
	Planktivorous fish	2	0.275[1]	0.275[1]	0.250[1]	0.300[1]	0.035[1]
	Benthivorous fish	10	0.205[2]	0.200[2]	0.200[2]	0.250[2]	0.016[2]
	Piscivorous fish	4	0.40[3]	0.20[3]	0.20[3]	1.0	0.40[3]
	Total consumers	*19*	*0.92*	*0.20*	*0.20*	*4.7*	*1.6*
Uranium (mg/kg dw)	Microbial mat	2	37	37	2.9	70	48
	Macroalgae	4	0.75	0.69	0.62	0.98	0.16
	Total producers	*6*	*13*	*0.84*	*0.62*	*70*	*28*
	Benthic fauna	3	0.27	0.26	0.21	0.33	0.058
	Planktivorous fish	2	0.0017[4]	0.0017[4]	0.00030[4]	0.0030[4]	0.0019[4]
	Benthivorous fish	10	0.0012[5]	0.00055[5]	0.00010[5]	0.0051[5]	0.0015[5]
	Piscivorous fish	4	0.00040	0.00040	0.00010	0.00070	0.00024
	Total consumers	*19*	*0.043*	*0.00060*	*0.00010*	*0.33*	*0.10*

[1] Both values below detection limit, varying between <0.5 and <0.6 mg/kg dw.
[2] All 10 values below detection limit, varying between <0.4 and <0.5 mg/kg dw.
[3] 3 of 4 values below detection limit (<0.4 mg/kg dw).
[4] Value below detection limit (analytical result: <0.0006 mg/kg dw).
[5] One value below detection limit (<0.0006 mg/kg dw).

3.11 Land use and human impact

The streams in the Forsmark area are greatly affected by human activities, whereas most lakes are relatively unaffected by human impact, although there are examples of lowering of the lake levels. Human settlement can affect limnic systems by e.g. water use and pollution. However, the population in the Forsmark area is small today.

3.11.1 Human impact on lakes

The largest human impact on lakes in the area has been to Gunnarsbo-Lillfjärden. According to /Brunberg and Blomqvist 1998/, the lake was isolated from the sea in 1970–72 (before the construction of the nuclear power plants at Forsmark). During the construction of the nuclear power plant, parts of the lake were filled in with construction material and a small road was constructed through the original lake basin, separating the lake into a north and a south basin. Water draining the catchment enters the northern basin, and drainage from the northern to the southern basin is channelled through a pipe, but diffuse drainage may also occur through the construction material. The main damage to the lake seems to be that the lake has been isolated from its natural outlet, and the water from the southern basin drains through pipes under the adjacent road. The altitude difference between the outlet pipe and the sea probably makes it difficult for aquatic organisms to migrate between the Baltic Sea and the lake basins /Brunberg et al. 2004a/.

The water level in Eckarfjärden has been lowered by dredging of the outlet stream, thereby lowering the lake threshold /Brunberg and Blomqvist 1998/.

Due to the special characteristics of the lakes (shallow water depth and thick loose sediments), they are not used for bathing. Some fishing may occur, but considering the closeness to the coastal areas, our opinion is that this activity has a very limited impact (if any) on the lake ecosystem. In Section 3.10.3 the amount of biota in lakes that can theoretically be used as food is described. This figure is certainly larger than actual food outtake from the lakes today. Theoretically lake organisms could also be harvested as food supply to cultivated animals but this does not occur today and is an unlikely scenario also for the future.

3.11.2 Human impact on streams

Most of the stream stretches in catchments 1 and 2 are affected by human activities (Table 3-27 /Carlsson et al. 2005/). Most of the streams consist of man-made ditches, and the original channels have most probably been straightened. The streams in catchment 1 are less affected than those in catchment 2. Beside the pipes in Gunnarsbo-Lillfjärden, there are three more pipes under small roads in catchment 1 and another 5 pipes in catchment 2.

A stretch of c. 130 m along the stream in catchment 2 is lined with wooden poles on both sides (see photo in Figure 3-47). We can only speculate about the reason, but one possible explanation is that it is some kind of structure previously used for fishing in the area. Another possible explanation is that the structure was built to brace the stream banks. Today the streams in the area are too small to be of any importance for fishing.

Table 3-27. Technical encroachments in the investigated stream stretches in the Forsmark area (%) From /Carlsson et al. 2005/.

Catchment	1			2				1 and 2			
Stream order	1	2	total	1	2	3	total	1	2	3	total
Natural, no excavation	–	21	18	10	–	–	4	9	9	0	9
Moderate excavation	–	25	21	2	12	–	7	2	17	0	11
Substantial excavation	100	54	60	88	88	100	89	90	73	100	80

Figure 3-47. *Wooden poles along the stream in catchment Forsmark 2.*

3.12 Streams and lakes in the region

This section describes the lakes and streams in the region in order to put the local conditions in the Forsmark area into a regional perspective (northern Uppland). The Forsmark area belongs to catchment 54/55 "Between Tämnarån and Forsmarksån". Data from two streams and a number of lakes in the three catchments 54/55, 55, and 56 are discussed in this section (Figure 3-48). In addition a large lakes in Uppland County, Lake Erken, is described to illustrate differences between the small Forsmark lakes and larger lakes but also to illustrate the possible functioning of some of the large lakes that will be formed in Forsmark in the future (see also Chapter 8).

3.12.1 Lakes

According to the SMHI system, the catchment situated west and north of the Forsmarksån catchment is called catchment 54/55 "Between Tämnarån and Forsmarksån" (Figure 3-48). The Forsmark area is part of this catchment and the lakes within catchment 54/55 are very similar to the lakes within the Forsmark area, i.e. most of them are oligotrophic hardwater lakes. Most of the lakes within the Forsmarksån catchment (55), on the other hand, are classified as brown-water lakes. Data for the lakes from these two catchments have been compiled in /Brunberg and Blomqvist 2000/ and are presented below. Data for the lakes within the catchment of Olandsån are described in /Brunberg and Blomqvist 1998/ and a summary of the information is presented below.

Lowering of water levels has been carried out for lakes in Uppland County, mainly during the 18th century when iron mills used the streams to supply hydropower to the mills, a practice that continued for more than 200 years. The main reason for lowering of lake levels in the county has been to gain new agricultural land. Compared to the rest of the county, lowering of lake water levels has been less extensive in the Forsmark area. The average lowering of the lake water levels caused by drainage in Sweden is 0.75 m, while the corresponding value for the lakes in the Forsmark area is 0.28 /Brunberg and Blomqvist 2000/.

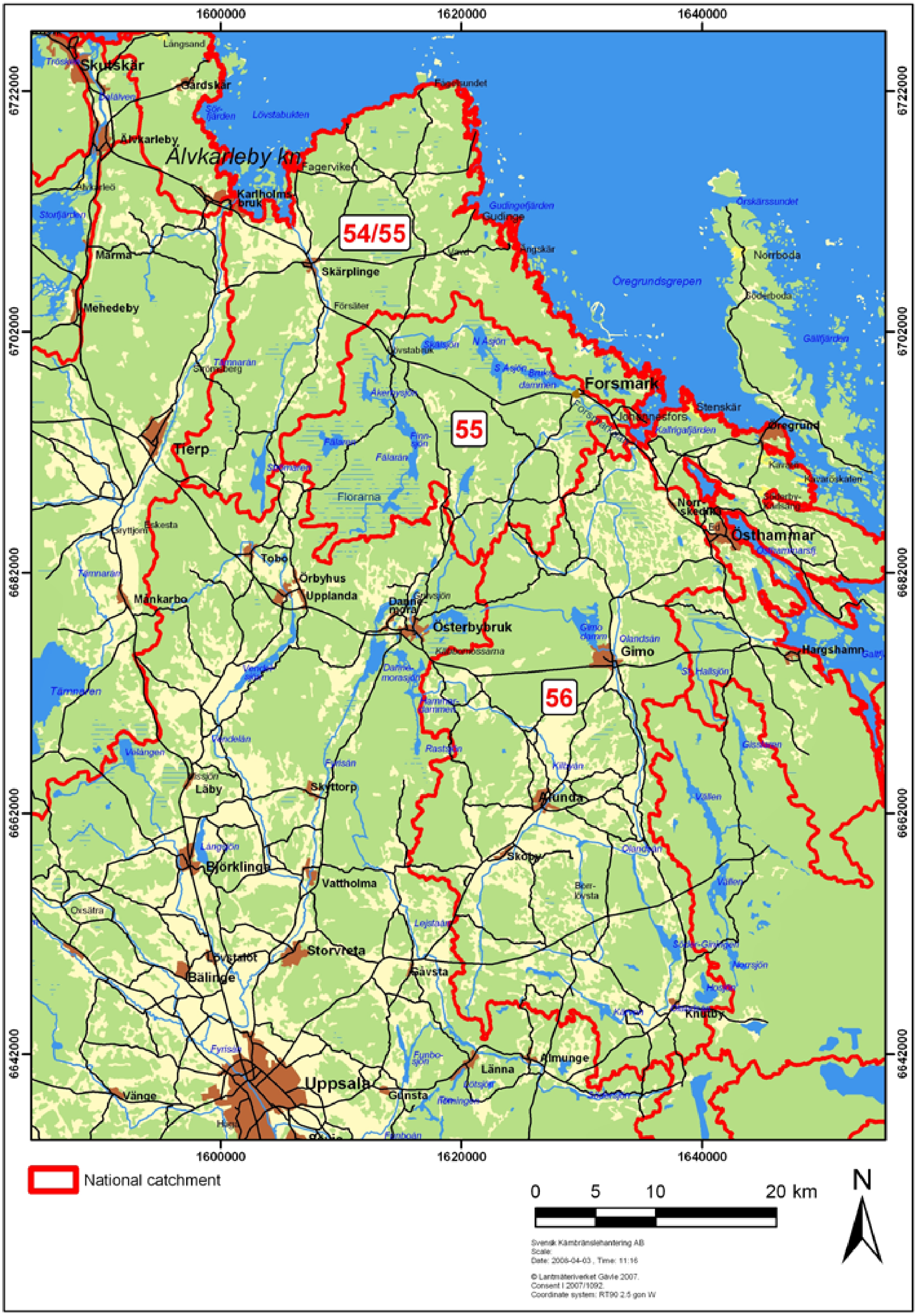

Figure 3-48. *National catchments in northern Upland according to the SMHI numbering system. The Forsmark area described in this report is part of catchment 54/55 "between Tämnarån and Stream Forsmarksån".*

Catchment 54/55 between Tämnarån and Forsmarksån – oligotrophic hardwater lakes

The lakes in catchment 54/55 are, like the lakes in the Forsmark area, characterized as oligotrophic hardwater lakes. A map showing the position of the lakes mentioned in the text is shown in Figure 3-49. The lakes are nutrient-poor and are very calcium-rich. The bedrock in the area is composed of granite and gneiss but covered with calcium-rich till and postglacial clays. The soils are easily weathered and contribute large amounts of dissolved salts to the surface waters. Phosphorus co-precipitates with calcium, leading to the nutrient-poor conditions in the oligotrophic hardwater lakes.

The lakes within this catchment are smaller, shallower and have smaller water volumes than the lakes in Uppsala County in general (Table 3-28). Their water retention time is also shorter. The Forsmark lakes belong to the catchment 54/55 and have similar area as the other lakes in the catchment but are somewhat shallower leading to smaller water volumes than in the rest of the catchment. Also the water renewal times are generally shorter in the Forsmark area than in the rest of the catchment (Table 3-28).

The catchments of oligotrophic hardwater lakes in catchment 54/55 are generally very small. The vegetation in the catchments is dominated by forest and wetlands and there is less intensive land use compared with the average situation in the county. This can be seen when comparing the percentage of the catchments consisting of wetlands and farmland, for example on average 4% are used as farmland in catchment 54/55 compared with 10% in the county (Table 3-29). Visible inlets as well as outlets are often more or less absent, unless drainage projects have been carried out in the catchment. Thus, much of the water transported through the catchments is more or less filtered through the surrounding wetlands before entering the lakes. Like the brown-water lakes in catchment 55, most of the oligotrophic hardwater lakes are surrounded by mires and common reed is often a dominant plant species along the shores.

The oligotrophic hardwater lakes in catchment 54/55 are well buffered and moderately nutrient-rich. The oligotrophic lakes are characterized by high conductivity and high concentrations of dissolved calcium and magnesium in the water. The amount of phosphorus transported to the lakes is limited, due to precipitation of calcium-rich particulate matter occurs due to both chemically and biologically induced processes. Nitrogen tends to be present in relatively high concentrations in the water, although concentrations of inorganic nitrogen in summer are low due to biotic uptake. The lakes have high concentrations of dissolved organic carbon, which is unusual in combination with their relatively moderate water colour /Brunberg and Blomqvist 2003/.The oligotrophic hardwater lakes within the catchment often experience oxygen deficit during the winter period (Table 3-30). When the water chemistry of the lakes is compared with that of the other lakes in the county, alkalinity, water colour and oxygen conditions are found to be quite similar, while lakes in catchment 54/55 are slightly less nutrient-rich compared with the average for the lakes in the county (Table 3-30).

Besides the lakes in the site investigation, another 5 lakes situated within the catchment 54/55 have been subject to standardized survey gillnet fishing /Brunberg and Blomqvist 2000/. Fish were caught in all lakes, and a total of 6 species were encountered: roach, Crucian carp, tench, perch, ruffe and pike (Table 3-31). The number of encountered species is thereby similar to the average for the lakes in the county (5.8). However, the catch per unit effort was lower in the oligotrophic hardwater lakes than in the average lake in the county. The lakes can be divided into two groups: one with low fish biodiversity and dominance by Crucian carp, and another group with a higher fish biodiversity. The lakes of the first class are smaller and shallower than the other lakes and the dominance of Crucian carp indicates severe oxygen deficiency in the water in the winter /Brunberg and Blomqvist 2000/. It seems that Crucian carp is more abundant in the oligotrophic hardwater lakes than in other lakes in the county.

Figure 3-49. *Lakes in the catchment 54/55 "Between Tämnarån and Forsmarksån".*

Table 3-28. Morphological parameters for lakes in three different catchments in northern Uppland, for lakes in the Forsmark area, and totally for all lakes in Uppland County. Data from [1]/Brunberg and Blomqvist 1998/ and [2](SKB site investigations, further described in Section 3.5). The lake in the Forsmark area belong to the catchment 54/55 but the presentation below of lakes in this catchment only includes data from 9 lakes derived from /Brunberg and Blomqvist 1998/ since by including the Forsmark data would give a strong bias to this smaller area.

Lake	Area (km²)	Average depth (m)	Max depth (m)	Volume (Mm³)	Theoretical water retention time, days
Lakes in the catchment between Tämnarån and Forsmarksån (54/55)[1] (oligotrophic hardwater lakes)					
Average	**0.14**	**1.0**	**1.8**	**0.155**	**194**
Median	0.07	0.9	1.7	0.066	229
N obs	11	9	9	9	9
Max	0.61	1.9	3.2	0.427	383
Min	0.03	0.5	0.9	0.022	1.2
Lakes in the catchment of Forsmarksån[1] (55) (brown-water lakes)					
Average	**1.30**	**1.5**	**2.6**	**2.14**	**69**
Median	1.14	1.5	2.7	0.999	31
N obs	14	11	12	11	11
Max	4.09	2.8	4	7.77	249
Min	0.09	0.5	1.2	0.17	2
Lakes in the catchment of Olandsån[1] (56)					
Average	**0.96**	**1.3**	**2.9**	**1.736**	**114**
Median	0.39	1.3	2.4	0.975	87
N obs	15	10	10.0	10	10
Max	3.02	1.5	5.9	6.1	273
Min	0.06	0.9	1.8	0.15	35
Lakes in the Forsmark area[2]					
Average	0.12	0.4	1.2	0.053	76
Median	0.05	0.3	1.0	0.018	44
N obs	25	25	25	25	25
Max	0.75	0.9	2.2	0.374	328
Min	0.01	0.1	0.4	0.002	5
Lakes in Uppland County[1]					
Average	1.04	1.98	3.8	2.35	263
Median	0.25	1.5	2.6	0.38	91
N obs	141	119	122	119	117
Max	36.7	22	52	47.8	6,954
Min	0.01	0.4	0.9	0.01	1

Table 3-29. Characteristics of the catchments of oligotrophic hardwater lakes in the catchment 54/55. From /Brunberg and Blomqvist 2000/.

Catchment	Area (km²)	Forest %	Wetland %	Farmland	Lakes %	Other land use %
Lake catchments in the catchment 54/55 (oligotrophic hardwater lakes)						
Mean	59	69	20	4	6	0
Median	15	69	20	2	6	0
Max	285	87	46	20	17	1
Min	0.22	50	5	0	0	0
N observations	29	29	29	29	29	29
Lake catchments in Uppsala County						
Mean	54	72	11	10	6	1
Median	9.9	74	8	5	5	0
Max	707	95	55	74	24	69
Min	0.22	14	0	0	0	0
N observations	142	142	142	142	142	142

Table 3-30. Water chemistry classification for lakes in the catchments 54/55, 55 and 56, and for lakes in the Forsmark area and in Uppland County. Data from /Brunberg and Blomqvist 2000/.

	Total P **µg L^{-1}**	**Alkalinity** **meq L^{-1}**	**Water colour** **mg Pt L^{-1}**	**Oxygen** **conditions**
	1=≤12.5 2=12.5–25 3=25–50 4=50–100 5=>100	1=>0.20 2=0.10–0.20 3=0.05–0.10 4=0.02–0.05 5=≤0.02	1=≤10 2=10–25 3=25–60 4=60–100 5=>100	1=small risk of low O2 2=risk of <5 mg O2/ 3=risk of <1 mg O2/ 4=risk of anoxic conditions
The lakes in the catchment of Forsmarksån[1] (brown-water lakes)				
Average	2.2	1.0	4.3	1.9
Median	2.0	1	4	2
Min.	2	1	4	1
Max.	3	1	5	4
No. of observations	12	13	14	13
Lakes in the catchment between Tämnaren and Forsmarksån (54/55) (including oligotrophic hardwater lakes)				
Average	2.1	1.0	3.5	3.1
Median	2	1	3.5	4
Min.	1	1	2	1
Max	3	1	5	4
No. of observations	8	10	10	7
Lakes in the catchment of Olandsån (56)				
Average				3.0
Median				4
Min.				9
Max.				4
No. of observations				1
Lakes in Uppland County				
Average	3.5	1.3	4.0	2.6
Median	3	1	4	2
Min.	2	1	1	1
Max.	5	5	5	4
No. of observations	105	121	131	107

Table 3-31. Data from standardized survey involving gillnet fishing in oligotrophic hardwater lakes of the catchment between Tämnarån and Forsmarksån. From [1]/Brunberg and Blomqvist 2000/, [2]/Borgiel 2004b/ and [3](Nordén, unpublished). Cr=Crucian carp, Pe=perch, Pi=pike, Ro=roach, Ru=ruffe, Rd=Rudd, Te=tench, Wh=white bream.

	Fish species	**CPUE** **No. of individuals**	**CPUE** **kg ww**	**Lake area** **ha**	**Mean depth** **m**
Catchment 54/55					
Storfjärden (Hållen)[1]	Cr, Pe, Pi, Ro,	18	2.2	11	0.6
Dalarna[1]	Cr, Pe, Ro, Ru	35	7.8	7	0.5
Käringsjön[1]	Cr	26	0.32	4	0.6
Västersjön (Stora Hållsjön)[1]	Cr, Pe,Pi, Ro, Ru	76	3.4	19	0.2
Strönningsvik[1]	Cr, Pe, Ro,	24	3.9	8	1.0
Eckarfjärden[2]	Pe, Pi, Ro, Ru, Te	63	3.7	28	0.9
Bolundsfjärden[2]	Cr, Pe, Pi, Ro, Ru, Rd, Te, Wh	29	2.5	61	0.6
Fiskarfjärden[2]	Cr, Pe, Pi, Ro, Ru, Te,	48	4.6	75	0.4
Gunnarsbo-Lillfjärden[2]	Cr, Pe, Ro	40	3.2	3	0.7
Labboträsk[3]	Cr	7	0.08	6	0.3

Fish species	CPUE No. of individuals	CPUE kg ww	Lake area ha	Mean depth m
Average	**37**	**3.17**	**22**	**0.6**
Median	32	3.30	9.5	0.6
Max	76	7.8	75	1.0
Min	7	0.08	3	0.2
N observations	10	10	10	10
Average Uppland County				
Lake size 0–10 ha	**44**	**2.62**		
Lake size 11–50 ha	**78**	**3.59**		
Lake size 51–150 ha	**130**	**4.36**		
Lake size > 150 ha	**88**	**3.63**		
Average Forsmark area (N=4)				
Mean for Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden	45	3.48		

Lakes in catchment 55 Forsmarksån – brown-water lakes

The lakes in catchment 55 are characterized as brown-water lakes, referring to their dark water colour. Brown-water lakes are characteristic of the boreal zone. The colour of the water stems from large amounts of dissolved organic matter in the form of humus, originating from the surrounding land in the catchment. Data from all lakes larger than 3 hectares is included in the following text. A map showing the locations of the lakes mentioned in the text is presented in Figure 3-50.

The catchments of the lakes vary considerably in size, but the median size of the catchments is larger than that of lake catchments in Uppsala County in general. The vegetation is dominated by forest. Wetlands contribute to a large part of the catchments (median 26%). The proportion of farmland is lower than in other parts of Uppsala County. The riparian zone of the lakes consists to a large extent of peatland, often in the form of mires, which are frequently flooded at high water flows. Common reed is often the dominant plant species along the shores.

The median surface area of the brown-water lakes in the Forsmarksån catchment (Table 3-28) is four times greater than that of the lakes in Uppsala County in general, and much greater than that of oligotrophic hardwater lakes in catchment 54/55. The mean depth is lower than the mean depth of lakes in the county, but larger than that of the Forsmark lakes. Hence, the brown-water lakes also have larger water volumes than the oligotrophic hardwater lakes. Because of their large catchments, the retention time of the brown-water lakes is shorter than that of both oligotrophic hardwater lakes and other lakes in the county. The short water retention time reflects the fact that the main stream passes through most of the lakes. Moreover, results from a few sediment investigations in lakes situated in the Forsmarksån catchment show that the lake sediments have a brown colour and are organogenic, with high C/N and C/P ratios. This indicates a large contribution by allochtonous material /Brunberg and Blomqvist 2000/.

The water chemistry in the brown-water lakes shows small differences between the different parts of the catchment. The water in the system has a relatively strong water colour and dominance of Ca^{2+} and HCO_3^- ions, which is typical for the brown-water lakes in lowland areas of Uppsala County in general /Brunberg and Blomqvist 2000/. Due to the large amounts of humic substances, brown-water lakes are typically high in total organic compounds (TOC), most of which are present as dissolved organic compounds (DOC). The phosphorus concentrations of the lakes in the catchment of Forsmarksån are usually moderately high (12.5–25 $\mu g\ P\ L^{-1}$). It is likely that a large part of the phosphorus is associated with dissolved organic compounds and thereby less available to the primary producers. The alkalinity is high and the oxygen situation during winter is normally good in most of the lakes (Table 3-30).

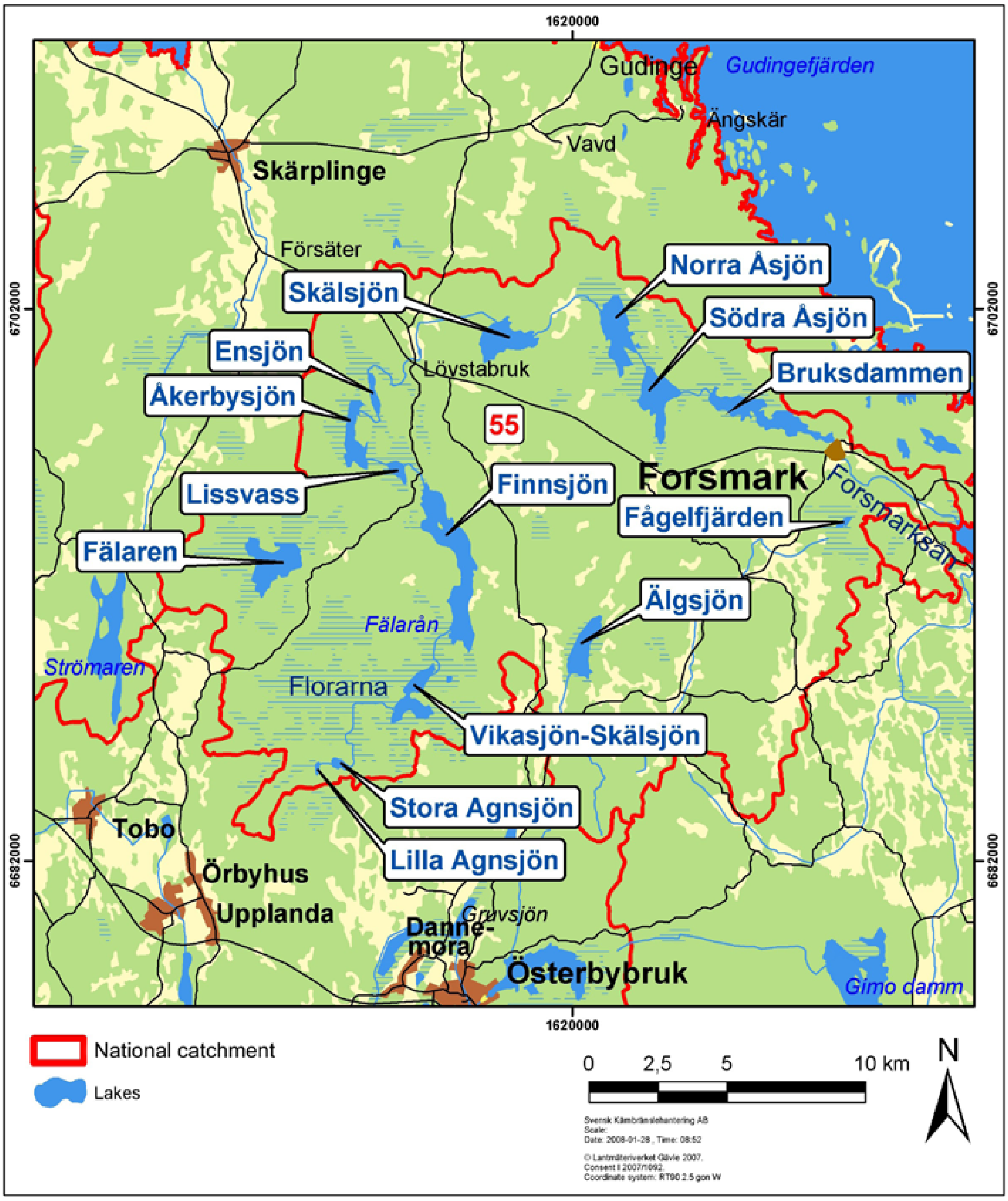

***Figure 3-50.** Lakes in catchment 55, Forsmarksån.*

According to a few studies of phytoplankton in lakes in the catchment of Forsmarksån, the biomasses were very low. Investigations of benthic fauna in Skälsjön, Lissvass, Ensjön and Åkerbysjön reported low biomasses. Chironomid larvae strongly dominated the species composition /Brunberg and Blomqvist 2000/. Twelve lakes in Table 3-32 have been subject to standardized gillnet fishing and fish were caught in all these lakes. A total of 9 species were encountered: pike, roach, perch, ruffe, bream, white bream, rudd, tench and Crucian carp. The average number of species per lake was 7.1. The results show a relatively diverse fish community, and the number of species caught was higher than the average for the county (5.8 species). On the other hand, the fish biomass and abundance was much lower than the county mean.

Table 3-32. Data from standardized survey involving gillnet fishing in lakes in the catchment of Forsmarksån (catchment 55). Pi=pike, Ro=roach, Pe=perch, Ru=ruffe, Br=bream, Wh=white bream, Rd=rudd, Te=tench, Cr=Crucian carp. From /Brunberg and Blomqvist 2000/.

	Fish species	CPUE No. of individuals	CPUE kg ww	Lake area ha
Catchment 55				
Bruksdammen	Pi,Ro,Pe,Ru,Br,Wh,Rd,Te,Cr	24	2.0	206
Södra Åsjön	Pi,Ro,Pe,Ru,Br,Wh,Rd,Te	34	1.8	198
Älgsjön	Pi,Ro,Pe,Rd,Te	49	2.2	117
Norra Åsjön	Pi,Ro,Pe,Ru,Br,Wh,Rd	51	1.3	177
Skälsjön	Pi,Ro,Pe,Ru,Br,Wh,Rd,Te,Cr	88	4.1	183
Ensjön	Ro,Pe,Ru,Br,Wh,Rd	38	1.2	34
Åkerbysjön	Ro,Pe,Ru,Br,Wh,Rd,Te	42	1.8	111
Lissvass	Pi,Ro,Pe,Ru,Br,Wh,Rd,Te	64	3.7	35
Finnsjön	Pi,Ro,Pe,Ru,Br,Wh,Rd,Te	57	1.6	409
Fälaren	Ro,Pe,Ru,Br,Wh,Rd,Te	18	1.2	205
Vikasjön-Skälsjön	Ro,Pe,Ru,Br,Wh,Rd	44	0.42	104
Stora Agnsjön	Ro,Pe,Ru,Br,Rd	32	1.7	24
Average		**45**	**1.92**	**150**
Median		43	1.75	147
Max		88	4.1	409
Min		18	0.42	24
N observations		12	12	12
Average Uppland County				
Lake size 0–10 ha		44	2.62	
Lake size 11–50 ha		78	3.59	
Lake size 51–150 ha		130	4.36	
Lake size > 150 ha		88	3.63	
Average Forsmark area				
Mean for Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden		45	3.48	

Lakes in catchment 56, Olandsån

The lakes in the catchment of Olandsån are larger and deeper than the oligotrophic hardwater lakes in the Forsmark area and therefore also have a much larger water volumes (Table 3-28). The catchments are also large, so the lakes have shorter water retention times than the lakes in catchment 54/55 and lakes in Uppland County in general. They are more similar to the brown-water lakes in the catchment of Forsmarksån. A map showing the position of the lakes mentioned in the text is presented in Figure 3-51.

The lakes show variable oxygen conditions: good oxygen conditions prevail in 2 lakes, while there is a risk of oxygen depletion beneath the ice during the winter period in 5 of the investigated lakes in the catchment (Table 3-30). Net fishing was performed in 10 lakes during 1991 (1992 for Vattenstasjön) (Table 3-33). In one of the lakes no fish were caught (Kolsjön), and one of the other not-investigated lakes (Markasjön) most probably has no fish according to /Brunberg and Blomqvist 2000/. Several of the other lakes have a diverse fish fauna. For lakes with fish, the average number of species per lake was 5.6, which is close to the average for the county (5.6). However, there was a large variation between lakes and number of species ranged from 1 to 9.

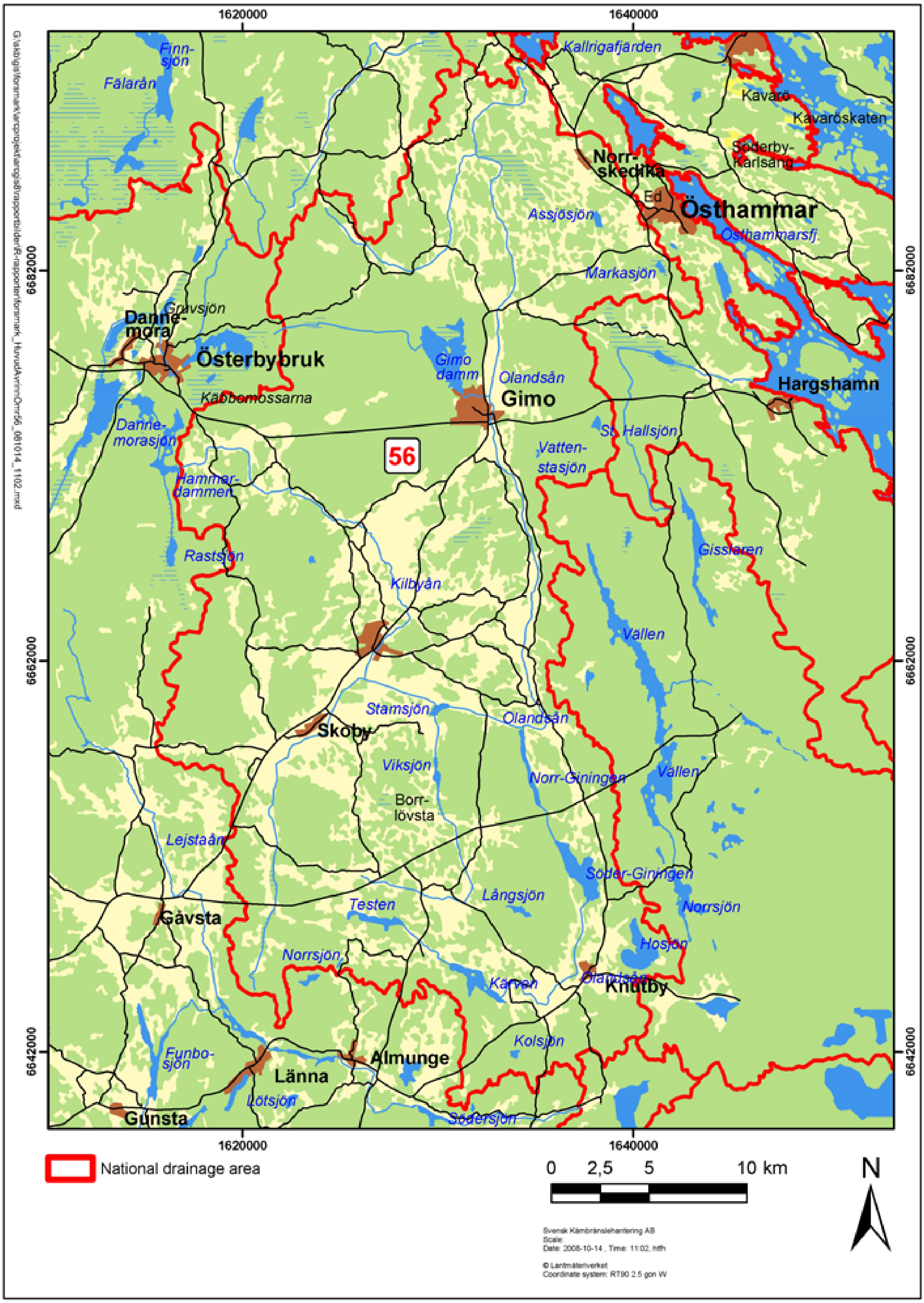

Figure 3-51. Lakes in the catchment of Olandsån.

Table 3-33. Fish data for some of the lakes in the catchment Olandsån. From /Brunberg and Blomqvist 1998/. Br=bream, Bu=burbot, Cr=Crucian carp, Ide=ide, Pe=perch, Pi=pike, Ro=roach, Ru=ruffe, Rd=rudd, Te=tench, Wh=white bream. The average represents the 10 lakes where fishing was not performed.

Lake	Fish species	CPUE No. of individuals	CPUE kg ww	Lake area ha
Markasjön*		*	*	18
Assjösjön	Cr, Pe, Pi, Ro, Te	58	6.33	25
Stora hallsjön	Pe, Pi, Ro	90.5	3.55	28
Gimo damm	Br, Cr, Pe, Ro, Rd, Ru, Te	66	3.44	297
Vattenstasjön	Cr	0.4	0.41	8
Stamsjön	Br, Ide, Pe, Ro, Rd, Te, Wh	17.7	1.8	45
Långsjön	Br, Pe, Pi, Ro, Rd, Ru, Te, Wh	43.8	2.6	31
Söder-giningen	Br, Cr, Pe, Ro, Rd, Ru, Te, Wh	160	9.03	303
Hosjön	Pi			
Kärven	Br, Bu, Cr, Pe, Pi, Ro, Rd, Ru, Te	62	3.9	186
Kolsjön	–	–	–	15
Testen	Br, Cr, Pe, Ro, Ru, Rd, Te	121.7	6.25	107
Average		**62**	**3.7**	**105**
Median		60	3.5	38
N obs		10	10	10
Max		160	9.0	303
Min		0	0	8
Average Uppland County				
Lake size 0–10 ha		44	2.62	
Lake size 11–50 ha		78	3.59	
Lake size 51–150 ha		130	4.36	
Lake size > 150 ha		88	3.63	
Average Forsmark area (N=4)				
Mean for Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden		45	3.48	

* most probably has no fish.

Deep eutrophic lakes in Uppland County used as reference of future deep Lakes in Forsmark

In order to characterise the deep eutrophic lakes that may be formed in the Forsmark area in the future, we have used data from two lakes situated in the Norrtälje area 60 km south of Forsmark; Lake Erken and Lake Limmaren. These two lakes are today situated at a level of 11.7 and 3.9 meters above the sea, respectively, thus at an altitude similar to that of many of the oligotrophic hardwater lakes and brown-water lakes described above and with a similar history of isolation from the Baltic Sea. A lot of data has been gathered about these two lakes. Lake Erken is well known from more than 50 years of limnological research, having a well-reputed limnological station (the Erken laboratory) situated on the shore. /Weyhenmeyer 1999/ has compiled limnological data from various sources regarding Lake Erken. The other lake, Lake Limmaren, has also been selected for several limnological studies, and has thereby been monitored for e.g. water chemistry parameters and plankton community composition. /Brunberg and Blomqvist 2000/ has made a thorough description of Lake Erken and Lake Limmaren summarising the studies performed in the lakes. Below follows a summary of knowledge from the lakes with a comparison to the Forsmark lakes. This summary, is unless otherwiae stated based on data from /Brunberg and Blomqvist 200 and references therein/.

The drainage area

The drainage areas of Lakes Erken and Limmaren are dominated by forest, while farmland makes minor contribution. This is similar to the other lakes in the county as well as the Forsmark lakes. In contrast to the other lakes described, wetland is almost totally lacking. Instead a large percentage of the catchments are made up by the lake area; 20 and 26%. The catchments of Lakes Erken and Limmaren, respectively, differ substantially in size, but so does also the size of the lakes (Tables 3-34 and 3-35). The geology is similar in both drainage areas and also similar to that of the Forsmark area. Thus, the bedrock is dominated by granites and gneisses and is covered by lime-rich till of glacial origin. Minor areas, both in the lake basins and on land (coinciding with agricultural areas), have glacial and post-glacial clay deposits.

In contrast to the lakes in the Forsmark area, Lake Erken and Lake Limmaren are not surrounded by a thick reed belt. Instead, both the shores of Lake Limmaren and Lake Erken are characterised by very narrow riparian zones, in most parts consisting of a thin zone of alder trees forming a border between mature coniferous forest and open water or a thin belt of Phragmites. Particularly in Lake Erken, which has the characteristic vegetation-free wind-exposed littoral zone in large parts of the main basin, there is a more or less direct transition from forest to open water. In Lake Limmaren, which is smaller and does not have so much of the wind-exposed habitat, the transition from mature forest to a Phragmites-belt of 10–30 m thickness is equally sharp. Due to the lowering of the water level, and particularly in Lake Erken, wetlands in the form of alder forest interspersed with Phragmites constitute a major share of the riparian zone in sheltered bays along the Western and Southern shores.

Lake bathymetry and retention time of water

In comparison with other lakes in Sweden (SMHI 1983) both Lake Limmaren and Lake Erken can be classified as large, both belonging to the 10% largest of the more than 50,000 lakes in the country. Lake Erken, with an area of 24 km^2 (Table 3-35), in fact belongs to the 380 largest lakes in the country. But also Lake Limmaren with and area of 5.9 km^2 is considerably larger than the lakes in Forsmark today (mean area 0.12 km^2 max 0.75 km^2). Also in comparison with the future lakes in Forsmark these lakes are somewhat larger, the largest future lake will be 2.7 km^2 at the start of the lake stage (Basin 117, see Chapter 8). However, as the future lakes will contain profundal zones and are several times larger than the lakes today, the future lakes will most probably more resemble Lake Erken or Lake Limmaren than the Forsmark lakes of today.

Both Erken and Limmaren have a relatively modest maximum depth for Swedish lakes in general. However, compared with other lakes in the province of Uppland, and particularly with those in Uppsala County, they belong to the deepest lakes with average depths of 9 and 4.7 m, respectively (Table 3-35). Some of the future lakes will have similar depths as Erken and Limmaren, e.g. basin 105 and 114 will have average depths of above 7 m at the start of the lake stage.

Because of their large volumes and limited drainage areas, the renewal time of the water in the lake basins, 7.4 years for Lake Erken and 5.8 years for Lake Limmaren, is long, especially compared to that of the lakes in the Forsmark area. This is considerable longer than for both the present and future Forsmark lakes where retention time is predicted to always be below 1 year.

Table 3-34. Characteristics of the catchments of Lake Erken and Lake Limmaren. Data from /Brunberg and Blomqvist 2000/.

Catchment		Area km^2	Forest km^2	Wetland %	Farmland %	Lakes %	Other land use %
58	Erken	141	70	0	10	20	0
59/60	Limmaren	21.1	68	0	6	26	0

Table 3-35. Lake bathymetry and retention times for Lake Erken and Lake Limmaren.

Lake	Area, km^2	Average v	Maximum depth, m	Volume, Mm^3	Water renewal time, days	Lowering of water level, m
Erken	24.2	9.0	20.7	213.5	2,701	1.5
Limmaren	5.9	4.7	7.8	27.3	2,137	1.1

Sediment characteristics

The sediments of Lake Erken have been thoroughly investigated from different aspects, and many investigations of the chemical composition of the surface soft-bottom sediments have been published. Both Lake Erken and Lake Limmaren have characteristic gyttja sediments, with a dark greenish-grey colour. The organic material within the sediments originates mainly from autochthonous production (*i.e.* material produced within the lake), and the ratios between carbon and nitrogen concentrations are typically low; 7.5 and 7.0, respectively. The sediment chemistry is generally similar between the two lakes /Weyhenmeyer 1999/. In both lakes, phosphorus are released from the sediments during some periods of the year. The "internal" phosphorus release from Lake Limmaren is large enough to cause a net transportation of phosphorus out of the lake /Pettersson and Lindqvist 1993/, but in Lake Erken there is a net accumulation of phosphorus in the lake when calculated on a yearly basis. This indicates that lake size alone is not enough to explain accumulation and release processes.

Due to the large size and wind exposure of the lakes, the accumulation of sediments at the bottom is very heterogeneously dispersed. Investigations of Lake Erken sediments show a difference between 1.5 and 10 m of sediment thickness (including both freshwater and marine sediments) in different parts of the lake /Fries 1969/. True accumulation sediments are found only in the deepest parts of the lakes, while other soft-bottoms are subject to substantial resuspension by waves and internal seiches, followed by further transport to the deeper areas ("sediment focusing"). This causes difficulties when assessing the sedimentation rate and sediment growth. A yearly sedimentation of ca 6 mm has been calculated for Lake Erken. This is in contrast to sedimentation rates calculated from /Fries 1969/, which gives averages for the period after isolation ranging between 0.4 and 0.8 mm per year in the deepest parts of Lake Erken. Hence, although initial sedimentation rates may be high, processes like redistribution, mineralisation, and compaction of the sediment contributes to considerably lower rates over longer time periods.

Water chemistry

Both Lakes Erken and Limmaren have water rich in salts, and pH values as well as alkalinity of the water are high. They are both typical hardwater systems with dominance of Ca^{2+} and HCO_3 (Table 3-36).

Table 3-36. Physical and chemical data from Lake Erken and Limmaren (table reproduced from /Brunberg and Blomqvist 2000/).

Parameter	Lake Erken	Lake Limmaren
Mixing regime	Dimictic	Monomictic
Duration of ice cover (days)	100–140	100–140
Duration of summer stratification (days)	100	–
Conductivity (mS/m)	25.4	24.7
pH value	8.0	8.0
Alkalinity (meq L^{-1})	1.8	1.4
Calcium, Ca^{2+} (meq L^{-1}l)	2.00 (64%)	1.53 (64%)
Magnesium, Mg^{2+} (meq L^{-1})	0.70 (23%)	0.31 (13%)
Sodium, Na^{+} (meq L^{-1})	0.35 (11%)	0.51 (21%)
Potassium, K^{+} (meq L^{-1})	0.06 (2%)	0.06 (2%)
Bicarbonate, HCO_3^{-} (meq L^{-1})	1.80 (60%)	1.40 (65%)
Sulphate, $SO4^{2-}$ (meq L^{-1})	1.00 (33%)	0.30 (14%)
Chloride, Cl^{-} (meq L^{-1})	0.21 (7%)	0.45 (21%)
Total N (µg L^{-1})	660	985
Total P (µg L^{-1})	27	54
Silica (µg Si L^{-1})	1.10	1.76
TOC (mg L^{-1})	8.5	9.2
Water colour (mg Pt L^{-1})	20	20

Regarding concentrations of total phosphorus, both lakes can be considered as nutrient rich, and particularly Lake Limmaren has very high concentrations of total phosphorus for a lake where influence of human activities is minimal. Concentrations of total nitrogen are moderately high, resulting in very low N/P quotients (24 and 18, respectively) in the lake water. Water colour is low while concentrations of total organic carbon (TOC) are high, together indicating that most of the organic carbon stems from the high autochthonous production typical of nutrient rich lakes. However, although the concentrations of TOC is considered high for these lakes the concentrations are much lower than in the Forsmark lakes indicating the even stronger influence of autochthonous production in the Forsmark lakes.

Stratification and ice coverage

In deep lakes, the water may be stratified one (monomictic) to two (dimictic) times a year. During stratification no mixing of deeper and shallower water occurs. The stratification influences several aspects of lakes. The thermal structure has for example a large impact on the oxygen profile /Wetzel 2001, Antonopoulos and Gianniou 2003/, exchange of phosphorus between the sediment and water /Boström et al. 1982, Wetzel 2001/, for plankton communities /Soranno 1997/ and for the location of fish /Wootton 1990/. The spring phytoplankton blooms are dependent on the thickness of ice-cover as well as the timing of the ice break up /Weyhenmeyer et al. 1999, Blenckner et al. 2003/.

Lake Erken and Lake Limmaren show great similarities in water chemistry, but differ regarding mixing regime (Table 3-36); Lake Erken is dimictic (stratifies both during summer and winter) while Lake Limmaren is unstratified during summer. Both lakes are covered by ice during three to four months, from December to April. Lake Erken normally stratifies in early June and stratification lasts till early September. The small lakes of Forsmark today are shallow and no stratification of the water column occurs. For lakes in the northern hemisphere, the onset of stratification has been shown to be dependent on lake size, mean annual air temperature, ratio of lake surface area to mean depth /Demers and Kalff 1993/.However, the information on future conditions is not enough to foresee the mixing pattern of future deep lakes.

Water biology

Characteristic of large lakes in general, both Lake Limmaren and particularly Lake Erken show high habitat diversity. A total of five key habitats can be identified in both lakes, i.e. a pelagic zone, a littoral zone dominated by emergent macrophytes, a wind-exposed littoral zone, a light-exposed soft-bottom zone, and a profundal zone.

There is a large phytoplankton production in the pelagic habitat of both lakes. Phytoplankton biomasses, measured as the concentration of chlorophyll *a*, are high both in Lake Erken (annual average 5.4 µg chl *a* L^{-1}) and in Lake Limmaren (annual average 21 µg chl *a* L^{-1}) and phytoplankton is the dominant constituent at the base of the pelagic food web. Phytoplankton primary production in Lake Erken is high during the open water season, and typically ranges between 600 and 900 mg C m^{-2} day /Pierson 1990/. /Bell and Kuparinen 1984/ estimated bacterioplankton production during spring on an areal basis to be some 20% of the primary production. The long water renewal times in the lakes, and subsequent low influence of allochtonous organic material, in combination with the high production of phytoplankton compared to bacterioplankton, indicate that bacterioplankton are dependent on organic carbon produced by biota within the lake basin (e.g. phytoplankton).

Because of the long water renewal time most of the autochtonously produced organic matter is retained and respired or stored within the lake basin. A considerable share of the primary production is utilised by bacterioplankton and higher trophic levels already in the lake water, but removal by sedimentation is also a significant loss of carbon from this habitat. Losses through the outlet, on the other hand, are minimal. Already /Rodhe 1958/ concluded that in terms of primary production of carbon per unit of surface area, the pelagial is by far the most important habitat in Lake Erken, a statement that most likely also holds true for Lake Limmaren.

The wind-exposed littoral is an important habitat for snails and mussels. The zebra mussel (*Dreissena polymorpha*), is a non-native species which was accidentally introduced in Lake Erken in the mid 1960'ies. It is now a major constituent of the fauna on hard bottoms at a depth of about

1–10 meters. Dreissena has been studied in Lake Erken and been found in high densities /Brunberg and Blomqvist 2000, Nadaffi et al. 2010/. The clearance rate of the mussels has been estimated to 50–300 ml/individual hour /Sprung and Rose 1988, Horgan and Mills 1997/. Multiplying this clearancerates with the densities found in Lake Erken /Brunberg and Blomqvist 2000, Nadaffi et al. 2010/, it is evident that the mussel has a potential to affect many of the organisms in plankton as has been suggested also in other studies /Horgan and Mills 1997/.

A light-exposed zone without macrophytes but with photosynthesising organisms in the form of cyanobacteria, diatoms and in certain areas also the green alga *Cladophora aegagrophila* is characteristic of both Lake Erken and Lake Limmaren /Blomqvist and Brunberg 2000, Kahlert 2001/. The productivity of this zone, which extends down to depths of 6–8 m in Lake Erken and to 2–3 m in Lake Limmaren is not known, but it seems likely that it may contribute substantially to the total production of carbon

The production of the emergent macrophyte habitat is high. Primary production of emergent macrophytes, calculated on an areal basis, may exceed pelagic phytoplankton production with between 5–8 times /Rodhe 1958, Wetzel 1992/. However, due to the large size of both Lakes Erken and Limmaren the pelagic zone is most likely the most important habitat contributing to total production of carbon.

Characteristic for the deep eutrophic lakes is that their profundal zone is the end station of the rich pelagic production. This autochtonously produced material to a great extent settles to the bottom and is utilised by various organisms living in the sediment. Due to the depth of these lakes, transformation and decomposition processes occurring already in the lake water may alter the composition and nutrient status of the organic material that reaches the profundal. However, compared to the brownwater lakes where most input of organic substances have allochtonous origin, the organic matter reaching the profundal zones of the eutrophic lakes is more available to and easily degradable by the benthic organisms. This is reflected in a comparatively higher biomass and diversity of the benthic fauna. The profundal habitat is also highly dynamic, immediately responding to seasonal variation in the input of organic matter /Brunberg and Blomqvist 2000/.

Both Lake Erken and Lake Limmaren have been subject to standardised gill net fishing, performed 1996 and 1991, respectively (Table 3-37). In Lake Erken a total of 9 different species were found, and the CPUE (catch per unit effort) was 66 individuals and 2.0 kg. Data from various studies performed over several of the past decades /Weyhenmayer 1999/ show that the fish community of lake Erken altogether includes at least 16 different species, with dominance of perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), smelt (*Osmerus eperlanus*), ruffe (*Acerina cernua*), pike (*Esox lucius*), burbot (*Lota lota*) white bream (*Blicca bjoerkna*), and bleak (*Alburnus alburnus*). The standardised gill net fishing in Lake Limmaren gave a CPUE of 165 individuals and 4.6 kg. In addition to the 7 different species caught in this investigation, earlier studies (referred in /Pettersson and Lindqvist 1993/) have found the additional species rudd (*Scardinius erythrophthalmus*) and pike (*Esox lucius*). Altogether, both lakes can be characterised as having a diverse and productive fish community including all species typical of lowland lakes and, in addition, pelagic planktivores and their predators. The CPUE are similar to CPUE in the small oligotrophic hardwater lakes.

Table 3-37. Data from standardised survey gillnet fishing in Lake Erken and Lake Limmaren. Pi=pike, Ro=roach, Pe=perch, P-P=pike-pearch, Ru=ruffe, Br=bream, Wh=white bream, Bl=bleak, Sm=smelt /Odelström et al. 1998, Pettersson and Lindqvist 1993/.

Lake	Fish species	No of species	CPUE	
			No of individuals	Kg
Erken	Pi,Ro,Pe,P-P,Ru, Br,Wh,Bl,Sm	9	66	2.0
Limmaren	Ro,Pe,P-P,Ru, Br,Wh,Sm	7	165	4.6
Average		8	116	3.3

3.12.2 Streams

There are two large streams in the Forsmark region: Forsmarksån and Olandsån. Each of them drains a large area and they discharge into the bay Kallrigafjärden (Figure 3-48) These two watercourses are much larger than the small streams in the site investigation area described earlier in this chapter, which might be characterized as ditches rather than streams. Data for the two large streams have been collected from /Brunberg and Blomqvist 1998/ and unless stated otherwise values given in the text are from this reference. Their catchments are named catchment 55 (Forsmarksån) and 56 (Olandsån) according to the SMHI numbering system.

Forsmarksån

The main catchment of Forsmarksån is 375 km^2 and it is, like the small catchments of the Forsmark area, dominated by forest (69%) and wetland (17%). Crop fields and hay-meadows make up 9% and lakes make up 5% of the catchment. The difference in altitude is 55 m, and the average slope is 0.7 m km^{-1}. The catchment is further divided into 16 sub-catchments. Land use within each sub-catchment is shown in Table 3-39. The sources are situated within the wetland area Florarna, which is a nature reserve. Almost all lakes in the catchment are affected by regulation dams that were created during the 17th and 18th centuries for hydropower generation, mainly for iron production. Two of the lakes (Stora and Lilla Agnsjön) originally drained into the Fyrisån catchment, but were diverted to the catchment of Forsmarksån during this period. Many of the dams are not in use today and some have been restored. There are about 20 dams (or remnant of dams) within the water system today.

Table 3-38. Fish data for some of the lakes in the catchment Olandsån. From /Brunberg and Blomqvist 1998/. Br=bream, Bu=burbot, Cr=Crucian carp, Ide=ide, Pe=perch, Pi=pike, Ro=roach, Ru=ruffe, Rd=rudd, Te=tench, Wh=white bream. The average represents the 10 lakes where fishing was not performed. Data from /Brunebrg and Blomqvist 2000/.

Lake	Fish species	CPUE No. of individuals	CPUE kg ww	Lake area ha
Markasjön*		*	*	18
Assjösjön	Cr, Pe, Pi, Ro, Te,	58	6.33	25
Stora hallsjön	Pe, Pi, Ro,	90.5	3.55	28
Gimo damm	Br, Cr, Pe, Ro, Rd, Ru, Te	66	3.44	297
Vattenstasjön	Cr	0.4	0.41	8
Stamsjön	Br, Ide, Pe, Ro, Rd, Te, Wh	17.7	1.8	45
Långsjön	Br, Pe, Pi, Ro, Rd, Ru, Te, Wh	43.8	2.6	31
Söder-giningen	Br, Cr, Pe, Ro, Rd, Ru, Te, Wh,	160	9.03	303
Hosjön	Pi			
Kärven	Br, Bu, Cr, Pe, Pi, Ro, Rd, Ru, Te,	62	3.9	186
Kolsjön	–	–	–	15
Testen	Br, Cr, Pe, Ro, Ru, Rd, Te	121.7	6.25	107
Average		**62**	**3.7**	**105**
Median		60	3.5	38
N obs		10	10	10
Max		160	9.0	303
Min		0	0	8
Average Uppland County				
Lake size 0–10 ha		44	2.62	
Lake size 11–50 ha		78	3.59	
Lake size 51–150 ha		130	4.36	
Lake size > 150 ha		88	3.63	
Average Forsmark area (N=4)				
Mean for Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden		45	3.48	

* most probably has no fish.

Table 3-39. Land use in the sub-catchments of Forsmarksån, from /Brunberg and Blomqvist 1998/.

Sub-catchment	Area (km^2)	Forest (%)	Wetland (%)	Farmland (%)	Lakes (%)	Other land use (%)	Difference in altitude (m)
Totally for Forsmarksån 55	375	69	17	9	5		55
1	24.2	77	10	13	0		25
2	65.7	74	6	20	0		50
3	17.0	62	22	4	12		15
4	38.0	77	12	6	5		30
5	31.6	78	5	14	3		35
6	17.0	59	21	9	11		15
7	24.2	75	11	7	7		45
8	29.3	83	7	10	0		30
9	8.63	66	31	0	3		25
10	12.1	69	21	2	8		25
11	2.58	51	34	1	14		10
12	37.9	65	19	4	11	1	20
13	21.0	59	31	0	10		20
14a+b	39.3	47	49	1	3		20
15	1.20	51	30	0	19		10
16	4.80	73	25	0	2		20

The large area of the Forsmarksån catchment makes the water flow relatively large in the summer. Forsmarksån is c. 40 km long and has an average water flow of 2.8 $m^3 s^{-1}$. This is about 100 times higher discharge than in the streams of the Forsmark area, where annual mean discharge varies between 0.01 and 0.03 $m^3 s^{-1}$ (Section 3.3.1). The normal high-water flow in Forsmarksån is 15 $m^3 s^{-1}$, the highest high-water flow is 35 $m^3 s^{-1}$, the normal low-water flow is 0.3 $m^3 s^{-1}$, and the lowest low-water flow is 0 $m^3 s^{-1}$.

The water in Forsmarksån is moderately nutrient-rich, strongly coloured and has a very high buffering capacity. The lower parts of Forsmarksån (including some tributaries) are reproduction areas for freshwater fish from the Baltic Sea (e.g. bream (*Vimba vimba*). Migrating sea trout are also found in the lower parts of the stream. During a fish inventory in 1990, 10 fish species were caught: bullhead, roach, perch, white bream, burbot, pike, sea trout, rudd and European brook lamprey /Brunberg and Blomqvist 1998/.

The ionic composition and water colour at two stations in Forsmarksån (Vikasjön 668814 161417 in the upper part of the catchment and at Johannisfors 669500 163246 1.5 km from the outlet to the Baltic Sea) are shown in Table 3-40 /Brunberg and Blomqvist 2000/. The county administrative board has two other water sampling locations in Forsmarksån: Forsmarks bruk (coordinates 669500, 163249) and Lövstabruk (670158, 161442) /Brunberg and Blomqvist 1998/. As in the Forsmark streams, calcium levels are very high.

Table 3-40. Ionic composition (equiv. %, average values) and water colour (mg Pt L^{-1}) at two stations in Forsmarksån: Vikasjön, in the upper part of the catchment, and Johannisfors, 1.5 km from the outlet to the Baltic Sea. Average values from regular monitoring programmes /Wilander et al. 2003/, compared with the "standard composition" of fresh water lakes according to /Rodhe 1949/. From /Brunberg and Blomqvist 2000/.

	Ca	Mg	Na	K	HCO3	SO4	Cl	Water colour
Lake Vikasjön, 28 m.a.s.l.	73	10	14	2	76	8	15	180
Johannisfors, 3 m.a.s.l.	79	8	11	2	74	15	11	75
Standard composition /Rodhe 1949/	63.5	17.4	15.7	3.4	73.9	16.0	10.1	–

Olandsån

The catchment of Olandsån is 886 km^2 and contains 67% forest, 4% wetland, 27% fields and meadowland and 2% lakes. The catchment of Olandsån is, like the catchment of Forsmarksån and the small catchments in the Forsmark area, strongly dominated by forest (almost 70%). Hence, although the catchment of Olandsån has somewhat more fields and meadows than the other catchments, there are no larger differences in land use between the catchments. The difference in altitude in catchment Olandsån is 70 m. The catchment is further divided into 26 sub-catchments. Land uses within each sub-catchment are shown in Table 3-41.

Today, there are 14 dams and three municipal wastewater treatment works in the catchment. The dams are mainly concentrated at Gimo bruk in the northern part of the catchment. Part of the catchment formerly drained into Fyrisån, but is now linked to Olandsån. Almost all lakes within the catchment have been subject to drainage activities, which have turned some former lakes into wetlands. All larger stream channels, and 95% of the smaller streams, have been excavated and turned into channels and ditches. However, the main channel is unique as it provides a free passage for migrating fish all the way up to the upper parts of the stream.

The main channel of Olandsån is c. 35 km long, whereas the eastern channel is c. 30 km and the western channel c. 25 km. The average water flow is 6 m^3 s^{-1}, the normal high-water flow is 35 m^3/s, highest high-water flow is 80 m^3/s, the normal low-water flow is 0.7 m^3/s and the lowest low-water flow is 0.1 m^3/s. The average flow is almost twice that in Forsmarksån, and accordingly the flow in Olandsån is much higher than that in the Forsmark streams.

Table 3-41. Land use in the sub-catchments of Olandsån, from /Brunberg and Blomqvist 1998/.

Sub-catchment	Area (km^2)	Forest (%)	Wetland (%)	Farmland (%)	Lakes (%)	Other land use (%)	Difference in altitude (m)
Total for Olandsån	886	67	4	27	2		70
1	155	63	3	33		1	40
2	51.4	77	1	22			45
3	35.0	56	7	36		1	20
4	8.65	67	8	24	1		25
5	9.35	66	2	30	2		20
6	19.6	84	5	11			35
7	4.14	83	11		6		20
8	17.7	66	12	1	21		25
9	58.3	92	7	1			40
10	1.85	89	7	1	3		15
11	18.0	71	8	17	4		30
12	92.5	56	1	43			60
13	11.1	74	11	11	3	1	30
14	53.3	63	3	34			40
15	4.99	83	10	1	6		25
16	118	64	2	33		1	45
17	23.6	68	4	28			25
18	35.9	77	4	19			60
19	25.3	72	8	20			30
20	28.0	65	5	20	10		30
21	13.8	60	12	16	12		30
22	40.4	60	5	34		1	40
23	29.9	66	6	23	5		30
24	3.72	88	9		3		15
25	4.21	80	8	11	1		20
26	21.3	61	4	31	4		20

The water in Olandsån is nutrient-rich, strongly coloured and has a very high buffering capacity. Fish data from the stream are not available, but fish data are available from many of the lakes in the water systems /Brunberg and Blomqvist 1998/.

The county administrative board has six water sampling locations in Olandsån: Ledsundet (coordinates 668303, 163357), Gimo damm (667566, 163131), Ekeby (666493, 163478), Ålsunda (665920, 163249) and Giningen (665415, 163555).

3.13 Confidence and uncertainties in site data

The amount of data from the limnic ecosystems in the Forsmark area is large, especially for the lakes in the area. This provides good conditions for a relevant and correct characterization of the limnic ecosystems in Forsmark today. An evaluation of the robustness and uncertainties associated with the different kinds of data from the limnic system in the Forsmark area follows below.

Catchment characteristics

The size and land use of the catchments have been investigated mainly with GIS and aerial photos. The delimitation of some of the subareas has been adjusted as a result of the evaluation of the runoff data. The evaluation revealed inexplicable differences between subareas sharing the same border, which triggered a new field investigation of the area of interest. This is an example of how several investigations within the same area can be compared with each other to find mismatches. In our opinion the updated catchment delimitation is of good quality and acceptable to use for area descriptions and for further use in e.g. calculation of mass balances. The delimitation of land use and soil characteristics within the catchments is more uncertain since no validation has been performed of that data.

Hydrological measurements

Hydrological measurements have been performed in several ways. The water flow in streams has been measured since April 2004, whereas data for lake water levels is available from May 2003 (the number of measuring stations increased during the site investigation). As the site investigations were carried out during a relatively short time period, the time series are not of impressive length but the spatial density is quite good. Monitoring data from larger streams in the region are available from a much longer time period, but these results are valid for considerably larger streams than the small brooks and ditches within the Forsmark area. Accordingly, these data cannot be used directly. Instead, for long-term calculations, the data series from the streams in the Forsmark area can be compared with data series from SMHI from the larger stream Olandsån. Irrespective of whether the streams are large or small, the same patterns with high and low flows should be about the same in the whole region. This permits the calculation of long-term flow series.

The extent of periodically flooded areas around streams in the Forsmark area has been investigated in two of the catchments. The areas were delimited in the field using a D-GPS, which gives very good spatial precision. The two investigated catchments are very different from each other in terms of stream length and flooded area per stream length, making it difficult to draw any general conclusions. A comparison of the results from field investigations with the extent of wet areas on the vegetation map created from aerial photos showed that the vegetation map was not always correct. If this information is of critical importance it may therefore be appropriate to delimit the borders in field.

Climate parameters

Climate parameters have been measured locally since May 2003. Measurements have been performed at two stations within the area, which show very similar data. This strengthens the assumption that climate data varies insignificantly within the small site investigation area, whereas a gradient is seen for some parameters (i.e. precipitation) when comparing inland with coastal areas. As with the hydrological data, the time series are short but can be compared with longer time series from the region.

Lake bathymetry

The lake bathymetry has been measured with good precision. The shorelines have been delimited in the field using a D-GPS and a distance between measuring points of approximately 4 m. The water depths were measured by means of echo sounding in larger lakes (i.e. Eckarfjärden and Bolundsfjärden) from a boat and in smaller lakes (i.e. Labboträsket) from ice. The distance between the measuring points differs /Brydsten et al. 2004/. However, this must be considered as acceptable spatial precision.

Physical characters of the streams

The physical characters of the streams in the Forsmark area have been investigated in the field in stretches of 10 m each and this must be considered as very good spatial precision. Bottom substrate, water velocity, bottom vegetation, shading from terrestrial vegetation and technical encroachments were investigated, so that large amounts of data are available to describe the stream character. The entire investigation was performed by the same person, so differences within the data as a consequence of different judgments of the somewhat subjective parameters can be excluded. However, this also means that the correctness of the investigation results cannot be validated since no stretches have been investigated independently by two persons. A comparison of the bottom substrate data from this investigation with the map of Quaternary deposits reveals large discrepancies, but the latter investigation reflects the composition at a soil depth of 0.5 m and no special effort has been made to investigate the stream channel. The data collected in the stream investigation are therefore most probably more correct in these cases.

Sediment

The amount of sediment data from lakes in the Forsmark area is substantial, although most of the data stems from one lake: Eckarfjärden. This lake has been well characterized with regard to stratigraphical information (n=13, see Section 3.6), sediment water (n=12 for gyttja layer and 6 for clay layer) and carbon content (n=8) as well as long-term sediment accumulation rate (based on 3 radiocarbon dates). The only parameter missing from this lake is water content from the gyttja clay–clay gyttja layer. As it is assumed that this sediment type settled in the marine phase, this information has been estimated using data for this sediment type in the shallow sea bays Kallrigafjärden and Tixelfjärden in the Forsmark area. The water content found there resembles the water content of this sediment layer in Frisksjön in the Laxemar-Simpevarp area, which also supports the use of this data. Data from Eckarfjärden have been compared with data from three other lakes in the region /Hedenström and Risberg 2003/. The comparison provides information on the variation in different sediment parameters in this special lake type and is further discussed in Section 5.2.3 and 5.6.

For other lakes in the Forsmark area, some sediment data are available for comparison. Water content in the gyttja layer is also available from Bolundsfjärden (n=15) and Puttan (n=21), representing one larger and one smaller lake in the area. Data on the carbon content of gyttja, gyttja clay–clay gyttja and clay layers are also available from Fiskarfjärden (n=6, 10 and 6, respectively) and Puttan (n=17 and 2, respectively (no clay data)). Stratigraphical data for a number of lakes in the Forsmark area are available in /Hedenström 2004/. The number of observation points in each lake varies with lake size. Overall, the sediment description is detailed and gives good estimates of order of magnitudes.

Lake habitats

The lake habitats have been delimited in the field using D-GPS equipment and are considered to be of good quality. The problem with the habitat delimitation is rather the delimitation between limnic and terrestrial ecosystems. The shoreline used in the lake investigation is the highest water level, which has the consequence that wetlands in direct contact with the lake are also included in the lake, as discussed earlier (see Section 2.3.1). As the water level is not constant, the impact of these wetland areas on the rest of the lake varies over time and we have no information about the exchange of substances between the wetlands and the lakes. It is expected to be a flow of substances from the wetland to the lake. In this report, all wetlands bordering on the lakes have been considered to be terrestrial areas (wetlands). The inflow of carbon from these areas is addressed in the chapter dealing with carbon mass balance calculations (Chapter 5).

Chemistry data

The amount of water chemistry data from limnic environments in the Forsmark area is unusually large, in space as well as in time, even though the data set is certainly not unique. The amount of data differs between different parameters, for example isotopes of certain elements have been measured only once every four months, compared with most other elements, which have been measured every month.

The sampling and measurements have been performed by qualified personal, and the analyses have been performed by accredited laboratories, which should guarantee high data quality. The data series for some of the sampling points are longer than for others: 5 years instead of 2. In the sampling points with data from 5 years there are no obvious differences in water chemistry between the 2 years monitored for all sampling stations and the additional 3 years. The 2 monitored years in the area can therefore be regarded as representative for a longer time period.

Chemistry data for sediments are less extensive. Analyses of carbon and water contents have been performed on sediments from more than one lake, and these data can therefore be considered to provide a robust estimate of the order of magnitude of these substances in lake sediments in the Forsmark area. A characterization of 64 elements has been performed once in Eckarfjärden /Hannu and Karlsson 2006/ and once in Stocksjön /Strömgren and Brunberg 2006/. This represents one of the larger and one of the smaller lakes. The data are from different sediment depths, thus representing different time periods. However, there is only one sediment core from each lake, so the characterization provides no estimates of variations within the lake.

Chemical characteristics of limnic biota in Forsmark have been investigated once in samples from three lakes: Bolundsfjärden, Eckarfjärden and Fiskarfjärden. The number of organism groups is restricted (fish, mussel, macroalgae and benthic microalgae) and the number of replicates differs, which means that the reliability of the data also differs between functional groups. Overall, the chemical distribution between biota can be viewed as robust with regard to the order of magnitudes of different elements in different functional groups, although the absolute figures may be more uncertain.

Biota in lakes

Biomass

The amount of data on biota in Forsmark lakes is extensive. For many functional groups, biomass data from several years are available. One weak point in the biota data is that most of the information is on biomass, and little effort has been spent on the quantification of biological processes. The exception is primary production, which has been investigated for phytoplankton, microphytobenthos and submerged vegetation, while data on respiration and consumption from the area are lacking. However, an unrealistic effort is required to measure the respiration and consumption of biota in Forsmark area, and it is unclear whether site-specific studies would provide a greater understanding of the sites than the literature data on respiration and consumption for functional groups we have used in this report (Chapter 5).

In many cases, biomass data are from one lake only, and in most cases this is Eckarfjärden. Some data have been collected from Bolundsfjärden and Fiskarfjärden. Data from the smaller lakes are scarce, which may be seen as a weak point. However, investigations of the thickness of the microbial mat, chlorophyll *a* concentrations in the water (a measure of phytoplankton biomass) and gillnet fishing permit comparison between smaller and larger lakes, and there is no reason to suggest any significant differences in terms of biota. The biomass estimates for the different functional groups are within values reported in the literature, which is an indication of robustness in the results.

The biomasses of the functional groups phytoplankton, microphytobenthos, benthic bacteria and bacterioplankton have been measured repeatedly in Eckarfjärden over a period of three years (n=38, 39, 36, 29 and 38, respectively), which must be considered good temporal coverage. Accordingly, calculated annual means can be seen as robust estimates. Zooplankton was divided into three subgroups, which were measured for different time periods: small heterotrophic flagellates (3 y), ciliates (2 y) and larger metazooplankton (1 y). Altogether, the zooplankton biomass can be considered a reliable estimate, although longer time series would be necessary to evaluate variation between years. The biomass of the macroalgae *Chara* has been measured on three occasions during one year, which makes it possible to estimate the within-year variation, but investigations provide no information on the between-year variation. The large number of replicates on each sampling occasion (n=20) indicates that the high variation and skewed distribution in biomass reflect a real within-lake variation.

The benthic fauna biomass was investigated in more than one lake, so variations between lakes in the area can be estimated. However, the benthic fauna was only investigated once in each lake and thus we have no information about between-year variation. In the studies of benthic fauna, two different sampling techniques (frames versus Ekman grabber) were used, making it difficult to compare the results. We have chosen to view the different techniques as different ways to sample two different microhabitats (areas covered with submerged vegetation versus vegetation-free bottoms). The number of samples is small, which is also indicated by a large variation. Moreover, small meiofauna is not included in the biomass of benthic fauna, and it is therefore likely that the biomass of benthic fauna is somewhat underestimated.

The fish biomass was investigated in several lakes, so variations between lakes in the area can be estimated. The study of fish biomass was performed using a standardized technique and the results must be considered robust and possible to compare with the results of other investigations. The biomass of fish was only investigated once in each lake, which provides no information about between-year variations. The most important uncertainty associated with this data is the conversion factor used to estimate the fish biomass from the CPUE (catch per unit effort) value gained during the standardized gillnet fishing. The conversion factor we used was recommended by a Swedish fish expert, but no conversion factors have been published in the scientific literature. The classification of fish species into different functional groups according to their size may also be somewhat uncertain. The conversion from zooplanktivore to piscivore may not be total and may differ between lakes depending on food resources and competition

The biomass of emergent macrophytes has been investigated once in the late summer in Eckarfjärden. The results provide an estimate of the maximum amount of biomass, but offer no information on variations within or between years or variations between lakes.

Primary production

Primary production by phytoplankton and microalgae has been measured with a relatively good temporal coverage over two years (n=18 and 16, respectively). The primary production of submerged vegetation (mainly *Chara sp.*) was measured on three occasions during one year. The calculated annual mean productions of phytoplankton, microphytobenthos and submerged vegetation provide rather rough estimates. Production of phytoplankton can be assumed to be directly proportional to light /Wetzel and Likens 1991/. This is not true of the phytoplankton at the water surface, but for the whole water column. The same direct proportionality between light and productions was assumed for microphytobenthos and submerged vegetation. However, the microphytobenthos and submerged vegetation are fixed at certain depths in the water column and may thus be more dependent on light limitation or light saturation, which would affect this proportionality. Moreover, we have extrapolated the production for all primary producers from measurements on a few dates to an entire year. Extrapolating production from light to a few days gives relatively accurate production values, whereas extrapolation for longer periods is more uncertain /Wetzel and Likens 1991/. Thus it is clear that our estimates of annual primary production are associated with uncertainty. However, they are probably good estimates of the order of magnitude of the production of phytoplankton, microphytobenthos and submerged vegetation.

Dark respiration of primary producers is difficult to assess and may have resulted in some uncertainties in the estimation of annual production. Dark respiration at night by the macroalgae *Chara sp.* was calculated from measured during experiments at day-time and estimated to correspond to 20% of primary production. However, respiration measured in experiments at daytime is not necessarily the same as plant respiration during the daytime. Nevertheless, we consider the estimate to be realistic, and even if dark respiration is somewhat altered, the magnitude should be correct. Net primary production by the microphytobenthos and phytoplankton was measured by ^{14}C incorporation and respiration was not assessed. Dark respiration by phytoplankton has been shown to be low compared to light respiration (e.g. /Stelmakh 2003/). The same is probably true for the microphytobenthos. Thus, although primary production by the phytoplankton and microphytobenthos may be overestimated, the error should not be greater than 20% (dark respiration by *Chara sp.*).

Biota in streams

The information on biota in the Forsmark streams consists of data on vegetation and on fish migration. No measurements of primary production or respiration have been performed. This may be seen as a weak point, but as the streams are mainly man-made ditches and long stretches are dry during part of the vegetation period this should not be an important information gap.

Vegetation in streams has been investigated in 10 m sections (in total c. 7 km stream length). The spatial distribution of data must therefore be regarded as very good, although parts of the streams were not investigated. The investigation was performed by one person, so differences within the data as a consequence of different judgements of the somewhat subjective parameters can be excluded.

Migration of spawning fish in the Forsmark streams was investigated during the course of one year. Fish migrating from the sea to Norra Bassängen in the spring of 2004 were caught and recorded, providing a good estimate of the magnitude of the migration though the study gives no information about variations between years.

Land use and human impacts

Land use and human impacts on limnic environments have been investigated in the two characterization studies of lakes and streams in the Forsmark area. Some human impact may have been overlooked, but considering the relative young age of the area this is less likely. The presence of barriers to migratory fish and human impacts in streams are well documented for the stretches that have been investigated, while information for other stretches is lacking.

Conclusions

In general, an impressive amount of data has been gathered from the area during the site investigations. The data quality is most often judged as high, whereas the spatial and/or temporal density in the available data varies.

4 Description of lakes and streams in the Laxemar-Simpevarp area

The Laxemar-Simpevarp regional model area contains 26 catchments, five lakes and a number of streams (Figure 4-1). Data for description of the limnic systems have been collected from site-specific investigations in streams and lakes. The following text describes these investigations with a focus on describing the limnic ecosystems. The sampling methods used are only briefly described.

4.1 General description of the lakes and streams

One lake, Frisksjön, is situated completely within the Laxemar local model area and another 4 lakes are situated within the Laxemar-Simpevarp regional model (Figure 4-1). In addition, a couple of lakes are situated partly within the area, and there are also some small but permanent pools. In this report, the lakes in the regional model area are described with a focus on Frisksjön.

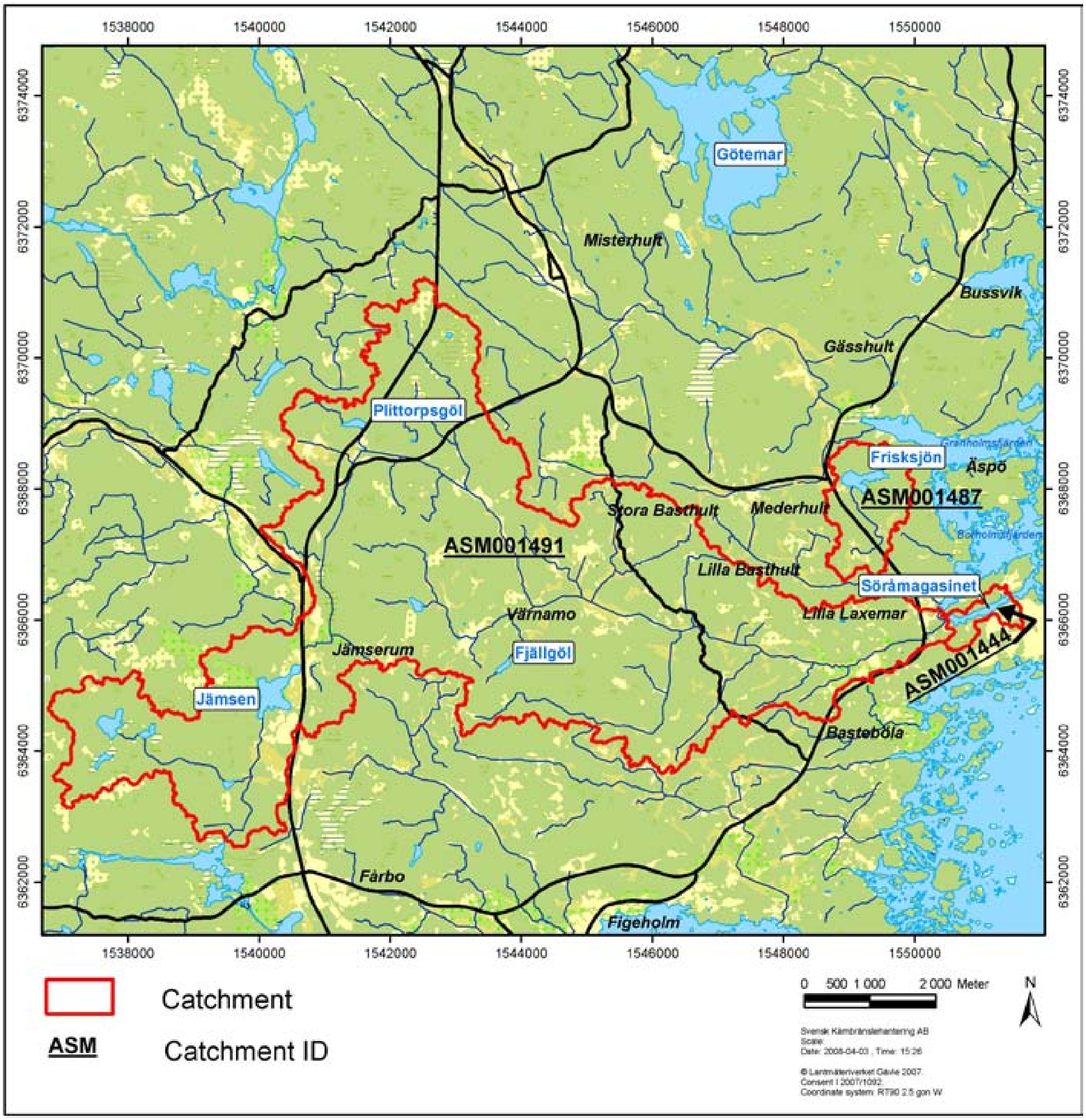

Figure 4-1. *Lakes in the Laxemar-Simpevarp regional model area.*

The bedrock in the Laxemar-Simpevarp area, as well as in most parts of south-eastern Sweden, is dominated by igneous rocks, and most of the bedrock in the area has a granite mineral composition. The lakes often have very thick sediment layers, and e.g. in Frisksjön the gyttja layer reaches a depth of 10 m.

The lakes are small with relatively shallow depths. They are characterized as mesotrophic brown-water lakes, i.e. with moderate nutrient concentrations and with brown water colour. The water colour is caused by a high input of organic matter from the surrounding catchment, and the concentration of organic carbon is very high in comparison with the majority of Swedish lakes. Because of the brownish water, light penetration is poor and the depth of the photic zone is generally small. In accordance, macrophyte coverage is small in the lakes and biota is dominated by heterotrophic organisms, particularly bacteria. Perch is the dominant fish species in numbers as well as in weight in the lakes in the area.

The lakes are small but generally deeper than the lakes in the Forsmark area. The retention time of the lakes varies between 218 days and as much as 829 days.

Most lakes in the area are affected by human activities. The names of some wetlands and minor fields indicate that a number of former lakes have disappeared during the past centuries due to human activities, probably with the aim of gaining farmland. There are also indications that the water level in several of the remaining lakes has been lowered by man.

The streams in the Laxemar-Simpevarp area are presented in Figure 4-2. Most of the streams are small with mostly calm or slowly flowing water. Many streams are dry in the summer but a few, such as Laxemarån, have a permanent water flow. The streams are characterized as mesotrophic brown-water systems. Similar to the situation in lakes, stream water is strongly coloured due to high amounts of humic substances, leading to very high concentrations of dissolved organic carbon. The streams are also relatively rich in nitrogen and phosphorus. Five fish species have been noted in Laxemarån: ide (*Leuciscus idus)*, roach (*Rutilus rutilus)*, burbot (*Lota lota)*, pike (*Esox lucius)* and ruffe (*Gymnocephalus cernua*), and there are indications that the stream is an important spawning ground for both ide and roach. The streams are to a large extent influenced by human activities, which have altered the channel by various technical encroachments.

4.2 Catchment characteristics

The catchment is the land area (including lakes) from which the water is drained to the same stream. The area is delimited by the topography and all precipitation falling within the catchment will eventually reach the sea through the same stream channel. The Laxemar-Simpevarp regional area contains 26 catchments of different sizes /Brunberg et al. 2004b/). Most catchments have a small area (median 0.6 km^2) although some catchments are large resulting in a relatively large mean catchment area (4.1 km^2). The catchments contain five lakes.

The catchment clearly regulates the characteristics of lakes and rivers within it /Wetzel 2001/. The geomorphology of the land determines the ionic composition and slope of the soil, and, in combination with the climate, also the vegetation of the area. The vegetation and soil composition influence the amount of runoff as well as the composition and quantity of organic matter that enters streams and lakes.

Morphological parameters as well as land use, soil composition and vegetation types of the different catchments in the Laxemar-Simpevarp area were examined in /Brunberg et al. 2004b/. The maximum elevation above sea level varies from 10 to 63 m, whereas the minimum level varies from 0 to 30 m. Most of the catchments are dominated by forest, which covers 90% of the total catchments. The lakes are relatively few and only 1% of the catchments are made up of water. Land use for the 5 lake catchments is shown in Table 4-1. Like the other catchments in the area, forest dominates completely, covering between 74 and 95% of the lake catchments.

The bedrock in the Laxemar-Simpevarp area, as well as in most parts of south-eastern Sweden, is dominated by igneous rocks, and most bedrock in the area has a granite mineral composition.

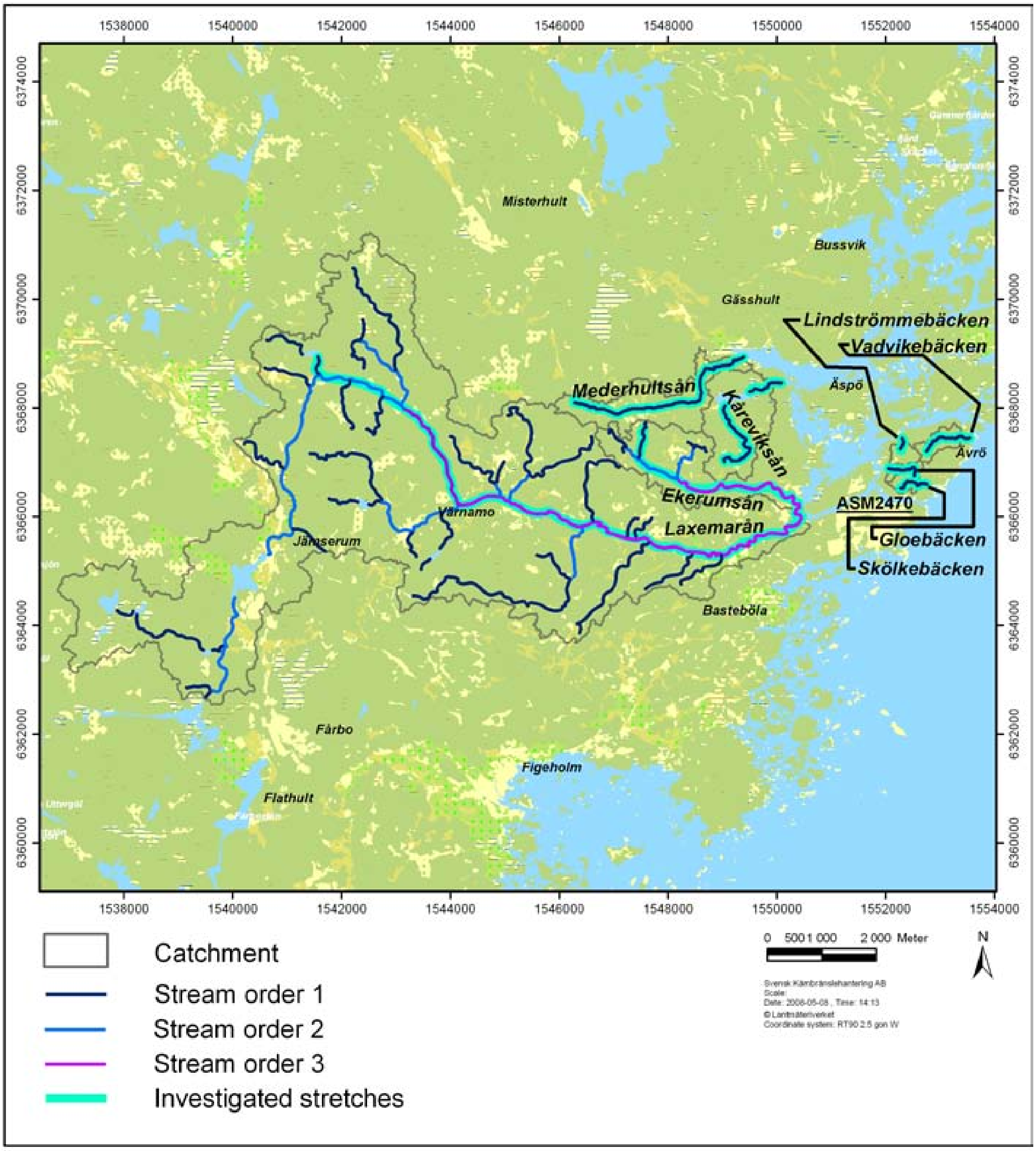

***Figure 4-2.** Streams in the Laxemar-Simpevarp area. The stretches which have been investigated are marked. Stream orders are also presented.*

Table 4-1. Land use data for the catchments of five lakes in parts of the Laxemar-Simpevarp area (data from /Brunberg et al. 2004b/).

	Size (km^2)	% forest	% open land	% water
Average	2.1	88	3	9
Median	0.7	91	0	7
Min.	0.3	74	0	3
Max.	7	95	7	20

4.3 Hydrology

Surface waters in the Laxemar-Simpevarp area are mainly located in low-lying areas. In most of these areas, the till is overlain by relatively low-permeable postglacial sediments. This means that surface waters interact to a large extent with overland flow and near-surface groundwater flow, which yields temporally variable surface water flows and dry streams in the summer. All streams are relatively small and many of the streams are affected by human activities such as excavation (Figure 4-3, human impact is further discussed in Section 4.11).

4.3.1 Discharge

Nine permanent automatic discharge gauging stations have been installed in the streams in the Laxemar-Simpevarp area as a basis for water balance calculations and for calculation of mass transport of different elements (Figure 4-4)/Werner et al. 2008/. Water levels, electrical conductivities, temperatures and discharges have been monitored at the stations. The available time series from the different stations differ due to the fact that the start of the measurements varied from March 2003 to February 2005 /Sjögren et al. 2007/. For all stations, the time period is relatively short and therefore the mean discharge values presented in Table 4-2 should be used with caution.

Figure 4-3. *Photos showing Laxemarån (upper left), one of the largest streams in the area, and Ekerumsån (lower left) and the outlet from Frisksjön (right), two of the smaller streams in the area.*

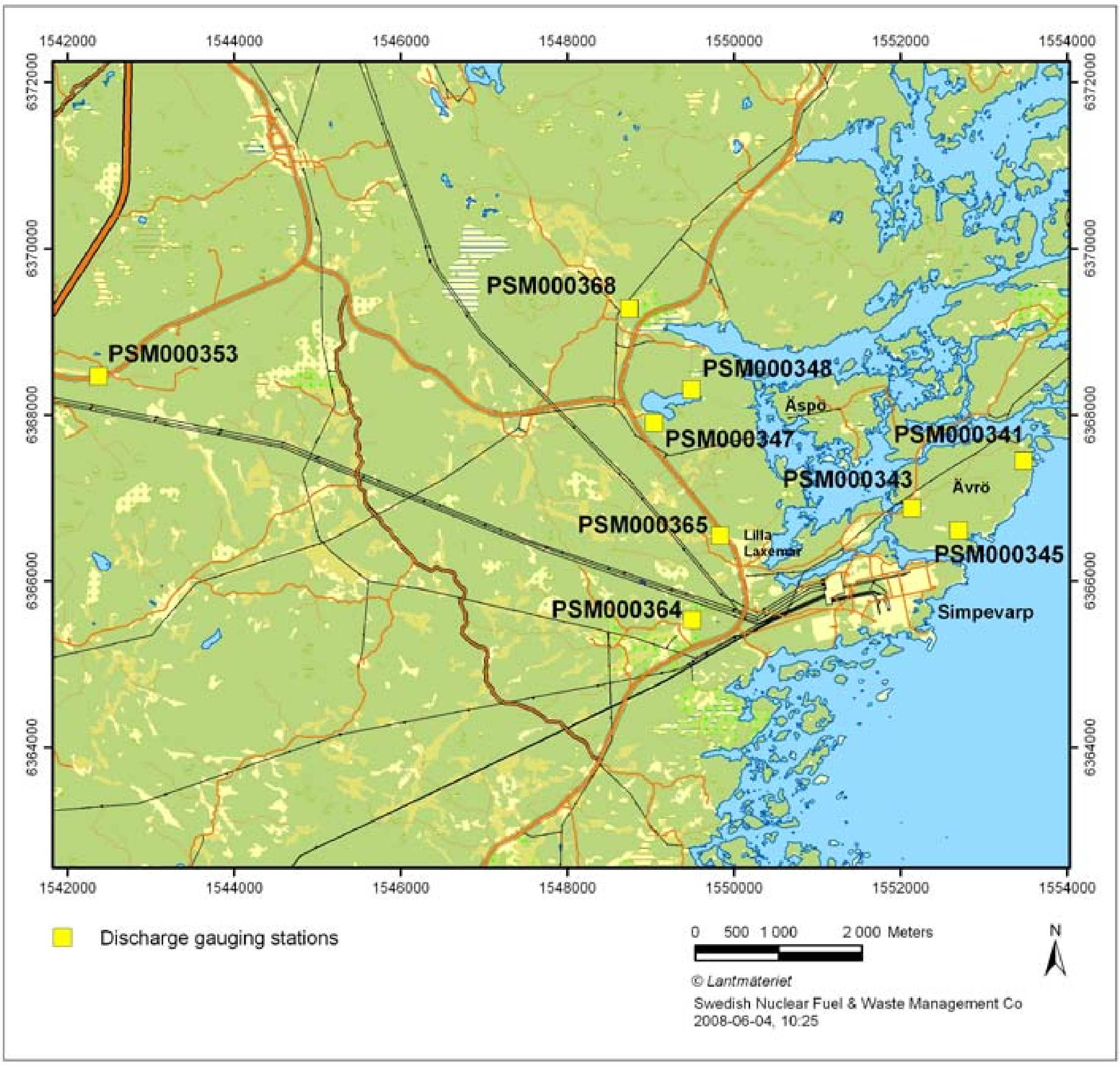

Figure 4-4. *Location of the nine discharge gauging stations in the Laxemar-Simpevarp area.*

The mean specific discharge during the monitored period ranged between 3.5 and 7.3 L s^{-1} km^{-2} at the different monitoring stations (Table 4-2). In comparison, the specific discharge in Forsmark varied between 4.9 and 5.6, which means that the specific discharge is of a similar magnitude but the variation is somewhat greater in Laxemar-Simpevarp. Overall, discharge rates were generally low in the Laxemar-Simpevarp area. The results for each station are presented in Table 4-2. The mean discharge of all stations was 60 L s^{-1}, but the maximum discharge in the largest catchment in the Laxemar-Simpevarp area is quite high, 4,260 L s^{-1} (Laxemarån). The lowest recorded discharge rate is zero due to that several of the streams are dry in the summer. In comparison, the mean discharge downstream of Forshulteån 35 km southwest of Simpevarp was 609 L s^{-1} (SMHI station 1619, time period 1955–August 2007, data from the SICADA[5]) and the mean discharge in the Dalälven River is 353,000 L s^{-1} at the outlet to the Baltic Sea (average for the time period 1976–2000 according to www.dalalvensvvf.se/omdal.htm, accessed 2008-04-16).

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[5] SKBs database SICADA, access might be given on request.

Table 4-2. Discharge characteristics for the nine gauging stations for various time periods (total available time series) in the Laxemar-Simpevarp area. From /Werner et al. 2008/.

	PSM 000341	PSM 000343	PSM 000345	PSM 000347	PSM 000348*	PSM 000353	PSM 000364	PSM 000365	PSM 000368	Mean all stations
Time interval	Mar 2003–Dec 2007	Mar 2003–Dec 2007	Mar 2003–Dec 2007	Nov 2004–Dec 2007	Jul 2004–Dec 2007	Sep 2004–Dec 2007	Nov 2004–Dec 2007	Feb 2005–Dec 2007	Jul 2004–Dec 2007	
Mean discharge ($L \cdot s^{-1}$)	1.5	0.5	0.7	4.6	6.6	59.4	293.4	13.2	164.0	60.4
Min. discharge ($L \cdot s^{-1}$)	0.0005	0	0	0	0.08	4	10	0	20	
Max. discharge ($L \cdot s^{-1}$)	44	19	27	140	98	988	4,261	449	4,260	
Specific discharge ($L \cdot s^{-1}\ km^{-2}$)	5.2	4.5	4.4	5.0	3.5	4.2	7.3	5.5	6.1	5.1
Specific discharge ($mm \cdot yr^{-1}$)	164	142	139	158	111	134	231	175	192	161
Catchment area (km^2)	0.29	0.11	0.16	0.91	1.88	14	40	2.38	27	9.6

* N.B. The measurements in the outlet of Frisksjön (PSM000348) are associated with great uncertainties, and the results from this station are probably erroneous (cf./ Werner et al. 2008/).

4.3.2 Water levels in lakes

The water level in the four lakes Frisksjön, Söråmagasinet, Jämsen and Plittorpsgöl are shown in Figure 4-5. The same pattern is seen for all lakes, i.e. maximum water levels occur in spring, during snowmelt, followed by a decrease until a minimum level is reached in late summer and early autumn. Then the levels rise again up to a new maximum level in the spring. The mean, minimum and maximum water levels in lakes measured during the site investigations are presented in Table 4-3 (data from SICADA[6]).

Table 4-3. Water levels (m.a.s.l.) in Jämsen, Plittorpsgöl, Frisksjön and Söråmagasinet.

	Jämsen	Plittorpsgöl	Frisksjön	Söråmagasinet
mean	25.6	25.0	1.6	1.8
median	25.5	25.0	1.5	1.8
min.	25.4	24.8	1.3	1.5
max.	26.0	25.4	2.2	2.1
n	1,256	1,256	1,256	1,228

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[6] SKBs database SICADA, access might be given on request.

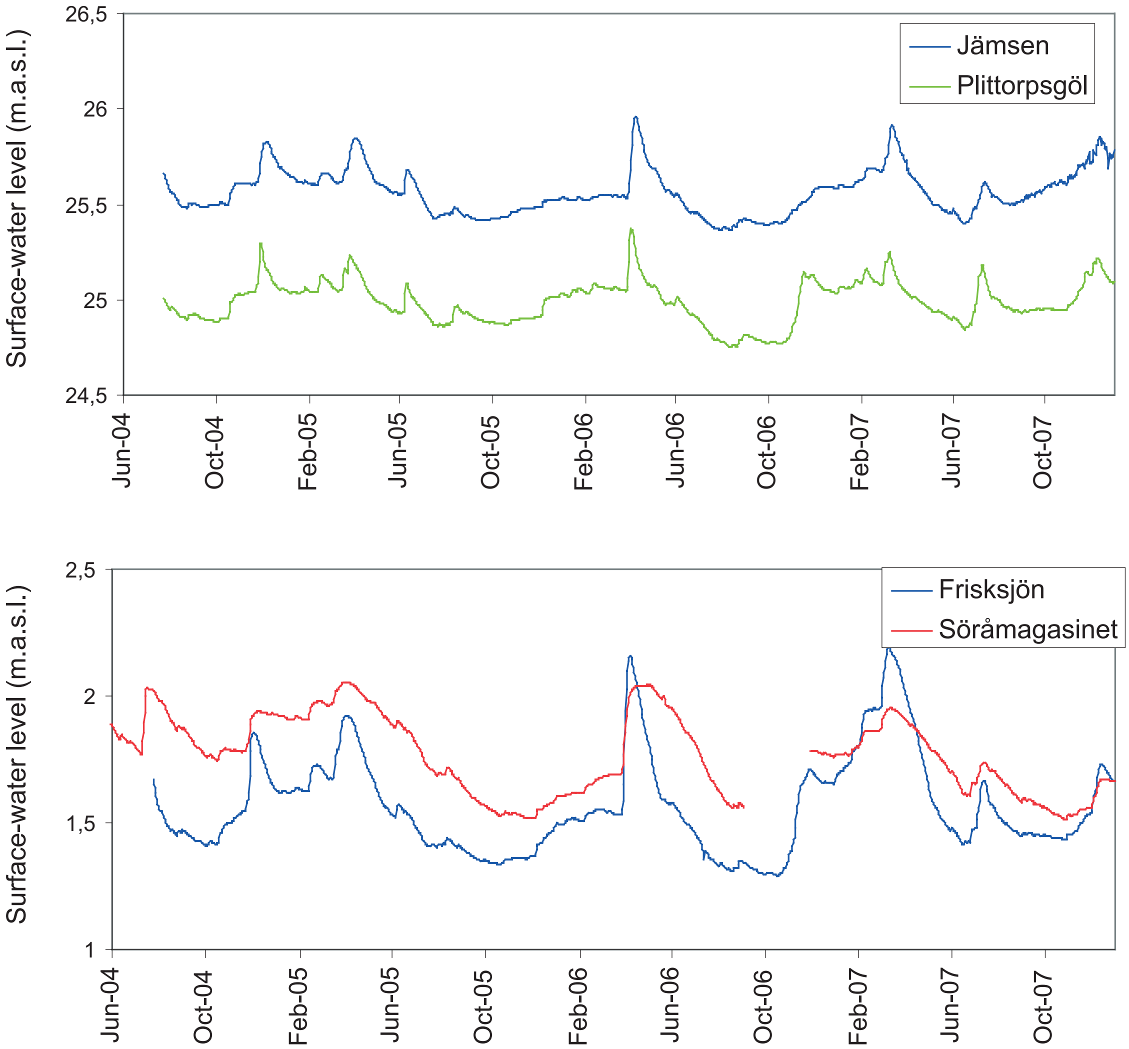

Figure 4-5. *Water levels in lakes Jämsen, Plittorpsgöl, Frisksjön and Söråmagasinet from June 2004 to December 2007.*

4.3.3 Groundwater discharge/recharge

The lakes in the Laxemar-Simpevarp area can function both as recharge and discharge areas for groundwater. Comparison of the groundwater table measured in till at the shoreline of Lake Jämsen (groundwater monitoring well SSM000035) and the lake water level indicates a temporally variable head gradient between the lake and the till (Figure 4-6a). The data indicate an upward head gradient for most of the year, shifting to a downward head gradient during dry periods in the summer. In Frisksjön, on the other hand, the data indicate a small downward gradient from the lake to the till for the entire year (Figure 4-6b).

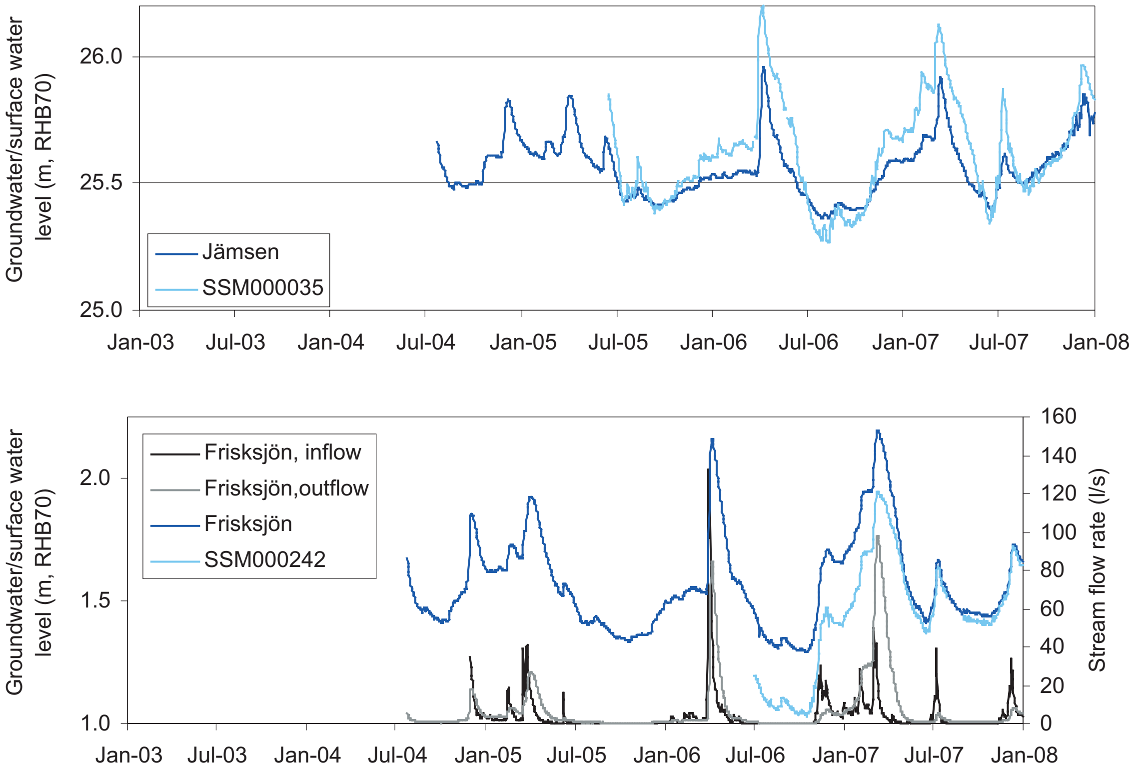

Figure 4-6. *Groundwater level and lake water level in a) Jämsen and b) Frisksjön.*

4.3.4 Flooded areas

Some parts of the Laxemar-Simpevarp area have small altitude gradients. During times of high water flows in the streams, surrounding areas are flooded. The extent of these areas has been investigated in four catchments (Figure 4-7) /Strömgren et al. 2006/. The sizes of the flooded areas were not determined, but the length of the stream stretches can be estimated from the investigation data (Figure 4-7, Table 4-4). The flooded areas are classified as wetlands belonging to terrestrial areas and are further described in /Löfgren 2010/.

4.4 Climate

Sweden in general has a maritime climate, distinguished by cool summers and mild winters. However, further north in Sweden the climate tends to be more continental with a greater difference between summer and winter. Laxemar-Simpevarp is located in the boreonemoral vegetation zone, dominated by pine and spruce.

Table 4-4. The investigated flooded areas of the streams in the Laxemar-Simpevarp area (data from /Strömgren et al. 2006/).

Catchment	Length of investigated stream stretch (m)	Share of stream stretch with flooded areas (%)
Mederhultsån 6	3,950	c. 2
Kåreviksån 7	2,530	c. 13
Ekerumsån 9	3,920	c. 4
Laxemarån 10[1]	25,700	c. 12
Total	36,100	c.10

[1] investigated stream length including tributaries, not the whole length of the stream.

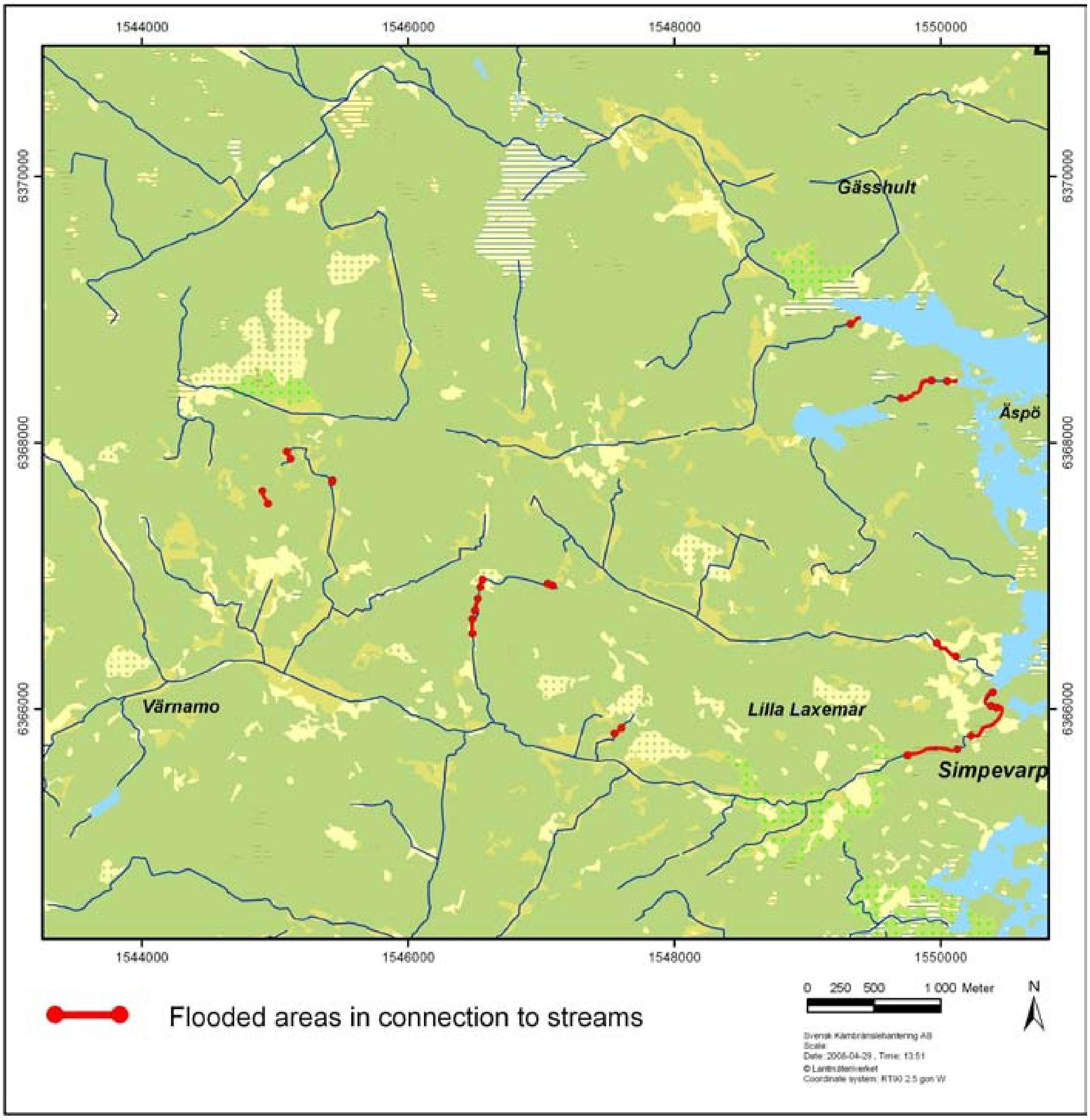

***Figure 4-7.** Stream stretches where flooding occurs in catchment 6, 7, 9 and 10 in the Laxemar-Simpevarp area.*

4.4.1 Air temperature

The mean annual temperature in the Laxemar-Simpevarp area is 6–7°C /Werner et al. 2008/. The mean temperature in January is –2°C and the mean temperature in July is 16–17°C. By comparison, the mean annual temperature in Stockholm is 6.6°C, in Malmö 8.2°C and in Östersund 2.5°C /Larsson-McCann et al. 2002/.

4.4.2 Precipitation

The mean annual precipitation during the period 2005–2007 was 580 mm in Äspö and 620 mm in Plittorp (Figure 4-1), so the average precipitation for Laxemar-Simpevarp is estimated at 600 mm /Werner et al. 2008/. Results from meteorological measurements in Äspö and Plittorp are available from the time period 2003 to 2007 and are presented in Figure 4-8, together with meteorological measurements at 6 SMHI stations nearby. Long-term measurements from Oskarshamn are available from SMHI for the period 1961 to 2007. Monthly precipitation in Oskarshamn for the period 2003 to 2007 is compared with monthly precipitation for the period 1961–2007 in Figure 4-9. The precipitation in 2003–2007 is within the range for the long-term measurements, so the precipitation from Äspö and Plittorp can also be assumed to be representative for a longer time period.

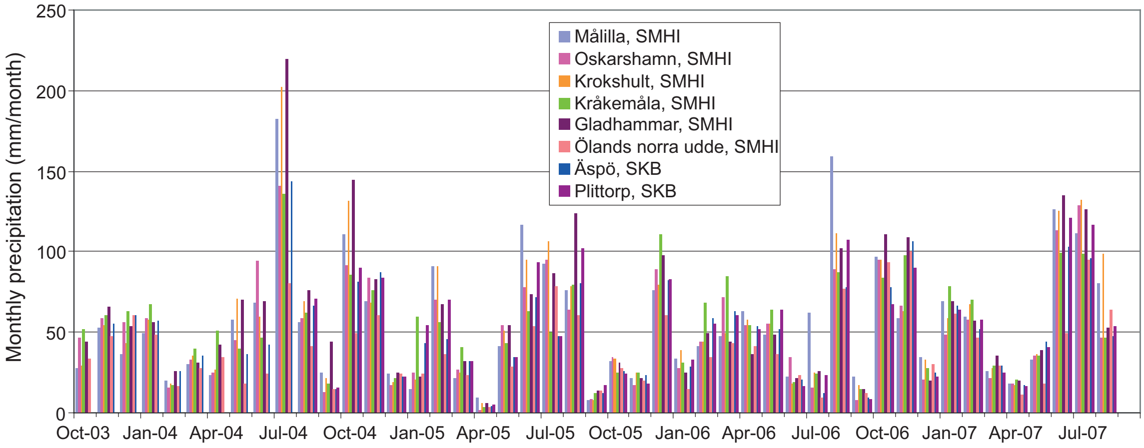

***Figure 4-8.** Monthly precipitation at the SKB and SMHI stations Oct. 2003–Aug. 2007. From /Werner et al. 2008/.*

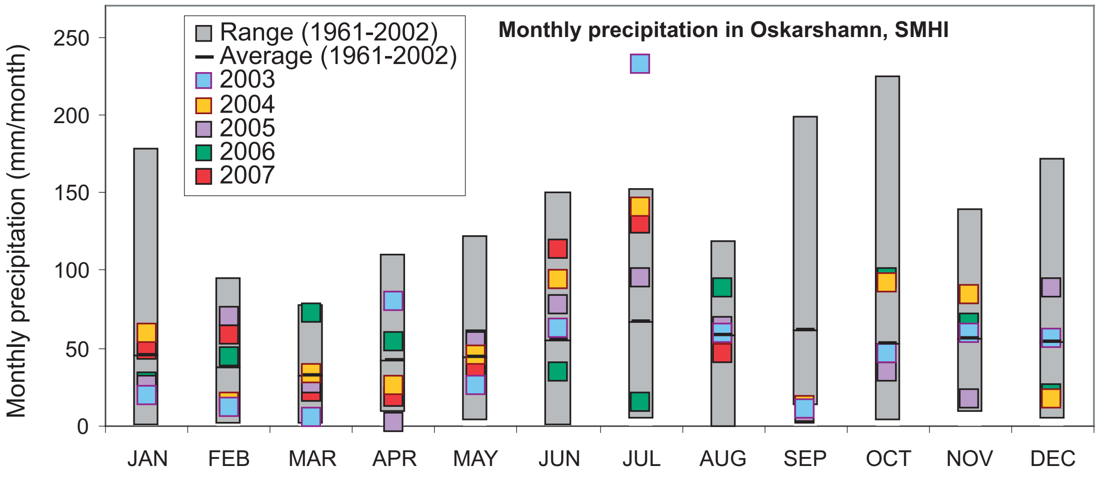

***Figure 4-9.** Monthly precipitation at Oskarshamn 1961–2002, also displaying the monthly precipitation at Oskarshamn for each of the years 2003–2007. There are no data for Sep.–Dec. 2007. From /Werner et al. 2008/.*

4.4.3 Snow cover

Snow cover was measured approximately biweekly during the period 2002/03 to 2006/07 at station ASM100224, Grillplatsen, Äspö /Werner et al. 2008 /. Generally, there was a snow cover for 70 days per year from December/January until March/April. However, short periods of snow were recorded as early as October, and late snow cover was recorded at the end of April. The average snow depth at Grillplatsen was 120 mm whereas the maximum observed snow depth was 370 mm. The period of snow cover at ASM100224 agrees well with the measured snow cover at four SMHI stations (Figure 4-10). Snow cover has been measured at the SMHI stations since 1994, making it possible to estimate snow cover for longer time periods for the Laxemar-Simpevarp area.

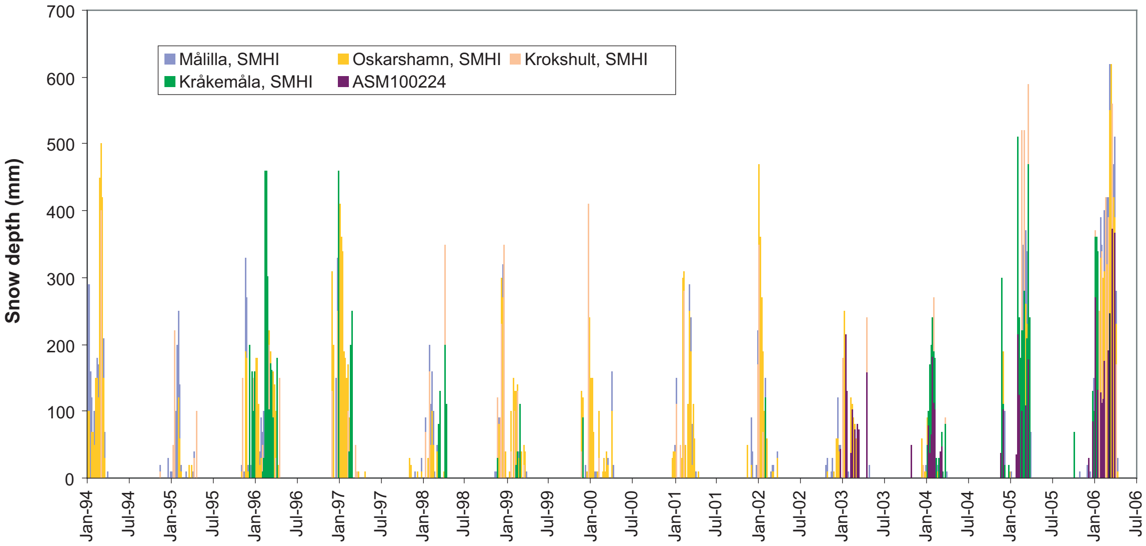

Figure 4-10. *Snow cover in the Laxemar-Simpevarp area (ASM100224) since 2002/03 and at nearby SMHI stations from 1994/95.*

4.4.4 Ice cover

Ice cover recordings were made in Jämsen (ASM100229) from 2002 to 2007. Ice freeze-up occurred at the end of November in three of the seasons, while in the 2003/2004 and 2006/2007 seasons freeze-up did not occur until January. On average, Jämsen was covered by ice for 96 days, but the range was great, 37–147 days (Table 4-5). In Lake Gnötteln, located inland c. 30 km west of Jämsen, ice cover has been measured continuously since 1957. In Gnötteln as well, there is a large range in the period of ice coverage, varying between 10 days and a maximum period of almost 6 month (time period 1957–2000) /Larsson-McCann et al. 2002/. On average, Gnötteln is ice-covered for a somewhat longer period than Jämsen (c. 4 months from the beginning of December to the beginning of April).

4.4.5 Global radiation

Global irradiance has been measured in the Laxemar-Simpevarp area at Äspö since September 2003 /Sjögren et al. 2007/. The mean annual radiation was 1,021 kWh·m^{-2} (SD 47). This is in agreement with /Raab and Vedin 2007/, where it is stated that global irradiation in Sweden normally varies within 15% of the normal value of 800–1,100 kWh·m^{-2}. Global radiation is highest in June followed by July and May (Figure 4-11). Daily values vary between 0.8 W m^{-2} (in November 2003) and 346 W m^{-2} (in June 2005).

Table 4-5. Periods of ice cover for Jämsen in Laxemar-Simpevarp 2002/03–2006/07, from /Werner et al. 2008/.

Winter season	Date for ice freeze-up	Date for ice break-up	Period of ice cover (days)
2002/03	2002-11-19 2002-12-19	2002-11-22 2003-03-28	3 100
2003/04	2004-01-07	2004-03-10	64
2004/05	2004-11-22	2005-04-01	129
2005/06	2005-11-22	2006-04-18	147
2006/07	2007-01-23	2007-03-01	37
Average 2002/03–2006/07			96

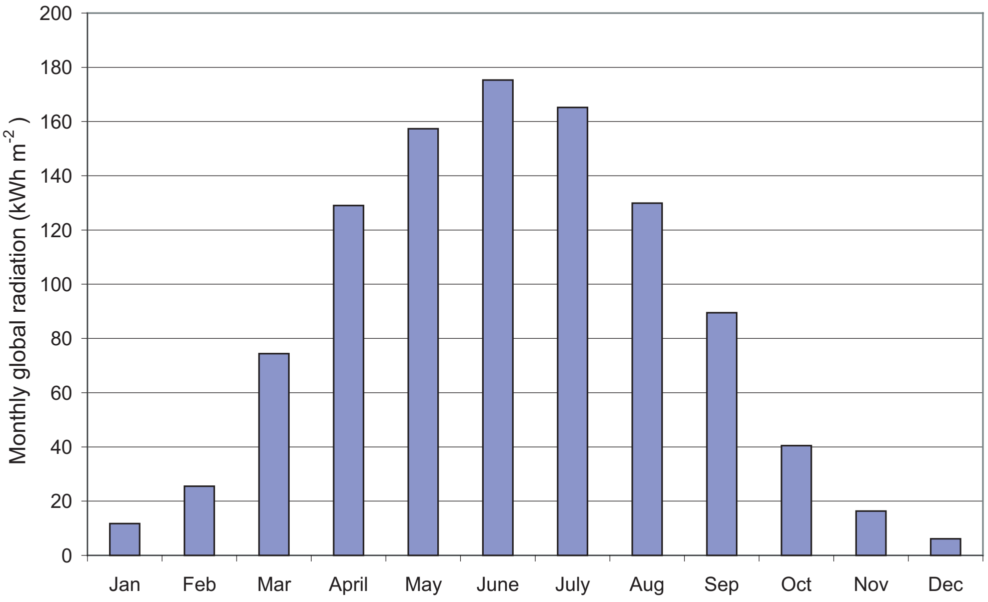

Figure 4-11. *Monthly averages (2004–2007) of global radiation at Äspö in the Laxemar-Simpevarp area.*

4.5 Lake bathymetry

The lakes in the Laxemar-Simpevarp area are small, but they generally have larger mean depths than the Forsmark lakes. Accordingly, the volumes of the Laxemar lakes are generally much larger than those of the Forsmark lakes. The retention time of the lakes varies between 218 days and as much as 829 days /Brunberg et al. 2004b/. In Table 4-6 some morphometric parameters are presented for the lakes in the area. Bathymetric maps illustrating the depths in the five lakes in the Laxemar-Simpevarp area is shown in Figure 4-12.

Table 4-6. Morphometry parameters for the 5 lakes in the Laxemar-Simpevarp area (data from [1]/Brunberg et al. 2004b/, [2]data from the database SICADA April 2008 (access might be given on request) and [3]calculated from SKB's GIS database).

Catchment **Lake**	**Simpevarp 7** **Frisksjön**	**Simpevarp 10** **Fjällgöl**	**Simpevarp 10** **Plittorpsgöl**	**Simpevarp 10** **Jämsen**	**Simpevarp 11** **Söråmagasinet**
Threshold elevation [m a RHB70] [2]	1.29	–	24.69	24.65	–
Area [km^2] [1]	0.13	0.03	0.03	0.24	0.10
Max depth [m] [1]	2.8	2.0	7.2	10.9	4.9
Mean depth [m] (Littoral I included) [1]	1.7	1.1	3.7	3.7	2.0
Mean depth [m] (Littoral I excluded) [3]	2.0	1.7	4.4	4.4	2.3
Volume [Mm^3] (Littoral I included) [1]	0.223	0.029	0.124	0.877	0.199
Volume [Mm^3] (Littoral I excluded) [3]	0.206	0.008	0.120	0.843	0.183
Shore length [m] [1]	2,632	864	933	4,036	2,992
Mean discharge [m^3/s] [1]	0.010	0.002	0.004	0.369	0.003
Retention time [days] [1]	264	218	399	275	829
Fetch [m] [1, A]	705	116	349	959	936
Width [m] [1, B]	248	55	119	603	184

[A] Fetch [m] Maximum length, the longest straight line over the water surface.
[B] Width [m] Maximum width, the longest straight line perpendicular to the length line.

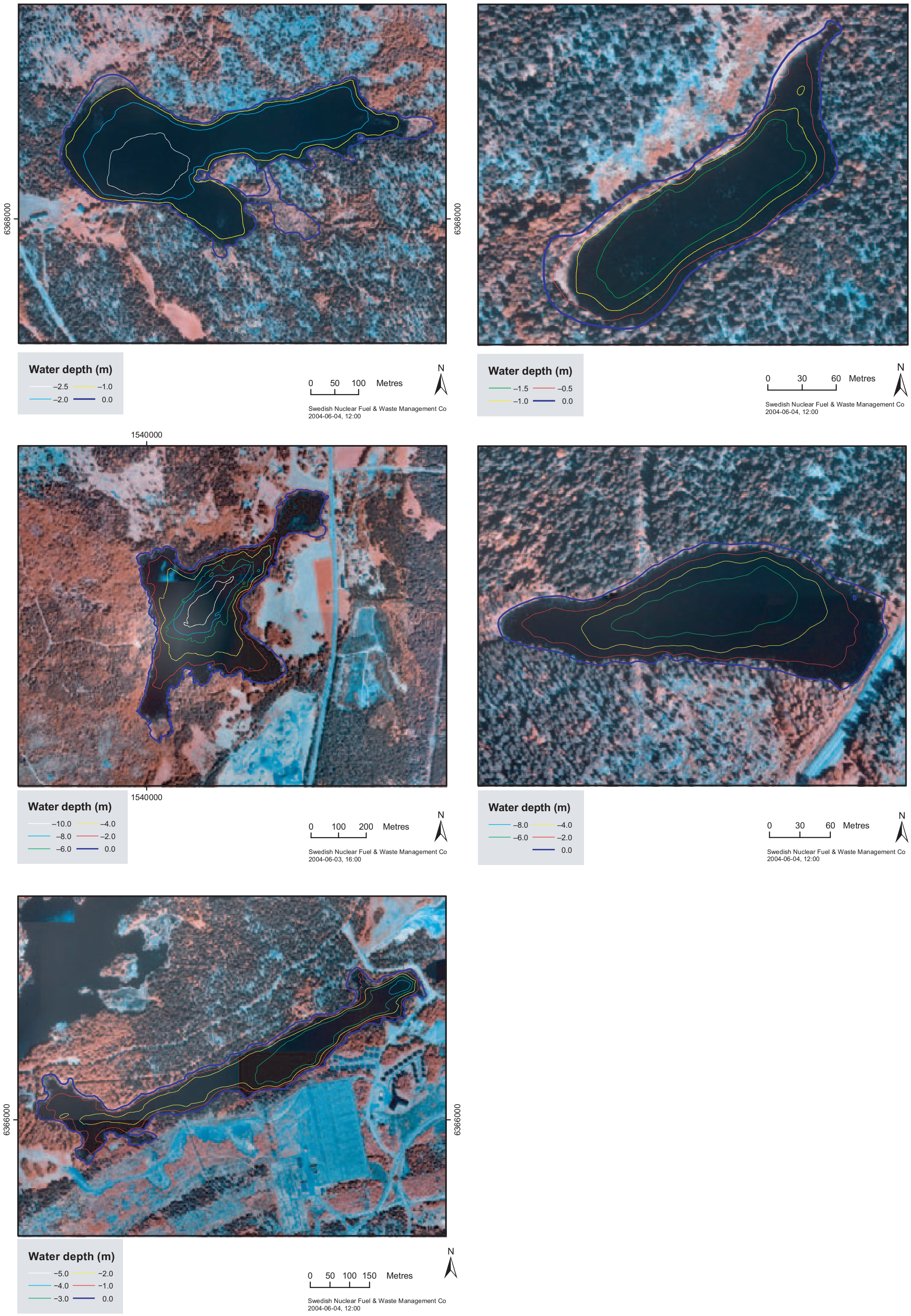

Figure 4-12. *Bathymetric maps for the five lakes in the Laxemar-Simpevarp area; Frisksjön (upper left), Fjällgöl (upper right), Jämsen (middle left), Plittorpsgöl (middle right) and Söråmagasinet (lower left). From /Brunberg et al. 2004b/.*

4.6 Lake sediments

In this section the sediments of four lakes in the Simpevarp-Laxemar area are described. The bays around the island Äspö are sheltered areas, and the physical conditions are in many respects similar to those in lakes. Some of the data from these sheltered bays are therefore also presented below.

4.6.1 Stratigraphy

All lakes in the area comprise a development stage in the transition from a marine environment into a terrestrial area (further described in Chapter 8). Accumulation of sediments starts already before isolation from the Baltic Sea, so some of the sediments in a lake are older than the lake itself. The stratigraphical distribution of the regolith is more or less the same in areas covered by lake or sea water as in terrestrial areas /Sohlenius and Hedenström 2008/. The general stratigraphy observed from the ground surface and down is gyttja, clay gyttja, sand and gravel, glacial clay underlain by till, which rests directly upon the bedrock surface (Table 4-7). The postglacial clay studied in the area contains organic matter and is therefore referred to as clay gyttja (6–20% organic matter). Some of these clay sediments may, however, have an organic content lower than 6% (gyttja clay). Gyttja is the sediment currently accumulating in lakes. For further description of the different sediment layers, see Section 3.6. In this report we have chosen to concentrate on the upper sediment layers, which contain most of the organic matter.

The sediments in the Laxemar-Simpevarp lakes are often very thick. The thickest recorded layer of gyttja sediments, more than 10 metres, was found in Frisksjön. Several metres of gyttja sediments have been recorded in other lakes as well. In a study of four lakes in the area (Frisksjön, Jämsen, Söråmagasinet and Plittorpsgöl), the clay layer was only penetrated in one of the lakes, indicating thick sediment layers, i.e. sediment depths were deeper than possible to measure with the technique used (Table 4-8).

Table 4-7. Sediment stratigraphy in Frisksjön (SSM000242) /Johansson et al. 2007/.

Layer	Depth (m)
Water	0–2.90
Gyttja	2.90–13.00
Clay	13.00–16.80
Till	16.80–17.40
Bedrock	17.40–

Table 4-8. Maximum investigated sediment depth in 4 lakes in the Laxemar-Simpevarp area. Each lake was sampled with three sediment cores. The sediment sampling did not reach bedrock except for in Jämsen and thus maximum depth is presented as values > metres for three of the lakes /Nilsson 2004/. *Data from the database SICADA, April 2008 (access might be given on request), **/Brunberg et al. 2004b/.

Sampling site	Elevation (m.a.s.l.)	Maximum thickness of sediment column (m)	Underlying material	Sediment strata in which the investigation ended
PSM006573–75 Jämsen	24.65*	5.1 meter	Sand layer	Sand layer
PSM006576–78 Söråmagasinet	1.94**	> 5.4 meter	Unknown	Gyttja
PSM006579–81 Plittorpsgöl	24.69*	> 4 meter	Unknown	Clay gyttja
PSM006570–72 Frisksjön	1.29*	> 7 meter	unknown	Gyttja

4.6.2 Redox zone

Sediments can be divided into aerobic (oxygenated) and anaerobic (oxygen-free) layers. The aerobic or anaerobic state affects the chemical environment and habitat for biota. Sediments containing organic material have a high oxygen demand due to intense microbial (and other consumers) respiratory metabolism. Moreover, elements such as Fe^{2+} accumulate in reduced form when released into the sediments from decomposing biota, and these elements react with oxygen leading to high oxygen consumption in the sediments. Even during circulation periods in the lake (spring and autumn), well oxygenated lake water only penetrates a few centimetres into the sediment due to slow diffusion rates in sediments. /Wetzel 2001/ reported oxygenated conditions to a depth of 5 mm during summer stratification and 10–12 mm during autumn and spring circulation in Lake Windermere. In Frisksjön, no data are available on the depth of the oxygenated zone, but based on the observations by /Wetzel 2001/ the top 1 cm was assumed to be aerobic. The assumption that the surface sediment in Frisksjön is aerobic is strengthened by observation of the sediments (Sohlenius, personal communication). Surface sediments in anaerobic environments are often laminated with the seasonal sediment accumulation, resulting in different layers due to different sedimenting matter during the year. In anaerobic environments, bioturbation does not occur and the lamination persists, whereas in aerobic environments bioturbation mixes the upper sediment and no seasonal dynamics in the surface sediments can be detected. The sediments in Frisksjön do not show any lamination, and this, together with the low water depth of the lake, indicates that the surface sediments are oxygenated at least during circulation periods.

4.6.3 Carbon content, accumulation rate and chemical composition

Chemical composition of sediments has been analyzed in several studies /Nilsson 2004, Sternbeck et al. 2006, Fredriksson R 2004, Engdahl et al. 2006/. Chemical characterization of 64 elements in the upper 4.4 m of the sediments from Frisksjön in the Laxemar area has been performed by /Engdahl et al. 2006/. Data from this study are presented in Appendix 9. The studies by /Nilsson 2004, Sternbeck et al. 2006, Fredriksson R 2004/ include fewer elements (C, N, S) but more sites in the Laxemar-Simpevarp area. The results from the two studies concerning carbon, nitrogen and sulphur in the clay gyttja agree relatively well with each other (Table 4-9).

The study by /Nilsson 2004/ shows that the concentrations of C, S and N increase with decreasing sediment age in lakes. The gyttja in Jämsen and Frisksjön had organic carbon contents of c. 20% and gyttja from Plittorpsgöl had organic carbon contents higher than 30%. The total contents of all these elements are relatively low in the glacial clay. The sediments deposited in lakes generally have a higher organic carbon content than sediments deposited in bays /Nilsson 2004/.

Table 4-9. The average contents (% of dry weight) of organic carbon (Org. C), nitrogen (N) and sulphur (S) in sediments in Frisksjön. From */Nilsson 2004, Sternbeck et al. 2006/ and from **/Engdahl et al. 2006/.

	n (C, N)	n (S)	Org. C	Max. C	Min. C	Tot. S	Max. S	Min. S	Tot. N	Max. N	Min. N
Clay gyttja in Frisksjön*	13	9	20.2±4.0	26.8	15.1	2.3±0.8	3.4	1.1	2.1±0.3	2.6	1.6
Clay gyttja in Frisksjön 0–2 cm**	1	1	12.0	12.0	12.0	1.9	1.9	1.9	1.3	1.3	1.3
Clay gyttja in Frisksjön 2–100 cm**	7	7	11.4±2.0	14.0	8.4	2.3±0.8	4.1	1.7	1.6±0.2	2.0	1.4
Clay gyttja in Frisksjön 100–440 cm**	4	4	11.8±1.7	14.0	10.0	2.5±0.2	2.7	2.2	2.1±0.3	2.3	1.7

The relative amounts of the 64 studied elements in the upper 4.4 m of the sediments in Frisksjön are shown in Figure 4-13 (data from /Engdahl et al. 2006/). The upper aerobic sediment has been assigned a separate pool in the lake. The distribution of elements in the upper (0–0.01 m) and lower sediments (0.01–4.40 m) is almost the same. Silicon is the most common element followed by carbon (Figure 4-13). Aluminium, iron, sulphur and nitrogen also comprise relatively large portions of the weight in both sediment layers. Oxygen and hydrogen are commonly occurring elements in the sediment as many of the elements above are found in oxygen complexes, and organic compounds often contain hydrogen. However, oxygen and hydrogen were not analyzed in the study by /Engdahl et al. 2006/ and are thus not shown in Figure 4-13 or included in the comparison of most common elements in the sediment.

The sediment in Frisksjön has a lower carbon content and higher content of silicon and aluminium than the gyttja layer in the Forsmark lakes (Section 3.6). The calcium content in Forsmark is higher than in Laxemar-Simpevarp. This is a result of the calcareous deposits in the Forsmark area. The sediment from Frisksjön more closely resembles the deeper clay gyttja layer of the Forsmark lakes. The chemical composition of sediments as well as other parts of the limnic ecosystems in the Laxemar-Simpevarp area is further discussed in Chapter 7.

Porosity and bulk density for sediments in the Laxemar-Simpevarp area have been calculated using data for the carbon and water contents from /Nilsson 2004/ and /Fredriksson R 2004/ (Table 4-10). Recent and long-term rates of sediment accumulation in the Laxemar-Simpevarp area have been studied by /Sternbeck et al. 2006/ (Table 4-11). The results were used to calculate the accumulation rates of carbon, nitrogen and phosphorus in Frisksjön and two coastal bays (Table 4-12). The average long-term accumulation covers a period of several thousands of years and the accumulation rates

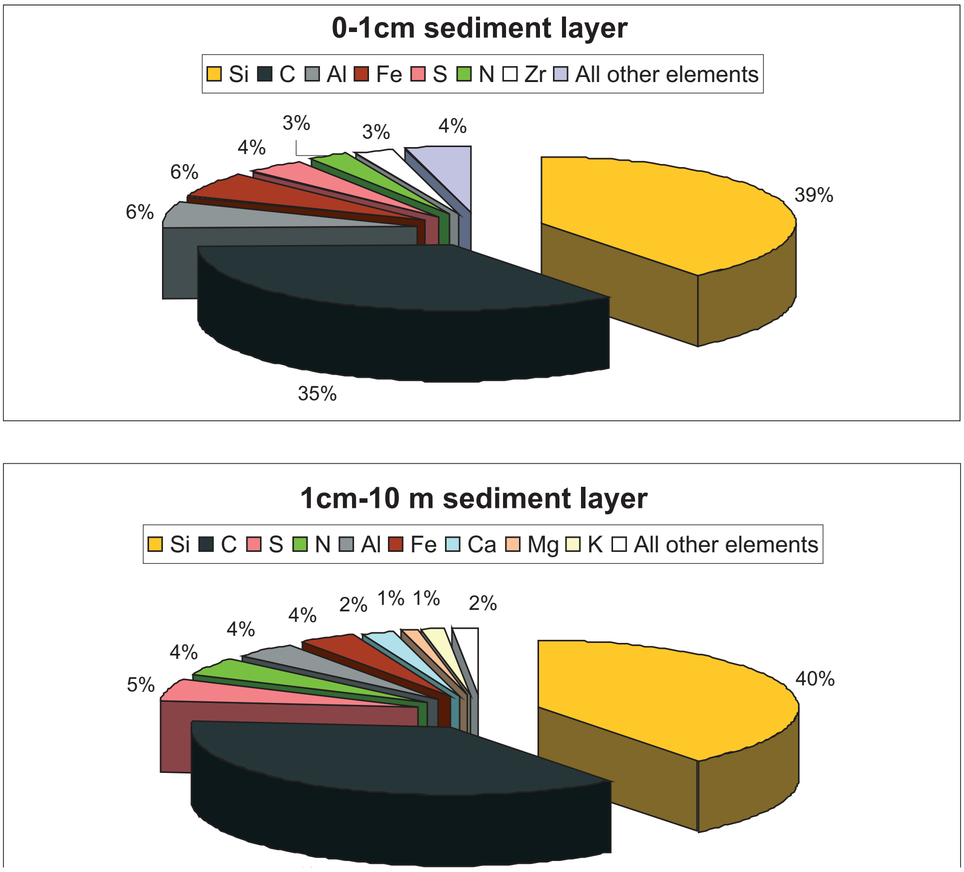

Figure 4-13. Relative amounts of investigated elements (%) in the two sediment layers in Frisksjön: upper (0–1 cm) and lower (1 cm–10 m).

have probably varied considerably throughout that period. Frisksjön is today situated at 1.3 m.a.s.l., indicating that the lake was isolated from the Baltic at 1200 AD (see Chapter 8). However, the lake threshold has been lowered by man by at least 1 m, and probably more, during the last centuries. This means that Frisksjön was isolated from the Baltic Sea much earlier, possibly already before year 0 BC/AD. The long-term accumulation rates shown in Table 4-11 and Table 4-12 reflect a period when the present lake probably was connected to the Baltic Sea. The accumulation rates for other elements have been calculated and are presented in Chapter 7.

Table 4-10. The average physical properties of the sediments in the Oskarshamn area (data from /Sohlenius and Hedenström 2008/).

	No. of obs.	Depth (m)	Water content (%)	Porosity (%)	Bulk density (kg/m^3)	Reference	Comments
Top sediment (clay gyttja, organic)	58	0–0.05	90.8±1.6	94.7±0.9	1,043±9	/Fredriksson R 2004/	Sheltered sea areas
Clay gyttja	42	0–6	83.4±5.4	90.0±3.4	1,081±33	/Nilsson 2004/	Data from lake, bays and peat areas

Table 4-11. Average mass accumulation rates (g dw m^{-2} yr^{-1}) in Frisksjön and in the two marine bays Borholmsfjärden and Norrefjärd. The ^{210}Pb record covers the 20th century and the ^{14}C dates have been used to calculate the long-term accumulation rate (from /Sternbeck et al. 2006/).

Site	Mass accumulation rate (g dw m^{-2} yr^{-1})			Long term cal (years ago)
	Average short term, ^{210}Pb	^{210}Pb, range	Average long term, ^{14}C	
Frisksjön	410	300–600	400±30	2,600–4,060
Borholmsfjärden	680	470–1,000	680±100	3,300–4,400
Norrefjärd	740	200–1,100		

Table 4-12. Average accumulation rates of carbon, phosphorus and nitrogen in Frisksjön and in the two marine bays Borholmsfjärden and Norrefjärd (from /Sternbeck et al. 2006/). The long-term averages are shown in bold.

Depth, cm	Organic carbon accumulation rate (g C m^{-2} yr^{-1})		Phosphorus accumulation rate (g P m^{-2} yr^{-1})		Nitrogen accumulation rate (g N m^{-2} yr^{-1})	
	Average	SD	Average	SD	Average	SD
Frisksjön						
20–22	79	14	0.63	0.13	6.3	0.9
188–431	**74**	**13**	**0.36**	**0.13**	**9.3**	**1.7**
Borholmsfjärden						
20–22	67	8	0.86	0.15	7.8	0.7
280–560	**95**	**18**	**0.49**	**0.07**	**13.6**	**2.1**
Norrefjärd						
2–4	151	22	1.82	0.35	19.3	2.2
10–12	151	22	1.66	0.32	18.1	2.2
20–22	108	16	1.13	0.22	12.5	1.5
32–34	47	7	0.40	0.08	5.6	0.6

4.7 Habitat distribution in the lakes

Lakes may be divided into five different habitats, Littoral I, II, and III, Pelagic and Profundal habitat. The areal distribution of each habitat has been investigated by /Brunberg et al. 2004b/. The habitat definitions are found in Section 3.7. All five habitats were found in four of the five investigated lakes (Table 4-13 and 4-14). Due to the brown water colour in the lakes, little light reaches the benthic habitat and profundal covers on average 47% of the lake areas. The sechi depth in Frisksjön is c. 1 m indicating a photic depth of 2 m. This is in accordance to findings of macrophytes (Nuphar lutea) down to a depth of 2.1 m. However, the stands of macrophytes are scarce in frisksjön and biomasses are low indicating low light climate also in the areas classified as littoral. The dominating littoral habitat differs between lakes. In Söråmagasinet Littoral III dominates, whereas in Fjällgöl, Plittorpsgöl and Jämsen (and also Frisksjön with the new habitat distribution) Littoral I dominates. Littoral II is present, although covering small areas, in all lakes except for in Fjällgöl, where only 4 habitats were found. The habitat distribution in Frisksjön is illustrated in Figure 4-14.

Table 4-13. Distribution (m^2) of habitats in the lakes in the Laxemar-Simpevarp area /Brunberg et al. 2004b/.

Catchment	Lake	Littoral I (m^2)	Littoral II (m^2)	Littoral III (m^2)	Profundal (m^2)	Pelagial (m^2)	Total lake area (km^2)
7	Frisksjön	24,200	1,430	49,130[1]	52,250	107,270	0.13
10	Fjällgöl	21,580	–	1,440	3,240	4,680	0.03
	Plittorpsgöl	6,630	290	4,260	22,800	27,340	0.03
	Jämsen	48,500	1,550	12,650	177,300	187,700	0.24
11	Söråmagasinet	20,430	740	39,690	39,140	82,700	0.10
Average		24,268	802	21,434	58,946	81,864	0.11
SD		15,168	682	21,635	68,656	72,071	0.09
Median		21,580	740	12,650	39,140	82,330	0.10
Min.		6,630	0	1,440	3,240	4,680	0.03
Max.		48,500	1,550	49,130	177,300	187,700	0.24

Table 4-14. Relative distribution (%) of the different habitats in the lakes in the Laxemar-Simpevarp area /Brunberg et al. 2004b/.

Catchment	Lake	Littoral I (%)	Littoral II (%)	Littoral III (%)	Profundal (%)	Pelagial (%)
7	Frisksjön	18	<2	38[1]	42	82
10	Fjällgöl	82	–	6	12	18
	Plittorpsgöl	20	<1	13	67	80
	Jämsen	21	<1	5	75	79
11	Söråmagasinet	20	<1	40	38	80
Average		32		20	47	68
Standard deviation		28		17	25	28
Median		20		13	42	80
Min		18	0	5	12	18
Max		82	<2	40	75	82

[1] Based on later investigations in Frisksjön this area is now defined as profundal since the light climate is too poor to sustain photosynthetic activity and no photosynthesizing organisms are found there.

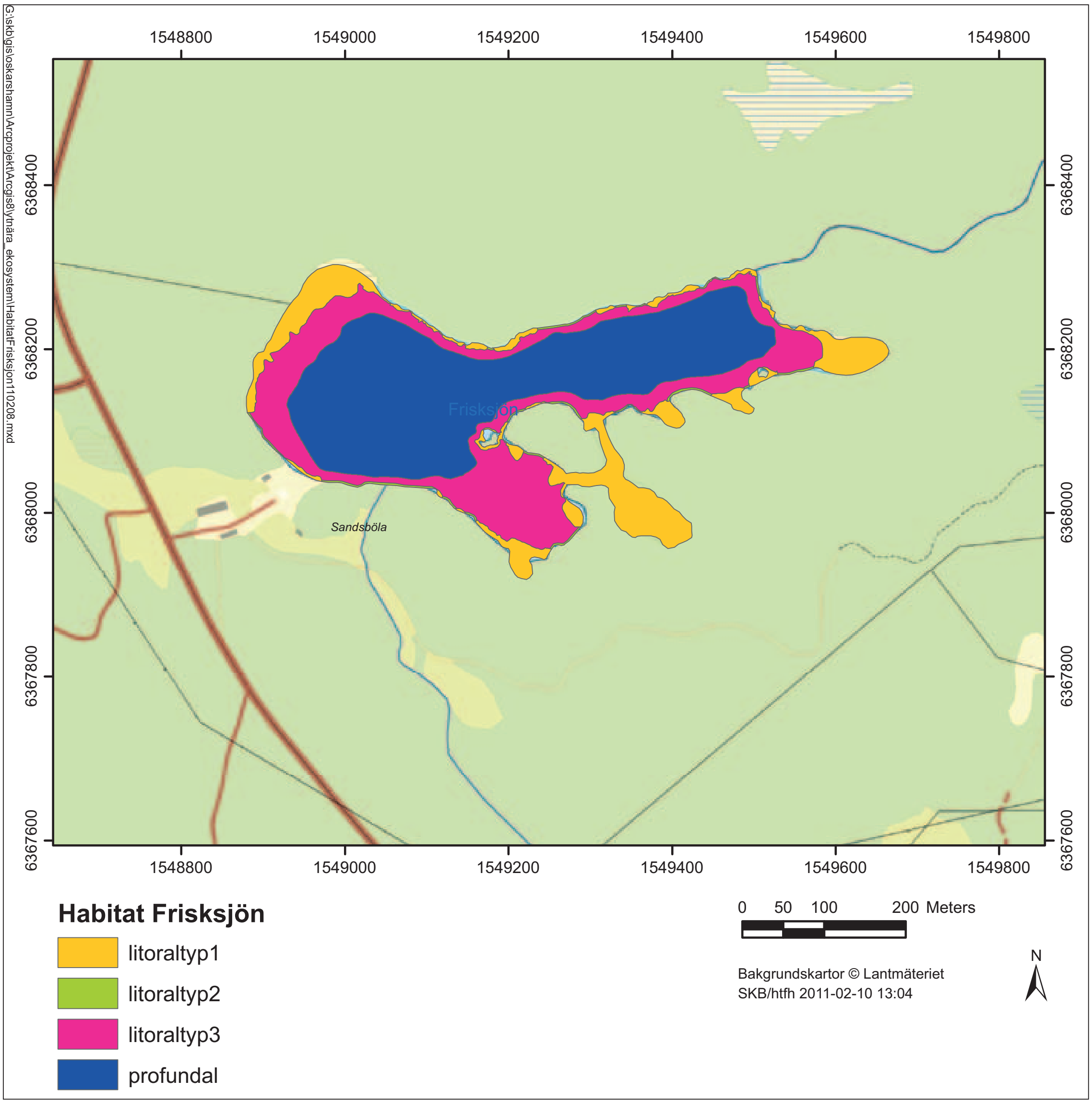

Figure 4-14. *Distribution of major habitats in Frisksjön.*

4.8 Physical characteristics of streams

Streams in parts of the Simpevarp regional model area have been investigated using the same methods as in the Forsmark area (Section 3.8) /Carlsson et al. 2005a/. Bottom substrate, water velocity, bottom vegetation, shading from terrestrial vegetation and technical encroachments were studied in 8 different catchments, and the total length of the investigated stretches was c. 20 kilometre long (Figure 4-2). Some of the streams are very small (e.g. four catchments on the island Ävrö) while others are larger. The largest is Laxemarån for which the entire stretch has not been investigated. Instead two stretches of totally c. 9.5 km have been examined. Three streams of medium size have also been investigated: Mederhultsån, Kåreviksån and Ekerumsån. In Mederhultsån, Kåreviksån and the four streams on Ävrö, all investigated stretches are of stream order 1. In Ekerumsån and Laxemarån stretches of stream order 1, 2 and 3 have been investigated.

The morphometry of the watercourses has also been investigated /Strömgren et al. 2006/. This investigation did not include the four small streams on Ävrö. Instead, additional stretches in Laxemarån were included. For Mederhultsån, Ekerumsån and Kåreviksån the same stretches as in /Carlsson et al. 2005a/ were investigated.

Of the investigated stretches most were of stream order 1 (49%) followed by stream order 3 (38%), whereas stream order 2 was the least represented in the investigated stretches (13% of total investigated stretch).

4.8.1 Bottom substrate

In the smaller streams, fine organic detritus or clay dominates as bottom substrate (Table 4-15), while conditions are different in Laxemarån, where clay or cobble is the dominant bottom substrate in stretches with stream order 1, fine organic detritus dominates stretches of stream order 2, and coarse organic detritus is most frequent in stretches of stream order 3.

4.8.2 Morphometry

Mederhultsån

Mederhultsån starts at roughly 13 m above sea level. The altitude gradient is quite steep at the beginning, but gradually becomes more moderate and after about 2,300 m it is hardly noticeable. At the time of the investigation, no flooded areas were found along Mederhultsån. The water flows partly in underground pipes, sometimes as long as several hundred metres.

Kåreviksån

Kåreviksån starts around 10 m above sea level and enters into the Baltic Proper after a little more than 2,800 m. Kåreviksån flows through Frisksjön on its way down to the Baltic Proper. The slope is relatively gentle, except for a stretch after approximately 300 m, a stretch close to the inlet into Frisksjön and a short stretch from the outlet from Frisksjön. The geometry of the stream channel is mostly clearly defined. The exception is a 300 m long section between Frisksjön and the Baltic Proper where the water overflows the bank.

Ekerumsån

Ekerumsån starts almost 13 m above sea level. The altitude gradient is low the first 3,000 m. Then it becomes very steep and the vertical drop is more than 6 m over only 300 m. After this stretch, the terrain flattens out all the way down to the Baltic Proper. There is an area where the water overflows the bank, close to the outlet into the Baltic Proper. This stretch is around 200 m long. Ekerumsån flows partly through pipes in the uppermost and lowermost parts.

Table 4-15. Distribution of different bottom substrates (%) in the investigated stream stretches in the Simpevarp regional model area (data from /Carlsson et al. 2005a/).

Stream name	**Mederhultsån**	**Kåreviksån**	**Streams on Ävrö**	**Ekerumsån**			**Laxemarån**			**Total**			
Stream order	**1**	**1**	**1**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Total**
Fine organic detritus	57	25	–	100	100	48		80	9	32	86	21	35
Coarse organic detritus	0	0	20						45	6	0	0	3
Clay	26	61	70			29	51	7		48	5	40	39
Sand	9	5	4			2		1	11	5	1	8	6
Gravel	3	4	0			4		1	9	2	1	8	4
Cobble	2	4	4			15	49	10	24	5	7	21	12
Boulder	1	0	2			1			3	1	0	2	1
Bedrock	2	–	–							1	0	0	0

Laxemarån

The stream Laxemarån begins south of Jämsen around 25 m above sea level and the total length down to the Baltic Proper is almost 15 km. The slope is steep the first 650 m, where the altitude decreases almost 10 m. After this section the slope becomes gentler. The exceptions are a 100 m stretch between 3,300 and 3,400 m, where the altitude decreases 2.5 m, and a 1,000 m long section from around 8,000 m where the terrain is very flat.

The geometry of the stream channel is generally clearly defined. After around 600 m the stream flows through a 1 km long, marsh area where the geometry of the stream channel is indistinct. The last kilometre is characterized by a very flat terrain where the stream overflows the bank. Laxemarån drains in pipes over only a couple of short sections near the outflow from Jämsen.

Eight tributaries to Laxemarån have been investigated. They are of different sizes and depths. In three of the tributaries the water overflows the bank in short stretches (tributary 10:5, 10:7 and 10:10). The highest altitude is recorded in tributary 10:7, which starts at 17 m.a.s.l. and enters Laxemarån at 6 m.a.s.l. All tributaries have a gentle slope except for short stretches with steeper conditions.

4.8.3 Shading

Terrestrial shading is highly dependent on catchment use. In areas with forest there are often densely shaded areas, whereas stream stretches passing agricultural land are not shaded at all.

In Mederhultsån most stretches are low to moderately shaded. There are some stretches passing through pipes, however, and these are totally shaded. Large parts of Kåreviksån passes through agricultural lands and these stretches are not shaded at all, but other parts pass through forest and these stretches are densely shaded (>50%). Ekerumsån and Laxemarån also have alternating stretches with dense shade and little shade. Most stretches of the streams on Ävrö are moderate to densely shaded.

4.9 Hydrochemical characteristics of lakes, streams and shallow groundwater

Surface water sampling was performed in a monitoring programme by SKB starting in March 2002. The sampling has been performed predominantly on a monthly basis. Four lakes belonging to separate catchments were monitored and 22 stations for running waters (Figure 4-15). The description of major constituents in water chemistry includes data from October 2002 to May 2005 for the Simpevarp regional model area /Tröjbom and Söderbäck 2006a/. Longer time series are available but no major difference in the data set can be seen. The water chemistry is compared with regional and national data from the national survey of lakes and watercourses, cf. /Wilander et al. 2003/ (data available for downloading from http://info1.ma.slu.se/db.html). The data were also compared with Swedish Environmental Quality Criteria (EQC) /Naturvårdsverket 2000/. Some of the comparison of the chemical composition in the lakes with regional and national reference data is presented as box plots. (Explanation of box plots are presented in Figure 3-22).

Concentrations of major elements and major ions, pH, temperature, oxygen and water colour in lakes, streams and groundwater are presented below and in Appendices 7 and 8. Water chemistry for minor elements is presented in Appendices 7 and 8 and in /Tröjbom and Söderbäck 2006a, Engdahl et al. 2008/.

4.9.1 Water chemistry in lakes

In the Simpevarp regional model area, the lakes are characterised as mesotrophic brown-water systems with the exception of Götemar, which is a clear-water lake. Most freshwaters are strongly coloured due to high amounts humic substances, leading to very high concentrations of dissolved organic carbon. The lakes are also relatively rich in nitrogen and phosphorus.

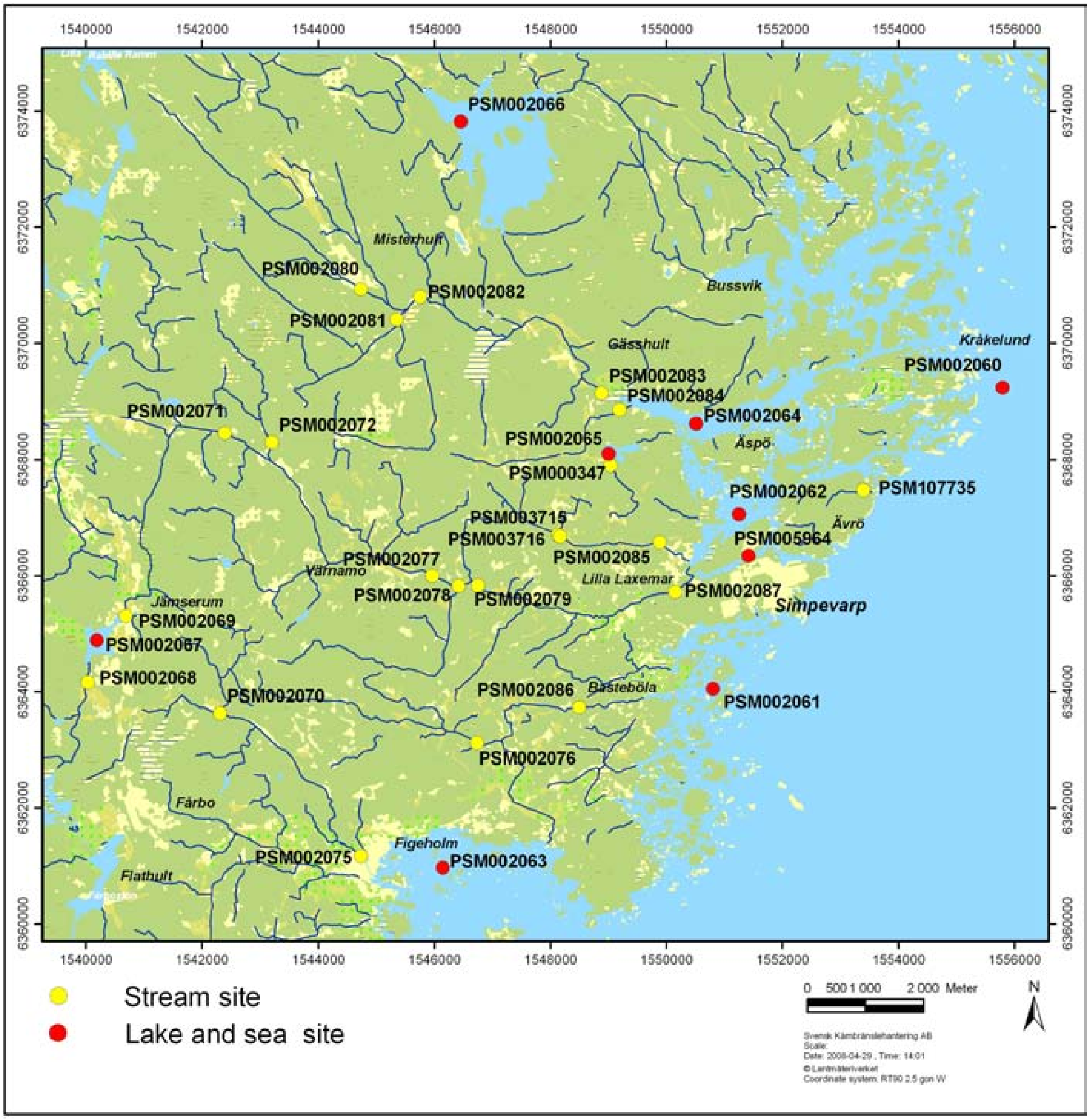

Figure 4-15. Monitored stream (yellow), lake and sea sites (red) in the Simpevarp regional model area. The SKB ID codes for each sampling site are given.

Acidity and alkalinity

The ***pH values*** are close to neutral (mean for all lakes 6.9 in surface water) and somewhat higher than the regional mean pH value (Table 4-16). The ***alkalinity*** is very good according to EQC and there is little sensitivity to acidification.

Table 4-16. Mean water chemistry (October 2002–May 2005) for major elements in the investigated lakes in the Simpevarp regional model area. Percentiles, mean, minimum, and maximum values have been calculated for all the monitored lakes. Values for surface water samples (0.5 m water depth), pH and conductivity have been measured in the field, while the other parameters are from laboratory analyses.

Element	N obs	Min.	25-p	Median	75-p	Max.	Mean	SD
pH (unit)	97	6.22	6.79	7.04	7.26	8.01	7.01	0.34
Conductivity (mS m^{-1})	102	9.4	11	12	15	18	13	3
Tot-P (mg L^{-1})	112	0.0054	0.015	0.018	0.023	0.043	0.019	0.008
POP (mg L^{-1})	111	0.0023	0.0064	0.0092	0.012	0.028	0.0097	0.005
PO$_4$-P(mg L^{-1})	112	<0.0005	0.00050	0.00080	0.0012	0.0050	0.00099	0.0008
Tot-N (mg L^{-1})	112	0.52	0.82	0.95	1.0	1.3	0.92	0.2
NH$_4$-N (mg L^{-1})	112	0.0013	0.0059	0.023	0.066	0.25	0.047	0.05
NO$_2$+NO$_3$-N (mg L^{-1})	112	0.00040	0.045	0.12	0.21	0.43	0.14	0.1
PON (mg L^{-1})	112	0.0084	0.048	0.081	0.11	0.28	0.087	0.05
TOC (mg L^{-1})	112	8.6	12	16	17	25	15	4
DOC (mg L^{-1})	111	8.6	12	15	17	24	15	4
POC (mg L^{-1})	112	0.077	0.43	0.70	0.89	5.5	0.78	0.6
SO$_4$-S (mg L^{-1})	112	2.7	3.6	4.3	5.5	8.4	4.7	1
Si (mg L^{-1})	112	0.33	2.1	3.9	4.6	6.4	3.4	2
Fe (mg L^{-1})	112	0.031	0.63	0.88	1.2	2.0	0.86	0.5
Mn (mg L^{-1})	112	<0.003	0.014	0.041	0.081	0.22	0.051	0.05
Cations								
Ca (mg L^{-1})	112	6.3	7.4	8.6	10	13	8.8	2
Mg (mg L^{-1})	112	1.9	2.2	2.3	2.9	4.3	2.6	0.6
Na (mg L^{-1})	112	2.7	8.7	9.6	11	17	10	2
K (mg L^{-1})	112	0.86	1.3	1.5	1.8	2.9	1.7	0.5
Anions								
Cl (mg L^{-1})	112	7.6	11	13	15	24	14	4
HCO$_3$ (mg L^{-1})	112	11	12	14	17	48	18	9
F (mg L^{-1})	110	<0.2	0.48	0.63	0.79	1.5	0.69	0.3
Br (mg L^{-1})	112	<0.2	<0.2	<0.2	<0.2	0.50	<0.2	0.05
I (mg L^{-1})	20	0.0040	0.0078	0.021	0.026	0.033	0.019	0.010

Major elements

The ***phosphorus*** concentrations are according to EQC moderate in Frisksjön, Jämsen and Söråmagasinet and low in Götemar (Figure 4-16). The phosphorus concentrations are elevated compared with the majority of Swedish lakes. Particulate phosphorus is coupled to primary production and shows elevated concentrations in the presence of phytoplankton. Phosphate phosphorus, on the other hand, shows low levels during the growing season, indicating that phosphorus may become limiting for primary production.

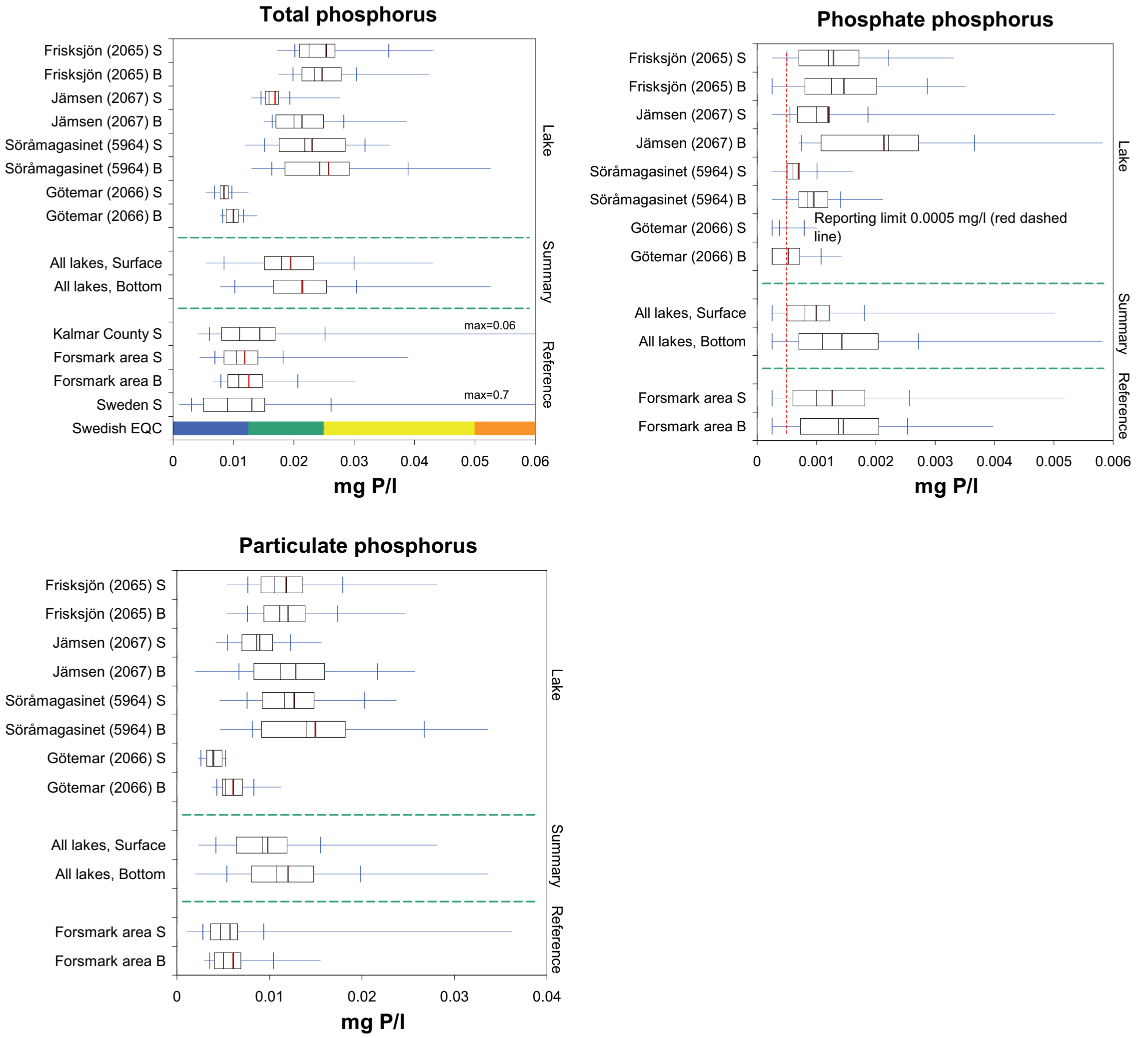

Figure 4-16. *Concentrations of total, phosphate and particulate phosphorus in surface (S) and bottom (B) water in lakes in the Laxemar-Simpevarp area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.*

The ***nitrogen*** concentrations are high according to EQC and compared with the majority of Swedish lakes (Figure 4-17). Götemar, which has low phosphorus concentrations, also has slightly lower nitrogen concentrations than the rest of the investigated lakes. There is seasonality in nitrogen fractions, and in the summer the particulate nitrogen levels are high whereas the inorganic fractions (NH_4, NO_3) are higher during winter.

The concentrations of total organic ***carbon*** (TOC) are very high according to EQC and high compared with the majority of Swedish lakes (Figure 4-18). The only deviating lake is Götemar with moderately high concentrations. About 90% of TOC is made up by dissolved organic carbon (DOC). The TOC concentrations in Frisksjön and Jämsen show a clear seasonality with higher concentrations during the warm season. Söråmagasinet and Götemar have only minor seasonal variations in TOC concentrations.

The ***sulphur*** concentrations in the lakes in the Simpevarp regional model area, as in the rest of the region, are elevated compared with the majority of Swedish lakes. There is a seasonal pattern with lower summer values. The high sulphate concentrations in most lakes can be attributed to leaching from the catchments, as atmospheric deposition in the region is the same as in many other parts of the country.

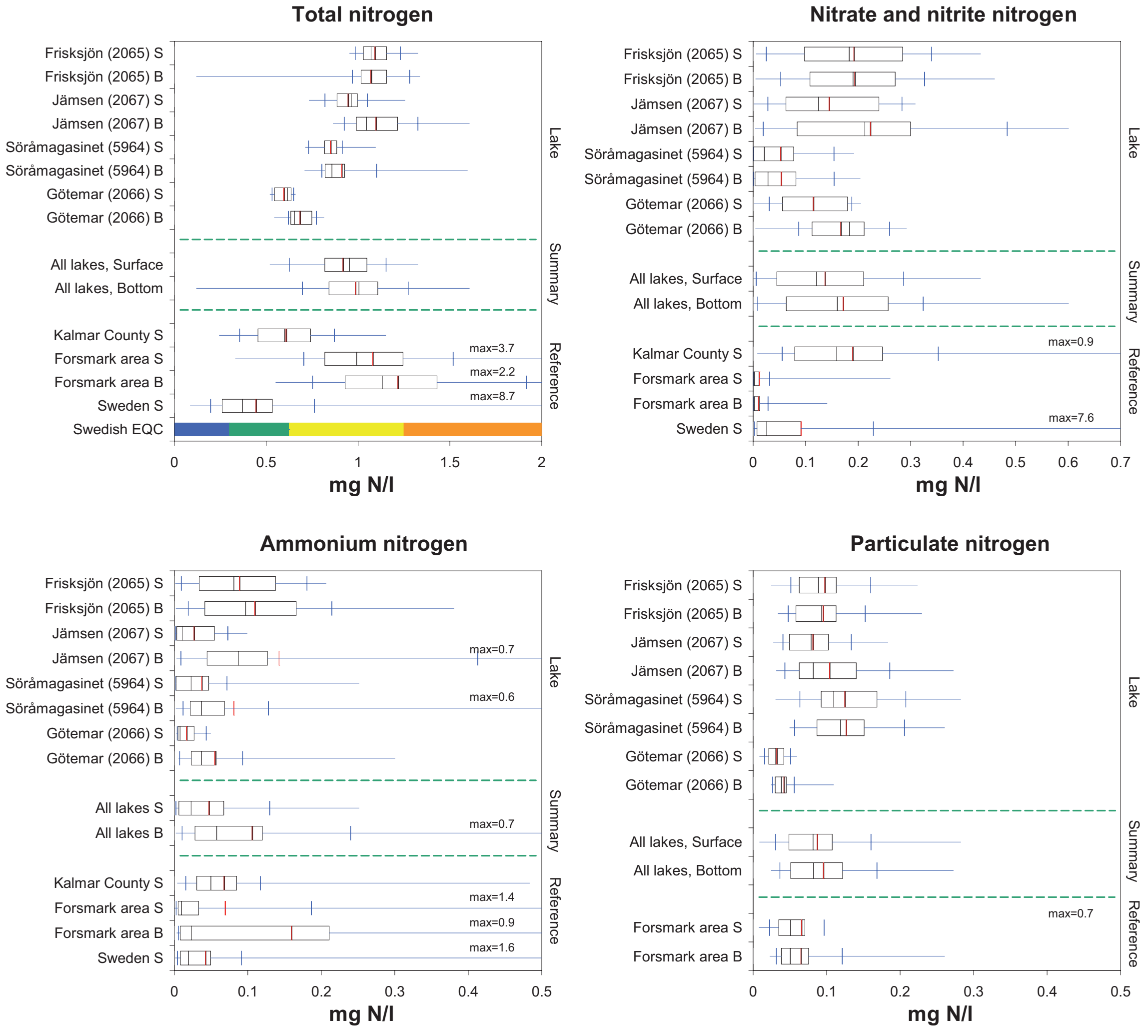

Figure 4-17. *Concentrations of total, nitrate and nitrite, ammonium and particulate nitrogen in surface (S) and bottom (B) water in lakes in the Laxemar-Simpevarp area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.*

Concentrations of ***silicon*** (Si) in Frisksjön and Jämsen are markedly elevated compared with most lakes in Sweden. Si is bioregulated and there is a clear seasonal pattern with low summer values when uptake by diatoms occurs. There was no diatom bloom recorded in the phytoplankton investigation. However, that investigation only included 8 samples over the entire year, so a diatom bloom may well have occurred between samplings.

Dissolved ions and conductivity

The total amount of dissolved ions, the ***electrical conductivity***, is somewhat elevated compared with most Swedish lakes (Table 4-16). However, it is much lower than in the Forsmark lakes.

Cations consist mainly of calcium, magnesium, sodium and potassium. These ions have slightly elevated concentrations compared with most Swedish lakes but are similar to those in the regional lakes. The concentrations are fairly constant on a seasonal basis.

Anions consist mainly of chloride, bicarbonate and sulphate. Fluoride and bromide occur at much lower concentrations and iodine only occurs at trace levels. Both chloride and fluoride concentrations are higher than in most Swedish lakes. Fluoride is also elevated compared to concentrations in regional lakes.

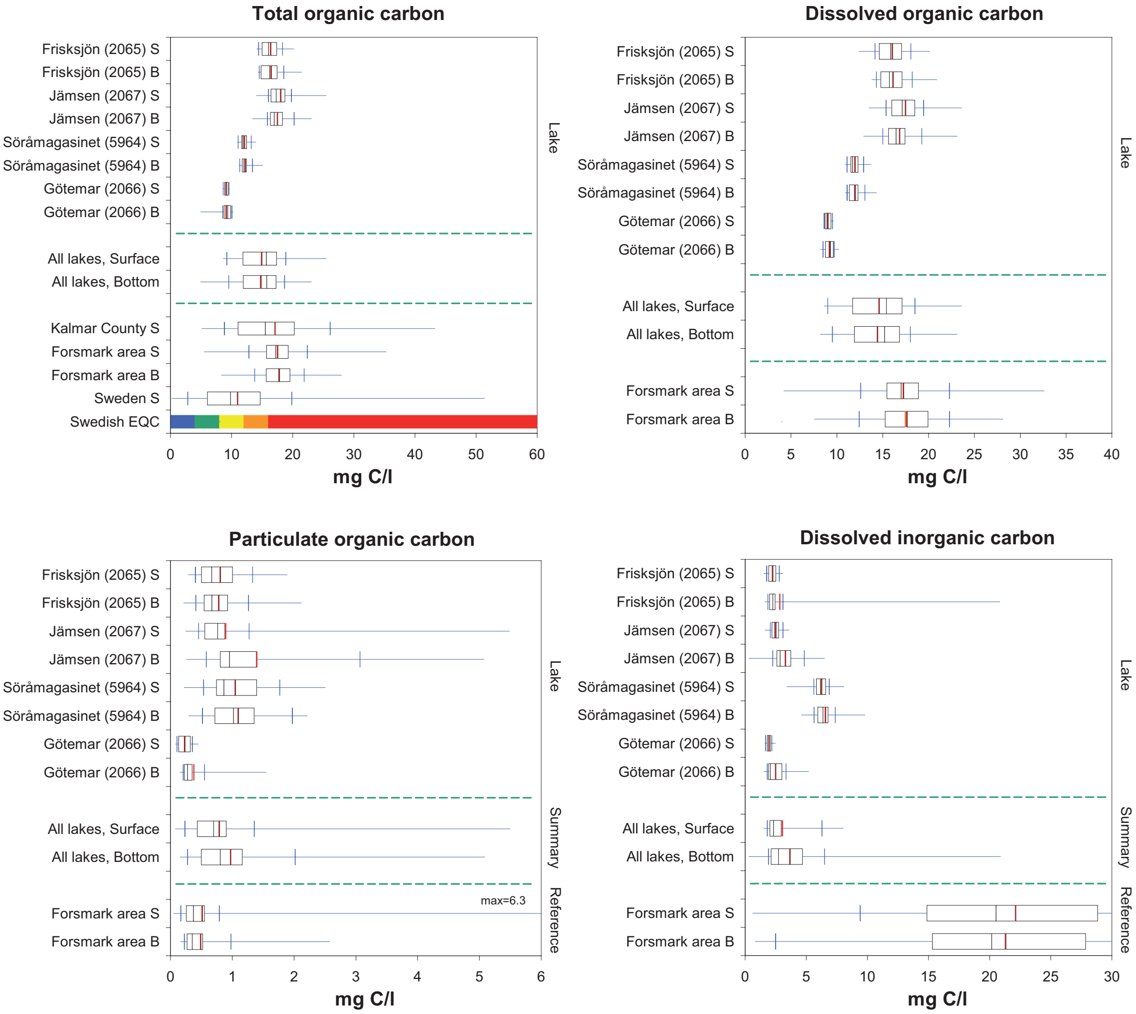

Figure 4-18. Concentrations of total, dissolved and particulate organic carbon, as well as contents of dissolved inorganic carbon, in surface (S) and bottom (B) water in lakes in the Laxemar-Simpevarp area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.

Iron concentrations are very high in Frisksjön, Jämsen and Söråmagasinet compared with most Swedish lakes. Götemar deviates from the rest of the lakes and has low iron concentrations. Götemar is a clear-water lake whereas the others are brown-water lakes. The high humic content in the brown-water lakes is most probably the reason for the high iron concentrations. ***Manganese*** occurs in moderately elevated concentrations in Frisksjön, Jämsen and Söråmagasinet whereas Götemar has lower concentrations.

Dissolved oxygen

The concentration of dissolved oxygen is dependent on mixing of the water column, temperature, inflow of oxygen-rich water, inflow of oxygen-depleted ground water, and the balance between primary production and decomposition of organic matter. In connection with primary production, dissolved oxygen is released to the water and the concentrations increase. In connection with decomposition, oxygen is consumed and concentrations decrease. The lakes in the Simpevarp area show recurrent episodes of low oxygen levels in the bottom water in both the summer and winter when the water column is stratified. When the water is completely mixed again in the spring and autumn, but also at other times (probably as a consequence of strong winds) the oxygen levels rises rapidly (Figure 4-19).

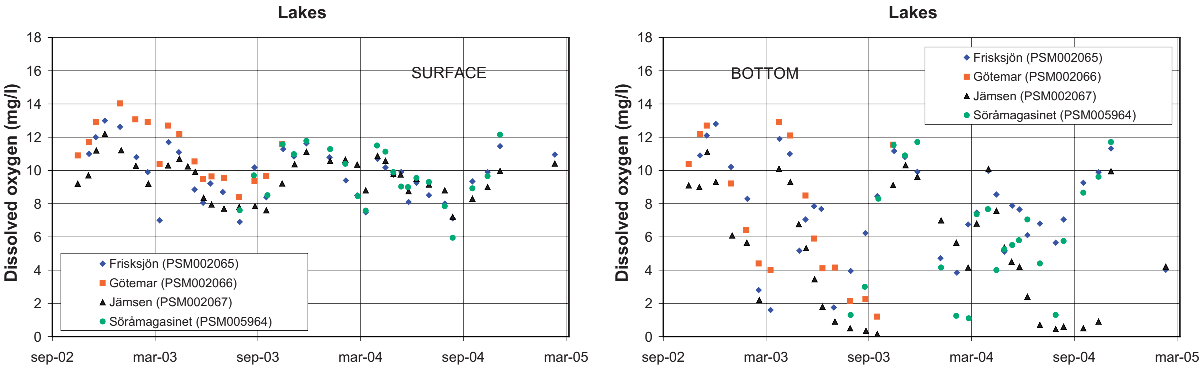

Figure 4-19. Oxygen concentrations in four of the lakes in the Laxemar-Simpevarp area.

Temperature

Water temperature has been measured in 4 of the Laxemar-Simpevarp for different time periods (the longest is for Frisksjön 2002–2007). The water temperatures varied between a few tenths of a degree above zero in the winter up to above 20°C in the summer (Figure 4-20). The same pattern is seen for all four lakes (data from SICADA[7], October 2007).

Water colour

The water colour has been measured as absorbance at 420 nm in two lakes in the Laxemar-Simpevarp area, Frisksjön and Jämsen. The water colour varies over the year, with the highest values in the spring and autumn (Figure 4-21) (max in Frisksjön was 0.24 in Absorbance_436) data from the database SICADA, April 2008). The annual mean water colour for Frisksjön varies somewhat between the two years when measurements were performed: in 2005 the annual average was 0.15 (Absorbance_436) and in 2006 it was 0.12(Absorbance_436). This indicates a moderate water colour. For comparison, the mean absorbance measured in 8,000 lakes in Sweden was 0.14 (Absorbance_436) and for lakes in Kalmar County 0.26 (Absorbance_436, data from the national survey of lakes, cf. /Wilander et al. 2003/).

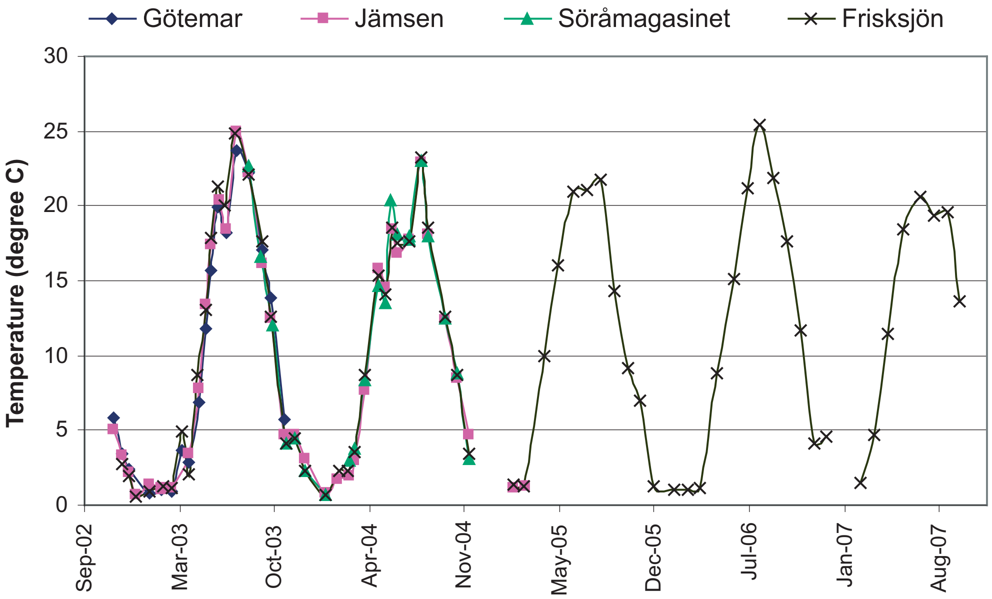

Figure 4-20. Water temperature in surface water of four lakes in the Laxemar-Simpevarp area. (Data from SICADA[8], October 2007).

[7,8] SKBs database SICADA, access might be given on request.

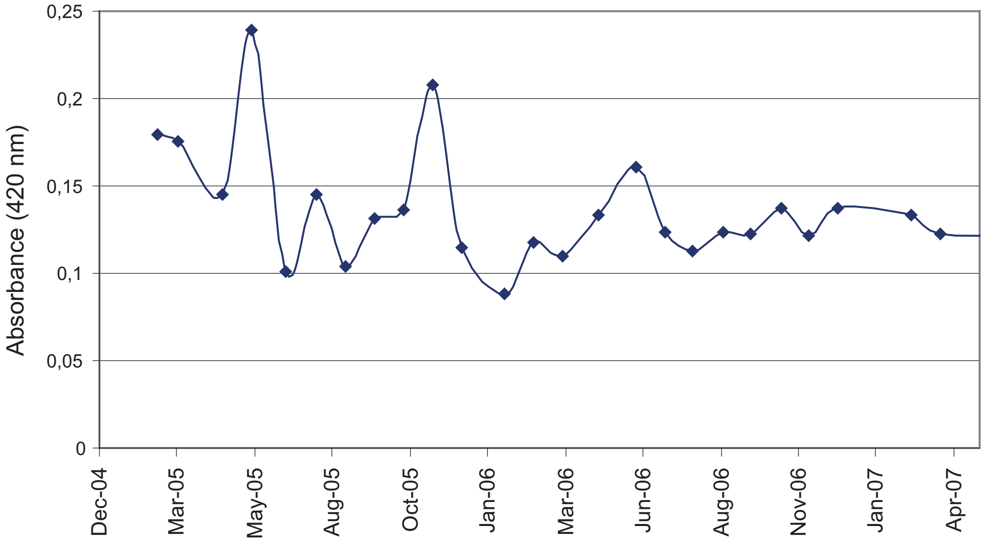

Figure 4-21. *Water colour, measured as absorbance at 420 nm, in Frisksjön. (Data from the database SICADA, April 2008).*

4.9.2 Water chemistry in streams

The streams in the Laxemar-Simpevarp area are characterized as mesotrophic brown-water systems. Most freshwaters are strongly coloured due to high amounts humic substances, leading to very high concentrations of dissolved organic carbon. The streams are also relatively rich in nitrogen and phosphorus.

The concentrations of most elements show more or less variation, due to both dilution effects caused by variations in runoff and to seasonal variations coupled to primary production and mobility of for example carbon. In the winter when the water in the superficial soil layers is frozen, the contents of carbon and carbon-related elements are usually low in the flowing water. The seasonal variations of dissolved ions are less accentuated and probably mainly governed by variations in water flow.

Acidity and alkalinity

Most freshwater sampling sites show “moderately acid” to “slightly acid” **pH values** and an alkalinity corresponding to “good buffering capacity” according to the EQC (Table 4-17) /Naturvårdsverket 2000/. There are, however, a few stream sampling sites which show “very acid” pH values and “no or negligible” buffering capacity, indicating presence of acid and maybe also acidified waters in the Simpevarp regional model area. A substantial proportion of the Simpevarp regional model area is covered by a very thin Quaternary layer or bedrock, creating conditions for acidification in small streams draining the catchments, which are dominated by thin soils.

Major elements

The concentrations of total ***phosphorus*** in the streams in the Simpevarp regional model area range from “moderately high” to “very high” according to the EQC (Figure 4-22, Table 4-17) /Naturvårdsverket 2000/. Also according to data from the National Survey (cf. /Wilander et al. 2003/), the phosphorus levels are elevated. There is a general tendency toward increasing concentrations of total phosphorus, phosphate and particulate phosphorus downstream in the watercourses (Figure 4-22). The highest phosphorus levels coincide with areas with the highest proportion of arable land. Nevertheless, two stream sites in the northern part of the area show elevated phosphorus levels despite a low proportion of arable land in the catchment. The reason for these elevated levels is unclear.

Table 4-17. Mean water chemistry (October 2002–May 2005) for major elements in the investigated streams in the Simpevarp regional model area. Percentiles, mean, minimum, and maximum values have been calculated for all the monitored streams.

Element	N obs	Min.	25-p	Median	75-p	Max.	Mean	SD
pH (unit)	570	5.01	6.12	6.42	6.65	7.85	6.40	0.46
Conductivity (mS/m)	571	5.8	11	13	17	34	14	5
Tot-P (mg L^{-1})	563	0.012	0.024	0.035	0.049	0.30	0.043	0.03
POP (mg L^{-1})	561	0.00060	0.0097	0.016	0.026	0.25	0.022	0.02
PO_4-P (mg L^{-1})	564	0.00050	0.0037	0.0061	0.0100	0.073	0.0082	0.008
Tot-N (mg L^{-1})	563	0.10	1.0	1.2	1.7	4.6	1.5	0.7
NH_4-N (mg L^{-1})	564	<0.0005	0.031	0.060	0.097	1.2	0.085	0.1
NO_2+NO_3-N (mg L^{-1})	564	0.0021	0.11	0.19	0.30	3.5	0.30	0.4
PON (mg L^{-1})	562	0.0087	0.060	0.099	0.16	1.6	0.14	0.1
TOC (mg L^{-1})	562	7.9	17	20	25	70	23	9
DOC (mg L^{-1})	564	7.6	17	20	24	70	22	8
POC (mg L^{-1})	560	0.080	0.75	1.3	2.2	15	1.8	2
SO_4-S (mg L^{-1})	573	0.92	8.6	13	18	66	16	10
Si (mg L^{-1})	555	2.9	6.5	8.2	10.0	20	8.4	3
Fe (mg L^{-1})	555	0.23	0.91	1.2	1.8	11	1.6	1
Mn (mg L^{-1})	555	0.0068	0.045	0.067	0.11	0.90	0.097	0.1
Cations								
Ca (mg L^{-1})	556	3.5	8.6	11	15	38	13	6
Mg (mg L^{-1})	556	0.90	2.0	2.4	3.2	5.8	2.6	0.9
Na (mg L^{-1})	556	2.7	6.1	8.6	11	31	8.9	4
K (mg L^{-1})	556	<0.4	0.95	1.3	1.7	7.8	1.5	0.9
Anions								
Cl (mg L^{-1})	573	2.0	6.0	10	14	51	11	6
HCO_3 (mg L^{-1})	572	<0.2	12	18	29	120	23	20
F (mg L^{-1})	565	<0.2	0.37	0.53	0.77	2.7	0.66	0.5
Br (mg L^{-1})	573	<0.2	<0.2	<0.2	<0.2	1.3	<0.2	0.2
I (mg L^{-1})	87	0.0020	0.0060	0.010	0.020	0.10	0.016	0.02

The concentrations of total ***nitrogen*** in the streams in the Simpevarp regional model area are "high" according to the Swedish EQC /Naturvårdsverket 2000/, and according to data from the National Survey (cf. /Wilander et al. 2003/) as well, the nitrogen levels are elevated (Figure 4-23, Table 4-17). As with phosphorus, the highest nitrogen concentrations are observed in streams that drain catchments containing a large proportion of arable land (Figure 4-23). The nitrogen levels are elevated in a catchment in the northern part of the area (compare with phosphorus). The ammonium fraction in particular is occasionally elevated. The total nitrogen content is fairly constant throughout the year, whereas the different nitrogen species show considerable seasonal variation. Nitrate, ammonium and particulate organic nitrogen comprise only a minor part of the observed total nitrogen contents.

The content of total organic ***carbon*** in the fresh waters of the Simpevarp regional model area is "very high" according to the EQC /Naturvårdsverket 2000/. According to data from the national survey (cf. /Wilander et al. 2003/) as well, the organic carbon levels are markedly elevated (Figure 4-24, Table 4-17). The high organic carbon content in the Simpevarp area is fairly uniformly distributed (Figure 4-24). The content of organic carbon shows a clear seasonal variation, with generally higher values in the warmer season. The variation is probably coupled to the mobility of water and transport of humic acids and other carbon compounds originating from the terrestrial ecosystems. Both particulate and dissolved organic carbon show similar seasonal patterns.

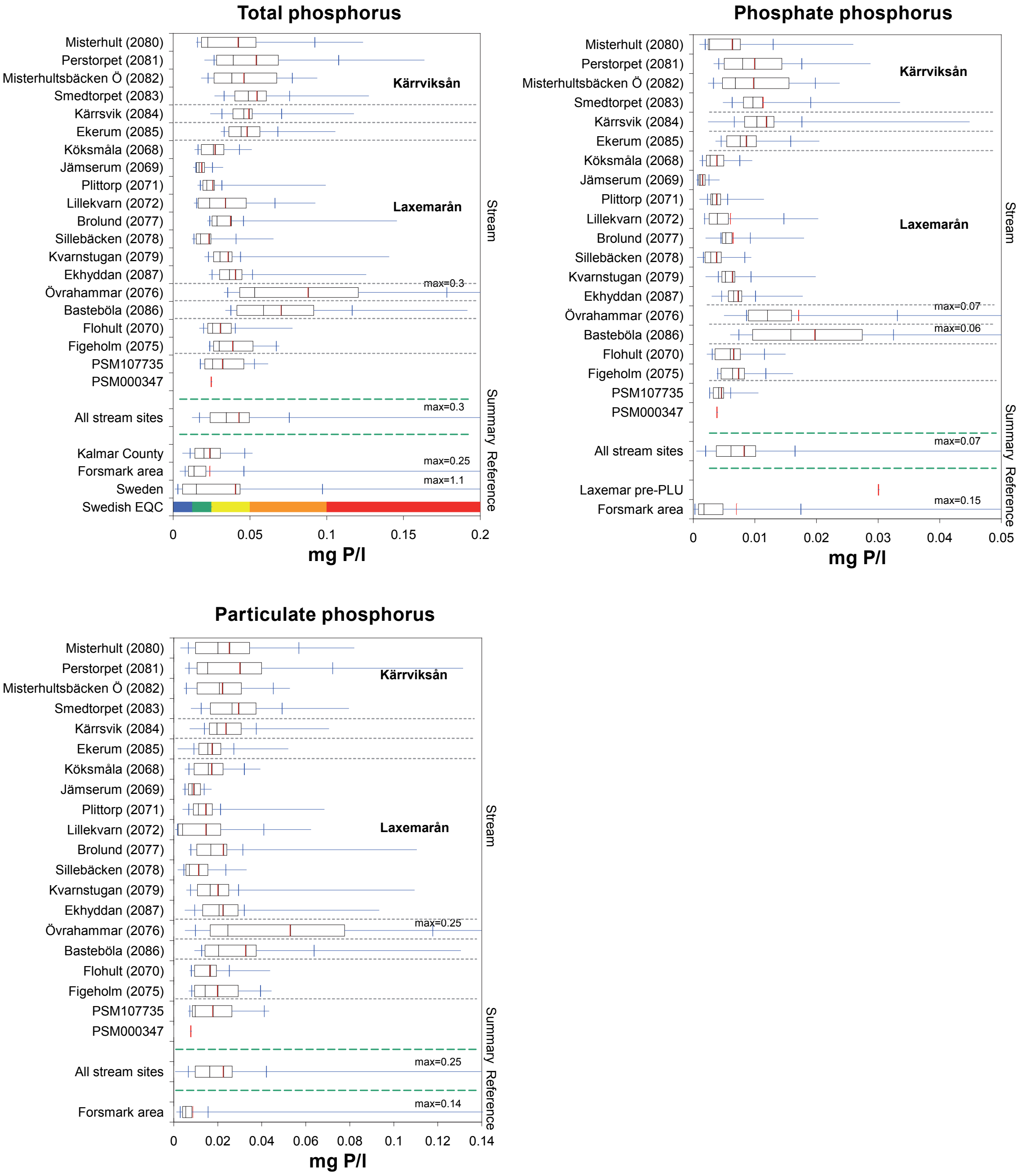

Figure 4-22. Concentrations of total, phosphate and particulate phosphorus in streams in the Laxemar-Simpevarp area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the id-code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.

The ***sulphur*** concentrations in the streams in the Simpevarp regional model area are, as in the rest of the region, elevated compared with most Swedish streams (Table 4-17). There is a general tendency for increasing sulphur concentrations along the watercourses in the area. As for phosphorus, the highest values are found nearest the outlets and coincide with the highest concentrations of arable land. These areas presumably have sulphur-containing sediments, which is probably an important reason for the elevated levels. A seasonal pattern with lower concentrations during summer is seen in most of the streams.

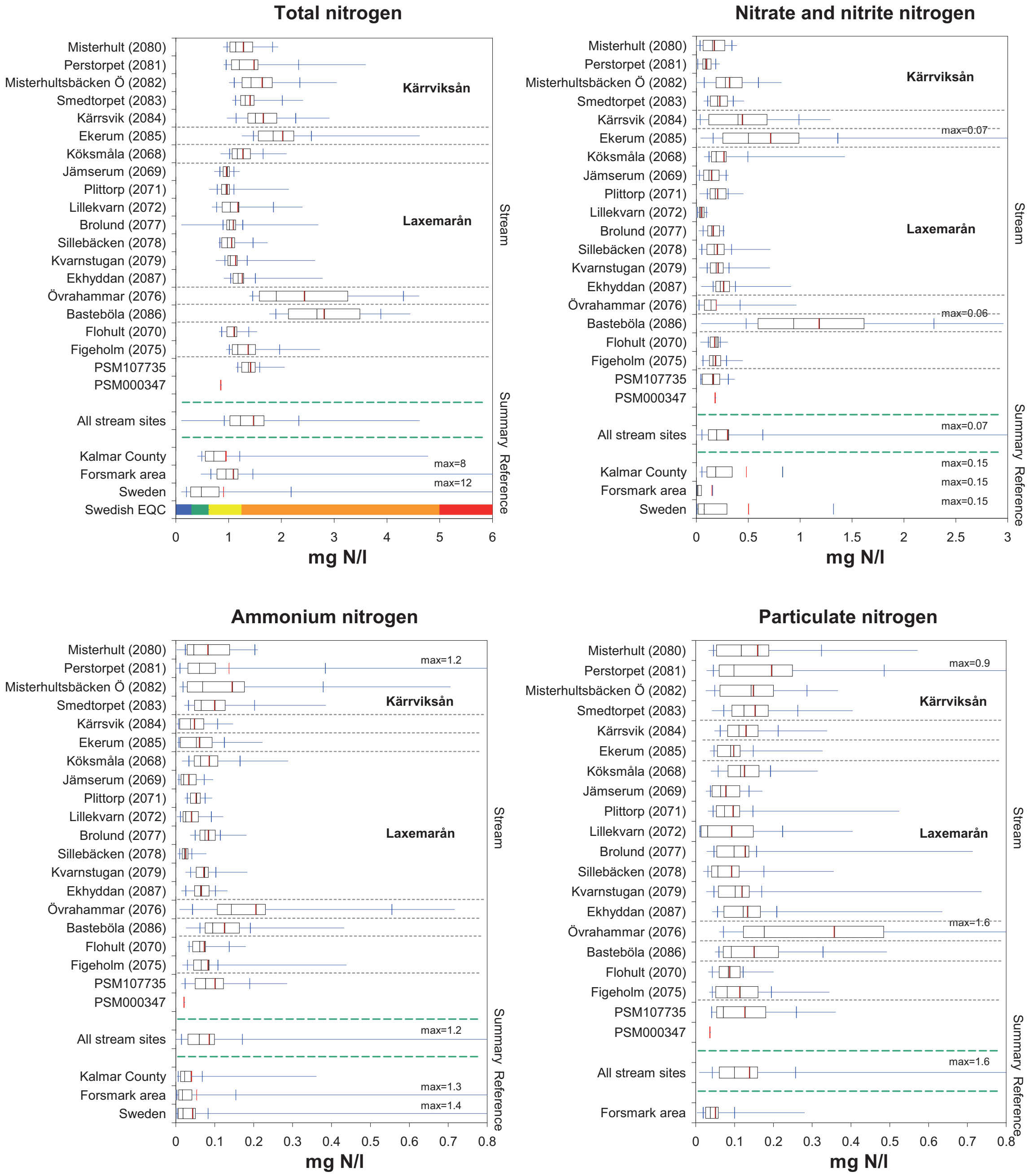

Figure 4-23. Concentrations of total, nitrate and nitrite, ammonium and particulate nitrogen in streams in the Laxemar-Simpevarp area. For an explanation of the box plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.

Most Simpevarp regional model area streams show significantly elevated concentrations of ***silicon*** compared with normal levels in Sweden (Table 4-17). The area also deviates from the region. The lowest silicon concentrations occur in the western part of the area, whereas the highest occur in the eastern part, especially in the catchments containing a lot of arable land and fine-grained sediments.

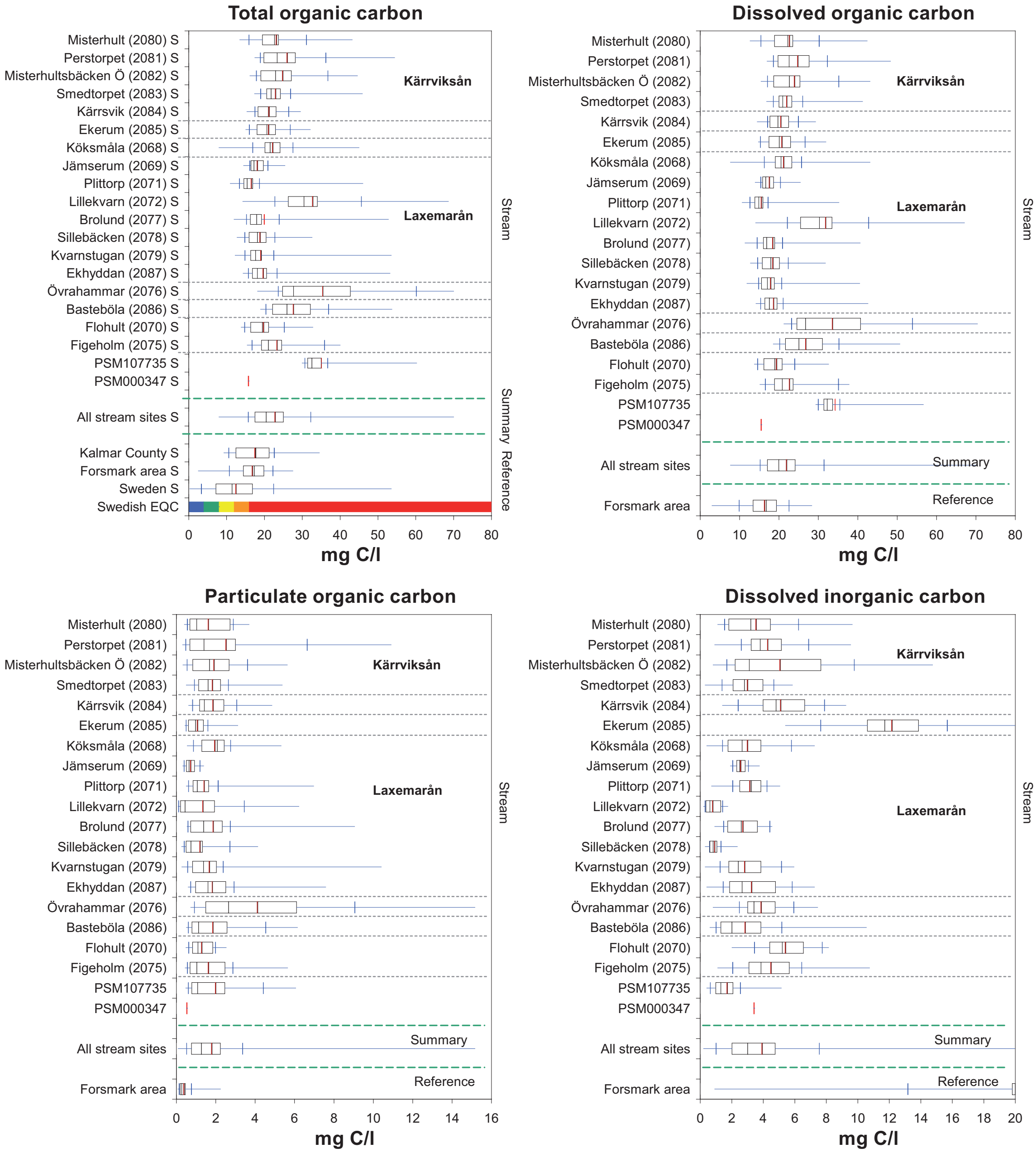

Figure 4-24. Concentrations of total, dissolved and particulate organic carbon, as well as contents of dissolved inorganic carbon, in streams in the Laxemar-Simpevarp area. For an explanation of the box-plots, see Figure 3-22. Numbers within brackets represent the last digits in the ID code used in the database SICADA. Data from /Tröjbom and Söderbäck 2006a/.

Dissolved ions

In conformity with the lake water chemistry, the total amount of dissolved ions in streams in the Laxemar-Simpevarp area lead to a somewhat elevated ***electrical conductivity*** compared with the situation in most Swedish freshwater bodies (Table 4-17). The electrical conductivity show high variability in streams. This variation, which shows no clear seasonal pattern, is probably caused by climatic variations in precipitation and runoff.

Cations consist mainly of calcium, magnesium, sodium and potassium (Table 4-17). These ions have slightly elevated concentrations compared with most Swedish streams but are similar to those in the regional streams. There is a general tendency for the highest concentrations of calcium, magnesium, sodium and potassium to be found in the streams near the coast, and the lowest concentrations in the western part of the Simpevarp regional model area. The concentrations are fairly constant on a seasonal basis. Many streams show very similar temporal patterns regarding these cations, even though they belong to different catchments. This may indicate that cation concentrations are mainly governed by climatic factors as precipitation and runoff.

In the streams in the Simpevarp regional model area, as well as in the lakes in the area, ***anions*** consist mainly of chloride, bicarbonate and sulphate (Table 4-17). Fluoride and bromide occur at much lower concentrations and iodine only occurs at trace levels. Both chloride and fluoride concentrations are higher than in most Swedish streams. Fluoride is also elevated compared with concentrations in regional lakes.

For ***iron*** and ***manganese,*** no national data are available for comparison. Compared with data from Forsmark streams, the values for streams in the Simpevarp regional model area are high (Table 4-17).

Dissolved oxygen

As in lakes, the concentrations of dissolved oxygen show a typical seasonal pattern due to the temperature-dependent solubility of oxygen (Figure 4-25). The solubility is higher at low temperatures leading to generally higher values during winter. In addition to temperature, decomposition of organic matter and primary production affect the concentrations of dissolved oxygen. Discharging groundwater is naturally depleted of oxygen, and during dry periods the increased proportions of groundwater in the streams may lead to decreased levels of dissolved oxygen in flowing waters. There are several observations of low oxygen concentrations in the summer in the streams in the Simpevarp regional model area, probably as a consequence of temperature, decomposition of organic matter and discharging groundwater.

Temperature

Water temperature has been measured in several of the streams in the Laxemar-Simpevarp area but the measurement period varies widely. The temperature in five streams is shown in Figure 4-26. The water temperatures varied between zero in the winter up to between 15 and 20°C in the summer.

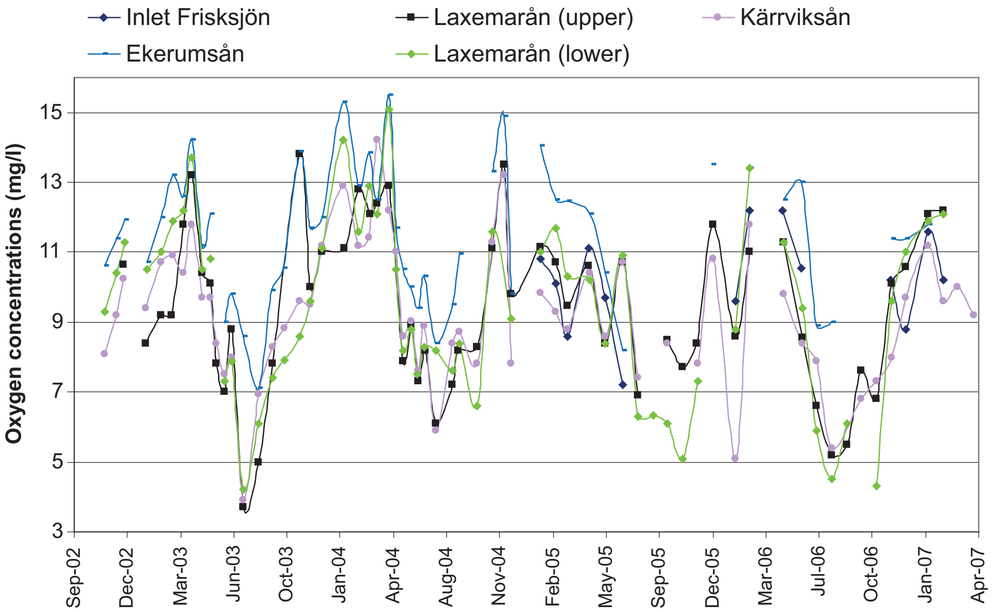

Figure 4-25. *Concentrations of dissolved oxygen in streams in the Laxemar-Simpevarp area. ID codes for the sampling locations are Inlet Frisksjön: PSM000347, Laxemarån (upper): PSM002079, Kärrviksån: PSM002083, Ekerumsån: PSM002085 and Laxemarån (lower): PSM002087. For location, see Figure 4-14.*

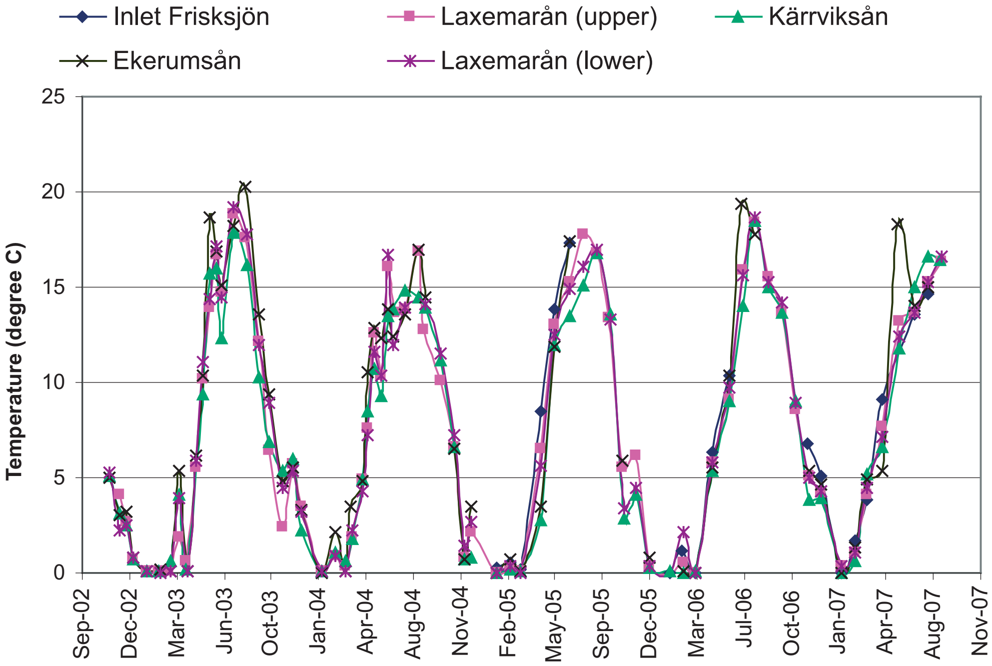

Figure 4-26. *Water temperatures in streams in the Laxemar-Simpevarp area. ID codes for the sampling locations are Inlet Frisksjön: PSM000347, Laxemarån (upper): PSM002079, Kärrviksån: PSM002083, Ekerumsån: PSM002085 and Laxemarån (lower): PSM002087. For location, see map in Figure 4-14.*

Water colour

Water colour is measured as absorbance at 420 nm and varies over the year (Figure 4-27) (data from SICADA[9], April 2008). The highest values are measured in the spring and autumn, which correlates with high runoff. Annual water colour measured for the time period 2005–2006 is 0.19 for Laxemarån (upper part) (2005=0.22 and 2006=0.16), 0.20 for Laxemarån (lower part) (2005=0.23 and 2006=0.18), and 0.23 for Kärrviksån (2005=0.28 and 2006=0.19). The water colour of the streams in the Laxemar-Simpevarp area has been measured in several of the streams in the Laxemar-Simpevarp area during different measurement periods. The longest time series are from two sites in Laxemarån (PSM002079 (upper part) and PSM002087 (lower part)) and from Kärrviksån (PSM002083) (Figure 4-27).

4.9.3 Chemistry in groundwater

The shallow groundwater in the Laxemar-Simpevarp area is characterized by neutral or slightly acid pH values, a normal content of major constituents, and alkalinity ranging from high to very low. Marine relicts influence groundwater in the area, resulting in elevated concentrations of e.g. chloride and sulphate. Several parameters show large deviation compared with national reference data. Iron and manganese show markedly elevated concentrations of about one order of magnitude. Fluoride, iron and strontium also show elevated concentrations compared to national references.

Acidity and alkalinity

The shallow groundwater is characterized by neutral or slightly acid pH values with a majority of observations between pH 6 and 7 (Table 4-18). Most alkalinity measurements are classified as high or very high according to EQC. However, there are a few observations with pH below 6 and with low or very low alkalinity. The low pH values are found in small, topographically elevated catchments where exposed bedrock and clay gyttja-covered peat dominate the overburden. Alkalinity is generally higher in shallower groundwater than in surface waters.

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[9] SKBs database SICADA, access might be given on request.

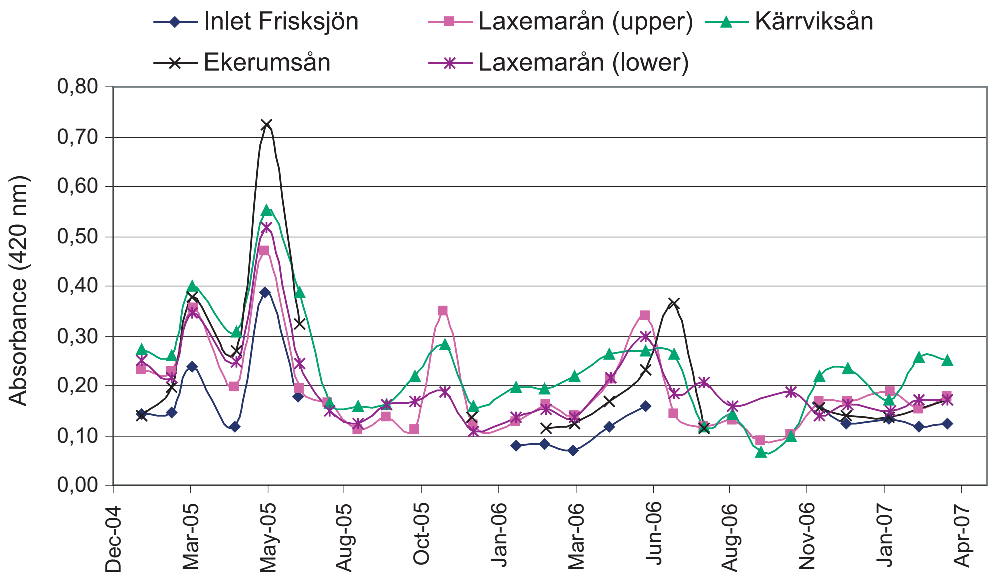

Figure 4-27. *Water colour, measured as absorbance at 420 nm, in streams in the Laxemar-Simpevarp area. ID codes for the sampling locations are Inlet Frisksjön: PSM000347, Laxemarån (upper): PSM002079, Kärrviksån: PSM002083, Ekerumsån: PSM002085 and Laxemarån (lower): PSM002087. For location, see map in Figure 4-14.*

Table 4-18. Mean water chemistry (October 2002–May 2005) for major elements in the shallow groundwater in the Laxemar-Simpevarp area /Tröjbom and Söderbäck 2006a/. Percentiles, mean, minimum and maximum values have been calculated for all the monitored locations. *Samples from soil tube SSM000240 (March 2006–September 2007) (data from the database SICADA, April 2008, access might be given on request).

Element	N obs	Min.	25-p	Median	75-p	Max.	Mean	SD
pH (unit)	63	5.17	6.33	6.68	6.95	7.97	6.68	0.58
Conductivity (mS/m)	63	4.0	19	29	57	120	42	30
Tot-P* (mg L^{-1})	5	0.078	0.13	0.13	0.24	1.8	0.48	0.75
POP* (mg L^{-1})	5	0.0005	0.0015	0.0078	0.0078	0.011	0.0056	0.0044
PO_4-P* (mg L^{-1})	5	0.036	0.040	0.13	0.20	2.2	0.51	0.92
Tot-N (mg L^{-1})*	5	1.2	1.6	1.9	2.1	2.9	2.0	0.65
NH_4-N* (mg L^{-1})	5	0.92	1.4	1.6	1.7	2.9	1.7	0.71
NO_2+NO_3-N* (mg L^{-1})	5	0.00040	0.00040	0.00050	0.00060	0.0022	0.00082	0.00078
PON* (mg L^{-1})	5	0.0065	0.0093	0.055	0.087	0.091	0.050	0.041
TOC* (mg L^{-1})	5	10	10	10	11	11	10	0.29
DOC* (mg L^{-1})	5	10	10	10	11	11	10	0.26
POC* (mg L^{-1})	5	0.011	0.055	0.42	0.75	0.85	0.42	0.38
DIC* (mg L^{-1})	5	244	261	265	273	276	264	13
SO_4-S (mg L^{-1})	41	0.26	5.2	8.7	20	59	14	10
Si (mg L^{-1})	41	4.3	8.5	11	15	26	12	5
Fe (mg L^{-1})	41	0.33	2.3	5.8	9.4	42	7.7	8
Mn (mg L^{-1})	41	0.082	0.22	0.49	0.61	6.1	0.58	0.9
Cations								
Ca (mg L^{-1})	41	6.1	23	34	47	100	38	20
Mg (mg L^{-1})	41	1.3	5.1	8.2	11	45	10	8
Na (mg L^{-1})	41	4.6	7.5	12	39	230	39	60
K (mg L^{-1})	41	1.1	2.5	4.8	7.0	46	7.7	10
Anions								
Cl (mg L^{-1})	55	3.2	5.4	7.4	24	200	36	50
HCO_3 (mg L^{-1})	63	2.0	52	93	190	550	130	100
F (mg L^{-1})	55	<0.2	0.82	1.4	2.2	5.4	1.6	1
Br (mg L^{-1})	55	<0.2	<0.2	<0.2	0.32	1.5	0.29	0.4
I (mg L^{-1})	17	0.0030	0.0060	0.010	0.016	0.050	0.013	0.01

Major elements (C, N, P)

Limited data are available concerning the elements carbon, nitrogen and phosphorus in groundwater and the compilation presented here is for a single soil tube in the area (SSM000240) located beneath a marine bay and for a relatively short time period (March 2006–September 2007). Total organic ***carbon*** concentrations consist almost entirely of dissolved organic carbon (Table 4-18). The concentrations of dissolved inorganic carbon are much higher than the organic concentrations. The mean and median values for the single soil tube SSM000240 are higher than the concentrations for a number of soil tubes in the Laxemar-Simpevarp area as well as for private wells in the Laxemar-Simpevarp area and in Kalmar County /Tröjbom and Söderbäck 2006a/. Most of the ***phosphorus*** occurs as phosphate, and in general only a minor fraction of total phosphorus consists of particulate phosphorus. The phosphate concentrations are somewhat higher than in private wells in the Laxemar-Simpevarp area and Kalmar County. The dominant ***nitrogen*** form is as ammonium, while nitrate and nitrite (NO_3 and NO_2) concentrations are low. The ammonium concentrations are much higher than those in private wells in the Laxemar-Simpevarp area and in Kalmar County, and the reverse is true for the concentrations of nitrate and nitrite. However, the concentrations are of the same order of magnitude as in soil tubes in lakes and sea in the Forsmark area.

Major constituents

Major constituents of the groundwater are generally calcium, chloride, magnesium, silica, sodium, sulphate, carbonate and bicarbonate (Table 4-18). Calcium, magnesium, sodium and potassium show normal levels compared with national reference data. Chloride, sulphate and silicon, however, show elevated levels compared with national references. The groundwater in the soil tubes can be classified as $Ca\text{-}HCO_3$ to Na-Cl type, i.e. dominated by either calcium ions or sodium ions. The $Ca\text{-}HCO_3$ type probably indicates recently infiltrated water and recharge areas. Higher localities are classified as $Ca\text{-}HCO_3$ type, whereas lower situated soil tubes are classified as $Ca\text{-}CHO_3$ or Na-Cl type.

Calcium concentrations are on the same level or lower than in private wells in Sweden. There are generally higher concentrations in the groundwater than in streams and lake water.

Magnesium and ***sodium*** concentrations are normal compared with regional and national wells. There is a tendency for the lowest concentrations to be found in topographically high-situated soil tubes. There is a difference between magnesium and sodium, however. The ratio between "lower" and "higher" soil tubes differs, the ratios being 1.5 for Mg and 4 for Na, indicating differences in mechanisms governing the concentrations of these elements. The concentrations of sodium in shallow groundwater are usually comparable to those in streams and lakes. The concentrations of magnesium, on the other hand, are 3–4 times higher than those found in lakes and streams.

Potassium concentrations are normal compared with regional and national wells but 3–4 times higher than concentrations in streams and lakes. As with magnesium, there is a tendency for the lowest concentrations to occur in the highest topographical locations in the western area.

Chloride concentrations in shallow groundwater in the Laxemar-Simpevarp area are slightly elevated compared with those in Swedish wells. The highest concentrations are found on the island of Ävrö and near the brackish basins. The concentrations are comparable to concentrations in streams and lakes.

Sulphate concentrations are elevated, almost twice the mean concentration for Swedish wells. The concentrations are also twice the concentrations in streams and lakes in the area.

The concentrations of ***silicon*** in shallow groundwater are quite high, twice the concentrations found in Forsmark. There is a high variation in concentrations of silicon (Si) within soil tubes.

Bicarbonate (HCO_3) concentrations show a large range from 500 to almost 0 mg L^{-1}, indicating very low alkalinity in some groundwater. Most observations however, are slightly elevated compared with those in Swedish wells.

Redox potential

No calculations based on redox pairs have been performed to evaluate the redox potential. However, a simplified classification based on iron, manganese and sulphate is presented /Tröjbom and Söderbäck 2006a/. Soil tubes in the Simpevarp area are classified as having a low redox potential.

Both ***iron*** and ***manganese*** concentrations (Table 4-18) are clearly elevated compared with median values for undisturbed shallow groundwater /Naturvårdsverket 1995/. Iron concentrations are generally higher in shallower groundwater than in both lakes and streams.

4.10 Biota

4.10.1 Biota in lakes

The biomass of biota in lakes in the Laxemar-Simpevarp area is dominated by consumers, particularly by benthic bacteria. Due to the brown water colour of the lakes, the distribution of primary producers is restricted leading to dominance of heterotrophic biota.

All functional groups are represented in the site investigation of the biomass of biota. Some samplings of biomasses have been spread over the year but most are concentrated in the summer period. In those cases, an average for each month was calculated and an annual average was estimated from the monthly average values. Primary production estimates for reeds and one respiration measurement have been performed in Frisksjön. All species of biota found during the site investigations are listed in Appendix 4. A description of biomass, primary production and respiration measured in the lakes follows below.

Biomass of primary producers

The annual mean ***phytoplankton*** biomass investigated by microscopic counts was 0.3 mg C L^{-1} (n=8) and the community was dominated for most of the year by truly autotrophic species (Table 4-19, Figure 4-28) /Sundberg et al. 2004/ (Andersson E, unpublished). Two phytoplankton blooms were recorded. The first one in July was mainly composed of the mixotrophic *Peridinium* (*Dinophyceae*) and had a total phytoplankton biomass of 0.7 g C m^{-3}. The second bloom was larger with a total phytoplankton biomass of 2.1 g C m^{-3} and was composed of the algae *Gonyostomum semen* (*Chloromonadophyceae*). The algae *G. Semen* can cause problems in bathing waters as it produces a slime that can cause skin reactions in sensitive persons and also creates problem by clogging of water filters. These are becoming more common in Sweden and Finland in the past century /Lepistö et al. 1994/. The biomass of *G. semen* in Frisksjön during 2003 however, was moderate according to Swedish Environmental Criteria (EQC, /Naturvårdsverket 2000/). The seasonal mean phytoplankton biomass from May to October was high and indicates eutrophic conditions in Frisksjön according to EQC.

The phytoplankton biomass was also estimated as concentrations of chlorophyll *a*. There was good correspondence with microscope counts and chlorophyll measurements and the phytoplankton blooms are detected by both methods. According to EQC, the chlorophyll *a* concentration in Frisksjön also indicates that the phytoplankton biomass is high. Nevertheless, the median chl *a* concentration of 5.5 µg L^{-1} is very close to the median chl *a* concentration in 206 coloured lakes (5.1 µg L^{-1}) in a review by /Nürnberg and Shaw 1999/.

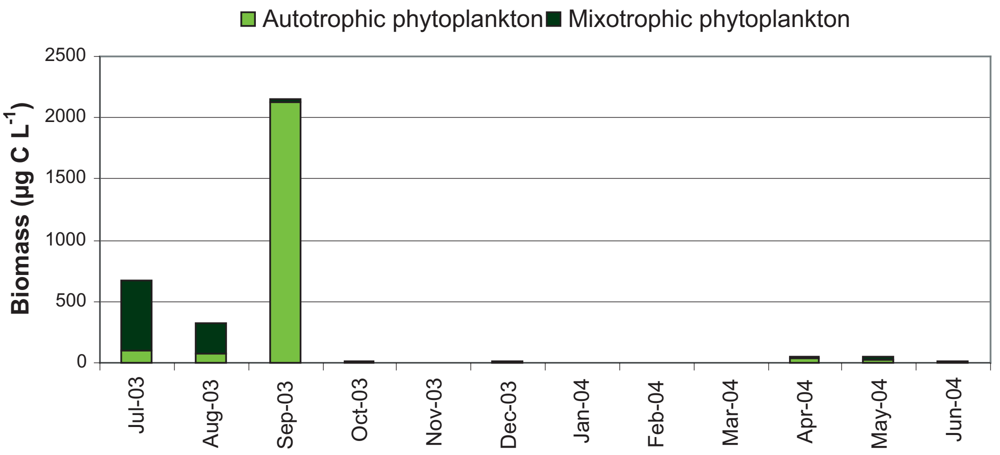

Figure 4-28. *Phytoplankton biomass in Frisksjön during 2003 and 2004 /Sundberg et al. 2004/ (Andersson E, unpublished).*

Table 4-19. Phytoplankton biomass measured in Frisksjön 2003 and 2004 /[1]Sundberg et al. 2004/ ([2]Andersson E, unpublished).

Year	Month	Biomass (µg C L^{-1})		
		Autotrophic phytoplankton	Mixotrophic phytoplankton	Sum
2003	July[1]	96	575	671
	August[2]	69	255	324
	September[2]	2,133	15	2,148
	October[2]	12	1	14
	December[1]	9	1	10
2004	April[1]	34	11	45
	May[2]	27	22	49
	June[2]	8	11	18

In total, 21 species of ***macrophytes*** were noted in a qualitative investigation of macrophytes in Frisksjön (Table 4-20) /Aquilonius 2005/. However, some of the species in the qualitative study includes wetland species as e.g. Carex and are not considered to be present within the lake. Quantitative investigations were performed in littoral I, II and III. In Littoral I, reed is clearly the dominant macrophyte. The above-ground biomass (measured in August) was 287 g C m^{-2} and the below-ground biomass was almost eight times higher, 2,242 g C m^{-2} (Table 4-21) /Andersson et al. 2006/. In comparison, other macrophytes in Littoral I were negligible with a biomass < 10 g C m^{-2} /Aquilonius 2005/. The above-ground biomass of reed is higher than the biomass in the Forsmark lakes (181 g C m^{-2}) and the straw density (94 m^{-2}) is higher than that reported from a lake in Netherlands (53 m^{-2}) /Meulemanns 1988/ but biomass was lower than that reported from a lake in northern Germany (687 g C m^{-2} /Gessner et al. 1996/) and thus the biomass estimate was within reported literature values.

The biomass of macrophytes in Littoral II was very low in the quantitative study, 5.5 g dw m^{-2} still, this is most certainly an over estimation as species of Carex was included in the biomass estimate. /Aquilonius 2005/. Also in littoral III the biomass was low, 4.0 g dw m^{-2} (equivalent to 1.6 g C m^{-2} using conversion factor of 0.395 from /Kautsky 1995/ and excluding 2 obviously erroneous values (two Carex samples were recorded at 1.4 and 1.8 m depths), without these values the biomass would be 6.6 g dw m^{-2}).

Table 4-20. Macrophytes found in a qualitative inventory in Frisksjön /Aquilonius 2005/. Some of the species below e.g. *Carex spp.* are to be considered to be present on the wetlands surrounding the lakes rather than present within the lake.

Latin name	Swedish name	English name
Alisma plantago-aquatica	Svalting	Water-plantain
Carex nigra	Hundstarr	Common sedge
Carex rostrata	Flaskstarr	Bottle Sedge
Carex vesicaria	Blåsstarr	Bladder-sedge
Equisetum fluviatile	Sjöfräken	Water Horsetail
Iris pseudacorus	Gul svärdslilja	Yellow Iris
Juncus conglomerates alt. J. effesus	Knapptåg alt. Veketåg	Compact Rush or Soft-Rush
Lysimachia thyrsiflora	Topplösa	Tufted Loosestrife
Lysimachia vulgaris	Videört (strandlysing)	Yellow Loosestrife
Lythrum salicaria	Fackelblomster	Purple-loosestrife
Menyanthes trifoliata	Vattenklöver	Bogbean
Nuphar lutea	Gul näckros	Yellow Water-lily
Nymphea alba	Vit näckros	White Water-lily
Oenanthe aquatica	Vattenstäkra	Fine-leaved Water-dropwort
Phragmites australis	Bladvass	Common Reed
Potamogeton natans	Gäddnate	Broad-leaved Pondweed
Schoenoplectus lacustris	Säv	Common Club-rush
Sparganium angustifolium	Plattbladig igelknopp	Floating Bur-reed
Sparganium emersum	Vanlig igelknopp	Unbranched Bur-reed
Typha latifolia	Bredkaveldun	Bulrush

Table 4-21. Biomass of primary producers in different habitats in Frisksjön. Data from /Andersson et al. 2006, Aquilonius 2005/.

Habitat	Biomass (g C m^{-2})
Littoral I	
Above-ground biomass of reed	287
Below-ground biomass of reed	2,242
Littoral II	2.1
Littoral III	1.6

Primary production

The annual above-ground production of reed in Frisksjön was assumed to be equal to the maximum biomass in August, i.e. 287 g C m^{-2} /Andersson et al. 2006/. No other data on primary production in the Simpevarp regional model area are available.

Biomass of consumers

The biomass of ***bacterioplankton*** in Frisksjön was investigated in June and August 2006 (one replicate on each occasion) and the biomass of ***benthic bacteria*** was investigated on one occasion in June 2006 (3 replicates) /Andersson et al. 2006/. The bacterioplankton biomass was 18 mg C m^{-3} in June and 34 mg C m^{-3} in August. Benthic bacterial biomass was 5.3 g C m^{-2} (standard deviation 1.0 g C m^{-2}). The biomass of bacterioplankton (1.6×10^7 cells ml^{-1}) may be considered somewhat low compared to the median cell number (2.7×10^7 cells ml^{-1}) for 73 coloured lakes reviewed by /Nürnberg and Shaw 1999/. However, the number of cells is well within the range for the coloured lakes (0.02–9.6 cells ml^{-1}). The number of sediment bacteria can vary within a wide span, but typically ranges between 10^8 and 10^{10} cells per ml sediment /Schallenberg et al. 1989/. Thus the bacterial cell number in Frisksjön 5×10^9 is also within the range reported in the literature.

The biomass of ***zooplankton*** in Frisksjön was measured on three occasions. The biomass was very high in July (1.68 g dw m^{-3}), while it was much lower in December (0.16 g dw m^{-3}) and April (0.14 g dw m^{-3}) (Figure 4-29) /Sundberg et al. 2004/. /Sundberg et al. 2004/ concluded that the zooplankton community in Frisksjön is typical of a small lake on the east coast of southern Sweden. However, the very high biomass in July was considered to be unrepresentative of the total summer value. Instead, the median zooplankton biomass in another humic lake, included in the Swedish national monitoring programme (Älgsjön; accessed from the web 2005-09-14 at: http\\info1.ma.slu.se\db.html), was used for the period June–September to estimate the annual mean biomass. The annual mean biomass was estimated to be 0.11 g C m^{-3}. The zooplankton biomass is somewhat low compared with that in 81 European shallow lakes /Gyllström et al. 2005/. In July the zooplankton community was dominated by cladocerans (mainly *Daphnia cucullata*). In December and April copepods dominated (mainly *Eudiaptomus*). Smaller zooplankton such as heterotrophic flagellates and ciliates were not included in the estimate of zooplankton since water was filtered through a 64 µm mesh.

Benthic fauna was investigated in the Frisksjön, Jämsen, Söråmagasinet and Plittorpsgöl /Ericsson and Engdahl 2004/ (Table 4-22). In all lakes, the biomass increased with depth and was lowest in Littoral I, intermediate in Littoral II and III and highest in the Profundal habitat. The species richness, on the other hand was highest in Littoral I. In most lakes detritus feeders were the dominant benthic fauna in Littoral I, followed by predators and shredders (Table 4-23). In Littoral II and III, predators were the dominant benthic fauna in all lakes except for in Jämsen where detritus feeders were the most common benthic fauna (Table 4-24). In Frisksjön, a large mussel was excluded from the biomass estimate in Littoral III since mussels are very scattered and the probability of catching one is extremely low and has an undue influence on the biomass estimate due to the very low number of samples in the study. Excluding the single mussel found in Frisksjön, filter feeders, scrapers and shredders made insignificant contribution to the biomass of benthic fauna in the lakes. In the Profundal habitat the most common benthic fauna in all lakes consisted of predators, representing 92% of the total biomass (Table 4-25). The predators mainly consisted of the phantom midge *Chaoborus flavicans*, which is able to migrate through the water column at night to feed on zooplankton but stays in the benthic habitat during day to avoid predators. The benthic fauna in Littoral I was sampled with a hand net (opening 0.25×0.25 m, mesh size 0.5×0.5 mm). An area of 0.25 m^2 was disturbed by the foot and the net was slowly swept over the area to collect the animals. In Littoral III, and in the Profundal, an Ekman grabber was used to collect the animals which were sieved through a 0.5 mm mesh.

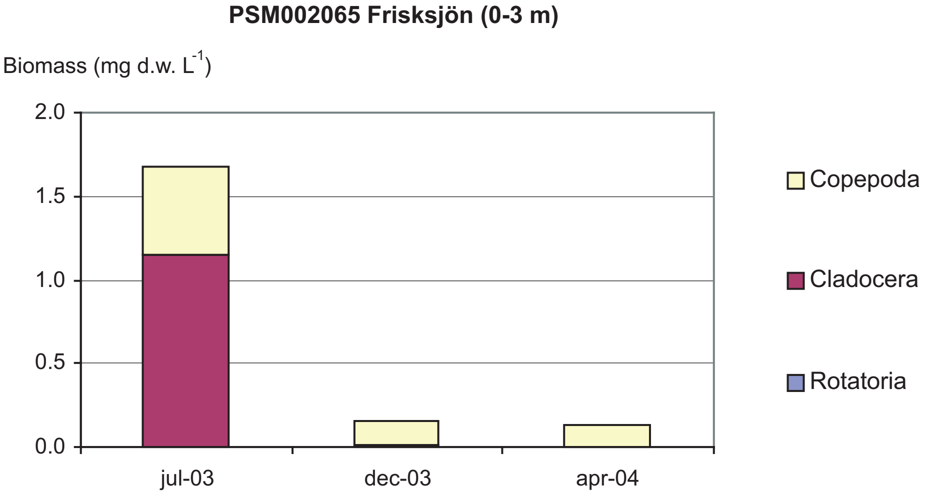

__Figure 4-29.__ Biomass of different zooplankton groups in the whole water column in the centre of Frisksjön (0–3 m) /Sundberg et al. 2004/.

Table 4-22. Biomass of benthic fauna (in g ww m^{-2}) in the Littoral and Profundal habitats in four lakes in the Simpevarp area (n=5 in all habitats).

	Frisksjön	Jämsen	Söråmagasinet	Plittorpsgöl
Littoral I	1.7	0.9	2.2	2.7
Littoral II+III	5.0*	3.7	3.6	8.8
Profundal	7.0	11.7	2.8	8.6

* One large mussel (Anodonta anatina) is excluded from this biomass estimate. Including the mussel the biomass would be 185 g ww m^{-2}.

Table 4-23. Biomass of different functional groups of benthic fauna in Littoral I (mean values n=5) in four different lakes in the Laxemar-Simpevarp area. Data from /Ericsson and Engdahl 2004/.

Functional groups	Frisksjön		Jämsen		Söråmagasinet		Plittorpsgöl		Average	
	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%
Filter feeders	0.03	2	0	0	0.13	6	0.08	3	0.06	3
Detritus feeders	0.48	29	0.35	37	0.79	36	1.76	66	0.85	42
Predators	0.73	44	0.12	13	0.89	41	0.64	24	0.60	31
Scrapers	0.04	2	0.05	5	0.32	15	0.03	1	0.11	6
Shredders	0.34	20	0.33	35	0.01	<1	0.11	4	0.20	20
Other unknown	0.04	2	0.09	10	0.05	2	0.06	2	0.06	4
Sum	1.66		0.94		2.18		2.68		1.87	

Table 4-24. Biomass of different functional groups of benthic fauna in Littoral II and Littoral III (mean values n=5) in four different lakes in the Laxemar-Simpevarp area. Data from /Ericsson and Engdahl 2004/.

Functional groups	Frisksjön		Jämsen		Söråmagasinet		Plittorpsgöl		Average	
	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%
Filter feeders	0.30	6	0	0	0	0	0.14	2	0.11	2
Detritus feeders	1.37	1	2.56	69	0.69	19	3.68	42	2.08	39
Predators	3.64	2	1.12	30	2.87	81	5.01	57	3.16	59
Scrapers	0	0	0	0	0	0	0	0	0	0
Shredders	0	0	0	0	0	0	0	0	0	0
Other unknown	0.002	<1	0.003	<1	0	0	0.01	<1	0	<1
Sum	5.31		3.68		3.56		8.8		5.34	

Table 4-25. Biomass of different functional groups of benthic fauna in the Profundal habitat (mean values n=5) in four different lakes in the Laxemar-Simpevarp area. Data from /Ericsson and Engdahl 2004/.

Functional groups	Frisksjön		Jämsen		Söråmagasinet		Plittorpsgöl		Average	
	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%
Filter feeders	0	0	0	0	0	0	0	0	0	0
Detritus feeders	0.38	5	1.76	15	0.16	6	0.62	7	0.73	8
Predators	6.67	95	9.87	84	2.62	94	7.98	93	6.79	92
Scrapers	0	0	0	0	0	0	0	0	0	0
Shredders	0	0	0	0	0	0	0	0	0	0
Other unknown	0	0	0.10	1	0	0	0	0	0.03	<1
Sum	7.05		11.73		2.77		8.60		7.54	

A total of 7 species of ***fish*** were caught in a fish survey 2004 in 4 of the lakes in the Laxemar-Simpevarp area /Engdahl and Eriksson 2004/. The most species were found in Jämsen (7), followed by Frisksjön (6), Söråmagasinet (6) and Plittorpsgöl (3). The catch per unit effort (CPUE = kg fish per net) differed between the lakes. Frisksjön and Söråmagasinet showed similar CPUE whereas Jämsen and Plittorpsgöl had much lower CPUE (Table 4-26). The low CPUE in Jämsen and Plittorpsgöl could be due to the fact that several nets were placed at low depths where the oxygen levels were probably low. In all lakes, perch (*Perca fluviatilis*, sw. *abborre*) dominated in terms of number of individuals as well as CPUE. Length and weight distribution diagrams for different species in the different lakes are presented in Appendix 5.

Fish were classified into the functional groups zooplanktivore fish (Z-fish), benthivore fish (B-fish) and piscivore fish (P-fish), based on the weight of individual fish according to /Holmgren and Appelberg 2000/ (Table 4-26). All the lakes were dominated by fish feeding on benthic fauna (B-fish). The fish survey was conducted using multi-mesh gillnets according to standardized methods /Fiskeriverket 2001, Naturvårdsverket 1999a, Naturvårdsverket 2000/. The species, length and weight of all fish were determined. A conversion factor of 33 kg fish ha^{-1} $CPUE^{-1}$ (i.e. 1 kg fish in the net represents 33 kg fish ha^{-1} in the lake) was used to calculate the total fish biomass (proposed by Per Nyberg at Fiskeriverket, Örebro).

Respiration

Respiration was measured once in the Profundal habitat /Wijnbladh and Plantman 2006/. The measured values varied a lot. The average respiration during the day (c. 9 am to 16 pm) was found to be 39 mg C m^{-2} h^{-1}, and during the evening (c. 16 pm–20 pm) an average value of 1 mg C m^{-2} h^{-1} was measured. The respiration was calculated from measured differences in oxygen concentrations in experimental chambers (n=5) at one location in the lake on one occasion (July 2005) /Wijnbladh and Plantman 2006/.

Table 4-26. Fish species in different lakes, categorized according to functional groups in Catch Per Unit Effort (kg ww), and total fish biomass in five different lakes in the Laxemar-Simpevarp area. Data from /Engdahl and Eriksson 2004/.

Functional group	Species	Frisksjön	Jämsen	Söråmagasinet	Plittorpsgöl
Zooplanktivore fish		0.044	0.037	0.003	0.009
	Perch	0.044	0.009	0.003	0.009
	Bleak	–	0.028	–	–
Benthivore fish		0.891	0.307	1.44	0.318
	Bream	0.272	0.138	0.602	–
	Ruffe	0.008	0.010	0.018	–
	Perch	0.267	0.084	0.326	0.054
	Roach	0.312	0.068	0.480	0.264
	Rudd	0.032	0.007	0.015	–
Piscivore fish		0.835	0.312	0.704	0.477
	Perch	0.112	0.203	0.565	0.344
	Pike	0.723	0.109	0.14	0.134
Total CPUE		1.77	0.66	2.15	0.80
Total fish biomass per hectare (kg ww ha^{-1})		58.4	21.6	70.8	26.5
Total fish biomass in lake (kg ww)		627	406	583	72

4.10.2 Biota in streams

Abundance of primary producers

Chlorophyll *a* (Chl *a*), which is a measure of the ***phytoplankton*** biomass, was measured in two different streams in the Laxemar-Simpevarp area (n=64) /Tröjbom and Söderbäck 2006a/: in the lower parts of Laxemarån and Kärrviksån. The chl *a* concentrations were low with a median for both streams of 1.8 µg chl *a* L^{-1}. This is what could be expected as the phytoplankton biomass is generally low in small streams /Wetzel 2001/. No identification of species was done but the phytoplankton composition was most probably similar to the ones found in the upstream lakes.

Streams in 8 catchments were investigated for vegetation in 2004 using the same method as in Forsmark, see Section 3.10.2 /Carlsson et al. 2005a/. Altogether, 42 species of ***macrophytes*** were noted in the streams. The abundance of vegetation fluctuated throughout the streams and was linked to the amount of shade. In Mederhultsån and Ekerumsån, more than half of the investigated stretches were classified as having "intense growth", while vegetation was lacking in c. 40% of the stretches in Kåreviksån and the four streams on the island Ävrö. In Laxemarån, 58% of the investigated stretches of stream order 1 had substantial growth, whereas in stretches of stream order 2, 30% had substantial growth and 29% had intense growth. For the stretches of stream order 3, 38% lacked vegetation while 30% had moderate growth (Table 4-27). Dominant species and coverage of the stream sections for the investigated catchments are described below:

The upstream part of Mederhultsån was dominated by *Lemna minor* (common duckweed, sw. *vanlig andmat*). This free-floating species are an indicator of relatively nutrient rich water conditions. Further downstream commonly dominating species were *Alisma plantago-aquatica* (water plain-tail, sw. *svalting*), *Juncus effusus* (soft-rush, sw. *veketåg*) and *Sparganium sp.* (bur-reed, sw. *igelknopp*). Large areas of Mederhultsån had intense growth (Figure 4-30).

In the most upstream parts of Kåreviksån *Alisma plantago-aquatica* was the dominating species, but there were also sections with substantial amounts of *Lemna minor*. *A. plantago-aquatica* was also among the dominant species in the lower part of Kåreviksån, downstream of Frisksjön, but *Potamogeton polygonifilus* (bog pondweed, sw. *bäcknate*) and *Lysimachia thyrsiflora* (tufted loosestrife, sw. *topplösa*) also dominated in some parts. Large parts of Kåreviksån were not investigated and still others lacked vegetation.

In Ekerumsån the vegetation was substantial in most parts. Among the dominant species were *Alisma plantago-aquatica* (water plain-tail, sw. *svalting*) and *Juncus effusus* (soft-rush, sw. *veketåg*). Large parts of Ekerumsån had intense growth (Figure 4-31).

Table 4-27. Total abundance of vegetation (%) growing in each section of the investigated stream stretches in the Laxemar-Simpevarp area. – indicates vegetation class not encountered for a specific stream order and catchment.

Stream name	Meder-hultsån	Kåreviks-ån	Streams at Ävrö	Ekerumsån			Laxemarån			Total			
Stream order	**1**	**1**	**1**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Total**
Vegetation lacking	5	40	42	7	4	9	4	6	38	17	6	29	21
Single plants (<5% cov.)	4	4	10	–	4	5	21	9	22	7	8	16	12
Moderate growth (5–50% cov.)	10	22	23	–	8	10	17	25	30	13	20	23	19
Substantial growth (50–75% cov.)	28	17	10	4	13	18	58	30	9	23	25	12	18
Intense growth (75–100% cov.)	53	7	15	89	72	59	–	29	2	40	41	20	30

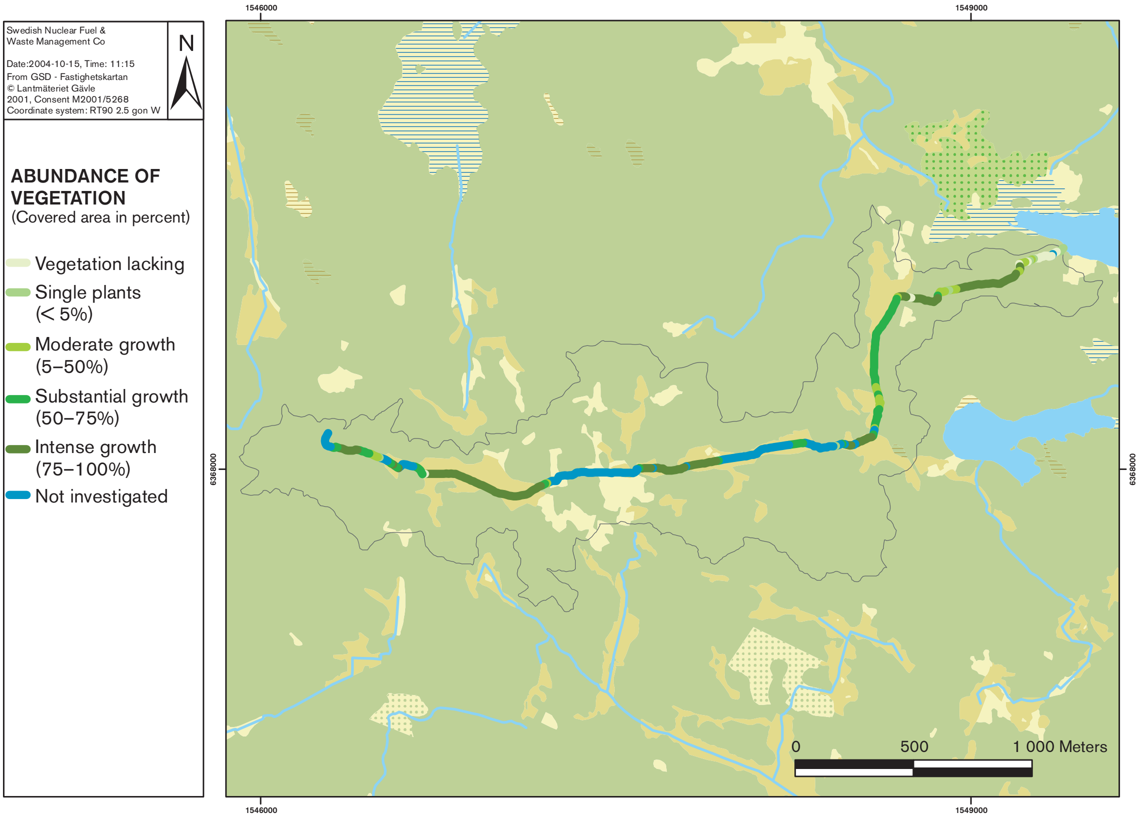

Figure 4-30. *Vegetation in Mederhultsån in the Laxemar-Simpevarp area.*

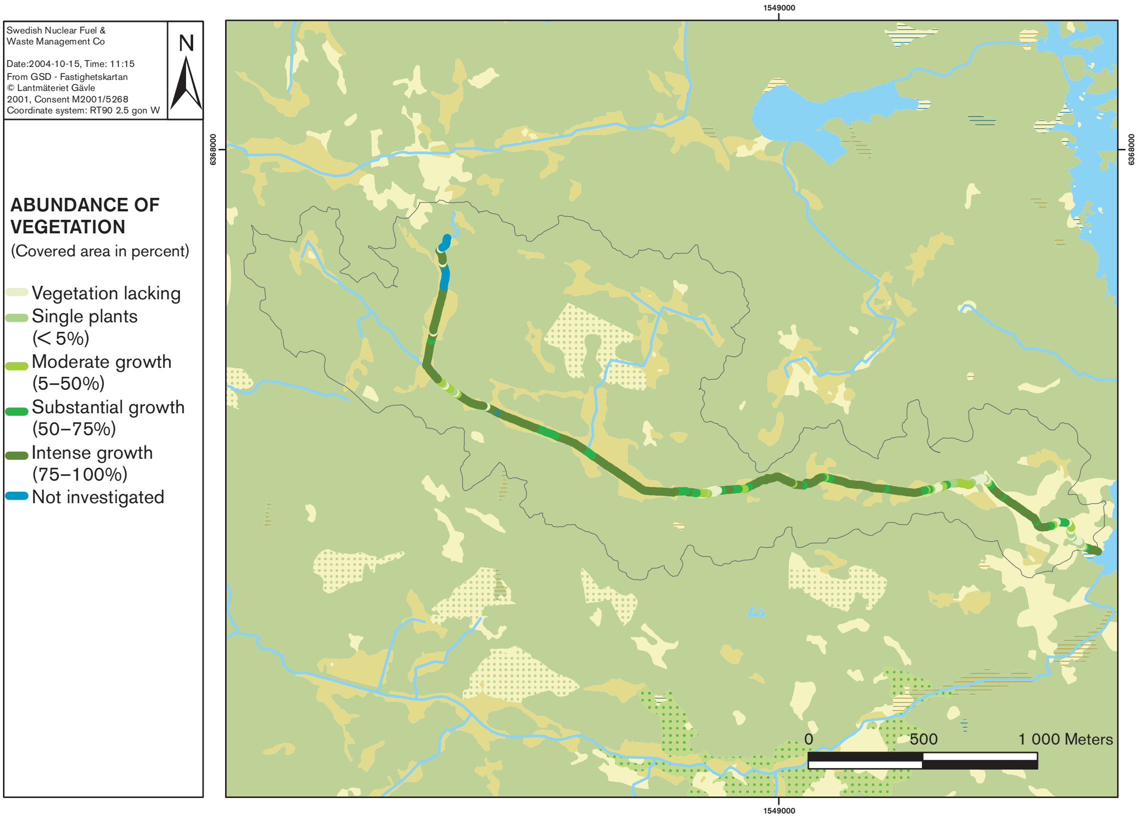

Figure 4-31. *Vegetation in Ekerumsån in the Laxemar-Simpevarp area.*

Species that frequently dominated the investigated sections in Laxemarån along the entire stream were *Alisma plantago-aquatica* (water plain-tail, sw. *svalting*) and *Nymphaeaceae* (water lily, sw. *näckros*). In the upstream part, sections dominated by *Typha latifolia* (bulrush, sw. *bredkaveldun*) were often found, while dominance of *Phragmites australis* (common reed, sw. *vass*) was commonly found in the most downstream part. The upstream part of Laxemarån had longer sections with intense growth than the lower stream stretches, where there were also sections lacking vegetation (Figure 4-32a and b).

In the four tiny streams on the island of Ävrö, most parts were dry and therefore no aquatic vegetation was found. The few sections containing vegetation contained *Equisetum fluviatile* (water horsetail, sw. *sjöfräken*) and *Lysimachia thyrsiflora* (tufted loosestrife, sw. *topplösa*) (in Vadeviksbäcken), *Typha latifolia* and *Fontinalis antipyretica* (common water moss, sw. *stor näckmossa*) (in Gloebäcken) and *Typha latifolia* and *Sparganium sp.* (bur-reed, sw. *igelknopp*) (in Skölkebäcken). Vegetation was lacking in large parts of the streams at Ävrö.

Biomass of consumers

Benthic fauna was sampled at three stream locations: downstream of the outlet from Frisksjön and at two different locations in Laxemarån /Ericsson and Engdahl 2004/. The site downstream of Frisksjön had a much larger biomass than the other two sites in Laxemarån as well as much larger proportion of filter feeders (Table 4-28). The difference is probably due to the proximity to Frisksjön and to the influx of plankton from the lake. Dominance of filter feeders, higher abundance and higher biomass are normal traits of stream sites close to lake outlets. The total number of taxa found differed between the sites with the highest number at the downstream site in Laxemarån. The benthic fauna was sampled with a hand net (opening 0.25×0.25 m, mesh size 0.5×0.5 mm). An area of 0.25 m^2 was disturbed by the foot and the net was slowly swept over the area to collect the animals.

Signal crayfish (*Pacifastacus leniusculus*) have been observed at a site in Laxemarån (Åby, LSM0000570). The observation was made during electrofishing /Andersson 2006/. Moreover, one specimen of the native noble crayfish (*Astacus astacus*) was observed in Kåreviksån, just downstream of the outlet of Frisksjön in 2006 (Erik Wijnbladh, pers. obs.).

The biomasses of ***bacteria** and **zooplankton*** were not investigated in the streams in the Laxemar-Simpevarp area. The bacterial biomass in streams can be high, especially in small streams that receive high inputs of allochthonous carbon sources /Wetzel 2001/. The zooplankton biomass in streams tends to be lower than in lakes /Wetzel 2001/. The zooplankton biomass also tends to be positively correlated to the phytoplankton chl *a* biomass. Thus, the low chl *a* concentrations in the two streams investigated in the area indicate that the zooplankton biomass was also low.

Table 4-28. Biomass (g ww m^{-2}) of different functional groups of benthic fauna in streams in the Laxemar-Simpevarp area. In the last row the biomass is presented in g dw m^{-2} where a conversion factor of 0.2 has used for conversion from wet weight to dry weight /Kautsky 2005/.

Functional group	Downstream Frisksjön		Laxemarån, upstream		Laxemarån, downstream		Average	
	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%	g ww m^{-2}	%
Filter feeders	4.07	55.2	0.39	13.6	0.27	10.3	1.58	26.4
Detritus feeders	1.76	23.9	0.55	18.9	1.19	46.1	1.16	29.6
Predators	0.35	4.8	0.70	24.2	0.51	19.7	0.52	16.2
Scrapers	0.077	1.0	0.002	0.1	0.056	2.2	0.045	1.1
Shredders	0.91	12.4	1.22	42.3	0.48	18.5	0.87	24.4
Other unknown	0.20	2.7	0.027	0.9	0.086	3.3	0.10	2.3
Sum	7.37	100	2.89	100	2.58	100	4.28	100
	g dw m^{-2}		g dw m^{-2}		g dw m^{-2}		g dw m^{-2}	
Sum	1.47		0.58		0.52		0.86	

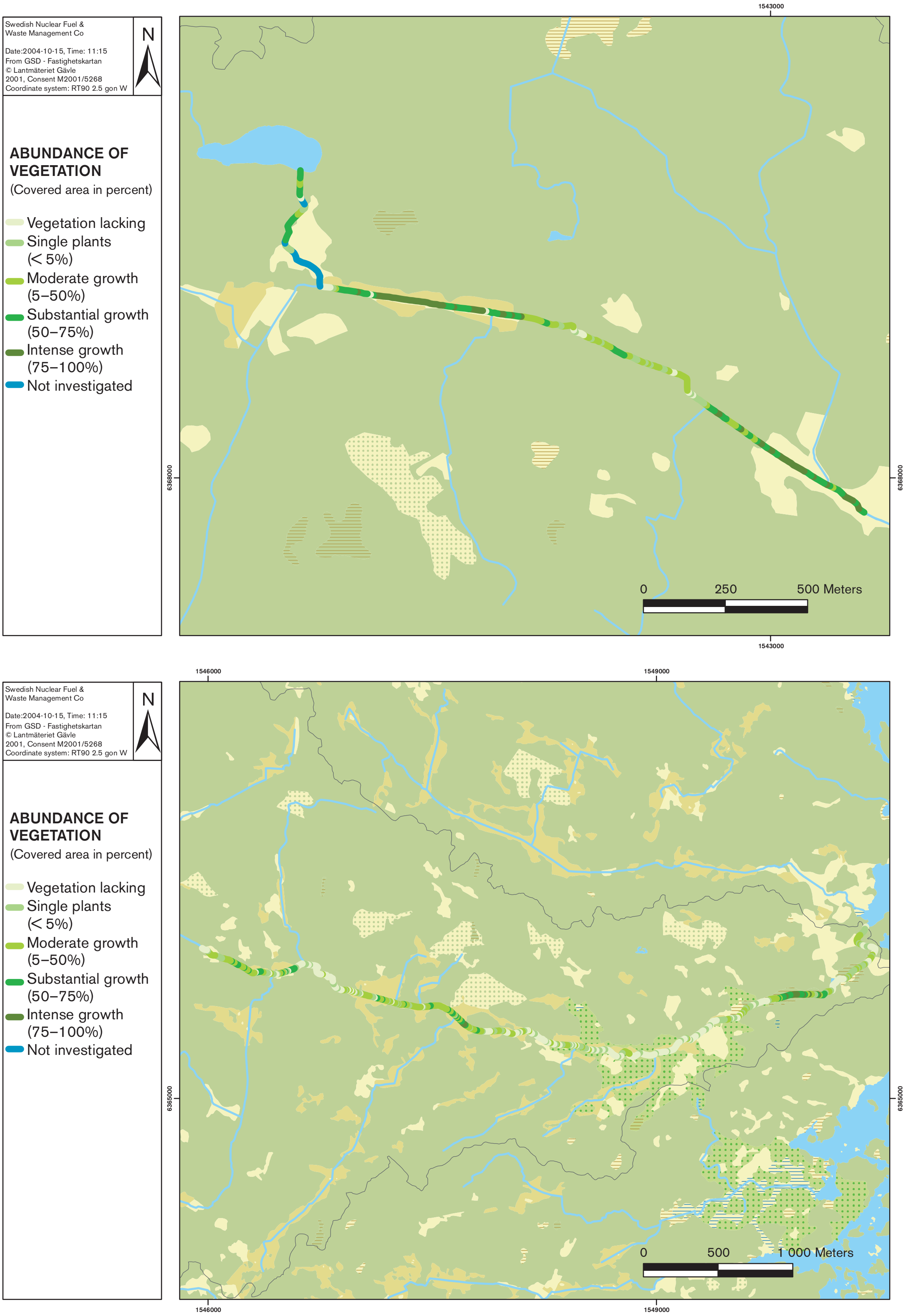

***Figure 4-32.** Vegetation in the upstream parts of Laxemarån (upper) and vegetation in the downstream sections of Laxemarån (lower).*

The occurrence of ***fish*** was investigated in two of the streams: Laxemarån and Ekerumsån, in May and August 2006 /Andersson 2006/. In this survey the only stretch that had properties required for salmonid spawning – fast-flowing water, a varied bottom structure and a relative stable water level – was in Laxemarån at the site LSM000569, Ekhyddan. However no trout (the most probable salmonid to find) were observed. Instead the survey indicated that Laxemarån may be an important spawning area for both ide and roach. Both species were observed spawning at the site LSM000569. The fact that no juvenile individuals of these species were observed in August indicated that the fry migrated to the Baltic Sea soon after hatching. Altogether five fish species were observed in Laxemarån (ide *Leuciscus idus*, roach *Rutilus rutilus*, burbot *Lota lota*, pike *Esox lucius* and ruffe *Gymnocephalus cernua*). The lower part of Ekerumsbäcken was of some importance as a feeding area for small pike. Later in the season, plant growth and low water levels made this stream an unsuitable habitat for fish. Altogether, two species were observed in Ekerumsbäcken (pike and tench *Tinca tinca*). The study was performed using electrofishing on four occasions in the spring (April and May) and on one occasion in the late summer (August).

Primary production

No estimations of primary production have been performed in the Simpevarp streams.

4.10.3 Edible biota in lakes and streams

It is of importance for the safety assessment to estimate the production of edible biota. Today, the use of biota in lakes is assumed to be negligible as fishing is assumed to take place predominantly in the coastal marine areas. Nevertheless, the production of food that can be sustainably produced by the limnic ecosystem has been estimated to provide input data for the models of the safety assessment since the future usage of the lakes as food source may be higher than today.

Food production was categorized as food normally consumed and edible products /SKB 2006a/. Food normally consumed for a lake includes fish, while edible products are everything that has some potential to be consumed by humans. Edible products could be worms, larvae, molluscs as well as fish etc above a certain practical size. In SR-Can this size was set at 1 mm (i.e. macrofauna).

Production was estimated for species or taxa of fish and crayfish. Production for most species was estimated by means of production per biomass ratios (P/B) from the literature. Some estimates (for e.g. fish) were based on calculations of the mass balance from metabolic demands and consumption using literature values /Kautsky 1995, Lindborg 2005/. Production was estimated as the weight of organic carbon (g C m^{-2} $year^{-1}$). This partly compensates for the energetic quality of food by that structural components such as bones, shells etc which normally are not eaten also contain a low fraction of organic carbon.

The P/B ratios are dependent on fish size (weight and length), and an allometric relationship has been established from studies of 79 freshwater species in Canada /Randall and Minns 2000/ Several of the fish species are similar to the Scandinavian species, the P/B ratio is well correlated to size for most animals /Banse and Mosher 1980, Downing and Plante 1993, Randall and Minns 2000/.

The maximum lengths of the fish species caught in the surveying gillnets were taken from the site study at Laxemar-Simpevarp /Engdahl and Eriksson 2004/. These ranges were compared with the data from /Randall and Minns 2000/ and for each species a mean P/B was estimated for this range (Table 4-29). This P/B ratio was multiplied by the estimated biomass per m^2 to obtain the area specific fish production for each tabulated species in each of the studied lakes: Frisksjön, Jämsen, Söråmagasinet and Plittorpsgöl. The total sum of fish production for each lake was used to obtain an average fish production estimate for the area, which is 0.3 g C m^{-2} $year^{-1}$. Different sources suggest that between 10 and 75% of the fish production can be sustainably harvested /Alanärä and Näslund 1995, Degerman et al. 1998, Näslund et al. 2000, Waters 1992/. However, it seems that the higher figure 75% is only valid an overestimate since severe effect on fish populations has eben notet at much lower catches and /Näslund et al. 2000/ and /Waters 1992/ states that 50% is the highest possible sustainable yield for a long time sustainable fish population. Since over-fishing leads to reduced catches for long time afterwards we have chosen a 50% cath of fish population to illustrate maximum annual yield. This corresponds to 0.13 g C m^{-2} y^{-1} and is assumed to be the maximum sustainable yield of fish from the Laxemar-Simpevarp lakes.

Table 4-29. Biomass, B (g C m^{-2} year^{-1}), and production, P (g C m^{-2} year^{-1}), of different fish species in Laxemar-Simpevarp area, based on average P/B ratios (1/y) of size range from /Randall and Minns 2000/. Biomass and size estimates from /Lindborg 2005/ and /Borgiel 2004b/, respectively.

Species	Size (mm)	P/B	Frisksjön		Jämsen		Sörå-magasinet		Plittorpsgöl		Mean
			B	P	B	P	B	P	B	P	P
Perch *Perca fluvialtilis*	300–400	0.5	0.30	0.15	0.09	0.04	0.26	0.13	0.12	0.06	0.098
Bleak *Alburnus alburnus*	100–200	1.5	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.003
Bream *Abramis brama*	200–400	0.9	0.08	0.07	0.04	0.03	0.17	0.15	0.00	0.00	0.063
Ruffe *Gymnocephalus cernua*	100–200	1.5	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.004
Roach *Rutilus rutilus*	200–300	1.0	0.09	0.09	0.02	0.02	0.14	0.14	0.08	0.08	0.080
Rudd *Scardinius erythrophthalmus*	50–150	1.6	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.006
Pike *Esox lucius*	700–1,300	0.2	0.03	0.01	0.03	0.01	0.04	0.01	0.04	0.01	0.008
Total			0.51	0.34	0.19	0.12	0.62	0.44	0.23	0.14	0.26

Although crayfish has been noted in the area today (see Section 4.10.2), there are probably no large colonies of crayfish in the lakes. The lakes could contain larger amounts of crayfish in the future. A generic yield of a good crayfish lake is about 50 kg ha^{-1} /Fiskeriverket 2003/, which corresponds to a production of 0.4 g C m^{-2} y^{-1}. Thus, a maximum total food production from a lake is less than 0.7 g C m^{-2} y^{-1}.

If the range is extended to other theoretical food items, molluscs and insect larvae could be eaten. There is no evidence that insect larvae from aquatic habitats are eaten on a regular basis, while molluscs are at least utilized in marine environments. Freshwater mussels of the family Unionidae (e.g. *Anodonta anatina*, duck mussel, sw. *allmän dammmussla*) are found in Frisksjön, although there are no biomass estimates. Comparing with production in the River Thames, a theoretical upper estimate of production is 132 g fw ha^{-1} y^{-1} /Negus 1966/. The abundance of mussels in the Thames is about 100 times higher compared with semi-quantitative estimates from Lake Mälaren in Sweden /Lundberg and Proschwitz 2007/. Thus, probably a very high estimate of the production of large molluscs is 0.3 g C m^{-2} year^{-1}. However, it is not likely that freshwater mussels will be eaten. Firstly, it does not taste good, and secondly, the effort required to collect the mussels is considered greater than that required to collect mussels from the nearby coastal areas. Even in other parts of the world where other species of freshwater mussels have been consumed, in the past, the contribution of freshwater mussels to total diet has been small due to low energy input from the mussels /Parmalee and Klippel 1974/.

Combining the production of fish and crayfish, which seem to be the only realistically utilised food products from limnic ecosystems, the maximum production of food from lakes similar to the present and future lakes in the Laxemar-Simpevarp area and is estimated to less than 0.7 g C m^{-2} year^{-1}.

4.10.4 Chemical characteristics of biota

The chemical composition of biota in Frisksjön was investigated in the autumn 2004 /Engdahl et al. 2006/. In total 21 samples from limnic environments were analyzed (Table 4-30). In addition to the content of the macronutrients carbon, nitrogen and phosphorus, the concentrations of 61 other elements were determined in the samples. No chemical data were available for biota in the Laxemar-Simpevarp streams.

Table 4-30. Description of biota samples analyzed for chemical composition /Engdahl et al. 2006/. When several replicates of the same sample were analyzed, this is indicated by (repl). Muscle samples were used for fish and benthic fauna. All sampled were stored in the frozen state before analysis.

	Sampling site/ID code	Number and description of samples	Individual/ sample
Fish	Frisksjön		
	ASM000192	Roach (benthivorous), 3 repl	4–5
	ASM000192	Perch (piscivorous), 3 repl	2
Aquatic vegetation	Frisksjön		
	ASM000110	Reed (standing crop and rhizome, respectively), 2 repl	At least 5
	ASM000110	Water lily (leaf and root, respectively), 2 repl	At least 3
	ASM000111	Reed (standing crop and rhizome, respectively), 2 repl	At least 5
	ASM000111	Water lily (leaf and root, respectively), 2 repl	At least 3
	ASM000112	Reed (standing crop and rhizome, respectively), 2 repl	At least 5
	ASM000112	Water lily (leaf and root, respectively), 2 repl	At least 3
Benthic fauna (mussel)	Frisksjön		
	ASM000110	Duck mussel	5
	ASM000111	Duck mussel	5
	ASM000112	Duck mussel	5

Data on four different functional groups were analyzed: macrophytes, benthic fauna, benthivorous fish and piscivorous fish. Two macrophyte species were represented: reed and water lily, which are present in different parts of the lake (Littoral I and III, respectively). Both the above-ground and below-ground parts of macrophytes were analyzed. The concentrations of carbon, nitrogen, phosphorus, iodine and uranium in different functional groups are presented in Table 4-31. The compiled data for all analyzed elements are presented in Appendix 10, while primary data are provided in /Engdahl et al. 2006/. For many of the trace elements (and sometimes also for other elements), the results of the analyses are below the detection limit. In these cases, a value equal to half of the detection limit was used in the calculation of mean concentrations.

The carbon content was quite constant between different functional groups and deviated only by a factor of 1.2. Comparing above-ground parts of macrophytes with roots reveals different patterns for water lily and reed: for the former the concentrations are somewhat higher in above-ground parts, while the opposite is true for reed.

The concentrations were more uneven for nitrogen. The highest concentrations of this element are found in fish and the lowest in macrophytes. For both macrophyte types, the nitrogen concentrations are lower in the roots than in the above-ground parts. The differences in concentrations between functional groups are even more pronounced for phosphorus. The highest concentrations were found in benthic fauna followed by fish, and the lowest values were found in macrophytes. The phosphorus concentrations are significantly lower in reed than in water lily. In water lily higher concentrations are found in the roots than in the above-ground parts, while the opposite is true for reed.

Two elements that are not main constituents of biota are also shown in Table 4-31, i.e. iodine and uranium. In the case of iodine, the highest concentrations were found in water lily followed by benthic fauna while the lowest concentrations were recorded in piscivorous fish. The levels in benthivorous fish were somewhere in between, in the same order as the concentrations in reed. In both macrophyte species, the iodine concentrations were higher in the roots than in the above-ground parts. The same pattern is seen for uranium. The concentrations in fish were very much lower than in the other sample types. The values for two of the piscivorous fish samples were below the detection limit. A difference of about one order of magnitude is seen for benthivorous and piscivorous fish as well as for water lily and reed. As uranium is toxic to biota, there may be an active avoidance of this element in higher biota such as fish, either through blocking of uptake and/or through effective excretion of this element.

Table 4-31. Concentrations of a number of selected elements in biological samples from Frisksjön /Engdahl et al. 2006/.

Element	Sample type	Count	Mean	Median	Min.	Max.	Sdev
Total carbon (g/kg dw)	Macrophyte, (Water lily) above	3	413	411	408	420	6.57
	Macrophyte, (Water lily) root	3	373	366	365	388	12.9
	Macrophyte, (reed) above	3	411	404	399	432	17.6
	Macrophyte, (reed) root	3	427	430	408	443	17.5
	Total producers	*12*	*406*	*408*	*365*	*443*	*24.2*
	benthic fauna	3	380	380	380	380	0
	benthivorous fish	3	426	426	421	430	4.75
	piscivorous fish	3	422	423	415	429	6.67
	Total consumers	*9*	*409*	*421*	*380*	*430*	*22.4*
Total nitrogen (g/kg dw)	Macrophyte, (Water lily) above	3	20.5	20.0	19.3	22.0	1.40
	Macrophyte, (Water lily) root	3	12.0	12.2	9.05	14.7	2.83
	Macrophyte, (reed) above	3	14,5	11.8	11.3	20.3	5.08
	Macrophyte, (reed) root	3	3.59	3.82	3.09	3.86	0.433
	Total producers	*12*	*12.6*	*12.0*	*3.09*	*22.0*	*6.82*
	benthic fauna	3	80.8	79.5	77.8	85.2	3.90
	benthivorous fish	3	139	139	137	142	2.77
	piscivorous fish	3	128	141	101	142	23.5
	Total consumers	*9*	*116*	*137*	*77.8*	*142*	*29.4*
Total P (g/kg dw)	Macrophyte, (Water lily) above	3	2.86	2.56	2.18	3.84	0.870
	Macrophyte, (Water lily) root	3	3.27	3.87	2.04	3.91	1.07
	Macrophyte, (reed) above	3	1.17	0.744	0.566	2.20	0.896
	Macrophyte, (reed) root	3	0.383	0.382	0.265	0.502	0.119
	Total producers	*12*	*1.92*	*2.11*	*0.265*	*3.91*	*1.43*
	benthic fauna	3	28.3	29.6	23.2	32.0	4.55
	benthivorous fish	3	13.3	13.3	13.1	13.4	0.153
	piscivorous fish	3	11.8	12.1	11.3	12.1	0.462
	Total consumers	*9*	*17.8*	*13.3*	*11.3*	*32.0*	*8.21*
Iodine (mg/kg dw)	Macrophyte, (Water lily) above	3	10.2	10.3	6.69	13.6	3.46
	Macrophyte, (Water lily) root	3	19.0	13.3	11.4	32.2	11.5
	Macrophyte, (reed) above	3	2.68	2.63	1.53	3.89	1.18
	Macrophyte, (reed) root	3	3.69	3.84	1.08	6.15	2.54
	Total producers	*12*	*8.88*	*6.42*	*1.08*	*32.2*	*8.58*
	benthic fauna	3	7.21	7.16	6.43	8.03	0.801
	benthivorous fish	3	1.40	1.34	1.23	1.63	0.21
	piscivorous fish	3	3.55	3.35	2.91	4.38	0.75
	Total consumers	*9*	*4.05*	*3.35*	*1.23*	*8.03*	*2.60*
Uranium (mg/kg dw)	Macrophyte, (Water lily) above	3	0.180	0.169	0.100	0.271	0.086
	Macrophyte, (Water lily) root	3	1.78	1.49	1.32	2.53	0.655
	Macrophyte, (reed) above	3	0.014	0.012	0.009	0.023	0.007
	Macrophyte, (reed) root	3	0.476	0.409	0.137	0.882	0.377
	Total producers	*12*	*0.613*	*0.220*	*0.009*	*2.53*	*0.794*
	benthic fauna	3	0.926	0.905	0.793	1.08	0.145
	benthivorous fish	3	0.002	0.002	0.002	0.003	0.001
	piscivorous fish	3	0.0001[1]	0.0001[1]	0.0001[1]	0.0002[1]	0.0001[1]
	Total consumers	*9*	*0.309*	*0.002*	*0.0001*	*1.08*	*0.468*

[1] 2 of 3 values below detection limit varying between 0.0001–0.0002 mg/kg dw.

A comparison between data from Laxemar-Simpevarp and Forsmark reveals as expected that, the concentration of carbon, nitrogen and phosphorus do not differ for the same kind of functional groups between the two sites. Different kinds of primary producers were analyzed: in Forsmark macroalgae were investigated and in Laxemar-Simpevarp macrophytes, and some differences could be seen between these two groups. The carbon concentration was slightly higher in macrophytes than in macroalgae, and the same pattern was seen for the nitrogen and phosphorus concentrations. The microalgae in Forsmark had a carbon content on the same order of magnitude as the macrophytes in Laxemar-Simpevarp, while the nitrogen concentrations were much higher. The phosphorus content of microalgae was higher than that of reed but lower than the concentrations found in water lily.

The concentrations of iodine differed between the two sites. In fish, the concentrations in Laxemar-Simpevarp were about 10 times higher than those recorded in Forsmark. The concentrations were also somewhat higher in benthic fauna. The iodine concentrations in macro- and microalgae (Forsmark) were higher than in reed but lower than the concentrations recorded in water lily (Laxemar-Simpevarp). As regards uranium, the concentrations in fish were about the same in the two areas. In benthic fauna, somewhat higher concentrations were recorded in Laxemar-Simpevarp, while the macroalgae (Forsmark) had a higher uranium content than the macrophytes (Laxemar-Simpevarp).

4.11 Land use and human impact

Human settlement can affect limnic systems via e.g. water use and pollution. In the Laxemar-Simpevarp area, examples of important human impact on the limnic systems are the excavation and ditching of streams, which affects most streams in the area, and the construction of a new lake by damming of a sea bay. Moreover, water levels have been lowered in some of the lakes, and the names of some wetlands and minor fields in the area indicate that a number of former lakes have disappeared during the last centuries due to human activities, probably with the aim of gaining farmland.

4.11.1 Human impact on lakes

Some major impacts on the limnic ecosystems in Laxemar-Simpevarp are the creation of the Söråmagasinet reservoir and the pumping of water between lakes and streams in the area (Figure 4-33). Söråmagasinet was originally a coastal bay, which was transformed into a lake in the seventies to ensure freshwater supplies for the nuclear power plant /Werner et al. 2008/. Occasionally, on the order of a few days each year or every second year, water is pumped from Ström in Laxemarån into Söråmagasinet in order to maintain the available water storage in the lake. Since 1983, drinking and process water for the nuclear power plant has been pumped from Lake Götemar (situated north of the Laxemar subarea) in a pipeline to a water works operated by OKG. At present, approximately 150,000–200,000 m^3 of water is pumped each year. Historically (up to 1987), water was pumped from Lake Trästen (situated west of the Laxemar subarea, upstream of Lake Fårbosjön) into Lake Jämsen, which discharges to the north into the Laxemarån in order to compensate for the pumping from Laxemarån. Past and present pumping activities in the Laxemar-Simpevarp area are further described in /Werner et al. 2008/.

Many of the lakes in the area have been subjected to lowering of the water level in order to gain farmland. For example, Frisksjön has been artificially lowered over the past few centuries, and the lowering may be 1 m or even more. Table 4-32 summarizes identified drainage operation /Werner et al. 2008/.

An attempt has been made to restore one of the lakes that disappeared due to previous drainage operations, Lake Gästern. The water level of Gästern was lowered in several stages during the 19th and early 20th centuries. The last lake-lowering operation was carried out in 1920. A project has recently (mid-2008) been finalized to raise the lake-water level up to the pre-1920 level. The new outlet is located in the north-eastern part of the wetland. Prior to the lake restoration, the low- and high water levels were 3 and 4.5 m.a.s.l., respectively, and the lake threshold was 2.4 m.a.s.l. Subsequent to the restoration, the low- and high water levels are 2.5 and 5 m.a.s.l., with a spillway level of 4.2 m.a.s.l. /Werner et al. 2008/.

Figure 4-33. *Pumping station in the Söråmagasinet reservoir pumping freshwater into the reservoir from Laxemarån.*

Table 4-32. Identified drainage operations in the Laxemar-Simpevarp area, from /Werner et al. 2008/.

Drainage operation	Area concerned	Year
Simpevarp drainage operation	Simpevarp peninsula	1955
Gässhult	The stream Kärrviksån, immediately upstream of the stream outlet to the Baltic Sea	1955
Lake Gäster	Lowering of Lake Gäster in Gässhult, also involving Kärrviksån	1918
Lake Götemar	Lowering of Lake Götemar	1933
Jämserum drainage operation	Lowering of Lake Jämsen and associated drainage operations	1937
	An area east of Lake Jämsen and downstream to stream Släthultebäcken. The drain depth was somewhat larger than in the other operations (c. 1.50–1.70 m)	1937
Köksmåla drainage operation	Part of the stream between the lakes Jämsen and Trästen, and an elongation south of the Jämserum drainage operation	1943
Lilla Laxemar and Mederhult drainage operations	Parts of the stream Ekerumsån	1933 and 1935
Mederhult drainage operation	The westernmost parts of the stream Mederhultsån	1949
Plittorp-Stora Basthult drainage operation	Part of Laxemarån	1944
Plittorp drainage operation	An area that drains into the stream Laxemarån	1939
Släthult drainage operation	The stream Släthultebäcken	1927
Stora Laxemar drainage operation	An area that drains into the stream Laxemarån	1922
Ström-Åby drainage operation	The stream Laxemarån, from Kvarnstugan in the west to Ström in the east	1933

The coastal area in the Laxemar-Simpevarp area is extensively used for recreational purposes such as fishing and bathing. There is probably less recreational use of the limnic environment. Someone may use Frisksjön for skating and Laxemarån for fishing, but to a very small extent. Bathing places are available in Götemaren and Fårbosjön (Kristina Dahlström, SKB, pers. com.). In Section 4.10.3 the amount of biota in lakes that can theoretically be used as food is described. This figure is certainly larger than actual food outtake from the lakes today. Theoretically lake organisms could also be harvested as food supply to cultivated animals but this does not occur today and is an unlikely scenario also for the future.

4.11.2 Human impact on streams

Most of the stream stretches in the Laxemar-Simpevarp area are affected by human activities in that they have been extensively excavated (Table 4-33). Kåreviksån is somewhat less affected than the others. Man-made technical encroachments in the stream such as installation of pipes (of the necessary diameter, length and height for water to descend to the substrate), construction of dams and filling of channels are described in detail in Appendix 5 in /Carlsson et al. 2005a/.

The largest impact of human activities on the stream today is probably the pumping of water between Laxemarån and the Söråmagasinet reservoir (further discussed in Section 4.12.1 and in /Werner et al. 2008/).

4.12 Lakes in the region

In order to put the lakes in the Laxemar-Simpevarp area in a broader context, the lakes in the region of Kalmar County are described. Regional lake size, catchment areas and catchment composition have been compared with data from 3,044 lakes included in the national survey of lakes in 2002 (cf. /Wilander et al. 2003/). Water chemistry in the lakes in the Laxemar-Simpevarp area was compared with regional and national lakes in Section 4.8 and will only briefly be discussed in the section below.

The median lake size in the Kalmar County is 1.2 km^2, which is close to the median size for Swedish lakes (2.1 km^2). The lakes in the region vary in size between 0.05 and 16 km^2. The investigated lakes in the Laxemar-Simpevarp area are small (mean lake size 0.1 km^2, median 0.1 km^2) and among the smallest 10% of lakes in Sweden.

The median catchment in the region is of the same size as the typical catchment in the national database (medians 116 and 114 km^2, respectively) (Table 4-34). The catchments in the Laxemar-Simpevarp area on contrary are very small (mean size 2.1 km, median 0.7 km^2). The catchments in the region are clearly dominated by forest (mean 81% coverage of total). On average, 10% of the catchment areas consist of open land and 8% of water. The catchments in the Laxemar-Simpevarp area are also dominated by forest (88%), but open land has a smaller impact on these lakes (mean 3% of total catchment areas). The mean Swedish catchment is also dominated by forest but to a much smaller degree (68%). The mean Swedish catchment contains more wetlands than the Kalmar regional catchments. Moreover, nearly 8% of the national mean catchment consists of bare mountain and glacier, land types not present in this region.

Table 4-33. Technical encroachments in the investigated stream stretches in the Laxemar-Simpevarp area (%). From /Carlsson et al. 2005a/.

Stream name	Mederhultsån	Kåreviksån	Streams at Ävrö	Ekerumsån			Laxemarån			Total			
Stream order	1	1	1	1	2	3	1	2	3	1	2	3	Total
Natural, no excavation	6	11	4			5				6	0	0	3
Moderate excavation	–	14	4	100	100	95	100	100	100	4	0	2	3
Substantial excavation	94	76	93							90	100	98	94

Table 4-34. Characteristics of the catchments in Sweden, in the Kalmar County and in the Laxemar-Simpevarp area.

	Size (km^2)	Land use Forest (%)	Open land (%)	Wetland (%)	Water (%)	Built-up area (%)
Lakes in Sweden (N=3044)						
Average	926	68	5	7	9	1
Median	114	74	1	4	8	0
Min	0.1	0	0	0	0	0
Max	46,881	100	79	58	43	50
Number of observations	3,044	3,044	3,044	3,044	3,044	3,044
Lakes in Kalmar County (N=122)						
Average	253	81	10	1	8	1
Median	116	82	10	0	7	0
Min	4	41	0	0	1	0
Max	1,359	98	37	6	20	13
Number of observations	122	122	122	122	122	122
Lakes in the Laxemar-Simpevarp area (N=5)						
Average	2.1	88	3	0	9	0
Median	0.7	91	0	0	7	0
Min	0.3	74	0	0	3	0
Max	7	95	7	0	20	0
Number of observations	5	5	5	5	5	5

The dominance of forest in the catchments influences the water chemistry in the lakes, and many of the lakes in the region can be described as brown-water lakes influenced by humic substances. The influence of humic substances is reflected in such aspects of the water chemistry as high water colour, high concentrations of TOC and high iron concentrations. The lakes in the region have high iron concentrations and somewhat higher water colour than the average Swedish lake. The concentrations of TOC are high, and the lakes in the region belong to the 25% of lakes with the highest TOC concentrations in Sweden.

4.13 Confidence and uncertainties in site data

The amount of data from the limnic ecosystems in the Laxemar-Simpevarp area is quite large. It is quite uncommon to have such a large dataset from the same site, and this ensures good confidence in the characterization of the lake and stream ecosystems in Laxemar-Simpevarp today. A detailed description of confidence and uncertainties follows below.

Catchment characteristics

The size and land use of the catchments have been investigated mainly with GIS and aerial photos. The delimitation of some of the subareas has been validated by field investigations in the area. In our opinion the updated catchment delimitation is of good quality and acceptable for area descriptions and further use in e.g. mass balances. The delimitation of land use and soil characteristics within the catchments is more uncertain, since that data has not been validated.

Hydrological measurements

Hydrological measurements have been performed in several ways. The water flow in streams has been measured since March 2003, whereas data on lake water level are available from June 2004. As the site investigations have been performed during a relatively short time period, the time series are not of impressive length but the spatial density is quite good.

The extent of periodically flooded areas adjacent to streams has been investigated in four of the catchments in Laxemar-Simpevarp. The length and flooded area were measured. These measurements were performed in the course of one year and different weather conditions between years may lead to different sizes of the flooded areas. However, the investigation gives an indication of the distribution and occurrence of flooded areas.

Climate parameters

Climate parameters have been measured locally since May 2003. Measurements have been performed at two stations within the area and show very similar data. Climate data also agree well with long-term measurements by SMHI, indicating that the data are valid for longer time periods as well.

Lake bathymetry

The lake bathymetry has been measured with good precision. The shorelines were digitized from ortophotos and, if necessary, checked in the field, and the water depths were measured by means of echo sounding. The distance between the measuring points differs /Brydsten et al. 2004/. However, this must be considered as acceptable spatial precision.

Physical characters of the streams

The physical characters of the streams in the Laxemar-Simpevarp area have been investigated in the field in stretches of 10 m each and this must be considered as very good spatial precision. Bottom substrate, water velocity, bottom vegetation, shading from terrestrial vegetation and technical encroachments were investigated, so that a large amount data are available to describe the stream character. The entire investigation was performed by the same person so differences within the data as a consequence of different judgments of the somewhat subjective parameters can be excluded.

Sediment

The amount of sediment data for Frisksjön in the Laxemar-Simpevarp area is substantial, including stratigraphical data, water content and concentrations of carbon and other elements as well as long-term sediment accumulation rate. In addition to Frisksjön, stratigraphical data are available for another three lakes. However, there is uncertainty associated to the stratigraphical data as bedrock was only reached in one of the four investigated lakes. Thus, the depth of the sediment is somewhat uncertain, although one investigation in Frisksjön has shown depth down to 10 m. Except for the description of bottom substrate, no sediment data are available from streams in the area and this gives rise to some uncertainties. However, in general the sediment data provide a reliable estimate of the sediments and sediment characteristics in the Laxemar-Simpevarp area.

Lake habitats

The lake habitats have been delimited in the field using D-GPS equipment and must be considered to be of good quality. The problem with the habitat delimitation is rather the delimitation between limnic and terrestrial ecosystems. The shoreline used in the lake investigation is the highest water level, which has the consequence that wetlands in direct contact with the lake are also included in the lake, as discussed earlier (see Section 2.3.1). As the water level is not constant, the impact of these wetland areas on the rest of the lake varies over time and we have no information about the exchange of substances between the wetlands and the lakes. There can be expected to be a flow of substances from the wetland to the lake. In this report, all wetlands bordering on the lakes have been considered to be terrestrial areas (wetlands). The inflow of carbon from these areas is addressed in the chapter dealing with carbon mass balance calculations (Chapter 5).

Chemistry data

The amount of water chemistry data from limnic environments in the Laxemar-Simpevarp area is unusually large in distribution, in space as well as in time, even though the data set is certainly not unique. The amount of data differs between different parameters, i.e. isotopes of certain elements have been measured only once every four month, compared with most other elements, which have been measured every month. The sampling and measurements have been performed by qualified personal and the analyses have been performed by accredited laboratories when possible which should guarantee high data quality.

Chemistry data for sediments are less extensive. However, analyses of carbon, nitrogen and sulphur content in Frisksjön from different studies provide similar results, providing good confidence in the data on the chemical composition of the sediments.

Chemical characteristics of limnic biota in the Laxemar-Simpevarp area have been investigated once. The number of species is restricted (fish, mussel, macrophytes) and the number of replicates differs and hence, the reliability of the data differs between functional groups. Overall, the chemical distribution between biota can be viewed as reliable with regard to orders of magnitude of elements in different functional groups, although absolute figures may be more uncertain.

Biota in lakes

The data set from biota in Laxemar-Simpevarp is large. Data are not as extensive as for the Forsmark lakes, but biomass data on almost all functional groups are available. Data on biomass of functional groups in the Laxemar-Simpevarp area are within values reported from literature, which is an indication of accuracy in the dataset.

For biota one weak point is that most of the information is on biomass and little effort has been spent on the quantification of biological processes. Respiration has been measured on one occasion in the benthic habitat in Frisksjön and macrophyte production has been estimated, but other than that, data on primary production, respiration and consumption from the area are lacking. However, an unrealistic effort is required to measure the respiration and consumption of biota in Laxemar-Simpevarp area, and it is unclear whether site-specific studies would provide a greater understanding of the sites than the literature data on respiration and consumption for functional groups we have used in this report.

In Frisksjön, the phytoplankton biomass has been measured eight times in the course of one year, and the result can be considered to be a good estimate of the annual mean. The biomasses of bacterioplankton, benthic bacteria, zooplankton, benthic fauna and macrophytes have been measured with lower frequencies (2, 1, 3, 1, 1 measurements each, respectively) and annual means are more uncertain. However, as biomasses of all functional groups have been measured in the lake, the magnitudes of the annual means should be correct. The results of one of the samples from the zooplankton study in Frisksjön were considered to be unrepresentative of the entire summer, so that zooplankton biomass data estimated in a nearby humic lake were used together with some of the site-specific results. In the benthic fauna estimate, small meiofauna is not included and it is therefore likely that the biomass of benthic fauna is somewhat underestimated. Benthic fauna has been measured in another three lakes in the area in addition to Frisksjön, which gives an estimate of the variation between the lakes.

The fish biomass has been investigated in Frisksjön, Jämsen, Söråmagasinet and Plittorpsgöl. The fish biomass was only investigated once in each lake, which gives no information about between-year variations. The most important uncertainty associated with this data is the conversion factor used to estimate the fish biomass from the CPUE (catch per unit effort) obtained from the standardized gillnet fishing. The conversion factor we use was recommended by a Swedish fish expert, but no conversion factors have been published in the scientific literature. The classification of fish species into different functional groups according to their size may also be somewhat uncertain. The conversion from zooplanktivore to piscivore may not be total and may differ between lakes depending on food resources and competition.

Since respiration was only measured on one occasion, this estimate is too uncertain to use for longer time periods. However, it can be used as an estimate of the magnitude of summer respiration and agrees well with modelled summer respiration in Chapter 5.

Biota in streams

The information on biota in the Laxemar-Simpevarp streams consists of data on vegetation, benthic fauna and fish. No measurements of primary production or respiration have been performed. This may be seen as a weak point, but as the streams are mainly small and long stretches are dry during part of the vegetation period this should not be an important information gap.

Vegetation in streams has been investigated in 10 m sections (in total c. 20 km stream length). The spatial distribution of data must therefore be regarded as very good, although parts of the streams were not investigated. The investigation was performed by one person, so differences within the data as a consequence of different judgements of the somewhat subjective parameters can be excluded. This also means that results cannot be validated since no stretches have been investigated independently by two persons.

Benthic fauna was measured at three localities at one occasion. Thus, the investigation provides estimates of variation in space but not in time. Fish were investigated by electrofishing on five occasions, providing reliable results on annual variation.

Land use and human impacts

Land use and human impacts on limnic environments have been recorded during the two characterization studies of lakes and streams in the Laxemar-Simpevarp area. In the lake characterization, no extra effort was made to find such information and only conditions known to the authors were recorded. Some human impact may therefore have been overlooked, but considering the relative young age of the area this may be less likely. The presence of barriers to migratory fish and human impacts in streams are well documented for the stretches that have been investigated. Information for other stretches is lacking.

Conclusions

In general, an impressive amount of data has been gathered from the area. The data quality is most often judged as high whereas the spatial and/or temporal density in the available data varies.

5 The lake ecosystem – conceptual and quantitative carbon models

From an ecosystem perspective lakes can be described in several ways. One general way to describe lakes is by using the mass balance concept. In a mass balance, the major flows to and from the lake are described, but no information is given about the dynamics within the system, e.g. the flows between organisms. Instead, the results of in-lake processes are described as net fluxes out of or into the system. The mass balance approach is very useful for describing the role of lake ecosystems in biogeochemical processing of organic matter at a landscape level. If the interest is in the food web itself, an ecosystem model, including major functional groups and the flows of elements or energy between them, is more appropriate. The latter may be essential when performing e.g. risk assessments. To get the whole view of pools and fluxes within the lake ecosystem, both these aspects are relevant. /Andersson and Sobek 2006/ suggested that a mass balance should be included in ecosystem modeling to strengthen the conclusion of the ecosystem model.

Ecosystem models and mass balances can be developed for any element. In this chapter, models and mass balances for carbon are presented. This element can be seen as the main constituent of biomass and carbon has often been used in literature when constructing ecosystem models (e.g. /Gessner et al. 1996, Jansson et al. 1999, Wetzel 2001, Andersson and Kumblad 2006, Sobek et al. 2006/). Another aspect is that a lake model based on carbon can be used to estimate the fate of radioactive carbon (C-14) in the lake environment. Of course, many other elements besides carbon are also of interest for the modelling of transport of radionuclides, and conceptual models for the transport of a number of other elements are described in Chapter 7.

In this chapter, mass balances and ecosystem models for carbon have been calculated for five lakes: Eckarfjärden, Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket in the Forsmark area, and Frisksjön in the Laxemar-Simpevarp area. The data presented in Chapter 3 and 4 were used as quantitative input when the mass balances and ecosystem models were set up. The lakes in Forsmark have been divided into larger and smaller lakes. The larger lakes are somewhat deeper and contain a relatively large area of submerged vegetation, whereas the smaller lakes are shallower and have a small water surface compared with the surrounding reed belts. Some lakes in the area have a thick microbial mat in the benthic habitat, while others lack a microbial mat (see Section 3.10). In order to describe more than one kind of lake, we decided to create quantitative models for two larger lakes (Bolundsfjärden and Eckarfjärden) and two smaller lakes (Gunnarsbo-Lillfjärden and Labboträsket). Of the two smaller lakes, one contains a microbial mat, whereas the other has none. The two large lakes are situated within the same catchment (no. 8), and Labboträsket and Gunnarsbo-Lillfjärden in a neighbouring catchment (no. 1, see Figure 3-1). In catchment 2, Eckarfjärden is situated upstream, whereas Bolundsfjärden is one of the most downstream lakes in the system. This means that Eckarfjärden was isolated from the sea before Bolundsfjärden. In catchment 1, Labboträsket is situated upstream of Gunnarsbo-Lillfjärden. The amount of data available for the different lakes has been an important factor in selecting candidates for the larger and the smaller lakes. Frisksjön is one of the five lakes situated within the Laxemar-Simpevarp area and is the only lake situated within the Laxemar subarea. Most of the lakes in the region are shallow brown-water lakes, and Frisksjön was chosen as a representative of all the lakes in the area.

5.1 Conceptual models

5.1.1 Carbon mass balances

The aim of the mass balance calculations in this report is to provide an overview of the major fluxes of different elements to and from the lake ecosystem. Carbon enters lakes with water through inlets, direct flow from the catchment and via groundwater inflow. The flow in the inlets is relatively easily assessed, whereas direct drainage to lakes is more difficult to measure directly *in situ*. Carbon also enters the lake from the atmosphere via direct deposition on the lake surface and there is also a constant carbon dioxide gas exchange via the air-water surface. The exchange with the atmosphere may be of limited importance for most elements, but for carbon an important part of the total export from lakes may be the emission of carbon dioxide to the atmosphere /Algesten et al. 2003/. Under certain conditions there may also be an influx of carbon gas to the lake /Andersson and Brunberg 2006a/, and the direction of the flow is an indication of whether the lake is a net heterotrophic or autotrophic system.

Beside the atmospheric exchange, carbon exits the lake ecosystem via the lake outlets and via sediment accumulation. The flow in the outlets is relatively easily assessed. Sedimentation is the process where particulate matter within the lake water sinks down to the lake floor. Some of the matter will be resuspended up to the water phase again, while the rest stays in the sediment, becomes buried and becomes part of the sediment for the rest of the lake phase. In a long-term perspective, the accumulation of carbon and other elements in the sediment is the most interesting process, whereas the sedimentation and resuspension processes may be interesting in a shorter time perspective. No site-specific estimations of sedimentation and resuspension have been performed at the two sites, but long-term accumulation has been investigated.

A conceptual mass balance model was set up (Figure 5-1) and in the calculations the following equation was applied:

$$TOC_{IN} + DIC_{IN} + DOC_{DEP} = TOC_{OUT} + DIC_{OUT} + CO_{2\ FLUX} + TC_{SED} + TC_{BIRD}$$

where:

TOC_{IN} represents the inflow of Total Organic Carbon via inlets and via direct drainage to the lake. The concentrations of organic carbon in groundwater are small /Tröjbom and Söderbäck 2006a, b/, so the flow of organic carbon via groundwater is considered negligible.

DIC_{IN} represents the inflow of Dissolved Inorganic Carbon to the lake via inlets, direct drainage and groundwater inflow to the lake.

DOC_{DEP} represents Dissolved Organic Carbon entering the lake through wet deposition.

TOC_{OUT} represents the outflow of Total Organic Carbon from the lake via the outlet. The flow of organic carbon via groundwater is small and is considered negligible.

DIC_{OUT} represents the outflow of Dissolved Inorganic Carbon from the lake via the outlet.

$CO_{2\ FLUX}$ represents the flux of CO_2 across the air-water interface as a result of the balance between carbonic acid dissolved in the lake water and CO_2 present in the atmosphere.

TC_{SED} represents the long-term accumulation of Total Carbon within the lake.

TC_{BIRD} represents the outflux of carbon from the system via birds feeding in the lakes.

Three identified processes which may potentially influence the mass balance, but which are not included in the equation, are the swarming of hatching of insects, migration of fish and fishing by humans. The influence of these processes on carbon dynamics in the Forsmark lakes is assumed to be minor. The reasons for not including them in the mass balance are described below.

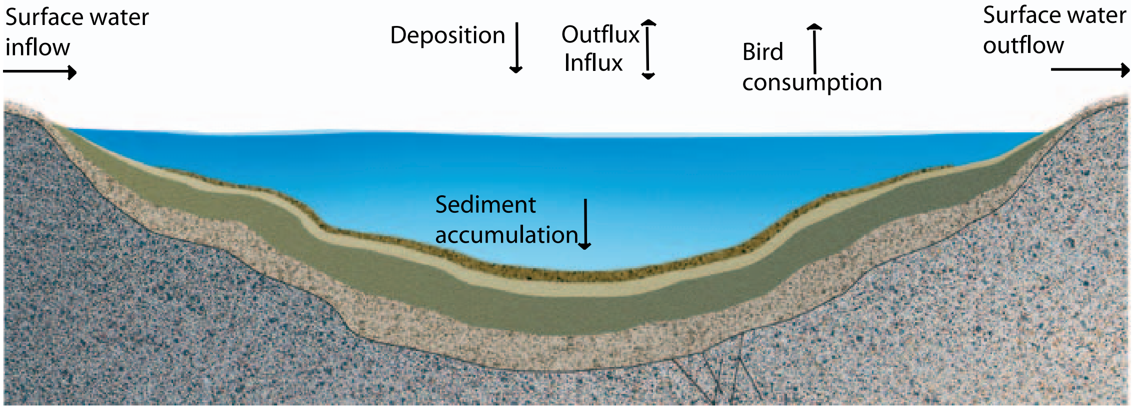

Figure 5-1. Transport processes considered in the carbon mass balance of lake ecosystems.

Swarming of hatching insects is a potential outflux of carbon from the lake. We have no information about how much of the biomass that potentially could be involved in this process, but assuming that the whole pool of benthic fauna in Bolundsfjärden should leave the lake this carbon outflow is only about 1% of the TOC outflow via the outlet. We therefore consider this process insignificant.

The contribution of carbon from fish migrating into Bolundsfjärden is assumed to be negligible. Ruffe (*Gymnocephalus cernua*) is the dominant fish species migrating into the lake /Loreth 2005/. This is a small species compared to many of the fish in the lake (i.e. tench), so in terms of biomass the migration is small compared to the stationary population in the lake. Moreover, the spawning fish are present within the lake for only a very short period (days) and even though they may lay large amounts of eggs, only a small fraction of them will actually hatch into fry that grow to the size where they can migrate out to the Baltic Sea. In the safety assessment of a future repository, the assumption that migrating fish are not relevant to include in the carbon model leads to a conservative estimate of radionuclide concentrations in the fish stock in the lake, as the small "dilution" of radionuclides per biomass from the (uncontaminated) migrating fish is not accounted for. In the investigation by /Loreth 2005/, the migration upstream from Bolundsfjärden was shown to be small and, accordingly, fish migration is assumed to be negligible for Eckarfjärden and Labboträsket as well.

Fishing in the lakes should be of minor importance for the mass balances. Some fishing may occur, but it is likely that most of the recreational fishing takes place in the nearby coastal areas today.

5.1.2 Ecosystem carbon models

The aim of the ecosystem model is to provide an overview of major pools and fluxes within the ecosystem. To do so, habitats, pools, and relationships between them have been identified as described below. Fluxes from abiotic pools to biotic pools are included in the ecosystem, but the main focus of the models is the biological processes, i.e. no effort has been made to quantify the fluxes between abiotic pools.

Habitats

The lakes are divided into three major habitats: the pelagic, littoral and profundal (Figure 5-2). The pelagic habitat is defined as the open water body. The littoral habitat is defined as the benthic zone reached by enough light to enable photosynthesis (comparable to the sum of Littoral II and III, see Section 3.7). The profundal habitat is the benthic habitat where light penetration is less than needed to sustain a permanent vegetation of primary producers.

The reed belts surrounding the lakes (comparable to Littoral I in Section 3.7) are dry in the summer and trees are found in them, hence the reed belts are to be considered as wetlands rather than parts of the lake. Thus, although it may seem controversial, Littoral I is classified as terrestrial area and is further described in /Löfgren 2010/. The main reason for this is to treat all kinds of wetlands within the areas in a similar way. The interface zones have to be considered as a transient stage in the succession of lakes turning into land. In the safety assessment of a repository for spent nuclear

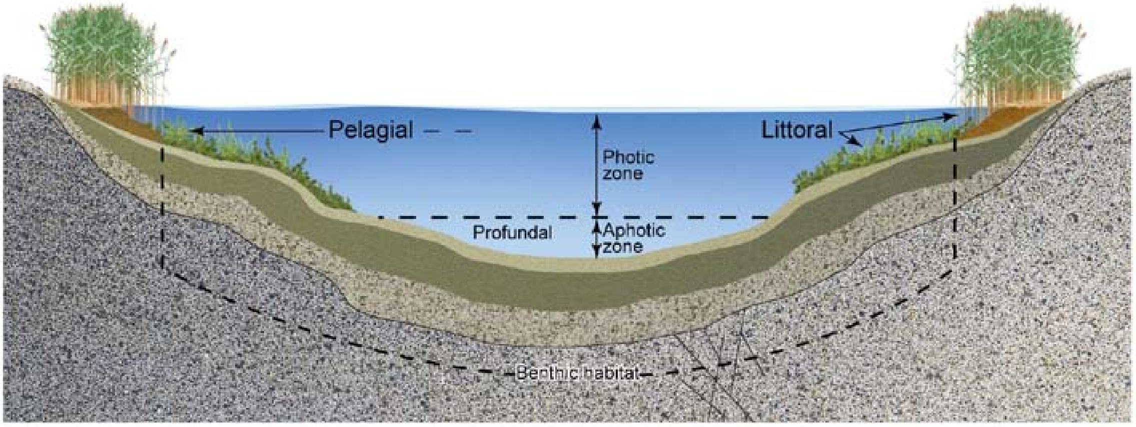

Figure 5-2. Lake habitats used in the ecosystem carbon models.

fuel, fluxes of elements are interesting on a landscape level and the models for the three ecosystem types (terrestrial, limnic and marine) will be linked together to model the overall fluxes. In this step it is not of specific importance how these areas are defined, the important thing is that these areas are included somewhere and later on linked in a proper manner.

Biotic carbon pools

The biota is divided into 7 functional groups according to food and habitat preferences (Table 5-1). Some functional groups occur within more than one habitat, for example benthic bacteria are present in both littoral and profundal habitats. Moreover, some functional groups, such as fish, were further divided into subgroups in the calculations based on their specific food preferences.

Primary producers

Primary producers consist of all autotrophic organisms, and these are divided into the functional groups phytoplankton (autotrophic and mixotrophic) and benthic primary producers (microphytobenthos, macroalgae emergent and submerged macrophytes). Phytoplankton is assumed to be evenly distributed within the pelagic habitat, whereas benthic primary producers occur in the littoral habitat.

Consumers

Consumers are defined as all heterotrophic organisms in the lake. Consumers are divided into the functional groups bacterioplankton, zooplankton, benthic bacteria, benthic fauna and fish. Bacterioplankton, zooplankton and fish are assumed to be evenly distributed within the pelagic habitat. Benthic fauna and benthic bacteria are assumed to be present in the littoral habitat and in the profundal habitat. Birds feeding on vegetation or fauna in lakes are also consumers linked to the limnic ecosystems. They do not live entirely on food produced in the lake and their importance for the ecosystem is limited. Therefore, birds using the lakes for feeding are not treated as a functional group in the ecosystem model. Instead, bird feeding is treated as an outflux in the mass balance calculations (Section 5.2.5).

Abiotic carbon pools

In the ecosystem models four abiotic pools were identified: inorganic carbon dissolved in water (DIC), organic carbon dissolved in water (DOC), particulate organic carbon in water (POC) and carbon in the sediments (sediment C).

Food web interactions

Phytoplankton and benthic primary producers are assumed to consume dissolved inorganic carbon (DIC) from the water (Figure 5-3). Due to the exchange at the air-water surface, DIC is assumed to always be available for primary production. In addition to photosynthesis, mixotrophic phytoplankton utilize bacterieplankton as a food source. Mixotrophic phytoplankton is capable of vertical migration /Smayda 1997/, so it is reasonable to assume that they can migrate and also utilize bacteria in the uppermost parts of the microbial mat on the sediment surface. It is therefore assumed that mixotrophic phytoplankton consume bacterioplankton and benthic bacteria from the top 0.5 mm of the microbial mat. Moreover, in Forsmark, benthic bacteria have been observed to be suspended in the water column during certain periods /Andersson 2005/, which would make the benthic bacteria available to mixotrophic phytoplankton.

Table 5-1. Functional groups in the lake ecosystems.

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

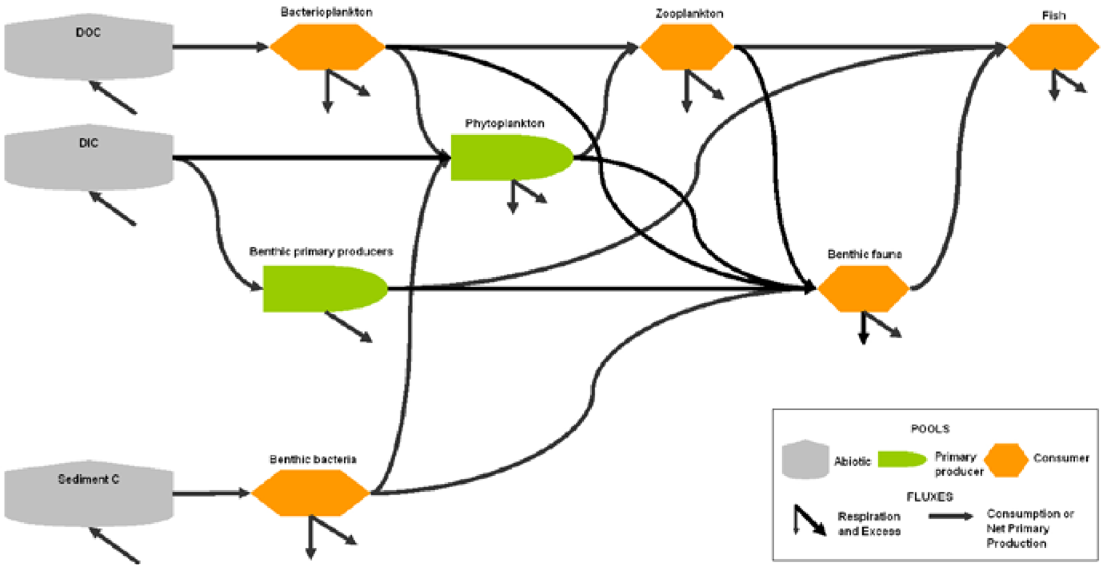

Figure 5-3. *Food web relationships in the conceptual model of the lake ecosystem.*

Bacterioplankton consume DOC and to some extent also POC as bacteria can be associated with particulate matter in the lake water. However, bacterioplankton dissolves the particulate carbon into smaller substances before utilising it, so for simplicity bacterioplankton was assumed to consume only DOC. Benthic bacteria consume organic carbon in the sediment.

In the model calculations, zooplankton is assumed to feed on phytoplankton, bacterioplankton and to some extent also on other zooplankton. Since we have no detailed information on feeding preferences of zooplankton we assume that 50% of the zooplankton community is available as a food source for zooplankton. This is most probably an overestimation but is chosen in order to not under estimate the transfer of matter from the base of the food web to the top predators.

Benthic fauna is composed of functionally different groups, such as filter feeders, detritus feeders, scrapers, shredders and predators, but these were treated as one group in the model calculations. Benthic fauna is assumed to consume phytoplankton, bacterioplankton, zooplankton, benthic primary producers, benthic bacteria from the top 1 cm of the microbial mat, and in addition also other benthic fauna. In reality, benthic fauna also consumes dead particulate organic carbon. However, the excess of organisms, i.e. production/consumption minus respiration and grazing/predation, is assumed to contribute to the POC and DOC pool. Thus, POC consumption is already accounted for in the consumption of live organisms.

Fish are divided into three subclasses in the calculations: zooplanktivores (Z-fish), benthivores (B-fish) and piscivores (P-fish), according to feeding preferences /Holmgren and Appelberg 2000/. Z-fish were assumed to consume metazooplankton, whereas B-fish were assumed to feed on benthic fauna and benthic primary producers. The only primary producer consumed by fish in Swedish lakes is the epiphytic growth on macroalgae/macrophytes, so the major part of the benthic primary producers is not consumed. The extent of epiphytic growth is not known, but it is included in the biomass estimates of the macrophtyes/macroalgae. We assume that 20% of the total biomass of macrophytes and macroalgae is available as a food source for the benthivores. Piscivores are assumed to feed on all three subclasses: Z-, B-, and P-fish.

Excess

Carbon that is not consumed or respired is assumed to contribute to the excess pool. Some of the excess will leave the lake through the lake outlet, but a large part of the excess may also contribute to the sediment accumulation in the lakes. By using the same values for carbon influx/outflux via inlets, outlets and atmospheric deposition as in the carbon mass balances described above, an estimate of sediment accumulation is derived. Thus the excess can be used to compare the results from the ecosystem model and the mass balance.

5.2 Model parameterization for the mass balances

Site-specific data in combination with literature data have been used to develop quantitative models from the conceptual mass balance model described in Section 5.1. A detailed description of the model parameterization done for mass balances follows below. The different transport processes identified in Section 5.1.1 have been calculated using different model assumptions. Most influxes and outfluxes are based on site- or lake-specific data (Table 5-2).

5.2.1 Carbon influx from the catchment via water (TOC_{IN}, DIC_{IN})

Forsmark

For the Forsmark lakes, the total transport of elements from the catchment was estimated based on simultaneous measurements of concentrations and discharge in streams over a period of two years /Tröjbom et al. 2007, Section 5.3/. Daily transport was calculated by multiplying total daily discharge by a concentration representative of the same time period, and these daily estimates were further added to obtain monthly and yearly transport. These values include water in- and outflow to/from lakes via in/outlets as well as diffusive in- and outflow of elements directly to the lake from the catchment as well as via groundwater. The mean value of the two years has been used as the best estimate, whereas the two individual values are presented as the range (minimum and maximum values) in Appendix 12. As only data from 2 years are available, the true range may of course be larger.

Extrapolations in both time and space had to be performed to compensate for the mismatch between concentration and discharge measurements. For Bolundsfjärden, which has a relatively large surface area, transport of carbon from areas draining directly into the lake was added to the calculated transport in the inlet stream by multiplying the area-specific transport rate (kg C km^{-2} y^{-1}) in the measuring point just upstream of the lake (PFM000068) (data from Table E-2 in Appendix E in /Tröjbom et al. 2007/), by the area draining directly into the lake. For Labboträsket, the area-specific transport of carbon in the upstream measuring point (PFM000066) was applied to the whole catchment (excluding the lake area) and was thus used to calculate total transport of carbon into the lake.

For Eckarfjärden, simultaneous measurements of concentrations and discharge were only available for the outlet stream during the period 2004 to 2006. However, monthly chemical measurements were performed in both the inlet (PFM000071) and outlet (PFM000070) streams during the period 2002 to 2004. To calculate annual transport of TOC and DIC into the lake, the ratio between concentrations in the inlet and the outlet streams was first calculated for each sampling occasion during the period 2002–2004 (data from SICADA[10], October 2007). These ratios were added to obtain monthly averages, and the monthly averages were used to calculate annual mean ratios. These annual mean ratios were then used to estimate concentrations in the inlet stream during the period 2004–2006 from measured concentrations in the outlet. Finally, the estimated concentrations were assumed to be representative of all water draining into the lake, and were thus used together with area-specific discharge in the downstream hydrological discharge station (PFM002668, cf. /Tröjbom et al. 2007/) to calculate the total annual transport of carbon into the lake.

Table 5-2. Site- (S) or Lake- (L) specific data used for mass balance calculations for the four modelled lakes in Forsmark (Fm) and Laxemar-Simpevarp (Lm).

Process	Eckarfjärden (Fm)	Bolundsfjärden (Fm)	Gunnarsbo-Lillfjärden (Fm)	Labboträsket (Fm)	Frisksjön (Lm)
Inflow via inlets, groundwater and direct flow from catchment (TOC_{IN}, DIC_{IN})	L	L	L	L	L
Influx via wet deposition from atmosphere (DOC_{DEP})	S	S	S	S	S
Outflow via outlets (TOC_{OUT}, DIC_{OUT})	L	L	L	L	S
Outflow to atmosphere ($CO_{2\ FLUX}$)	L	L	L	L	L
Sediment accumulation (TC_{SED})	L	S	S	S	L
Bird consumption	S	S	S	S	S

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[10] SKBs database SICADA, access might be given on request.

Laxemar-Simpevarp

For Frisksjön, the total transport of elements from the catchment was estimated based on simultaneous measurements of concentrations and discharge in streams over a period of one year /Tröjbom et al. 2008, Section 5.3.3/. Extrapolations in both time and space had to be performed to compensate for the mismatch among the measurement stations. Daily transport was calculated by multiplying total daily discharge by a concentration representative of the same time period, and these daily estimates were further added to obtain monthly and yearly transport. These values include water in- and outflow to/from lakes via in/outlets as well as diffusive in- and outflow of elements directly to the lake from the catchment as well as via groundwater. In order to estimate a range, the lowest and highest area-specific transports (kg C km^{-2} y^{-1}) calculated for different catchments in Laxemar-Simpevarp area were used together with the catchment area of the lake to estimate minimum and maximum values (presented in Appendix 12).

5.2.2 Carbon influx/exchange with the atmosphere (DOC_{DEP} and $CO_{2\ FLUX}$)

Forsmark

For the Forsmark lakes, the annual deposition of carbon, DOC_{DEP}, was calculated from mean concentrations in precipitation from two stations in the Forsmark area /Tröjbom and Söderbäck 2006b/ and from annual precipitation (calculated as an annual mean from two years: 2004 and 2005) /Johansson et al. 2008/. Minimum (0.8 g C m^{-2}) and maximum (2.3 g C m^{-2}) values are based on literature data /Dillon and Molot 1997, Willey et al. 2000/.

The CO_2 flux across the air-water surface was calculated from chemical equilibriums. There is equilibrium of CO_2 between air and surface waters as a response to the partial pressure of the gas within the lake water resulting in a flux of carbon dioxide across the air-water interface of lakes. The partial pressure of CO_2 (pCO_2) in the surface water of each lake was calculated from DIC, pH, temperature and air pressure at each sampling occasion using equilibrium constants /Stumm and Morgan 1996/ and Henry's constant according to /Weiss 1974/. Atmospheric pCO_2 was assumed to be 365 µatm (corresponds to 365 ppmv). The flux of CO_2 across the air-water interface ($CO_{2\ FLUX}$) was calculated from the difference between lake pCO_2 and atmospheric pCO_2, and wind speed /Cole and Caraco 1998/. In Forsmark, wind was measured at the meteorological station Högmasten, situated 3 km north of Eckarfjärden. In the winter, the ice cover prevents gas exchange with the atmosphere, and the accumulating CO_2 is rapidly degassed during the spring melt /Striegl et al. 2001/. We accounted for the spring melt emission of CO_2 by subtracting the CO_2 concentration measured shortly after ice-out from the CO_2 concentration prior to ice-out, and by adding the resulting flux to the flux estimate for the open-water period. Dates for ice-on and ice-out are based on observations from the site investigations /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/. The CO_2 flux across the air-water interface was calculated for the years for which data are available (four years for Eckarfjärden, three years for Bolundsfjärden and Labboträsket and one year for Gunnarsbo-Lillfjärden), and the average annual CO_2 flux (best estimate) was calculated as the mean of these years. The lowest and highest annual flux values for each lake have been assumed to represent the range (minimum and maximum values).

Laxemar-Simpevarp

For Frisksjön, the annual deposition of dissolved organic carbon, DOC_{DEP}, was based on concentration in precipitation from station Rockneby Kalmar /Phil Karlsson et al. 2008/ and from mean precipitation in Laxemar-Simpevarp /Werner et al. 2008/. Minimum (0.8 g C m^{-2}) and maximum (2.3 g C m^{-2}) values are based on literature data /Dillon and Molot 1997, Willey et al. 2000/.

The CO_2 flux across the air-water surface in Laxemar-Simpevarp was calculated in the same way as for Forsmark (see above). The wind speed in Laxemar-Simpevarp was measured at the meteorological station in Plittorp, c. 8 km west of Frisksjön. Dates for ice-on and ice-out are based on observations from the site investigations (from the SICADA[11], April 2008, cf. Section 4.4.4). The CO_2 flux across the air-water interface was calculated for the years for which data are available (4 years), and the average annual CO_2 flux (best estimate) was calculated as the mean of these years.

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[11] SKBs database SICADA, access might be given on request.

The lowest and highest annual flux value have been assumed to represent the range (minimum and maximum values).

5.2.3 Carbon outflux by sediment accumulation (TC_{SED})

Forsmark

In Forsmark, long-term accumulation of dry matter has been estimated to be 1 mm year^{-1} in sediments from Eckarfjärden /Hedenström and Risberg 2003/. The accumulation rate of carbon within the lake sediment has been estimated using data from the study /Hedenström and Risberg 2003/ on accumulation rate of dry matter combined with the average carbon content of the gyttja layer in Eckarfjärden (27% of dry weight), together with data from /Nordén 2007/ on the average water content of that sediment layer. Further, the density of minerals was assumed to be 2,650 kg m^{-3} (the commonly used density factor for quartz) and that the amount of organic matter was calculated by multiplying the carbon content by 1.7 /Hedenström and Sohlenius 2008/. For Bolundsfjärden, lake-specific data on water content in the gyttja layer (90%) /Nordén 2007/ have been used together with the average carbon content for the gyttja layer in three lakes in the area (Eckarfjärden /Hedenström and Risberg 2003/, Fiskarfjärden and Puttan /Hedenström 2004/) and the accumulation rate of dry matter from Eckarfjärden. No lake-specific sediment data are available for Gunnarsbo-Lillfjärden and Labboträsket. Instead the same data on carbon content and accumulation rate as for Bolundsfjärden were used together with the average water content of the gyttja layer from three lakes in the area (Eckarfjärden, Bolundsfjärden and Puttan) /Nordén 2007/. In the calculations, it is assumed that the sediment accumulation is evenly spread over the entire lake area (reed belts excluded).

The carbon concentration of 27% /Hedenström and Risberg 2003/ that is used in the calculation of sediment accumulation deviates slightly from the 35% carbon reported in /Hannu and Karlsson 2006/. The study by /Hannu and Karlsson 2006/ is used in the estimation of the sediment carbon pool below, in order to use data from the same sampling event as in the estimations of pools for all other elements (presented in Chapter 7). However, the study by /Hedenström and Risberg 2003/ includes more replicates and is supposed to give a more accurate estimate of the sediment accumulation.

In this report, different estimates of the accumulation of dry matter, water and carbon content of the gyttja layer were used to estimate the minimum and maximum carbon accumulation rate in lake sediments. Sediment accumulation rates for four oligotrophic hardwater lakes in the region (including Eckarfjärden) are presented in /Hedenström and Risberg 2003/, showing a range between 0.2 and 4 mm year^{-1}. The lowest value is for Barsjö (a small lake resembling Labboträsket) before isolation, while the highest value is for the lagoon surface in Landholmssjön (larger lake resembling the larger lakes in the Forsmark area).

Data on water content in lake sediments are available from three lakes in the Forsmark area: Eckarfjärden, Bolundsfjärden and Puttan /Nordén 2007/. The lowest and highest values for this parameter in gyttja samples from these three lakes (78% in Bolundsfjärden and 98% in Puttan) are assumed to represent the range. Data on the carbon content of the gyttja layer are available in /Hedenström and Risberg 2003/. The range presented for Eckarfjärden is 10–45% and for Barsjön 8–45% of dry weight. The latter range is used for this parameter. There is a clear positive correlation between the carbon and water content of lake sediments (see e.g. Figures 4-3, 4-6, 4-9 and 4-13 in /Hedenström and Risberg 2003/), so minimum and maximum values for these two parameters have been combined with minimum and maximum values for sediment accumulation rates in order to find minimum and maximum carbon accumulation rates. The minimum carbon accumulation rate was thereby estimated using high carbon and water content in combination with low accumulation rate. The maximum carbon accumulation rate was estimated using low carbon and water content combined with high accumulation rate.

Laxemar-Simpevarp

In Laxemar-Simpevarp, the long-term accumulation rate of carbon has been estimated in Frisksjön by dating of sediment cores /Sternbeck et al. 2006/. The study reveals an average rate of 79 g C m^{-2} y^{-1} (SD = 14 g C m^{-2} y^{-1}) in the upper part of the sediment layer (20–22 cm sediment depth) that represents the lacustrine phase of the lake. The estimation is based on two sediment cores (one used for analysis of sediment age and the other for carbon content) from the deepest part of the lake. When calculating the permanent sediment accumulation (TC_{SED}) it was assumed that the whole lake area (excluding the reed belt) functions as an accumulation bottom and that the accumulation rate is the same over the whole area.

The minimum accumulation rate was estimated using a carbon accumulation rate 2 standard deviations lower than the mean value together with a smaller area of accumulation bottoms (52,000 m^2 which is the area classified as profundal in /Brunberg et al. 2004b/). The maximum accumulation rate was estimated using a carbon accumulation rate 2 standard deviations higher than the mean value and the same accumulation area as for the best estimate (the whole lake area, excluding the reed belt).

5.2.4 Carbon outflow via water (TOC_{OUT} + DIC_{OUT})

Forsmark

For the Forsmark lakes, the outflow of carbon *via surface water* was estimated from simultaneous measurements of concentrations in the lake and discharge in streams over a period of two years (data from Table E-1 in Appendix E in /Tröjbom et al. 2007/). For Eckarfjärden, the concentrations measured in the sampling point downstream of the lake were used, while the concentrations in lake water were used for Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket. Daily transports were calculated by multiplying total daily discharge by a concentration representative of the same time period, and these daily estimates were further added to obtain monthly and yearly transports. Extrapolations in both time and space had to be performed to compensate for the mismatch among the measurement stations. The outflow of TOC and DIC via the outlets was estimated using measured water flow and concentrations for two years. The mean value of the two years is used as best estimate value, whereas the two individual values are assumed to represent the range (minimum and maximum values).

Laxemar-Simpevarp

The outflow of carbon via surface water from Frisksjön was estimated from concomitant measurements of concentrations in lake water (surface) and discharge in streams during three years (2005–2007). Since the discharge estimates from the gauging station downstream Frisksjön most likely are erroneous (cf. /Werner et al. 2008/), we used instead monthly mean values for specific discharge from the gauging station just upstream Frisksjön (PSM000347) (discharge data are presented in /Werner et al. 2008/). The monthly means were combined with monthly measurements of TOC and DIC in lake water to calculate monthly transport of carbon via the outlet, and these estimates were further summarized to calculate yearly transport. For a few months, missing chemical data was replaced by the mean value of data from the previous and the succeeding months. The mean value of the three years is used as a best estimate, and minimum and maximum are assumed to represent the range.

5.2.5 Carbon outflux by birds feeding in the lake (TC_{BIRD})

Forsmark and Laxemar-Simpevarp

Bird consumption (g C m^{-2} $year^{-1}$) has been estimated using data on bird territories in the two areas (Green unpubl.) and the metabolic rate in birds, calculated from an equation given in /Nagy et al. 1999/. The calculations are described in /Löfgren 2010, Section 4.2.2/. It may be argued that birds also contribute to the carbon pool in lakes through deposition of faeces. As the species of birds in question use the lakes only for feeding and do not nest in the lakes, this influx is assumed to be negligible.

In the Forsmark and Laxemar-Simpevarp areas, the outflow of carbon from the aquatic systems via consumption by birds feeding in lakes and shallow bays (0–5 m depth) is dominated by herbivorous species (contribute 52% of total outflux via consumption by birds). Given that the dominant bottom vegetation in the Forsmark lakes is stoneworts, a group of plants consumed by very few bird species (mainly ducks which have not been observed in the lakes), we have assumed that birds are mainly feeding in the shallow bays in the area and that the outflow of carbon via herbivorous birds is negligible. Likewise, macrophytes in Frisksjön are practically absent except for reed, which is not utilised by birds. Hence, the same assumptions as for Forsmark have been used when calculating the consumption by birds feeding in Frisksjön. The consumption in lakes by birds is thereby dominated by piscivorous bird species (72%), followed by omnivorous birds (23%) and insectivorous birds (5%). No estimates of variation are available for this data. An estimate of minimum consumption was achieved by considering only bird species specifically feeding in lakes (the above estimates include birds feeding in both lake and marine habitats). An estimate of maximum consumption was achieved by also including the herbivorous birds occurring in the lakes.

5.3 Model parameterization for ecosystem models

5.3.1 Abiotic carbon pools

All abiotic pools in the water phase can be assumed to be available for the biotic pools. The sediment carbon, on the other hand, is a very large pool in most lakes and it is reasonable to assume that only the uppermost part of the sediment is available for biota. In the ecosystem models, no effort has been made to quantify the size of the carbon sediment pool available for biota, but sediment carbon is assumed to be available in excess for the functional groups that utilize that pool.

The concentrations of ***DOC*** in Bolundsfjärden, Eckarfjärden Gunnarsbo-Lillfjärden and Labboträsk have been measured in the site investigation and data from 2004-06-01 to 2006-05-31 were used in this evaluation (data from SICADA[12], October 2006). Data on ***POC*** is also available for the time period 2004-06-01 to 2006-05-31 (SICADA, October 2006).

The carbon content of the ***sediment*** in Eckarfjärden was derived from Appendix 1 in /Hannu and Karlsson 2006/. The available samples were divided into three deposit layers: gyttja, clay gyttja and clay. In Bolundsfjärden, the carbon content was not analyzed but the depth of the different sediment layers are measured /Hedenström 2004/. In Gunnarsbo-Lillfjärden and Labboträsk no measurements on the sediments have been performed. Instead, sediment depths were estimated from other lakes in the area situated at the same altitude (i.e. isolated from the Baltic Sea at approximately the same time and thus lakes of similar age). In the case of Gunnarsbo-Lillfjärden (1.92 m.a.s.l.) data from Gällsboträsket (1.47 m.a.s.l.) was used, and in the case of Labboträsket (2.7 m.a.s.l.) data from Stocksjön (2.65 m.a.s.l.) was used. For Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsk, the carbon content in different sediment layers was assumed to equal the carbon content in the sediment layers of Eckarfjärden.

The abiotic pool DIC is assumed to always be available for biota due to a continuous exchange of CO_2 between the air and water. Therefore this pool is not quantified.

5.3.2 Biomass

Forsmark

Most biomass data used in the ecosystem carbon models are site specific (Table 5-3). Much of the site-specific biomass data used were available in grams wet or dry weight and this has been converted into grams C using conversion factors presented in Table 5-4. Site data from Eckarfjärden /Blomqvist et al. 2002, Andersson et al. 2003/ were used together with chlorophyll *a* concentrations in surface waters (0.5 m) /Tröjbom and Söderbäck 2006b/ to calculate ***phytoplankton*** biomass in Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket (Table 5-3). The mean monthly biomass (g C m^{-3}) in Eckarfjärden was divided by the mean monthly chl *a* concentration in Eckarfjärden, and this ratio was multiplied by the chl *a* concentrations in the other lakes to achieve the biomass there. The biomass was measured in Bolundsfjärden during 2001 /Franzén 2002/, but the replicates were few and there were only autumn values. The phytoplankton biomass in Bolundsfjärden was therefore calculated from Eckarfjärden data. The calculated autumn values agreed well with the measured autumn values.

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[12] SKBs database SICADA, access might be given on request.

Benthic primary producers consist of microphytobenthos, submerged vegetation and emergent macrophytes. Site data on the microphytobenthos biomass from Eckarfjärden /Andersson et al. 2003/ was used also for Bolundsfjärden and Gunnarsbo-Lillfjärden (Table 5-3). Only autumn values of the microphytobenthos biomass were available for Bolundsfjärden /Franzén 2002/, so values from Eckarfjärden were used for this lake as well. The few measured data from Bolundsfjärden agree well with autumn values from Eckarfjärden. Since only 1 of 23 samples in Labboträsket contained a microbial mat (Section 3.9.1), the biomass of the microphytobenthos there was assumed to be negligible. The biomass of submerged vegetation (mainly the macroalgae *Chara sp.*) was taken from site-specific investigations in Bolundsfjärden 2006 (Table 5-3) /Karlsson and Andersson 2006/. Biomass estimates of *Chara sp.* were also available from Bolundsfjärden and Fiskarfjärden from 2004 /Huononen 2005/. However, that investigation included few replicates and only autumn values, so the biomass values of submerged vegetation from the study in 2006 were also used for Eckarfjärden, Gunnarsbo-Lillfjärden and Labboträsket. The biomass of emergent macrophytes is very small compared to submerged macrophytes. It is therefore assumed to be negligible and is not included in the model calculations.

Table 5-3. Biomass and primary production values used for the different functional groups in the lake ecosystem models. E-fjärden = Eckarfjärden, B-fjärden = Bolundsfjärden, GL-fjärden = Gunnarsbo-Lillfjärden and L-träsk = Labboträsket.

Functional group	Biomass (*g C m^{-2}, ** g C m^{-3})				Primary production (* g C m^{-2} y^{-1}, ** g C m^{-3} y^{-1})			
	E-fjärden	B-fjärden	GL-fjärden	L-träsk	E-fjärden	B-fjärden	GL-fjärden	L-träsk
Phytoplankton**	0.04	0.04	0.03	0.03	16.2	18.6	13.1	10.2
Benthic primary producers*:								
Macroalgae	22.23	22.23	22.23	22.23	87.0	87.0	87.0	87.0
Microphytobenthos	3.82	3.82	3.82	–	55.7	55.7	55.7	–
Emergent macrophytes	–	–	–	–	–	–	–	–
Bacterioplankton**	0.05	0.05	0.05	0.05				
Zooplankton**	0.07	0.07	0.07	0.07				
Benthic bacteria*	3.68	3.68	3.68	3.68				
Benthic fauna*	0.43	0.56	0.43	0.43				
Z-fish*	0.03	0.001	0.002	–				
B-fish*	0.74	0.62	0.77	0.68				
P-fish*	0.31	0.11	0.26	–				

Table 5-4. Conversion factors used for converting biomass in grams wet or dry weight into grams carbon (C).

Available data	Conversion factor (ww to dw)	Conversion factor (g C g dw^{-1})
Primary producers		
Benthic primary producers Submerged macroalgae		0.268 [a)]
Consumers		
Zooplankton		0.48 [b)]
Benthic fauna		0.435 [c)]
Fish		
Planktivorous	0.198 [a)]	0.440 [a)]
Benthivorous	0.203 [a)]	0.445 [a)]
Piscivorous	0.203 [a)]	0.432 [a)]

[a)] /Hannu and Karlsson 2006/
[b)] /Anderson and Hessen 1991/
[c)] average of conversion factors for different taxa given in /Liess and Hillebrand 2005/.

The estimated biomass of ***bacterioplankton, benthic bacteria,*** and ***zooplankton*** from studies in Eckarfjärden were used for all the lakes in the area /Blomqvist et al. 2002, Andersson et al. 2003, Andersson 2005, Andersson and Brunberg 2006a/.

Site-specific data on the biomass of ***benthic fauna*** were used for Bolundsfjärden /Huononen 2005/. Two methods were used for sampling and an average of the results from the two methods was used in the model. The average biomass of benthic fauna from Bolundsfjärden and Fiskarfjärden was used to model Eckarfjärden, Gunnarsbo-Lillfjärden and Labboträsket. The biomass of benthic fauna was measured once in Eckarfjärden, but was most probably underestimated on this occasion since only areas lacking submerged vegetation were sampled /Andersson et al. 2003/. Benthic fauna biomass have been shown to correlate with biomass of benthic vegetation /van den Berg et al. 1997/ and large areas of Eckarfjärden are covered by *Chara sp.*, which makes estimates from the survey in Fiskarfjärden and Bolundsfjärden more accurate. The benthic fauna was sorted into subgroups according to feeding preferences.

Site-specific biomass data have been used for ***fish*** biomass in Eckarfjärden, Bolundsfjärden and Gunnarsbo-Lillfjärden /Borgiel 2004b/. No biomass data are available for fish in Labboträsket, but it is known that only small Crucian carp live there (see Section 3.10.1). It was assumed that Crucian carp are mainly benthic feeders and the biomass of zooplanktivorous and carnivorous fish was therefore set at zero in Labboträsk. The biomass of benthivorous fish in Labboträsket was estimated using the mean biomass per unit area of benthivorous fish in Eckarfjärden and Bolundsfjärden.

Laxemar-Simpevarp

Most of the assumptions used in the quantitative lake models for the lakes in the Forsmark area are also valid for Frisksjön. The text below therefore includes site-specific information and, when appropriate, references to the descriptions in the Forsmark text. As for Forsmark, most biomass data in the Laxemar-Simpevarp ecosystem carbon models are site-specific (Table 5-5). For conversion from wet weight to carbon weight for biota, the same conversion factors as for Forsmark were used for data from Laxemar-Simpevarp (Table 5-4).

Site-specific data on the ***phytoplankton*** biomass in Frisksjön were used in the calculations (see Chapter 4). Measurements in Frisksjön were used to estimate biomass each month. For missing months the following assumptions were made: January to March was assumed to have the same biomass as December and for November a mean from October and December was used. The mean of monthly biomasses was used to calculate an annual mean biomass of phytoplankton.

Table 5-5. Biomass, primary production, respiration and consumption values used for the different functional groups in the ecosystem model for Frisksjön. Some of the phytoplankton are mixotrophic, so this functional group has both primary production and respiration.

Functional group	Biomass (*g C m^{-2}, **g C m^{-3})	Primary production (g C m^{-2} y^{-1})	Respiration (*g C m^{-2} y^{-1}, ** g C m^{-3} y^{-1})	Consumption (* g C m^{-2} y^{-1}, ** g C m^{-3} y^{-1})
Phytoplankton**	0.28	40	14.5	28.9
Benthic primary producers*				
Macrophytes	0.81	1.0	–	–
Microphytobenthos	–	–	–	–
Submerged vegetation	–	–	–	–
Bacterioplankton**	0.03	–	58.7	78.3
Zooplankton** [a)]	0.11	–	2.9	8.8
Benthic bacteria*	5.32	–	63.6	84.8
Benthic fauna*				
Littoral	0.43	–	2.5	7.5
Profundal	0.60	–	3.5	10.5
Z-fish*	0.01	–	0.1	0.1
B-fish*	0.29	–	1.7	2.9
P-fish*	0.27	–	1.6	2.7

[a)] 2 of 3 measured values have been used together with values from another lake, see text for details.

Benthic primary producers consist of the microphytobenthos emergent and submerged macrophytes. In Frisksjön submerged macrophytes (i.e. nymphea) are found in a small area comparable to Littoral II in Section 3.7 /Aquilonius 2005/. The biomass of the microphytobenthos is assumed to be negligible due to the poor light climate of the entire benthic area.

Site-specific data were used for the biomasses of ***bacterioplankton, benthic bacteria, benthic fauna and fish*** /Andersson et al. 2006, Ericsson and Engdahl 2004, Engdahl and Eriksson 2004/. Site-specific data on ***zooplankton*** were only available for three dates, so, in addition to site-specific data, data from Lake Älgsjön were used to estimate the annual mean zooplankton biomass (see Section 4.10.1).

5.3.3 Primary production

Forsmark

Primary production data used in the ecosystem carbon models are compiled in Table 5-3.

Site data from Eckarfjärden /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/ were used together with chlorophyll *a* concentrations to calculate production of ***phytoplankton*** in Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket. The production per litre and month was divided by the mean monthly chl *a* concentration in the surface water of Eckarfjärden. The production in Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket was then calculated by multiplying the production per chl *a* in Eckarfjärden by the mean monthly chl *a* concentration in the lakes. Annual production (Table 5-3) was achieved by adding together the monthly means.

The production of ***benthic primary producers*** was calculated as the sum of the production of microphytobenthos and macroalgae. *Microphytobenthos* production estimates for Eckarfjärden, Bolundsfjärden and Gunnarsbo-Lillfjärden were taken from site-specific data in Eckarfjärden /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/. Labboträsket lacks a microbial mat, so the production by the microphytobenthos was assumed to be negligible there. Higher biomass and production of phytoplankton in Bolundsfjärden could potentially lead to less light reaching the microphytobenthos and thus lower primary production by the microphytobenthos. However, the shallower depth in Bolundsfjärden probably enables as much light to reach the benthic habitat as in Eckarfjärden, so the same production has been assumed.

Net primary production and respiration of *macroalgae* was obtained from site-specific investigations in Bolundsfjärden /Karlsson and Andersson 2006/. We assume the same respiration rate under dark and light conditions, resulting in a night respiration by the macroalgae in the summer of approximately 20% of their net primary production. Respiration by *Chara sp.* in the winter was assumed to be negligible due to the low temperature and biomass. The same value of primary production by macroalgae was used for all 3 lakes in the area.

Laxemar-Simpevarp

Primary production data used in the ecosystem carbon models are compiled in Table 5-5.

Phytoplankton production was estimated from literature data showing correlations between phosphorus and annual production and chl *a* and primary production in a number of humic lakes /Nürnberg and Shaw 1999/. By comparing phosphorus and chl *a* concentrations in Frisksjön with correlation graphs in /Nürnberg and Shaw 1999/ a primary production of about 40 g C m^{-2} are assumed to be a relaisitc estimate of annual primary production in Frisksjön.

Submerged macrophytes, which are the only ***benthic primary*** producers of significance in Frisksjön, were assumed to lose part of their annual production during the growing season (e.g. due to grazing), and it was therefore assumed that the August biomass measured in the lake constituted 80% of the total annual production. Like biomass, the production of submerged microphytobenthos was assumed to be negligible.

5.3.4 Respiration

Forsmark

Respiration data used in the ecosystem carbon models are compiled in Table 5-6. As respiration has not been measured for any functional group in the Forsmark lakes, we have no site-specific data for this process. Instead, respiration has been estimated using conversion factors.

The ***phytoplankton*** in Eckarfjärden is to a large extent made up of mixotrophic species which, in addition to performing photosynthesis, are able to consume bacteria /Blomqvist et al. 2002, Andersson et al. 2003/. Therefore, both respiration and consumption have been calculated for phytoplankton. The mixotrophic phytoplankton was assumed to contribute to the primary production in proportion to its biomass. The mixotrophic phytoplankton was assumed to achieve 2/3 of its carbon assimilation from consumption of bacteria /Jansson et al. 1999/ and its growth efficiency was assumed to be 50%. The same proportion of mixotrophic phytoplankton to total phytoplankton biomass as in Eckarfjärden was assumed for Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsk.

The commonly used growth efficiency of 25% /del Giorgio et al. 1997a, see also Tranvik 1988/ was used for calculating ***bacterioplankton*** respiration. Secondary production by bacterioplankton (n=24) was measured by thymidine incorporation in situ in Eckarfjärden during 2001 and 2002 /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/. The annual respiration was calculated from an annual mean production calculated from these measurements (13.1 g C m^{-3} y^{-1}, n=2 years, min 12.4 g C m^{-3} y^{-1}, max 13.7 g C m^{-3} y^{-1}).

Respiration of ***benthic bacteria, zooplankton***, ***benthic fauna***, and ***fish*** was calculated using conversion factors from biomass (Table 5-7), together with temperature variation over the year measured in the investigated lakes, and assuming a direct linear response of respiration to temperature. The biomasses of benthic bacteria and zooplankton were investigated in Eckarfjärden, the biomass of benthic fauna in Bolundsfjärden and Fiskarfjärden, and the biomass of fish in Eckarfjärden and Bolundsfjärden. The temperature data used for Eckarfjärden and Bolundsfjärden are based on measurements from April 2002 to December 2005, whereas the same temperature data for Fiskarfjärden are based on measurements from January to December 2004 (data from SICADA[13], October 2006).

Laxemar-Simpevarp

Respiration data used in the ecosystem carbon models are compiled in Table 5-5. The ***phytoplankton*** in Frisksjön was to a large extent (40%) composed of mixotrophic species (see Section 4.10.1), which in addition to photosynthesis are able to consume bacteria. Therefore, both respiration and consumption have been calculated for phytoplankton. The mixotrophic phytoplankton were assumed to achieve 2/3 of its carbon assimilation from consumption of bacteria /Jansson et al. 1999/. The growth efficiency was assumed to be 50%, and thus respiration was assumed to be half of consumption (see the section "Consumption" below).

Table 5-6. Respiration and consumption values used for the different functional groups in the lake ecosystem models. E-fjärden = Eckarfjärden, B-fjärden = Bolundsfjärden, GL-fjärden = Gunnarsbo-Lillfjärden and L-träsk = Labboträsket. Note that phytoplankton contains mixotrophic species with both primary production and respiration.

Functional group	Respiration (*g C m^{-2} y^{-1}, ** g C m^{-3} y^{-1})				Consumption (* g C m^{-2} y^{-1}, ** g C m^{-3} y^{-1})			
	E-fjärden	B-fjärden	GL-fjärden	L-träsk	E-fjärden	B-fjärden	GL-fjärden	L-träsk
Phytoplankton**	8.4	8.7	6.8	5.4	16.8	17.5	13.5	10.9
Bacterioplankton**	39.2	39.2	39.2	39.2	52.3	52.3	52.3	52.3
Zooplankton**	1.0	1.0	1.0	1.0	3.2	3.2	3.2	3.2
Benthic bacteria*	44.7	44.7	44.7	44.7	84.1	84.1	84.1	84.1
Benthic fauna*	2.4	3.3	2.4	2.4	7.3	9.8	7.3	7.3
Z-fish*	0.16	0.01	0.01	–	0.28	0.01	0.02	–
B-fish*	4.4	3.7	4.7	4.1	7.6	6.5	8.1	7.0
P-fish*	1.9	0.6	1.6	–	3.2	1.1	2.7	–

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[13] SKBs database SICADA, access might be given on request.

Table 5-7. Conversion factors derived from /Kautsky 1995/ for calculation of respiration from biomass.

Functional group	Respiration g C g C^{-1} day^{-1}
Zooplankton	0.115
Benthic bacteria	0.069
Benthic fauna	
Benthic filter feeders	0.028
Benthic detritivores	0.032
Benthic herbivores	0.029
Benthic carnivores	0.033
Fish	0.033

Bacterioplankton respiration was calculated from the literature. /del Giorgio et al. 1997a/ showed a correlation between bacterial cells per ml and bacterial respiration for a number of lakes, estuaries and marine areas. We applied the summer value for bacterial abundance in Frisksjön to the respiration graph presented by /del Giorgio et al. 1997a/, and obtained the respiration value 9 µg C L^{-1} day^{-1}. To estimate the annual respiration we corrected for temperature measured in Frisksjön assuming a direct linear response of respiration to temperature and assuming that the summer respiration was valid for 20°C.

Respiration of ***benthic bacteria, zooplankton***, ***benthic fauna***, and ***fish*** was calculated using conversion factors from biomass (Table 5-7), together with the temperature variation over the year measured in Frisksjön, and assuming a direct linear response of respiration to temperature (temperature data from SICADA[14], October 2007).

5.3.5 Consumption

Forsmark

Consumption data used in the ecosystem carbon models are compiled in Table 5-6. In the model calculations it was assumed that consumption is equal to the sum of secondary production, respiration and egestion (unassimilated food/faeces). The biomass was considered to be constant on an annual basis, i.e. there are variations in biomass within the year but there is no increase or decrease in biomass between years. The sum of secondary production and egestion was here treated as one unit, excess. All functional groups of heterotrophic biota are assumed to consume their different food sources in proportion to the available biomass of the food sources.

The mixotrophic phytoplankton are assumed to achieve 2/3 of their carbon assimilation from consumption of bacteria and 1/3 from primary production /Jansson et al. 1999/. In primary production measurements in Eckarfjärden, primary production was measured on a community level and there was no distinction between autotrophic and mixotrophic primary production. In this report we have assumed the same proportion for primary production as for biomass of mixotrophic phytoplankton to total phytoplankton.

Bacterial consumption (both pelagic and benthic) was calculated as the sum of bacterial secondary production and bacterial respiration. Secondary production by bacterioplankton was measured in Eckarfjärden /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/ (see the section "Respiration" above). Secondary production by benthic bacteria was measured in Eckarfjärden during 2001 and 2002 /Blomqvist et al. 2002, Andersson et al. 2003, Andersson and Brunberg 2006a/. Mean annual benthic bacterial production was calculated from these measurements (39.5 g C m^{-3} y^{-1}, n=2 years, min 35.3, max 43.7 g C m^{-3} y^{-1}).

Consumption by zooplankton and benthic fauna was assumed to be 3 times respiration /Elmgren 1984/. For fish, consumption was assumed to be 1.74 times respiration according to the results of probabilistic modelling of ecosystem parameters by /Kumblad et al. 2006/.

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[14] SKBs database SICADA, access might be given on request.

Laxemar-Simpevarp

Consumption data used in the ecosystem carbon models are compiled in Table 5-5. In almost all cases, the assumptions made concerning consumption in Frisksjön are the same as those for the Forsmark lakes. The only exception is bacterial consumption which, due to lack of data on secondary bacterial production, was calculated from respiration, assuming a growth efficiency of 25%. For the other functional groups, consumption was calculated in the same way as for Forsmark.

5.4 Quantitative mass balances and ecosystem carbon models

The ecosystem model and mass balance approaches are two ways of describing the lake ecosystem. The mass balances describe the flows to and from lakes, whereas the ecosystem models describe the flows within the lakes. Both models can be used to estimate whether a lake is a net sink or source of carbon (i.e. a heterotrophic or autotrophic system). Thus, although the models mainly cover different aspects of the ecosystem, parts of the models can be compared with each other. The amount of site-specific data in the models is large, but the data have been sampled during a short time period, so one should be aware of the uncertainties of the absolute numbers presented in this chapter. The most important result is the general picture: the important in- and outflows to and from the lakes, the important flows and pools within the lakes, and whether the lakes sources or sinks of carbon (i.e. heterotrophic or autotrophic systems). The results of the ecosystem carbon models as well as the mass balances are presented for each lake in the following text, together with short comments on the agreement of the results obtained from the two models. The best estimates are presented in the text below whereas the ranges of the fluxes are presented in Appendix 12.

5.4.1 Lakes in Forsmark

Quantitative models for Eckarfjärden, Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket are described in this section. Eckarfjärden and Bolundsfjärden represent the larger lakes in the area and Gunnarsbo-Lillfjärden and Labboträsket represent the smaller ones.

Eckarfjärden

Eckarfjärden is one of the larger lakes in the Forsmark area. It is the deepest (maximum depth 2.1 m) and highest situated lake in the regional model area. Eckarfjärden is a clear-water lake surrounded by reed, with bottoms covered by the macroalgae *Chara sp.* and a thick microbial mat (Figure 5-4).

Mass balance

According to the mass balance for Eckarfjärden, the influx of carbon is dominated by the DIC and TOC inflow from the catchment (10,400 and 3,500 kg C y^{-1}, respectively). The atmospheric deposition of dissolved organic carbon (230 kg C y^{-1}) makes a minor contribution to the carbon influx to the lake. The major outflux of carbon is the downstream flow of DIC and TOC (6,800 and 5,700 kg C y^{-1}, respectively), followed by sediment accumulation (3,700 kg C y^{-1}), while birds feeding in the lake (300 kg C y^{-1}) are less important.

The flux of carbon dioxide across the lake-air interface is negative, indicating an uptake of about 900 kg C y^{-1} and a net autotrophic metabolism (Figure 5-5).

There is an imbalance in the mass balance in that outfluxes exceed influxes by c. 1,400 kg C y^{-1}. This is equivalent to 8% of the carbon outflux and 9% of the total carbon influx. There are large ranges in some of the flows, and the mass balance can be balanced by using other estimates within the ranges of flows.

***Figure 5-4.** Lake Eckarfjärden, one of the larger lakes in the Forsmark area. Eckarfjärden is a shallow oligotrophic hardwater lake surrounded by reed. Photo: Eva Andersson, April 2005.*

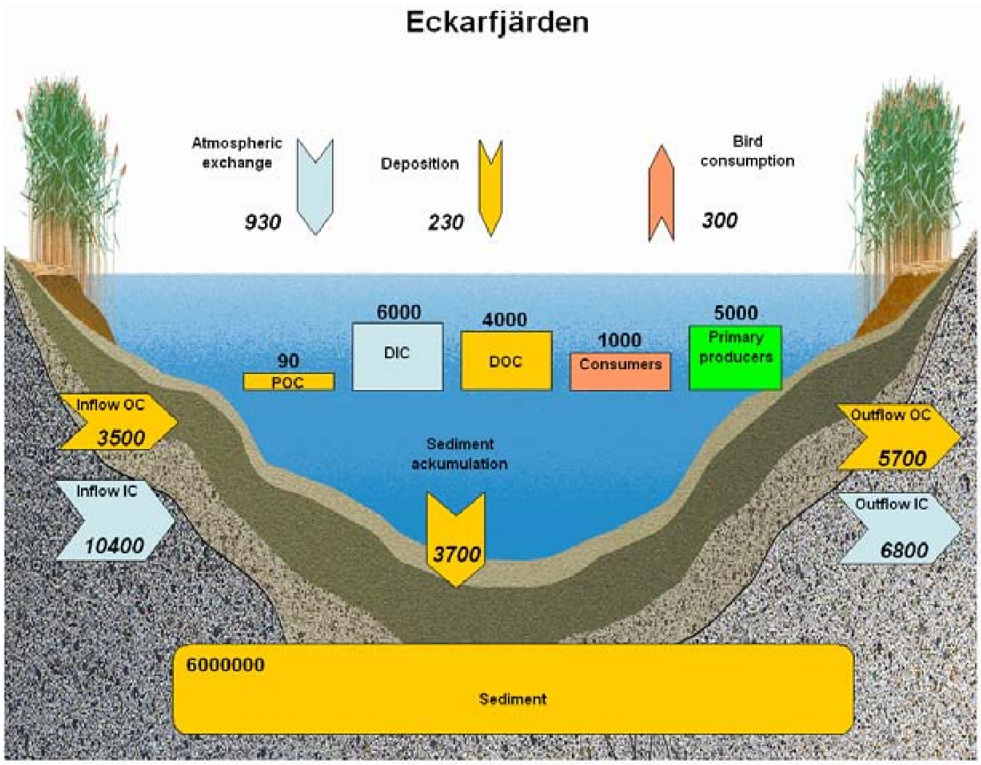

***Figure 5-5.** Carbon mass balance for Eckarfjärden, components in kg C, and fluxes in kg C y^{-1}.*

Ecosystem carbon model

Based on the conceptual ecosystem model, the annual mean *biomass* in Eckarfjärden is estimated to be 5,900 kg C and is concentrated in the littoral habitat (96% of total biomass is found in the littoral, Figure 5-6a, Table 5-13). Primary producers comprise most of the total mean biomass in the lake, and the dominant group is benthic primary producers (comprising 83% of the total biomass). Benthic bacteria contribute 12% of the total biomass, while each of the other functional groups comprises 3% or less of the total biomass.

According to the model, annual *primary production* is 30,600 kg C y^{-1} and is, like the biomass, concentrated in the littoral habitat where the benthic primary producers contribute 88% of total primary production (Figure 5-5, Table 5-13). Annual *respiration* is 21,100 kg C y^{-1} and thereby smaller than primary production. This indicates that the lake is a net autotrophic system with a positive net ecosystem production (NEP) of 9,500 kg C y^{-1}. In contrast to biomass and production, a large part of the respiration occurs in the pelagic habitat (58% of the total respiration). Benthic bacteria and bacterioplankton dominate respiration, together comprising 82% of the total respiration. Other important functional groups in terms of respiration are mixotrophic phytoplankton and fish, comprising 9 and 6% of the total respiration, respectively. The other functional groups make only small contributions to the total respiration.

With the food web structure and feeding rates assumed in the conceptual model, only about 7% of the carbon fixed through primary production was directly consumed by higher organisms. Instead, most carbon was consumed in the form of DOC and POC. Bacterioplankton and benthic bacteria, which are the two functional groups that consume most DOC and POC, comprise 77% of the total carbon consumption (Table 5-13). Mixotrophic phytoplankton comprised another 11% of the total carbon consumption in the lake, whereas fish, benthic fauna and zooplankton represented only a small fraction of the total carbon consumption. Many organisms are sustained by carbon from adjacent habitats, for example the pelagic habitat needs support from the littoral habitat. To sustain bacterioplankton, DOC produced by primary producers in the littoral needs to be used. To sustain mixotrophic phytoplankton, benthic bacteria from the top of the microbial mat in the littoral habitat need to be utilized. Fish are mainly composed of species/sizes feeding on benthic fauna from the littoral habitat. In turn, the pelagic habitat contributes POC to the littoral habitat. The largest carbon flow to the top predator fish goes from benthic primary producers via benthic fauna to fish (Figure 5-7).

On an annual basis, all organisms with the exception of benthic fauna show a carbon excess when grazing is subtracted from production/consumption. As the abundance of benthic fauna is similar from year to year, it is clear that the assumed feeding pressure on benthic fauna is somewhat overestimated by the model. Assuming a small change in the food choice of fish and that a larger share of the fish consumption consists of zooplankton, the benthic fauna will also show carbon excess.

Table 5-13. Total mean biomass (kg C) and annual metabolic rates (kg C y^{-1}) of functional groups in Eckarfjärden. Phytoplankton includes both autotrophic and mixotrophic species, so net primary production, heterotrophic respiration and consumption have been reported.

Functional group	Biomass		Net Prim. Prod.		Respiration		Consumption	
	kg C	%	kg C y^{-1}	%	kg C y^{-1}	%	kg C y^{-1}	%
Pelagic habitat	**239**	4	**3,670**	12	**12,220**	58	**18,411**	52
Phytoplankton	9	<1	3,670	12	1,900	9	3,800	11
Bacterioplankton	12	<1			8,876	42	11,800	33
Zooplankton	15	<1			235	1	719	2
Fish	203	3			1,209	6	2,092	6
Littoral habitat	**5,683**	96	**26,900**	88	**8,878**	42	**17,272**	48
B. primary producers	4,910	83	26,900	88				
B. bacteria	693	12			8,421	40	15,900	44
Benthic fauna	80	1			457	2	1,372	4
Total	**5,922**		**30,570**		**21,099**		**35,683**	

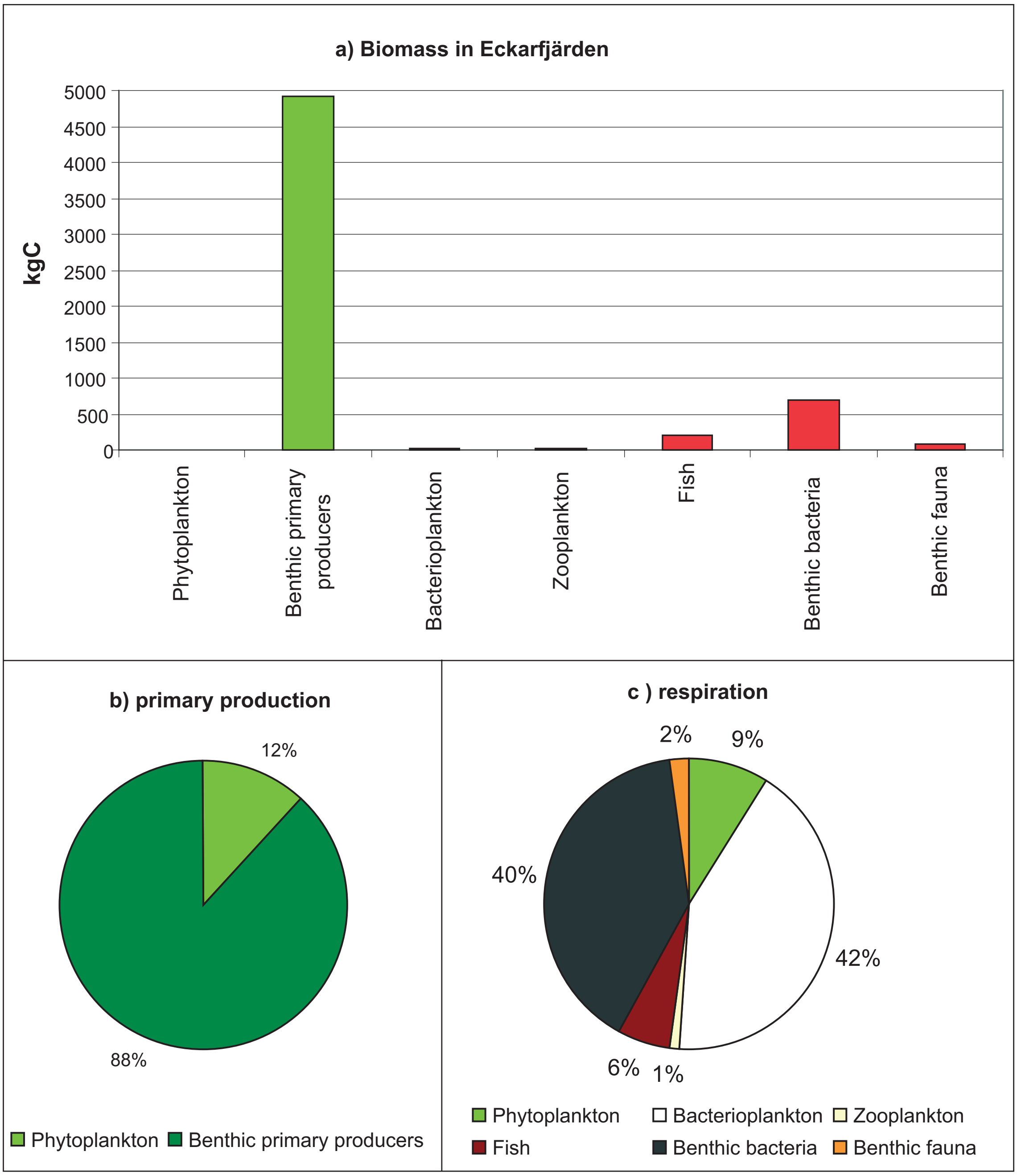

Figure 5-6. *Distribution of a) biomass, b) primary production and c) respiration among functional groups in the benthic and pelagic habitats in the ecosystem model for Eckarfjärden.*

The carbon excess will contribute to sediment accumulation in the lake, as well as to outflow through the outlet. Using the calculated values in the mass balance for carbon influx (influx via water and carbon deposition) and carbon outflux (outflux through outlet, sediment accumulation, and bird consumption), the ecosystem carbon model for Eckarfjärden has a shortage of c. 1,100 kg carbon. However, this mismatch is small compared with the flows of carbon in the model. For example it constitutes only 3 and 5% of total primary production and respiration, respectively.

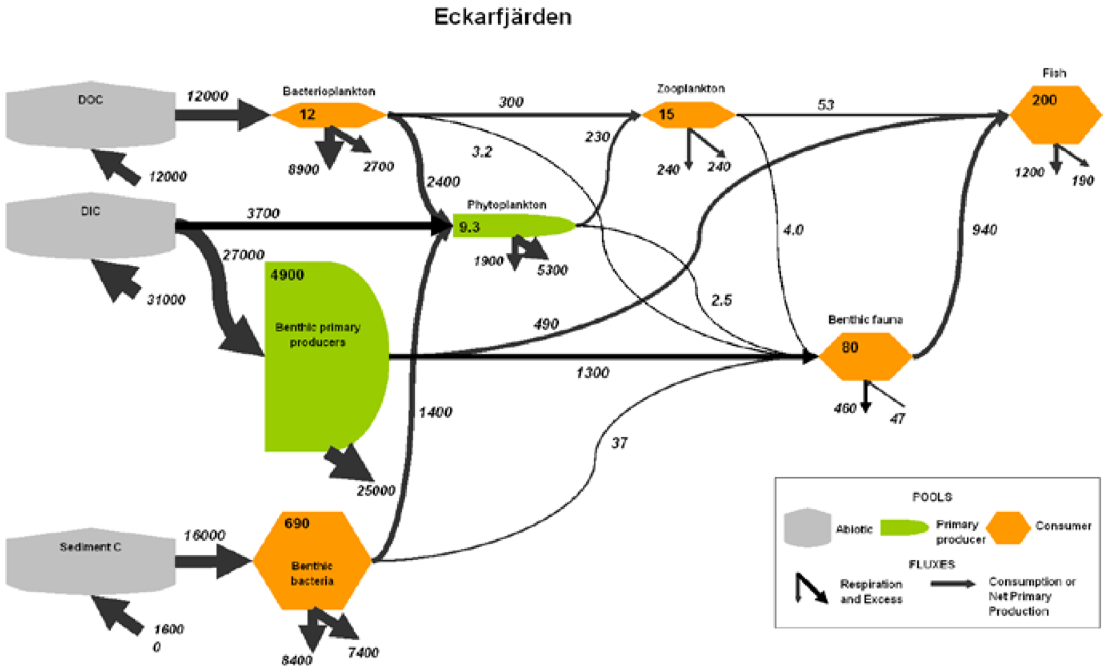

Figure 5-7. *Carbon flow (kg C y^{-1}) in the ecosystem model for Eckarfjärden. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.*

Bolundsfjärden

Bolundsfjärden is the largest lake in the Forsmark area, with an area about 3 times larger than Eckarfjärden (Figure 5-8). It is somewhat shallower than Eckarfjärden (maximum depth 1.8 m) and is situated near sea level (0.64 m.a.s.l.). Under extreme weather conditions, brackish water enters the lake from the sea. The water is therefore sometimes more brackish than what is normal for limnic conditions. Bolundsfjärden is a clear-water lake surrounded by reed and with bottoms covered by the macroalgae *Chara sp.* and a thick microbial mat.

Mass balance

According to the mass balance for Bolundsfjärden, the influx of carbon to the lake is dominated by the DIC and TOC inflow from the catchment (32,000 and 22,500 kg C y^{-1}, respectively) (Figure 5-9). Atmospheric deposition of dissolved organic carbon (500 kg C y^{-1}) makes only a small contribution to the carbon influx to the lake. The major outflux of carbon is the downstream flow of DIC and TOC (32,000 and 21,900 kg C y^{-1}, respectively), followed by carbon accumulation in the sediments (9,000 kg C y^{-1}), whereas the outflux by birds feeding in the lake (700 kg C y^{-1}) is of minor importance.

The flux of carbon dioxide across the lake-air interface is negative, indicating an uptake of about 2,800 kg C y^{-1} and a net autotrophic metabolism.

There is an imbalance in the mass balance: the outflux exceeds the influx by 5,400 kg C y^{-1}. This corresponds to 10 and 9% of the total carbon influx and outflux, respectively. The imbalance in the mass balance can therefore be considered small.

***Figure 5-8.** Lake Bolundsfjärden is the largest lake in the Forsmark area. The smaller lake at the front edge is Lake Graven.*

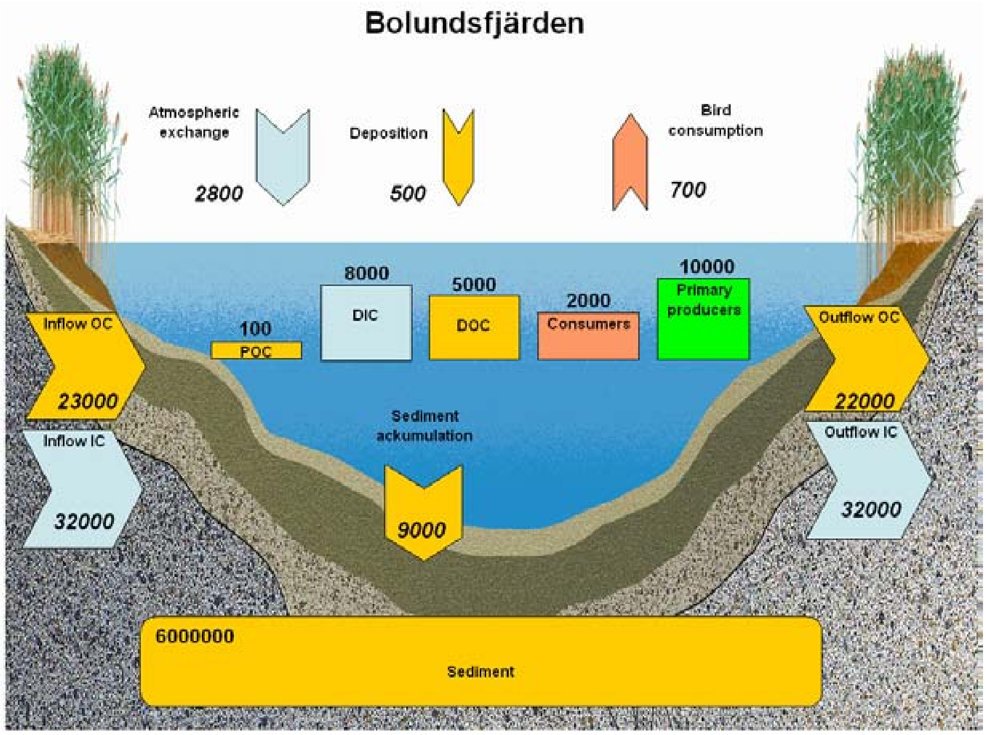

***Figure 5-9.** Carbon mass balance for Bolundsfjärden, components in kg C, and fluxes in kg C y^{-1}.*

Ecosystem carbon model

Based on the conceptual ecosystem model, the annual mean *biomass* in Bolundsfjärden is estimated to be 12,600 kg C and is concentrated in the littoral habitat (97% of the total biomass, Figure 5-10a, Table 5-14). Primary producers make up the major part of the total biomass in the lake, and the dominant functional group is benthic primary producers (comprising 84% of the total biomass). Benthic bacteria comprise 12% of the total biomass, while each of the other functional groups comprises 2% or less of total biomass.

According to the model, *primary production* is 63,700 kg C y^{-1} and it is concentrated in the littoral habitat, where benthic primary producers comprise 91% of the total primary production (Figure 5-10b, Table 5-14).

According to the model, annual *respiration* (37,000 kg C y^{-1}) is less than primary production. In contrast to primary production, a large part of the respiration occurs in the pelagic habitat (48%). The most important functional groups in terms of respiration are benthic bacteria (49%), followed by bacterioplankton (34%) and mixotrophic phytoplankton (8%, Figure 5-10c, Table 5-14).

With the food web structure and feeding rates assumed in the conceptual model, only about 8% of the carbon fixed through primary production is directly consumed by higher organisms. Instead, most carbon is consumed in the form of DOC and POC. Bacterioplankton and benthic bacteria, which are the two functional groups that consume most DOC and POC, comprise 79% of the total carbon consumption. Mixotrophic phytoplankton makes up another 9% of the total consumption, whereas fish, benthic fauna and zooplankton represent only a minor share of the total carbon consumption in the lake. Many organisms get part of their food supply from other habitats than the habitat where they live. For example, organisms in the pelagic habitat are dependent on carbon produced in the littoral habitat. To sustain bacterioplankton, DOC produced by primary producers in the littoral needs to be used. To sustain mixotrophic phytoplankton, benthic bacteria from the top of the microbial mat in the littoral habitat need to be utilized. Fish feed to a large extent on benthic fauna from the littoral habitat. In turn, the pelagic habitat contributes POC to the littoral habitat. The largest carbon flow to the top predator fish goes from benthic primary producers via benthic fauna to fish (Figure 5-11).

Table 5-14. Total mean biomass (kg C) and annual metabolic rates (kg C y^{-1}) of functional groups in Bolundsfjärden. Phytoplankton includes both autotrophic and mixotrophic species, so net primary production, heterotrophic respiration and consumption have been reported.

Functional group	Biomass		Net Prim. Prod.		Respiration		Consumption	
	kg C	%	kg C y^{-1}	%	kg C y^{-1}	%	kg C y^{-1}	%
Pelagic habitat	**348**	3	**6,034**	9	**17,628**	48	**26,669**	41
Phytoplankton	14	<1	6,034	9	2,825	8	5,650	9
Bacterioplankton	17	<1			12,699	34	16,932	26
Zooplankton	21	<1			337	1	1,029	2
Fish	294	2			1,768	5	3,059	5
Littoral habitat	**12,256**	97	**57,698**	91	**19,395**	52	**38,007**	59
B. primary producers	10,540	84	57,698	91				
B. bacteria	1,487	12			18,072	49	34,037	53
Benthic fauna	229	2			1,323	4	3,970	6
Total	12,604		63,732		37,023		64,676	

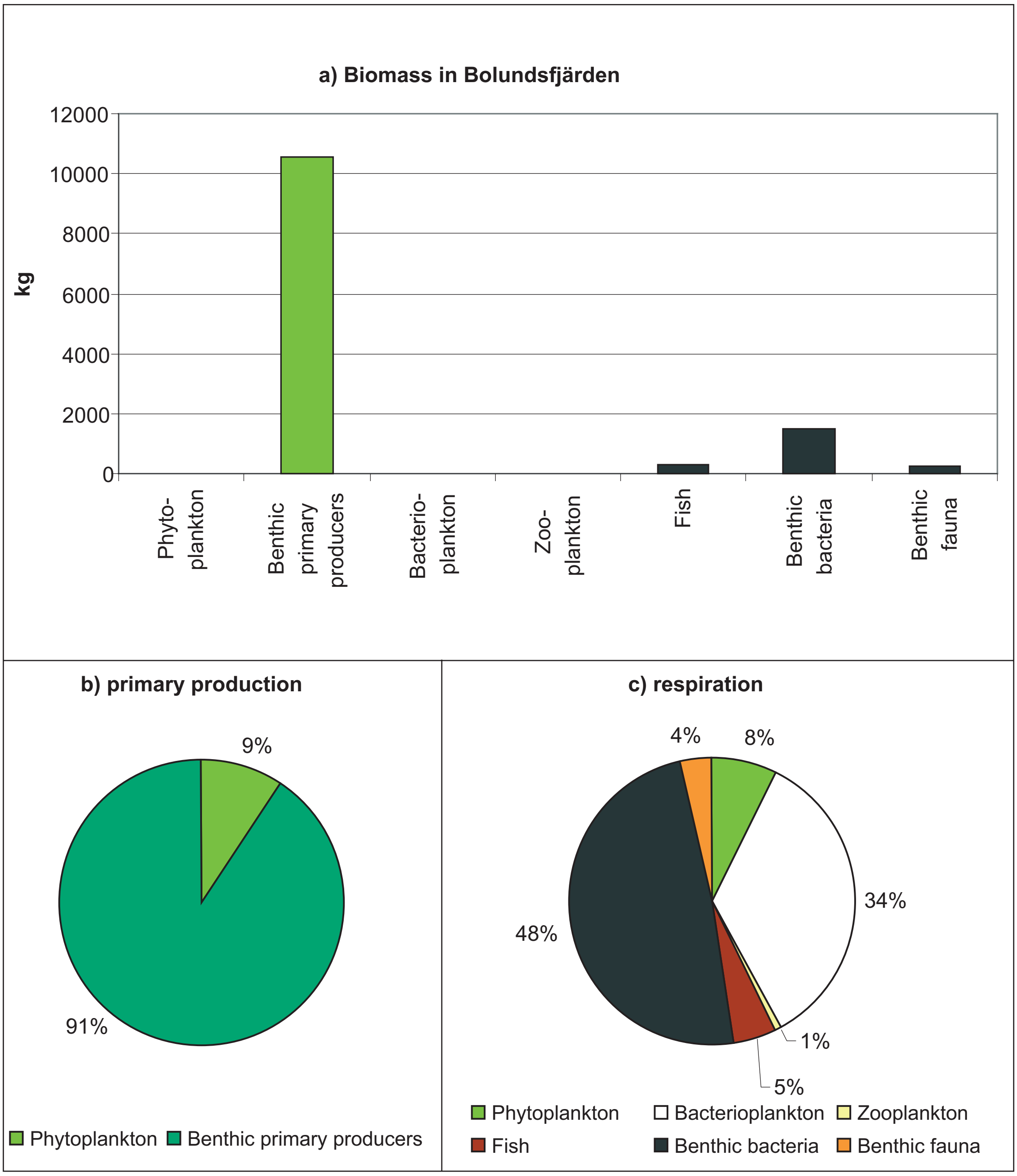

Figure 5-10. *Distribution of a) biomass, b) primary production and c) respiration among functional groups in the benthic and pelagic habitats in the ecosystem model of Bolundsfjärden.*

On an annual basis, all organisms show a carbon excess when grazing is subtracted from production/consumption. The carbon excess will contribute to sediment accumulation in the lake, as well as to outflow through the outlet. Using the calculated values in the mass balance for carbon influx (influx via water and carbon deposition) and carbon outflux (outflux through outlet, sediment accumulation, and bird consumption), the ecosystem carbon model for Bolundsfjärden still has an excess of c. 18,100 kg C y^{-1}. This excess is larger for Bolundsfjärden than for e.g. Eckarfjärden, and it is also relatively large compared with the total primary production (28%) and respiration (29%) in Bolundsfjärden.

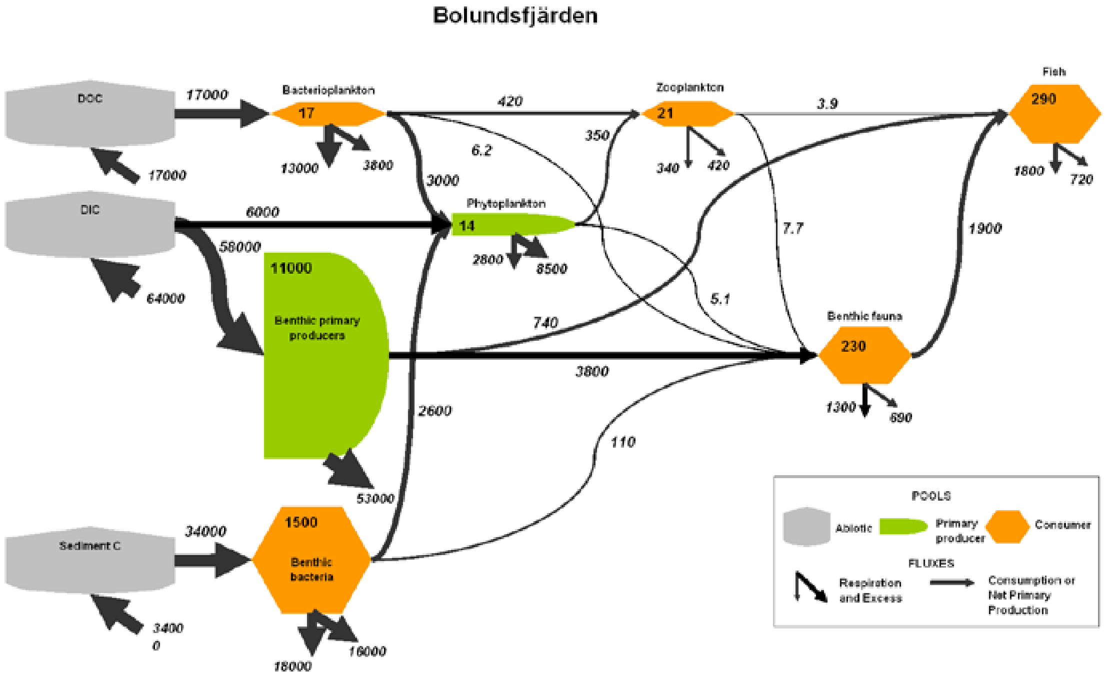

***Figure 5-11.** Carbon flow (kg C y^{-1}) in the ecosystem model for Bolundsfjärden. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.*

Gunnarsbo-Lillfjärden

Gunnarsbo-Lillfjärden (south basin) is one of the smaller lakes in the area (0.03 km^2), although its maximum depth is relatively deep, 2.2 m. The lake is situated 1.6 m.a.s.l. Gunnarsbo-Lillfjärden is a clear-water lake surrounded by reed and with bottoms covered by the macroalgae *Chara sp*. and a thick microbial mat. A high proportion of fish species resistant to low oxygen conditions indicates that low oxygen conditions prevail in the winter.

Mass balance

According to the mass balance for Gunnarsbo-Lillfjärden, the influx of carbon to the lake is strongly dominated by DIC inflow via water (26,700 kg C y^{-1}, c. 67% of total influx) (Figure 5-12). The second largest influx is TOC inflow via water (13,100 kg C y^{-1}). In comparison, the carbon influx by atmospheric deposition (22 kg C y^{-1}) is negligible. The major outflux of carbon is the downstream flow of DIC (26,200 kg C y^{-1}, c. 64% of total outflow) followed by TOC outflow via water (13,100 kg C y^{-1}), while carbon accumulation in the sediments (400 kg C y^{-1}) and birds feeding on fish (30 kg C y^{-1}) are of less magnitude.

The flux of carbon dioxide across the lake-air interface is positive, indicating an outflow of about 1,400 kg C y^{-1} and a net heterotrophic metabolism.

There is a small imbalance in the mass balance in that outflux exceeds influx by 3,200 kg C y^{-1}. This corresponds to 2% of the total carbon outflux and 2% of the total carbon influx; hence, the imbalance can be considered small.

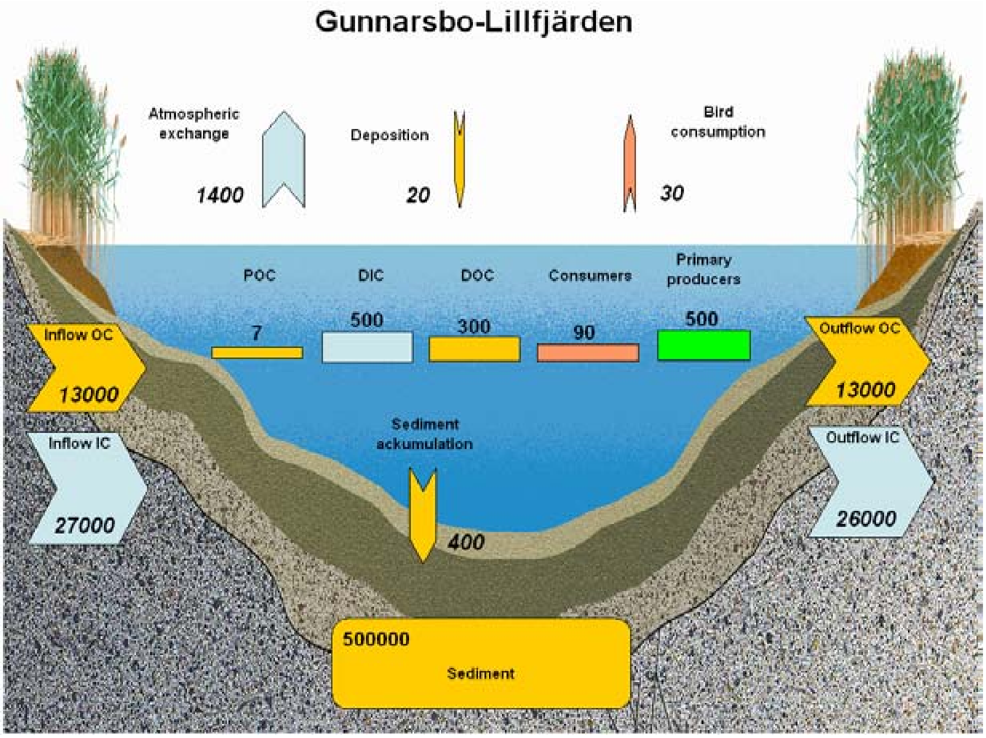

Figure 5-12. Carbon mass balance for Gunnarsbo-Lillfjärden, components in kg C, and fluxes in kg C y^{-1}.

Ecosystem carbon model

Based on the conceptual ecosystem model, the annual mean *biomass* in Gunnarsbo-Lillfjärden is estimated to be 560 kg C and is concentrated in the littoral habitat. Only 4% of the biomass occurs in the pelagic habitat (Figure 5-13a). Benthic primary producers comprise 83% of the total biomass and benthic bacteria comprise 12%. The other functional groups comprise 3% or less of the total mean biomass. Benthic primary producers constitute 92% of the total *primary production* (2,800 kg C y^{-1}) (Figure 5-13b, Table 5-15).

According to the model, *respiration* (1,800 kg C y^{-1}) is smaller than primary production, indicating net autotrophic conditions in the lake. The respiration is almost evenly distributed between the pelagic and littoral habitats, with 53% of the respiration occurring in the pelagic habitat. The most important functional groups in terms of respiration are benthic bacteria and bacterioplankton, comprising 45 and 39% of total respiration, respectively (Figure 5-13c, Table 5-15).

Table 5-15. Total mean biomass (kg C) and annual metabolic rates (kg C y^{-1}) of functional groups in Gunnarsbo-Lillfjärden. Phytoplankton includes both autotrophic and mixotrophic species, so net primary production, heterotrophic respiration and consumption have been reported.

Functional group	Biomass		Net Prim. Prod.		Respiration		Consumption	
	kg C	%	kg C y^{-1}	%	kg C y^{-1}	%	kg C y^{-1}	%
Pelagic habitat								
Phytoplankton	1	0.1	232	8	120	7	240	8
Bacterioplankton	1	0.2			696	39	928	30
Zooplankton	1	0.2			18	1	56	2
Fish	19	3			112	6	194	6
Littoral habitat								
B. primary producers	467	83	2,557	92				
B. bacteria	66	12			801	45	1,508	49
Benthic fauna	8	1			43	2	130	4
Total	**562**		**2,789**		**1,791**		**3,058**	

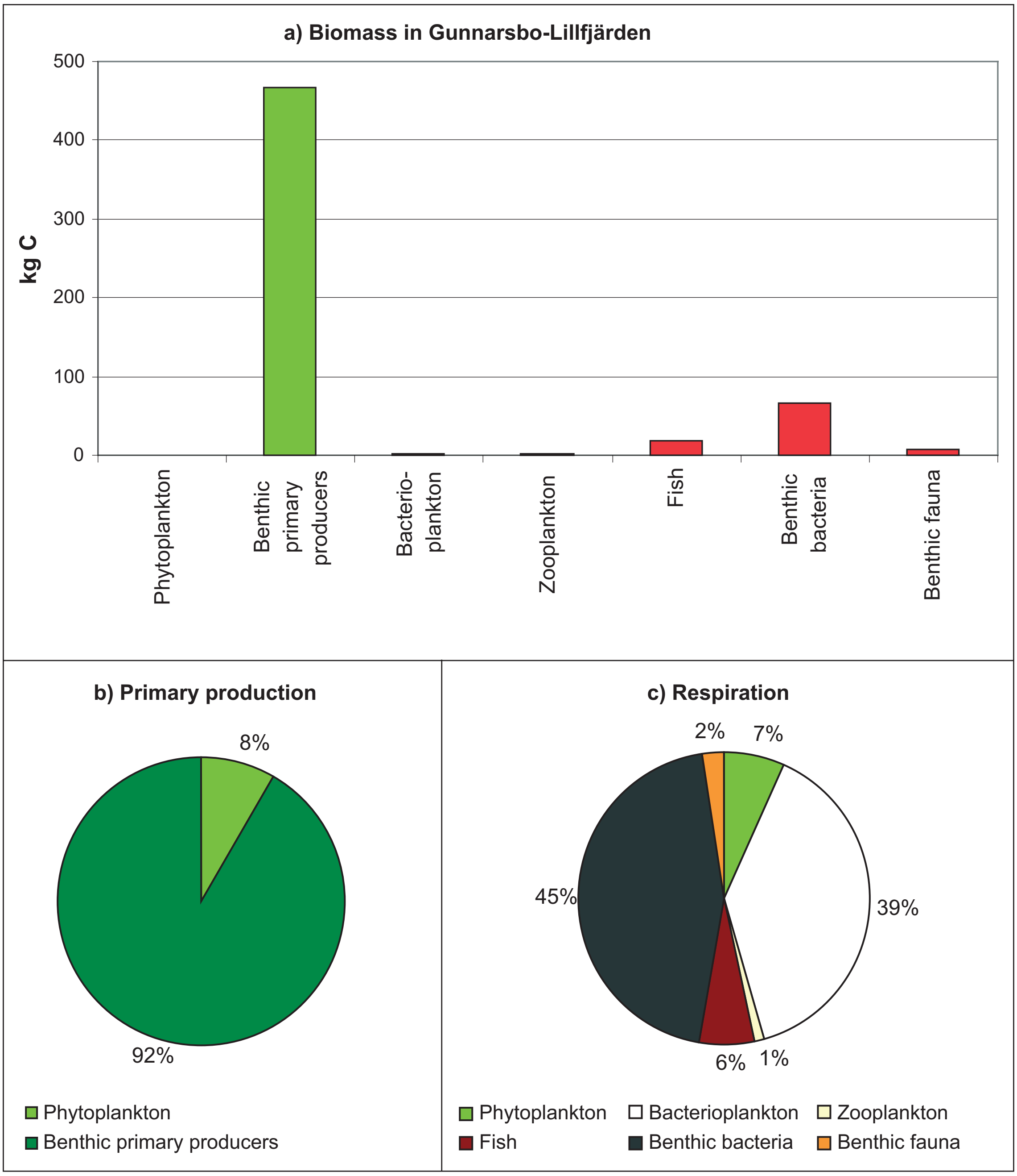

***Figure 5-13.** Distribution of a) biomass, b) primary production and c) respiration among functional groups in the benthic and pelagic habitats in the ecosystem model of Gunnarsbo-Lillfjärden.*

With the food web structure and feeding rates assumed in the conceptual model, only about 7% of the carbon fixed through primary production is consumed by higher organisms. Instead, most carbon is transferred via the pools of DOC and POC. Bacterioplankton and benthic bacteria, which are the two functional groups that consume most DOC and POC, comprise 80% of the total carbon consumption (Table 5-15). Mixotrophic phytoplankton comprises 8% of the total consumption and fish comprises 6% of the total consumption. All other functional groups comprise 4% or less of the total consumption. Many organisms feed from adjacent habitats, for example fish feed to a large extent on benthic fauna from the littoral habitat. In turn, the pelagic habitat contributes POC to the littoral habitat. The largest carbon flow to the top predator fish goes from benthic primary producers via benthic fauna to fish (Figure 5-14).

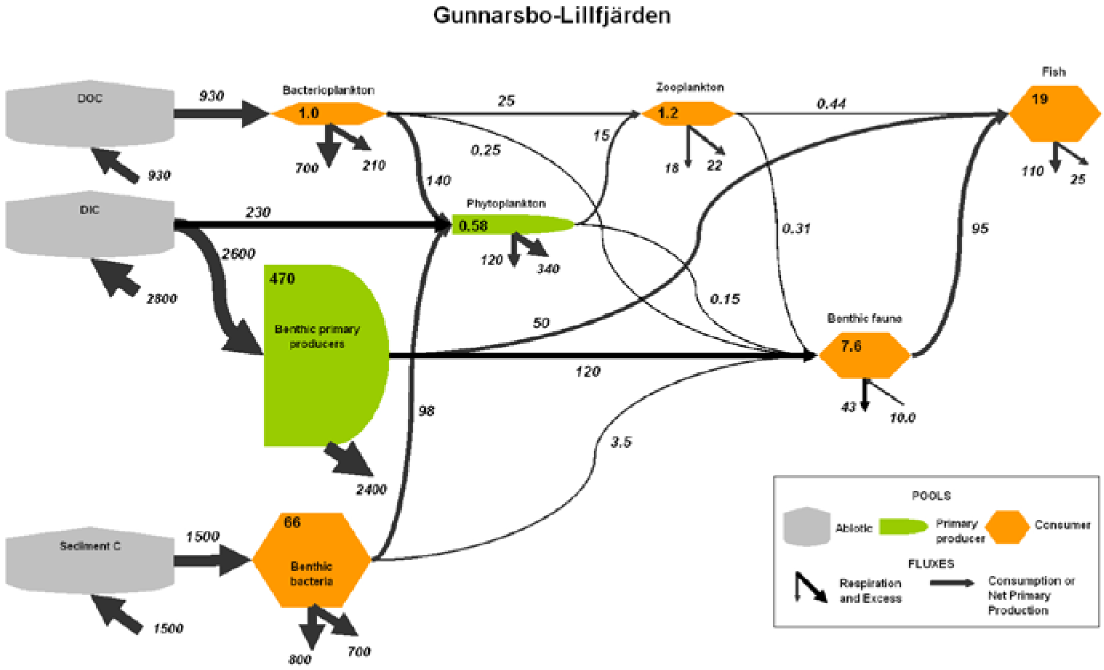

Figure 5-14. *Carbon flow (kg C y^{-1}) in the ecosystem model for Gunnarsbo-Lillfjärden. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.*

On an annual basis, all organisms with the exception of benthic fauna show a carbon excess when grazing is subtracted from production/consumption. As the abundance of benthic fauna is similar from year to year, it is clear that the assumed feeding pressure on benthic fauna is somewhat overestimated by the model. Assuming a small change in the food choice of fish and that a larger share of the fish consumption consists of zooplankton, the benthic fauna will also show carbon excess. The carbon excess will contribute to the sediment accumulation in the lake as well as outflow through the outlet or to the atmosphere. Using the calculated values in the mass balance for carbon influx (influx via water and deposition directly on lake surface) and carbon outflux (outflow through outlet, sediment accumulation, and bird consumption), the ecosystem carbon model for Gunnarsbo-Lillfjärden still shows an excess of c. 2,600 kg C y^{-1}. Compared with total primary production and respiration, this excess is large (92 and 143%, respectively). Compared with the inflow and outflow via inlet and outlet, on the other hand, the excess is relatively small (6 and 7% of inflow and outflow via water, respectively). Thus, the models are very sensitive to the fluxes to and from the lake, whereas the in-lake processes have a minor impact on the result.

Labboträsket

Labboträsket is one of the smaller lakes in the Forsmark area, with an area about 10% of the area of Bolundsfjärden. It is much shallower than the two larger lakes: maximum depth is 1.1 m. Labboträsket is situated 3.56 m.a.s.l. Labboträsket is a clear-water lake surrounded by reed and with bottoms covered by the macroalgae *Chara sp*. In contrast to the three Forsmark lakes described above, Labboträsket lacks a microbial mat. Long periods with low oxygen conditions occur in the winter.

Mass balance

According to the mass balance for Labboträsket, the influx of carbon to the lake is dominated by the DIC and TOC from the catchment (19,200 and 9,200 kg C y^{-1}, respectively) (Figure 5-15). By comparison, the carbon influx by atmospheric deposition (3 kg C y^{-1}) is negligible. The major outflux of carbon is the downstream flow of DIC and TOC (21,000 and 9,500 kg C y^{-1}, respectively), while carbon accumulation in the sediments (45 kg C y^{-1}) and birds feeding on fish (4 kg C y^{-1}) are of less magnitude.

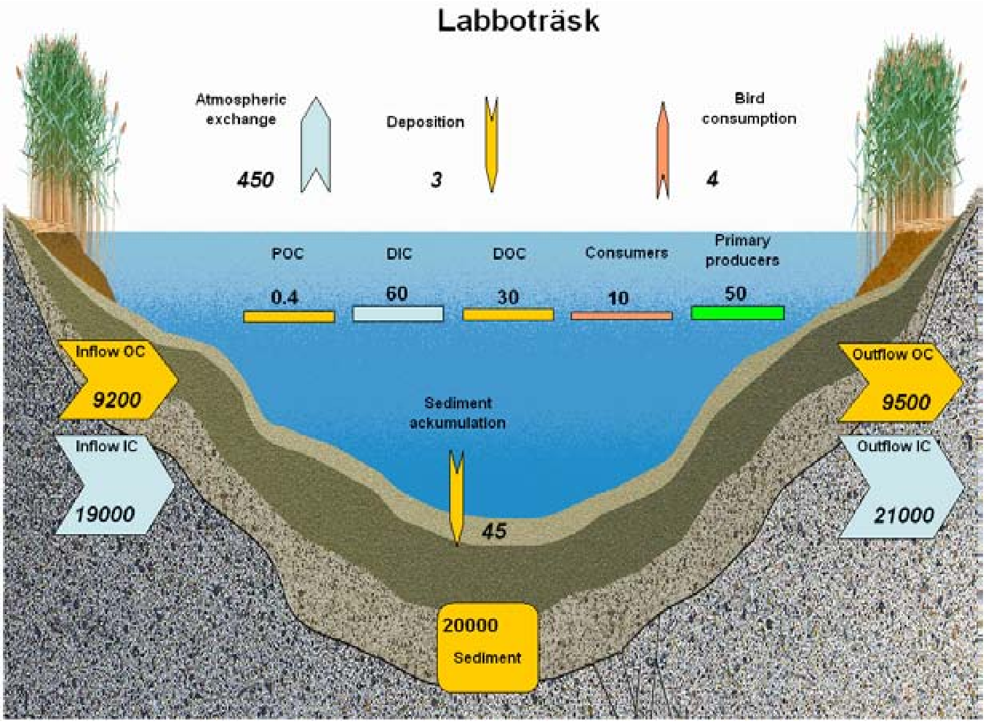

__Figure 5-15.__ Carbon mass balance for Labboträsket (kg C y^{-1}).

The flux of carbon dioxide across the lake-air interface is positive, indicating an outflux of about 400 kg C y^{-1} and a net heterotrophic metabolism.

There is a small imbalance in the mass balance in that outflux exceeds influx by 2,600 kg C y^{-1}. This corresponds to 8% of the total carbon outflux and 9% of the total carbon influx; hence, the imbalance can be considered small.

Ecosystem carbon model

Based on the conceptual ecosystem model, the annual mean *biomass* in Labboträsket is estimated to be 60 kg C and is concentrated in the littoral habitat. Only 3% of the biomass occurs in the pelagic habitat (Figure 5-16a). Benthic primary producers comprise 82% of the total biomass and benthic bacteria comprise 14%. The other functional groups constitute 2% or less of the total mean biomass. Benthic primary producers comprise 91% of the total *primary production* of 209 kg C y^{-1} (Figure 5-16b, Table 5-16).

According to the model, *respiration* (193 kg C y^{-1}) is similar in magnitude to primary production. The respiration is almost evenly distributed between the pelagic and littoral habitats, with 46% occurring in the pelagic habitat. The most important functional groups in terms of respiration are benthic bacteria and bacterioplankton, comprising 51 and 36% of total respiration, respectively (Figure 5-16c, Table 5-16).

With the food web structure and feeding rates assumed in the conceptual model, only about 10% of the carbon fixed through primary production is consumed by higher organisms. Instead, most carbon is transferred via the pools of DOC and POC. Bacterioplankton and benthic bacteria, which are the two functional groups that consume most DOC and POC, comprise 84% of the total carbon consumption (Table 5-16). All other functional groups comprise 6% or less of the total consumption. Many organisms feed from adjacent habitats, e.g. fish consist to a large extent of individuals feeding on benthic fauna from the littoral habitat. In turn, the pelagic habitat contributes POC to the littoral habitat. The largest carbon flow to the top predator fish goes from benthic primary producers via benthic fauna to fish (Figure 5-17).

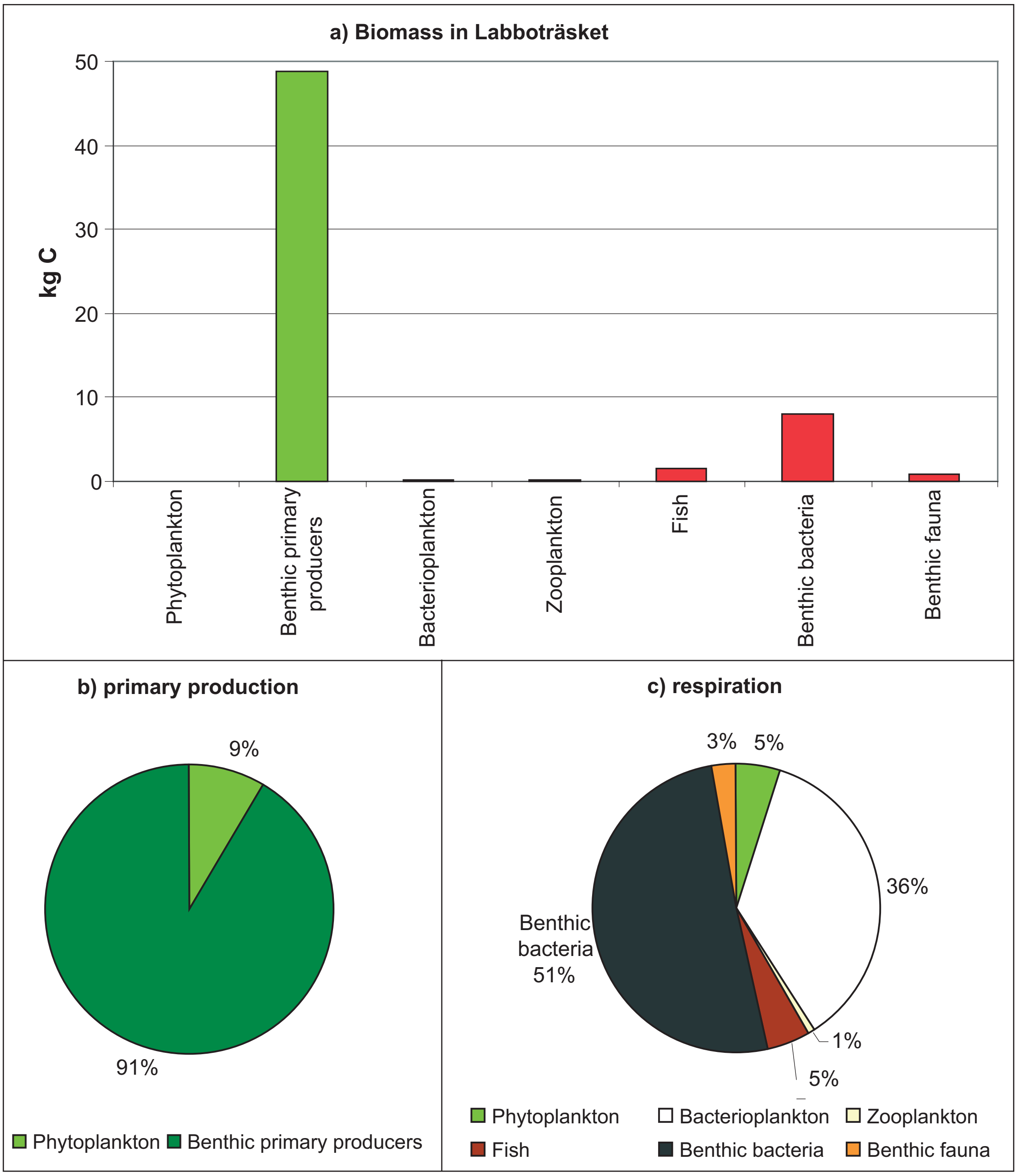

Figure 5-16. *Distribution of a) biomass, b) primary production and c) respiration among functional groups in the benthic and pelagic habitats in the ecosystem model of Labboträsket.*

On an annual basis, all organisms show a carbon excess when grazing is subtracted from production/consumption. The carbon excess will contribute to the sediment accumulation in the lake as well as outflow through the outlet or to the atmosphere. Using the calculated values in the mass balance for carbon influx (influx via water and carbon deposition) and carbon outflux (outflux via water, sediment accumulation, and bird consumption), the ecosystem carbon model for Labboträsket has a deficit of c. 2,100 kg C y^{-1}. Compared with total primary production and respiration, this deficit is very large (1,000% and 1,100%, respectively). Compared with the inflow and outflow via inlet and outlet, on the other hand, the shortage is small, only 8 and 7%, respectively. This illustrates that the lake model is very sensitive to the flows to and from the lake, whereas the in-lake processes have a minor impact on the main result.

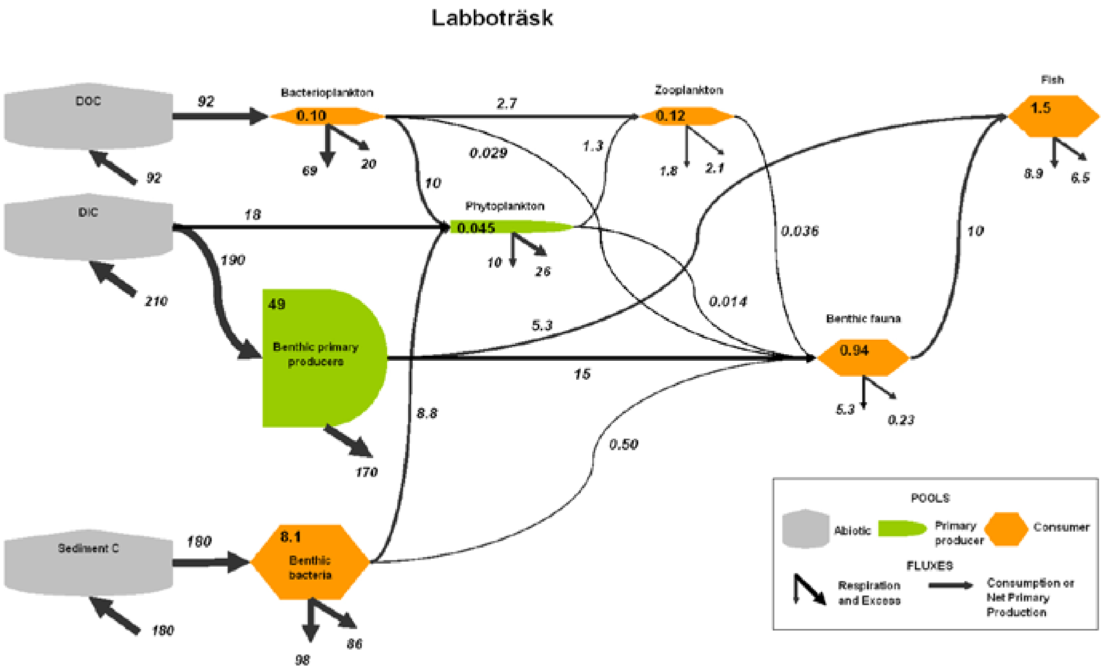

Figure 5-17. *Carbon flow (kg C y^{-1}) in the ecosystem model for Labboträsket. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.*

Table 5-16. Total mean biomass (kg C) and annual metabolic rates (kg C y^{-1}) of functional groups in Labboträsket. Phytoplankton includes both autotrophic and mixotrophic species, so net primary production, heterotrophic respiration and consumption have been reported.

Functional group	Biomass		Net Prim. Prod.		Respiration		Consumption	
	kg C	%	kg C y^{-1}	%	kg C y^{-1}	%	kg C y^{-1}	%
Pelagic habitat	**2**	3	**18**	9	**89**	46	**132**	40
Phytoplankton	<1	<1	18	9	10	5	19	6
Bacterioplankton	<1	<1			69	36	92	28
Zooplankton	<1	<1			2	1	6	2
Fish	1.5	3			9	5	15	5
Littoral habitat	**58**	97	**190**	91	**104**	54	**206**	60
B. primary producers	49	82	190	91				
B. bacteria	8	14			98	51	190	56
Benthic fauna	1	2			5	3	16	5
Total	**60**		**208**		**193**		**338**	

5.4.2 Lakes in Laxemar-Simpevarp

Frisksjön

Frisksjön is shallow and of medium size compared to other lakes in the region. It is situated 1.37 m.a.s.l. and is humic-rich with strongly coloured water (Figure 5-18).

Mass balance

According to the mass balance, the largest influx of carbon to Frisksjön is the inflow of TOC via water (8,300 kg C y^{-1}, Figure 5-19). The most important carbon outflux from Frisksjön is sediment accumulation (8,000 kg C y^{-1}). Other important outfluxes are the emission of carbon dioxide to the atmosphere (4,500 kg C y^{-1}), followed by the downstream outflow of TOC (4,300 kg C y^{-1}). Other carbon fluxes, such as DIC inflow and outflow via water, atmospheric wet deposition and bird consumption in the lake, are of minor importance.

Figure 5-18. *Frisksjön in Laxemar-Simpevarp.*

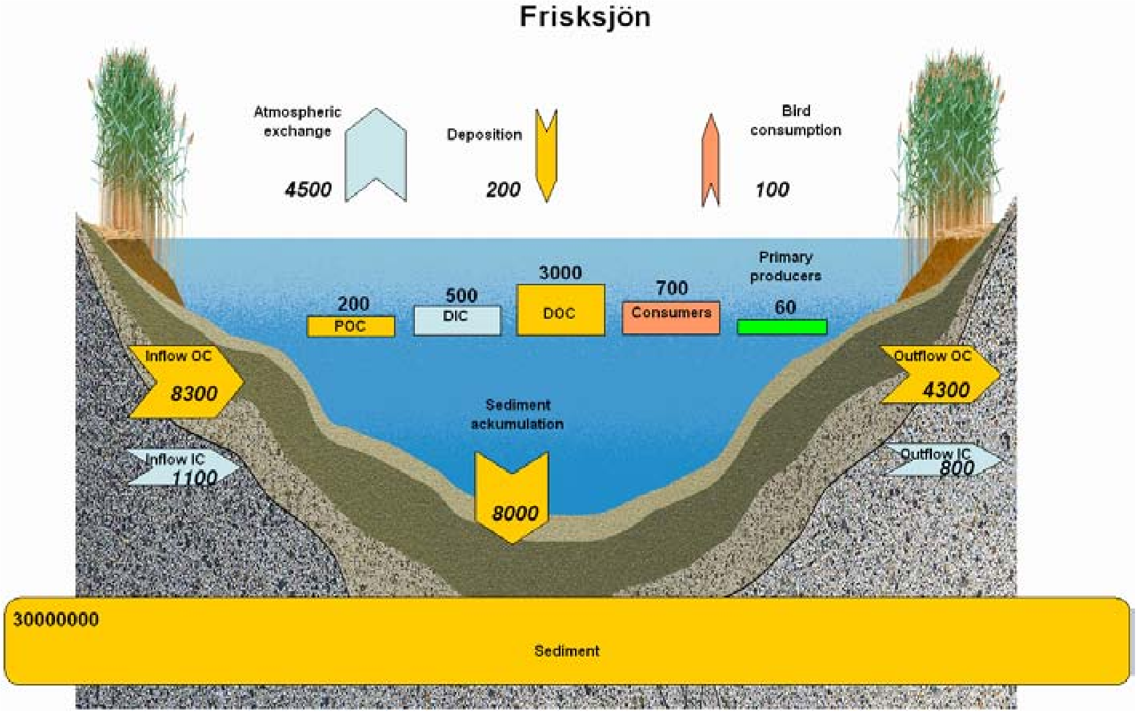

Figure 5-19. *Carbon mass balance for Frisksjön (kg C y^{-1}).*

There is a positive flux of carbon dioxide across the lake-air interface of 4,500 kg C y^{-1}, indicating a net heterotrophic metabolism. This is in agreement with the results of the carbon ecosystem model of Frisksjön, which show much higher respiration than primary production.

The mass balance is heavily imbalanced with 8,100 kg C y^{-1} lower influx than outflux of carbon. This corresponds to 85% of total carbon influxes or 46% of total carbon outfluxes. There is a large uncertainty in some of the fluxes, especially the larger fluxes: TOC inflow, CO_2 emission and sediment accumulation. If values in the higher range of TOC inflow from the catchment and values in the lower range of sediment accumulation and CO_2 emission are used, the mass balance will instead indicate higher influx than outflux of carbon. Thus, the wide span in estimates of different parameters leads to uncertainties in the mass balance, and the calculated flows should be seen as indicators of magnitude rather than absolute numbers.

Ecosystem carbon model

Based on the conceptual ecosystem model, the annual mean *biomass* in Frisksjön is estimated to be 750 kg C and the biomass is concentrated in the littoral and profundal habitat. Benthic bacteria is the dominant functional group (73% of total biomass), followed by phytoplankton, fish and benthic fauna (7–8% each of total biomass), while the other functional groups each contributed 3% or less to the total biomass (Figure 5-20a, Table 5-17).

According to the model, annual *primary production* is 4,300 kg C y^{-1} and is totally dominated by phytoplankton production. Benthic primary producers accounted for less than 1% of primary production (Table 5-17). Annual *respiration* is 12,600 kg C y^{-1} and is thus much higher than primary production, indicating a negative net ecosystem production (NEP). Despite the low biomass in the pelagic habitat (20% of total biomass), a large share of total respiration occurs there (46% of total respiration). Benthic bacteria contribute most to total respiration (52%) followed by bacterioplankton (26%) and mixotrophic phytoplankton (12%) (Figure 5-20b). All other functional groups each contribute 5% or less to total respiration.

With the food web structure and feeding rates assumed in the conceptual model, a relatively large portion (c. 34%) of the carbon fixed through primary production is directly *consumed* by higher organisms. Thus, any radionuclides incorporated into the food web through primary production may be transported upwards in the food chain. The rest of the primary produced carbon is incorporated into the DOC and POC pools. Bacterioplankton and benthic bacteria, the two functional groups that consume most DOC and POC, comprise 67% of the total carbon consumption in the lake (Figure 5-20c, Table 5-17). DOC and POC consumption by bacteria is larger than primary production, which means the lake is dependent on allochtonous carbon entering the lake from the catchment.

Table 5-17. Total mean biomass (kg C) and annual metabolic rates (kg C y^{-1}) of functional groups in Frisksjön. Phytoplankton includes both autotrophic and mixotrophic species and, hence, net primary production, heterotrophic respiration and consumption has been reported.

Functional group	Biomass		Net Prim. Prod.		Respiration		Consumption	
	kg C	%	kg C y^{-1}	%	kg C y^{-1}	%	kg C y^{-1}	%
Pelagic habitat	**147**	20	**4,291**	100	**5,744**	46	**9,839**	51
Phytoplankton	57	8	4,291	100	1,553	12	3,105	16
Bacterioplankton	5	1			3,233	26	4,310	22
Zooplankton	23	3			603	5	1,809	9
Fish	62	8			355	3	615	3
Littoral and profundal	**602**	80	**1**	0.03	**6,846**	54	**9,641**	49
B. primary producers	1	0.2	1	0.03				
B. bacteria	547	73			6,539	52	8,718	45
Benthic fauna	53	7			308	2	923	5
Total	**749**		**4,292**		**12,590**		**19,480**	

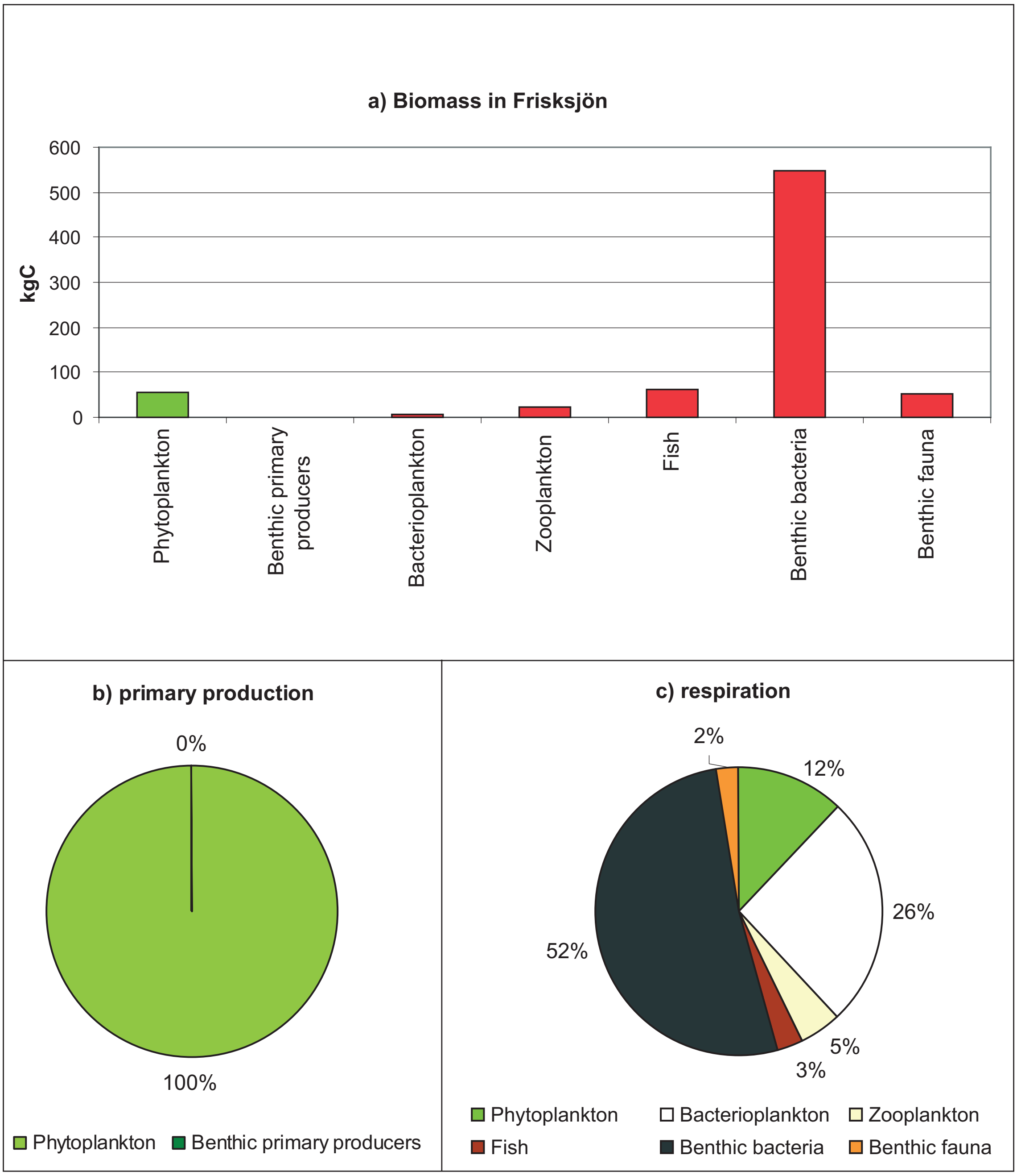

Figure 5-20. *Distribution of a) biomass, b) respiration and c) consumption among functional groups in the benthic and pelagic habitats in the ecosystem model of Frisksjön.*

Carbon is transported to the top predator fish mainly through benthic bacteria via benthic fauna to fish (Figure 5-21). When grazing is subtracted from production/consumption for the different functional groups on an annual basis, most groups show a carbon excess. The exceptions are fish, bacterioplankton and macrophytes which all show a small carbon deficit. Obviously, these functional groups will not go extinct but some assumptions in the model may be inaccurate. For example, if the food choice of carnivorous fish is altered by assuming more grazing of zooplankton and benthic fauna, fish will also show carbon excess.

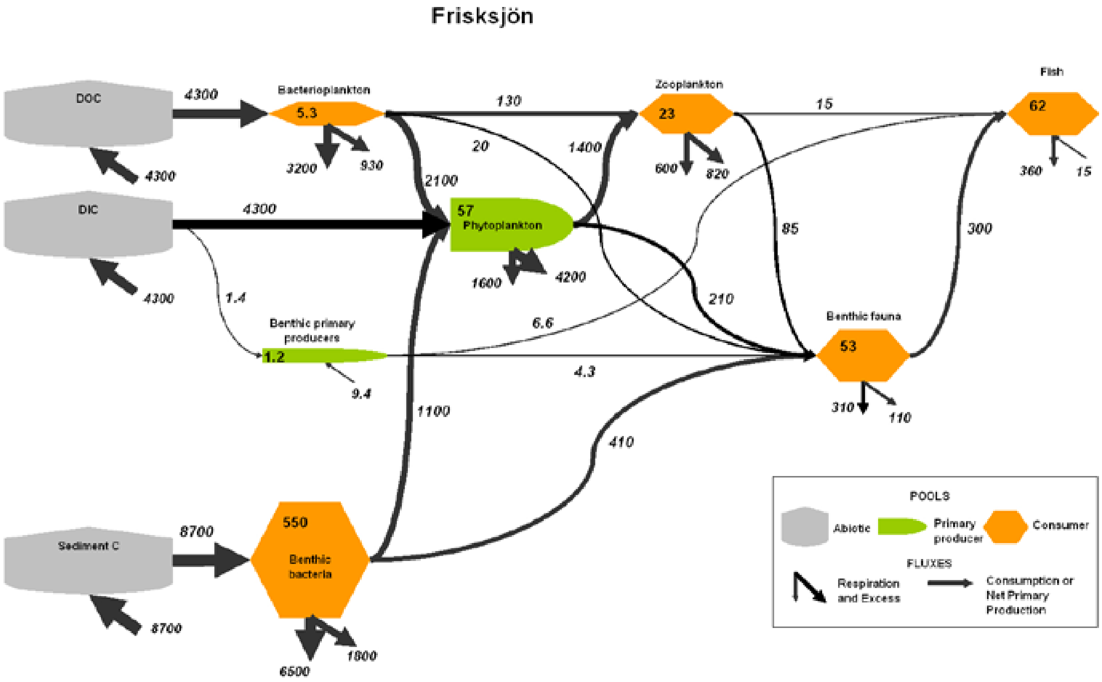

Figure 5-21. *Carbon flow (kg C y^{-1}) in the ecosystem model for Frisksjön. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.*

Theoretically, on an annual basis, the result of subtracting grazing from production/consumption for all functional groups should give rise to a carbon excess. The carbon excess will contribute to the sediment accumulation in the lake, as well as to outflow through the outlet or to the atmosphere. When the calculated values are included in the mass balance for carbon influx (influx via water and carbon deposition) and carbon outflux (outflux via water, sediment accumulation, and bird consumption), the ecosystem carbon model for Frisksjön indicates a large deficit of c. 12,000 kg C y^{-1}. This deficit is mainly caused by the large imbalance in the mass balance and is not a measure of the robustness of the ecosystem carbon model.

5.5 Conclusions from the carbon models

5.5.1 Forsmark

In the larger lakes Eckarfjärden and Bolundsfjärden in Forsmark, the annual flows to and from the lakes are small compared to the in-lake processes, indicating that the lakes may be important sites for biogeochemical processing of carbon in the landscape (Table 5-18). Due to the great demand for inorganic carbon by primary producers and the demand for organic carbon by bacteria, there is a high probability that carbon entering the lakes will be incorporated into the food web. In the smaller lakes Labboträsket and Gunnarsbo-Lillfjärden, on the other hand, the biological processes within the lake are small compared with carbon flowing to and from the lake via inlets and outlet. For example, in Labboträsket the carbon incorporated into biota via primary production is, on an annual basis, only 2% of the flow of organic carbon via the inlet and outlet (Table 5-18). However, this may not be the case for all small lakes in the area, but the relationship between fluxes to and from the lake, and the internal processes within the lake are also affected by the relationship between lake volume and catchment area. Both Labboträsket and Gunnarsbo-Lillfjärden have relatively large carbon inflows via water, but many other small lakes in the area have more moderate influxes of carbon via water. For these lakes, internal processes may be of similar size as the fluxes to and from the lakes.

Table 5-18. Carbon flows to/from lakes compared with biotic processes and pools within the lakes for Eckarfjärden, Bolundsfjärden and Labboträsk in the Forsmark area and for Frisksjön in the Laxemar-Simpevarp area.

Flows to/from the ecosystem	**Eckarfjärden**	**Bolundsfjärden**	**Gunnarsbo-Lillfjärden**	**Labboträsket**	**Frisksjön**
	kg (% of influxes/ outfluxes)	**kg (% of influxes/ outfluxes)**	**kg (% of influxes/ outfluxes)**	**kg (% of influxes/ outfluxes)**	**kg (% of influxes/ outfluxes)**
Inflow via inlet	+3,500 (+41)	+23,000 (+39)	13,100 (+33)	+9,200 (+32)	+8,300 (+87)
Organic carbon	+10,400 (+49)	+32,000 (+55)	26,700 (+67)	+19,200 (+68)	+1,082 (+11)
Inorganic carbon					
Inflow via deposition	+230 (+2)	+500 (+1)	20 (0.1)	+3 (+0.01)	+160 (+2)
Atmospheric exchange	+930 (+8)	+2,800 (+5)	–1,400 (–3)	–450 (–1)	–5,700 (–25)
Outflow via outlet	–5,700 (–35)	–22,000 (–34)	–13,100 (–32)	–9,500 (–31)	–4,300 (–24)
Organic carbon	–6,800 (–41)	–32,000 (–50)	–26,200 (–64)	–21,000 (–68)	–800 (–5)
Inorganic carbon					
Sediment accumulation	–3,650 (–22)	–9,000 (–14)	–400 (–1)	–45 (–0.1)	–8,000 (–45)
Bird consumption	–300 (–2)	–700 (–1)	–30 (–0.1)	–4 (–0.01)	–100 (–1)
Total influxes	15,100	58,300	39,800	28,400	9,600
Total outfluxes	16,500	63,700	41,100	31,000	17,700

Processes within the ecosystems	**Eckarfjärden**	**Bolundsfjärden**	**Gunnarsbo-Lillfjärden**	**Labboträsket**	**Frisksjön**
	kg C y^{-1}	**kg C y^{-1}**	**kg C y^{-1}**	**kg C y^{-1}**	**kg C y^{-1}**
Primary production	30,600	63,700	2,800	209	4,300
Respiration	21,100	37,000	1,800	193	12,600

Biotic and abiotic pools in the ecosystem	**Eckarfjärden**	**Bolundsfjärden**	**Gunnarsbo-Lillfjärden**	**Labboträsket**	**Frisksjön**
	kg C (% of total)	**kg C (% of total)**	**kg C (% of total)**	**kg C (% of total)**	**kg C (% of total)**
Primary producers	5×10^{3} (0.1)	1×10^{4} (0.2)	5×10^{2} (0.1)	5×10^{1} (0.2)	6×10^{1} (0.0002)
Consumers	1×10^{3} (0.02)	2×10^{3} (0.03)	9×10^{1} (0.02)	1×10^{1} (0.05)	7×10^{2} (0.003)
DIC	6×10^{3} (0.1)	8×10^{3} (0.1)	5×10^{2} (0.1)	6×10^{1} (0.3)	5×10^{2} (0.002)
DOC	4×10^{3} (0.1)	5×10^{3} (0.1)	3×10^{2} (0.1)	3×10^{1} (0.1)	3×10^{3} (0.01)
POC	1×10^{2} (0.002)	1×10^{2} (0.002)	7×10^{0} (0.001)	4×10^{-1} (0.002)	2×10^{2} (0.001)
Sediment carbon	6×10^{6} (99.7)	6×10^{6} (99.6)	5×10^{5} (99.7)	2×10^{4} (99.4)	3×10^{7} (99.99)

The mass balances show that the largest influx of carbon to the Forsmark lakes is the inflow via the inlets. The largest outflux is the outflow via the outlet in all lakes. However, sediment accumulation is also relatively large in Bolundsfjärden and Eckarfjärden (14 and 22% of total outflux, respectively). Thus, these lakes may function as sinks of carbon, which may be incorporated either into biota or into the sediments. In Gunnarsbo-Lillfjärden and Labboträsket, on the other hand, sediment accumulation is negligible compared with the outflow via the outlet, and the lake may be regarded as a flow-through system. There are also examples in the Forsmark area of small lakes where outflows are of small magnitude, and in these lakes sediment accumulation constitutes a relatively large portion of total outflux (for example Lake Puttan, further described in Chapter 7). That kind of lake cannot be considered a flow-through system, although the amount that may be trapped in these small lakes is small compared with the larger lakes.

In all Forsmark lakes, biomass is concentrated in the littoral habitat, where between 96% and 97% of the total biomass in the lake is found. Primary production is concentrated in the littoral habitat, where between 88% and 92% of the total primary production occurs. This is expected in the shallow hardwater lakes, where bottoms to a large extent are covered by macroalgae and benthic production may be large.

In contrast to biomass and primary production, a large part of the respiration and consumption in all four lakes occurs in the pelagic habitat. The deepest lake, Eckarfjärden, has a higher proportion of respiration in the pelagic habitat compared with the shallower lakes Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket. The dominant functional group in terms of respiration in Eckarfjärden is bacterioplankton, while the dominant functional group in Bolundsfjärden, Gunnarsbo-Lillfjärden and Labboträsket is benthic bacteria.

The majority of lakes in the world are net heterotrophic, i.e. with respiration exceeding primary production (in contrast to net autotrophy where primary production exceeds respiration), e.g. /del Giorgio et al. 1997b/. The amount of dissolved organic carbon are assumed to influence if lakes become net autotrophic or net heterotrophic and /Jansson et al. 2000/ and /Prairie and Bird 2002/ have shown that net autotrophy occurs at DOC concentrations below 5–10 mg DOC L^{-1} although net heterotrophy are found also in lakes with lower DOC concentrations (e.g. /Karlsson 2001/). This is in contrast to both Eckarfjärden and Bolundsfjärden, which have high DOC concentration (about 20 mg C L^{-1}) and where the ecosystem models show that the dominant process within the lake is primary production, which clearly exceeds respiration. In the case of Gunnarsbo-Lillfjärden as well (the smaller lake with a microbial mat), the ecosystem model indicates that primary production is much larger than respiration. In contrast, the ecosystem model for Labboträsket (the lake lacking a microbial mat) indicates that primary production and respiration are equally important processes. The ecosystem models thus indicate that the largest impact on the net ecosystem production (NEP) is the presence of microphytobenthos in the benthic habitat. Another factor influencing the NEP is the depth of the water column, since the pelagic habitat is net heterotrophic and the benthic habitat is net autotrophic. The mass balance for the larger lakes Eckarfjärden and Bolundsfjärden show results consistent with the ecosystem models, indicating net autotrophic conditions. For both the smaller lakes Gunnarsbo-Lillfjärden and Labboträsket, the mass balances indicate net heterotrophic conditions. The ecosystem model and mass balance model for Gunnarsbo-Lillfjärden thereby does not show consistent results. The mass balances indicate that the relative sizes of primary production and respiration are not the same in the smaller and larger lakes, as both the smaller lakes show net heterotrophic conditions. Moreover, many of the smaller lakes in the area have lower chlorophyll *a* concentrations than the larger lakes, which may be an indication of lower primary production in the smaller lakes and a lower net ecosystem production.

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

Overall, the main conclusion of the mass balance and carbon ecosystem model is that the larger lakes may be important sites in the landscape for biogeochemical processes, whereas the smaller lakes are more likely to function more as flow-through systems. In the larger lakes, primary production and respiration are processes that involve much larger carbon fluxes than in- and outfluxes. There is therefore a large potential for elements entering the large lakes from the surrounding to be incorporated into the lake food web. In some of the smaller lakes in the area, primary production and respiration are much smaller than the inflow and outflow of carbon to/from the lake and elements entering the small lakes should to a large degree be transported further downstream in the water system.

5.5.2 Laxemar-Simpevarp

The mass balance shows that Frisksjön is a site of intense processing of organic matter. The lake receives large influxes of organic matter from the catchment, and these influxes are to a large extent mineralized to CO_2 and emitted to the atmosphere. Furthermore, a substantial part of the organic carbon is permanently buried in the sediments. Hence, it is evident that Frisksjön significantly alters the terrestrial export of organic carbon to the sea.

The mass balance shows that the largest influx of carbon to Frisksjön is the inflow via the inlets and the largest outflux is sediment accumulation (Table 5-17). Thus, these lakes may function as sinks of carbon, which may be incorporated either into biota or into the sediments.

Biomass and respiration are concentrated in the littoral habitat and benthic bacteria. The ecosystem model shows that respiration is much larger than primary production and the system is net heterotrophic. This result is supported by the mass balance model, which indicates a large outflux of carbon dioxide from the water to the air.

A relatively large portion (34%) of the primary produced carbon is consumed by higher organisms. Thus, any pollutant incorporated into organic matter during primary production would to a large extent be transported upwards in the food web. Moreover, a large proportion of the consumption by the top predator fish is derived from the benthic habitat, so any pollutants settling on the sediments could easily be reincorporated into the food web.

5.5.3 Comparison between Forsmark and Laxemar-Simpevarp

The lakes in Forsmark differ considerably from Frisksjön in the Laxemar-Simpevarp area. The Forsmark lakes are hardwater lakes dominated by high primary production and at least the larger lakes are net autotrophic systems. Frisksjön, on the other hand, is a brown-water lake dominated by respiration and a net heterotrophic system. Labboträsket, and potentially other lakes lacking a microbial mat in Forsmark, have a higher share of respiration than lakes with a microbial mat, and the mass balance for Labboträsket indicates that it is a heterotrophic system. However, Labboträsket still shows high primary production in comparison with Frisksjön and resembles the larger Forsmark lakes more than Frisksjön.

In the Forsmark lakes, a small portion (7–10%) of the primary produced carbon is directly consumed by higher organisms, indicating that pollutants incorporated into primary producers would to a large extent circulate within the microbial loop. In Frisksjön, on the other hand, as much as 34% of primary produced carbon is directly consumed by higher organisms. Thus, in Frisksjön, pollutants incorporated by primary producers have a larger probability of being transported upwards in the food web than in the Forsmark lakes. Moreover, there is a large secondary production in Frisksjön by bacteria utilizing organic carbon, and according to the models a large portion of the organic carbon entering the system from the catchment will be incorporated into bacteria. As bacteria to a great extent utilized by higher organisms, this is another possible pathway for pollutants to travel upwards in the food web.

There are also similarities between the lakes in the two areas. The larger lakes in Forsmark, as well as Frisksjön, are important sites in the landscape for biogeochemical processing. In the larger lakes in Forsmark, the in-lake processes (primary production and respiration) involve larger carbon masses than are transported into or out of the systems, indicating that there is a high probability for elements entering the lake to be incorporated into the food web. In Frisksjön, a large part of the carbon entering the system is processed by bacteria and thereby incorporated into the food web or emitted to the atmosphere as carbon dioxide. The smaller lakes Gunnarsbo-Lillfjärden and Labboträsket in Forsmark differ both from the larger lakes in Forsmark and from Frisksjön in the sense that the in-lake processes are of small importance compared with the carbon flow to and from the system.

Other similarities between lakes in the two areas are that phytoplankton plays a minor role as a primary producer and that the main food web to the top predator fish goes from benthic fauna to fish. However, there are also differences in the food web between the two areas. For example, in the Forsmark lakes the benthic fauna obtains most of its carbon from benthic primary producers, whereas the benthic fauna in Frisksjön obtains most of its carbon from benthic bacteria.

In conclusion, there are both similarities and differences between the lakes in Forsmark and Laxemar-Simpevarp. The most important similarity between the areas is that the larger lakes in both areas are important for biogeochemical processing and can alter the fate of carbon transported in the landscape. The most important difference between the areas is the dominance of primary production in Forsmark and of respiration in Frisksjön, which leads to different pathways for carbon. In addition, the fate of pollutants incorporated into the food web by primary production probably differs between the areas since a considerably smaller share of the primary produced carbon is directly consumed by higher organisms in Forsmark compared with Frisksjön.

5.6 Confidence and uncertainties

5.6.1 Forsmark

Both the mass balances and the ecosystem models for Forsmark rely on extraordinary amounts of data, site-specific as well as generic. Generally, the models are close to balanced which may indicate that the results are correct. On the other hand, the models for one of the lakes, Gunnarsbo-Lillfjärden, show contradictory results when compared with each other, indicating that there are uncertainties in the models. As in all models, some simplifications of the systems have been made and some parameters are associated with a higher degree of uncertainty than others. A description of the confidence and major uncertainties of the two models follows below.

Mass balances

Most influxes and outfluxes of carbon have been measured at the sites and can be considered to be relatively reliable estimates. The most important carbon fluxes are the inflow from the catchment and the outflow through the outlet. Sediment accumulation is of intermediate importance in Eckarfjärden and Bolundsfjärden but of small importance in Gunnarsbo-Lillfjärden and Labboträsket, while other carbon flows are of minor importance in the mass balances of all lakes. Generally, the carbon outflow via the outlet is well constrained, whereas the estimates of TOC and DIC inflow from the catchment and of sediment accumulation are associated with a higher degree of uncertainty. A discussion of the confidence of separate carbon flows in the mass balances follows below.

Carbon influxes

One of the largest influxes, TOC_{IN}, is most probably underestimated. Water chemistry data have been used together with discharge data to estimate the transport of different elements within the landscape. Extrapolation has been employed to estimate the diffusive inflow from the catchment and, as an example, estimated concentrations in the water from the inlet to Eckarfjärden were assumed to be representative for all water draining into the lake. However, TOC concentrations in water draining directly from the reed belts to the lake are probably higher than in the drainage from an average boreal catchment. A higher influx of carbon from the reed belts probably contributes to the imbalance in the mass balances. Macrophytes decompose slowly /Gessner et al. 1996, Gessner 2001/, but 30–40% of the annual reed production in lakes is assumed to be released as DOC and incorporated into the heterotrophic lake metabolism /Bertilson and Jones 2003/. During high water levels, large parts of the DOC in the reed surrounding the lakes should enter the lakes. Thus, the reed production in Littoral I is probably contribution to the TOC influx and balance in the mass balances can be achieved by assuming a TOC influx from the macrophytes. As an example, if as little as 8% of the reed production in Littoral I (Section 3.10.1) enter Eckarfjärden the mass balance of the lake will be balanced. The inflow of TOC via groundwater is assumed to be negligible compared with the amounts reaching the lake water from other sources. The assumption is realistic since TOC concentrations measured in shallow groundwater are about 10% of the DIC concentrations (Appendix 1 and 2 in /Tröjbom and Söderbäck 2006b/). Overall, the annual TOC inflow (1.7–3.9 g C m–2 y–1) is well within reported values (1.2–8.75 g C m–2 y–1) of TOC export from boreal catchments /Algesten et al. 2003, Matsson et al. 2005, Hope et al. 1994/. Thus, the estimates are, although probably somewhat low, still most probably of the right order of magnitude.

The inflow of DIC via inlets is reliable, as it has been measured once a month over a period of two years. The annual mean DOC deposition (1.03 g C m^{-2} y^{-1}) has been measured at the site and is within the range of reported literature values (1 and 1.4 g C m^{-2} y^{-1}) for Sweden and Southern Finland /Willey et al. 2000, Lindroos et al. 2001/.

During some years there are occasions with sea water intrusion to Bolundsfjärden which may potentially lead to an influx of carbon. This influx was calculated to be c. 2,700 kg C (DIC and TOC concentrations from Asphällsfjärden in the marine area outside Bolundsfjärden and an inflow of 200,000 m^3 which is somewhat higher than the estimated inflow during 10 h in January 2007 to account for the total inflow at the entire storm) and although a large momentarily inflow it only accounts for c. 10% of total annual influx.

CO_2 flux

The exchange of CO_2 between the lake and the atmosphere is well constrained, as the calculations are based on chemical equilibrium constants, and because wind speed, which strongly affects the gas flux between the air-water interface, is usually low above small lakes (Eckarfjärden and Bolundsfjärden are also considered small in a wider perspective). The calculations are based on site specific data on water chemistry covering several years and the variation between years is rather small values in the same order of magnitude.

Carbon outfluxes

The largest outfluxes of carbon in the mass balances, the outflow of TOC and DIC via the outlet (TOC_{OUT} and DIC_{OUT}, respectively), can be considered to be reliable estimates as they have been calculated from measured discharge data and concentrations in the water at the site.

The estimated accumulation of carbon in sediments (TC_{SED}), which is of intermediate importance for the larger lakes, is based on data from Eckarfjärden. The carbon accumulation rate in sediments is dependent on several parameters which vary between lakes in the area (e.g. water flow rate and organic content, depending on lake morphometry, catchment area etc), and accordingly accumulation may vary substantially between lakes in the same area. As mentioned earlier (Section 3.6), the estimated range for sedimentation in lakes in the region is quite large (minimum c. 10% of mean value and maximum value c. 4 times the mean). The estimated accumulation in Eckarfjärden is somewhat higher than was found for small lakes in Finland /Pajunen 2000/ (19 g C m^{-2} y^{-1} in Eckarfjärden, compared with 6 g C m^{-2} y^{-1} for lakes in the size class <1 km^2 in /Pajunen 2000/). However, the estimate for Eckarfjärden is in good agreement with carbon accumulation rates estimated for the coastal area of Forsmark (14 g C m^{-2} y^{-1}) /Sternbeck et al. 2006/. Thus, the carbon accumulation rate in sediments in Eckarfjärden is probably of the correct order of magnitude.

The estimate of consumption by birds is relatively uncertain. It is difficult to determine how large a percentage of birds in the area that actually feed in the lakes, and the feeding rates of birds are estimated from literature studies. On the other hand, bird consumption comprises c. 1% of total carbon outflux in the mass balances, so the uncertainty of this estimate is of minor importance. The confidence and uncertainty of the bird consumption data is further described in /Löfgren 2010/.

Ecosystem carbon models

Overall, biomass in the ecosystem carbon models is based on site-specific data, while most of the processes (excluding primary production) have been estimated using conversion factors found in the literature. The model is therefore strongly dependent on the choice of conversion factors.

A major objection to the ecosystem models may be that all data are not lake-specific. Most of the data on biota and processes in the Forsmark lakes are site-specific and have been obtained from measurements in the larger lakes Eckarfjärden and Bolundsfjärden. In the model calculations, the data have also been applied to the smaller lakes Gunnarsbo-Lillfjärden and Labboträsket. In contrast to Eckarfjärden and Bolundsfjärden, Labboträsket has a much more trivial fish fauna, containing only species resistant to low oxygen levels. Moreover, the benthic microbial mat, which is very thick in the two larger lakes, is almost absent in Labboträsket. Moreover, results from the mass balances indicate that the smaller lakes are net heterotrophic, although ecosystem models based on data from the larger lakes indicate net autotrophic conditions. Thus, there may be significant differences between smaller and larger lakes. Some abiotic parameters such as sedimentation may vary much between lakes (see above) indicating differences between lakes. However, others factors such as water chemistry, and a high abundance of *Chara* vegetation and relatively low chlorophyll *a* concentrations (a measure of phytoplankton biomass) in all lakes indicate that the biota is similar and that the results are reliable for the small lakes as well.

Biomass

The biomasses of all functional groups have been measured in at least one lake in Forsmark. Overall, the number of site-specific biomass estimates is quite unique, and although data for some functional groups are based on few replicates, the biomasses of most functional groups are based on extensive datasets and the biomass estimates can be considered well constrained. The confidence of the biomass data is further discussed in Section 3.13.

Primary production

Primary production has been measured for all functional groups of primary producers in Forsmark. While some studies (microphytobenthos and phytoplankton) have good coverage over the year, other studies (macroalgae) have few replicates over the year, leading to higher uncertainties of the annual primary production. Dark respiration by primary producers is somewhat uncertain since only day-time respiration has been measured, which also lead to some uncertainties in the annual net primary production. However, dark respiration should not affect the net result by more than c. 20%. Overall, the primary production estimates in the model can be considered reliable. Even if the absolute figures are somewhat uncertain, the order of magnitude should be correct since site-specific data are available for all functional groups. The confidence in primary production data is further discussed in Section 3.13.

Respiration

Overall, respiration must be regarded as being heavily dependent on the choice of conversion factors. Benthic and pelagic bacteria are the most important functional groups in terms of respiration and together comprise between 84 and 88% of total respiration in the lakes. Therefore, the conversion factors used to calculate bacterial respiration from bacterial biomass and production play a significant role for the overall model calculations. In Eckarfjärden, secondary production by bacterioplankton has been measured in situ for two years (n=24) and can be considered reliable /Blomqvist et al. 2002, Andersson et al. 2003/. This production can be used together with a range of growth efficiencies to estimate a range of possible respiration by bacteria. In the models, the commonly used bacterial growth efficiency (BGE) of 25% /del Giorgio et al. 1997a/ was used to calculate bacterioplankton respiration. However, /Andersson and Brunberg 2006a/ suggested that bacteria in the Forsmark lakes should assimilate algal exudates and the BGE on algal exudates is often above 50% /del Giorgio and Cole 1998/. A BGE of 50% results in considerably lower respiration than calculated in this model, and our estimate may well be too high. Benthic bacterial respiration was calculated with a biomass conversion factor. This results in a BGE of close to 50%, which can be considered realistic considering the extremely high density of algae surrounding the bacteria in the microbial mats.

For other functional groups, respiration was calculated using conversion factors from biomass and temperature in the lakes. The conversion factors lead to uncertainty in the results, but we have no estimates of the size of the error. Since most biomass estimates are reliable, the respiration estimates should be of the correct order of magnitude even if the absolute numbers are more uncertain.

Consumption

The consumption estimates are entirely based on conversion factors from literature, which of course leads to some uncertainty in the results. As for respiration, benthic bacteria and bacterioplankton are the most important functional groups (contributing between 80% and 85% of total consumption).

Therefore, the conversion factor for bacteria plays the most important role for the overall model. Bacterial consumption is calculated as the sum of production and respiration. Secondary production by bacteria has been measured in Eckarfjärden, so the consumption assumption is as good/bad as the estimation of respiration.

The conversion factor for calculating fish consumption is based on modelling of a marine area outside Forsmark and is probably of the right order of magnitude. All other functional groups of consumers have been assumed to have a consumption of 3 times the respiration /Elmgren 1984/, a rather rough conversion factor for which we have no verification of its correctness. Based on the uncertain respiration values (see above) this is also one of the most uncertain parameters in our models. However, although uncertain we can assume that it is of the right order of magnitude due to the fact that all estimates are based on site-specific biomass data.

5.6.2 Laxemar-Simpevarp

Both the mass balance and the ecosystem models for Frisksjön rely on large amount of site-specific data. Still, the models are heavily imbalanced, which suggests that they are associated with uncertainties. One explanation for the unbalance could be that the systems are not in balance. However, there are no indications of tat the system are in unbalance and the imbalance is probably due to parameter uncertainties. The most uncertain parameters are the influx of carbon to the lake from the catchment and sediment accumulation, which are parameters of the mass balance. A detailed description of the confidence and major uncertainties of the two models for Frisksjön follows below.

Mass balance

The largest flows in the mass balance are the carbon inflow from the catchment, the carbon outflow via the outlet, sediment accumulation, and CO_2 emission to the atmosphere. Of these flows, only CO_2 emission can be considered to be well constrained, while the others are associated with a high degree of uncertainty. The ranges of possible in- and outflow and sediment accumulation are large. Using values in the outer ranges of these flows ensures that the mass balance will be balanced. This, together with the fact that most flows are calculated from site-specific parameters, indicates that the magnitudes of the flows are correct, although the absolute numbers are associated with large uncertainties. A discussion of the certainties and uncertainties of separate carbon flows follows below.

Carbon influxes

The estimates of TOC export from the catchments in the Laxemar-Simpevarp area range from 3.5 to 7.3 mg C m^{-2} y^{-1} /Tröjbom et al. 2008/ (average 5.0 mg C m^{-2} y^{-1}). The estimated carbon influx is an extrapolation from measuring stations in the Laxemar-Simpevarp area and not specific data from Frisksjön. This makes the estimate uncertain, although it should be of the right order of magnitude. The estimated carbon inflow from catchment is within reported export rates of TOC from boreal catchments in literature (1.2–8.75 mg C m^{-2} y^{-1} /Algesten et al. 2003, Mattson et al. 2005, Canham et al. 2004/). Still, the carbon influx is probably an underestimate of the true influx due to underestimation of the carbon influx from the reed belt, which has not been included in the lake system (see discussion in the Forsmark section).

The accuracy of the estimated DIC inflow is the same as for the TOC inflow, i.e. the magnitude is certainly correct, although the absolute influx is uncertain. The DOC deposition, which is of minor importance for the mass balance, is considered a reliable estimate.

CO_2 flux

The exchange of CO_2 between the lake and the atmosphere is well constrained, as the calculations are based on chemical equilibrium constants, and because wind speed, which strongly affects the gas flux between the air-water interface, is usually low above small lakes. The calculations are based on site-specific data on water chemistry covering several years and the variation between years is rather small.

Carbon outfluxes

Estimates of TOC and DIC outflow are based on measurements in the Laxemar-Simpevarp area, although they are not specific for Frisksjön. Thus, the estimates are uncertain although the magnitude should be correct.

The estimate of organic carbon accumulation sediments is possibly somewhat high, as the sediment cores did not include the water-rich top 15–30 cm of sediments /Nilsson 2004/. Thus, our estimate of organic carbon accumulation in the sediments (79 g C m^{-2} y^{-1}) is very high compared with recent estimates of carbon accumulation rates in small Finnish lakes (4–13 g C m^{-2} y^{-1}) /Pajunen 2000/. On the other hand, the comparably high concentrations of inorganic nutrients in Frisksjön, together with substantial production of emergent macrophytes surrounding the lake, may contribute to an elevated carbon accumulation rate.

Bird consumption can be viewed as a relatively uncertain estimate as it is difficult to determine how large a percentage of the birds in the area that actually feed in the lakes, and as the feeding rates of birds are estimated from literature studies. Nevertheless, even with a wide range in the calculations, the contribution of bird consumption in the lakes to the overall carbon fluxes is minor, and thus this uncertainty in the actual number is of little importance for the mass balances.

Ecosystem carbon models

In general, the biomasses in the ecosystem carbon models are based on site-specific data, whereas the processes have been estimated using conversion factors found in the literature. The model is therefore to some extent dependent on the choice of conversion factors. Overall, the ecosystem model for Frisksjön is much more uncertain than the Forsmark models due to a much smaller data set. For most functional groups there are only few measurements of biomasses and no whole-year studies, which may be of importance when calculating a whole-year model. However, the single measurements available are nevertheless an asset as they indicate that the estimates are of the right order of magnitude.

Biomass

The biomasses of all functional groups have been measured at least once in Frisksjön. For phytoplankton, the annual mean is based on 8 replicates over the year, which can be considered a good estimate of the annual mean. For other functional groups, on the other hand, replicates are few and therefore the calculated annual means are more uncertain. However, since all estimates are based on actual measurements in the lake they are good indicators of the magnitude of the biomasses.

Primary production

Primary production by phytoplankton has not been measured in Frisksjön, but has been estimated from literature values for humic lakes. /Nürnberg and Shaw 1999/ showed correlations between phosphorus concentrations and annual production, as well as between chl *a* concentrations and annual production. Inserting our chl *a* concentration and phosphorus concentrations in these graphs independently gives an estimate of the phytoplankton production of c. 40 g C m^{-2} y^{-1}. The estimate is of course rough, but since it is based on in-lake phosphorus and chlorophyll concentrations we consider it to be realistic.

Respiration

Overall, respiration must be seen as heavily dependent on the choice of conversion factors. Bacteria are the most important functional groups in terms of respiration and are responsible for 86% of the total respiration in the lakes. Therefore, the conversion factors used to calculate bacterial respiration from bacterial biomass play a significant role in the overall model calculations. This estimate is connected with several uncertainties. First, the bacterial biomass is measured only in two occasions. Secondly, the biomass estimate is total biomass of although studies have shown that there is a better correlation between active bacteria and respiration than between bacterial respiration and total bacterial biomass /del Giorgio et al. 1997a/. Thirdly, there is a large range in growth efficiencies of different bacterial communities. Nevertheless, the bacterial respiration calculated in Frisksjön seems to be in the right order of magnitude. Community respiration in the benthic habitat has been measured on one occasion. The measured respiration was found to be 40 mg C m^{-2} h^{-1}, which is twice the calculated benthic bacterial respiration during July (16 mg C m^{-2} h^{-1}). Considering the uncertainty of the conversion factors and the fact that the measured values are the result of a few replicates in a single day, we consider the measured respiration to be reasonably close to the modelled one, i.e. they are of the same order of magnitude.

In the pelagic habitat we have no respiration data to use for comparison. Bacterioplankton are responsible for most of the respiration in the lake. The literature on bacterioplankton respiration seldom includes whole-year studies, and many studies focus on bacterioplankton secondary production and not respiration. However, it is clear that the estimates of bacterial respiration in the literature span a wide range. The biomass estimates narrows the range of respiration down to two order of magnitudes (5×10^5 – 1×10^7 g C year $^{-1}$ /Mason 1977, del Giorgio et al. 1997b, Nürnberg and Shaw 1999, Wetzel 2001, Boulion 2005/). We choose to use an estimate in the middle of the range (3×10^6 g C year^{-1}). Without biomass estimates there is an even larger range of bacterial respiration. Thus, pelagic respiration is subjected to a relatively high degree of uncertainty, but the biomass estimates give a respiration that is if not absolutely correct probably of the right order of magnitude.

Consumption

As for Forsmark, consumption is entirely based on literature conversion factors, which of course may lead to uncertainty in the results. Bacteria are the most important group, and since the respiration of bacteria is somewhat uncertain, so is their consumption. However, since biomass estimates are available, the order of magnitude is realistic.

6 The stream ecosystem – conceptual model and model assumptions for carbon

In this report, we have chosen a concept where stream ecosystems are treated as a special case of a lake. The habitats defined in a lake may also be present in streams. The same functional groups are also relevant for streams, see Table 6-1. One obvious difference between streams and lakes is the water flow, which is often much more rapid in streams than in lakes. Shading from terrestrial vegetation is often also more pronounced in streams than in large lakes, where the vegetation border on the shoreline can only shade a very limited fraction of the lake area. The small streams present in the Forsmark and Laxemar-Simpevarp areas are completely dry for parts of the year. The lack of water means that stationary populations of most functional groups cannot be present in the streams.

6.1 Habitats and functional groups

The habitats defined for lakes (see Section 5.2) are also used for the streams. With the data set available today a distinction between Littoral I (soft-bottoms with emergent and floating-leaved vegetation) and Littoral III (soft-bottom with submerged vegetation) cannot be made without a lot of data processing. These habitats have therefore been merged to one habitat called Littoral I/III in the sections dealing with streams.

The streams in Forsmark consists mostly of Littoral I/III (92% of investigated stretches), but there are also Littoral II (hard-bottom habitats) on short stretches (c. 8%). Littoral I/III is also the dominant habitat in the Laxemar area, but here there is a clear difference between small and larger streams. In the large Laxemarån, c. 40% of the stretches are composed of hard-bottom habitats (Littoral II), while the equivalent figure for the other smaller streams is c. 10% (7–17%). The pelagic habitat occurs temporarily, when water levels are high (spring and autumn flows). All streams in both areas are assumed to lack profundal habitats due to their shallow depth. Some of the future streams in Forsmark are assumed to contain profundal (see Chapter 11).

6.1.1 Primary producers

Large parts of the streams are dominated by benthic primary producers (see Section 3.10.2 and 4.10.2). In Forsmark and Laxemar-Simpevarp streams the benthic primary producers are mainly made up by emergent macrophytes. Such vegetation has an annual cycle where the vegetation withers away in the autumn. The non-living matter can be transported downstream if the water flow is strong enough; otherwise the withering vegetation remains at the site and degradation processes start. As we see no filling up of the streams we assume that the matter that is initially deposited on the bottom when the macrophytes are withering is transported downstream not later than the next spring flood. Thus, no long-term deposition of organic matter in stream sediments is expected. The organic matter is assumed to be part of the particulate organic carbon pool in the water, first in the stream itself and later in the downstream lake or bay. When water from the stream enters a basin the water velocity often decreases drastically and sedimentation of particulate matter occurs, bringing at least some of the organic matter to the sediments.

Table 6-1. Functional groups in the lake ecosystems. In both Forsmark and Laxemar-Simpevarp present-day streams are to shallow to include profundal habitat.

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

Phytoplankton is of course present in the waters of the streams but is most likely of less importance (estimates from chlorophyll measurements indicate low amounts, see Sections 3.10.2 and 4.10.2). In comparison with macrophytes, phytoplankton is also more dependent on the actual presence of water in the streams for its existence, whereas macrophytes can often withstand brief periods of draught, making the phytoplankton "growing season" in the small streams in these two areas somewhat shorter.

6.1.2 Consumers

The abundance and biomass of benthic fauna naturally varies geographically in streams, depending on the local conditions. In streams that periodically dry up, the populations are also temporary and we assume that no stationary communities of benthic fauna exist in large parts of the streams in any of the two areas.

The streams in Forsmark and Simpevarp may be of some importance for fish as feeding areas during periods of high water flow, but no stationary fish populations can be sustained in the small streams. It is possible that there are stationary fish populations in parts of the larger Laxemarån in Laxemar-Simpevarp, but that is not supported by the results from investigations (see Section 4.10.2). Fish migration for spawning has been observed in streams in both the Forsmark and Simpevarp areas. The reproducing fish migrate back to the sea after spawning, so the time they spend in the stream is very short – a couple of weeks per year.

During the periods the streams have water in them, other consumers such as zooplankton, bacterioplankton and benthic bacteria are present. But as with benthic fauna and fish, if stationary populations of these groups are present in the smaller streams they are not active during the dry periods. The situation is somewhat different in the larger Laxemarån. Here species that can tolerate low oxygen levels may be permanently present in the stretches that do not dry out.

6.1.3 Transport and accumulation in stream ecosystems

Large amounts of literature exist on the inputs and degradation of particulate organic carbon to streams whereas literature are scarcer on the long-term dynamics of other elements in streams /Wetzel 2001/. Carbon and other elements enter streams from the catchments as leafs, particulate and dissolved substances. Large amounts of the matter are transported downstream to lakes and seas. Any obstruction within streams can create protected habitats were sedimentation may occur whereby elements may be retained in the streams. Small streams with low discharge are better to retain elements than larger streams /Reddy et al. 1999/. However, in both small and large streams particulate matter may be transformed to dissolved substances and fine particulate matter which is easily transported downstream. Especially at high discharge events during the year, large amounts of the trapped elements are resuspended and transported further downstream (e.g. /Verhoff et al. 1982, Munn and Prepas 1986, Cushing et al. 1993, Wallace et al. 1995/). In small streams in New Hampshire transport of carbon and phosphorus was high at increased discharge and a phosphorus budget illustrates that although phosphorus was retained in the stream on a short time scale, no annual retention occurred /Bilby and Likens 1979, Meyer and Likens 1979/. Another process that decreases the accumulation in streams is the respiration of dissolved organic carbon by microscopic organisms which emit carbon to the atmosphere as carbon dioxide. Moreover, it is stated in a review by /Reddy et al. 1999/ that in contrast to wetlands uptake of phosphorus by macrophytes in streams ecosystems is often minimal.

Therefore it is reasonable to conclude that in the Forsmark and Laxemar area, elements are retained in the streams on a short time scale but at high discharge events the major part of element pools are transported further downstream and eventually reaches lakes or sea.

7 Pools and fluxes of different chemical elements into, out of and within lakes

The aim of this chapter is to visualize how other elements than carbon (described in Chapter 5) move and/or accumulate in the lake ecosystems in Forsmark and Laxemar-Simpevarp. Different elements have different properties and can be expected to behave differently in nature. Some will be transported rapidly through the lakes, accompanying the flowing water, while others may be incorporated into the food web and/or into the sediments and accumulate in the lake ecosystems. The fate of an element is dependent both on the properties of the actual element and on the character of the specific lake ecosystem. By estimating in- and outfluxes and accumulation in the ecosystems it is possible to visualize the fate of elements and thereby to identify hot spots in the ecosystems for e.g. pollutants and radionuclides. Mass balances for a large number of elements at landscape level are described in /Tröjbom and Grolander 2010/. This section focus on the limnic part of the landscape and on chemical composition of limnic components.

7.1 Conceptual model and model assumptions

The same mass balance concept as for carbon (Chapter 5) is used to describe fluxes of elements into, within (accumulation in sediment) and out of the lake ecosystem. The processes (*fluxes*) considered in the mass balances are illustrated in Figure 7-1 and the following equation was set up:

$$TX_{IN} + TX_{DEP} = TX_{OUT} + TX_{SED}$$

where:

TX_{IN} is the inflow of element X from the catchment via the inlet and direct drainage to the lake and via groundwater inflow.

TX_{DEP} is the wet deposition of element X from the atmosphere directly onto the surface of the lake.

TX_{OUT} is the outflow of element X via surface water (through the outlet).

TX_{SED} is the long-term accumulation of element X in the lake sediment.

Compared with the mass balance concept used for carbon (Chapter 5), two fluxes have been neglected: in/outflux via atmospheric gas exchange and outflux from the lake systems via consumption by birds. Gas exchange with the atmosphere is of limited importance for most elements, but it can be an important process for e.g. nitrogen and carbon. Nitrogen is transported in gaseous form from the lake water to the atmosphere and vice versa as a result of nitrification/denitrification processes in the lake ecosystem. Other elements for which gas exchange with the atmosphere

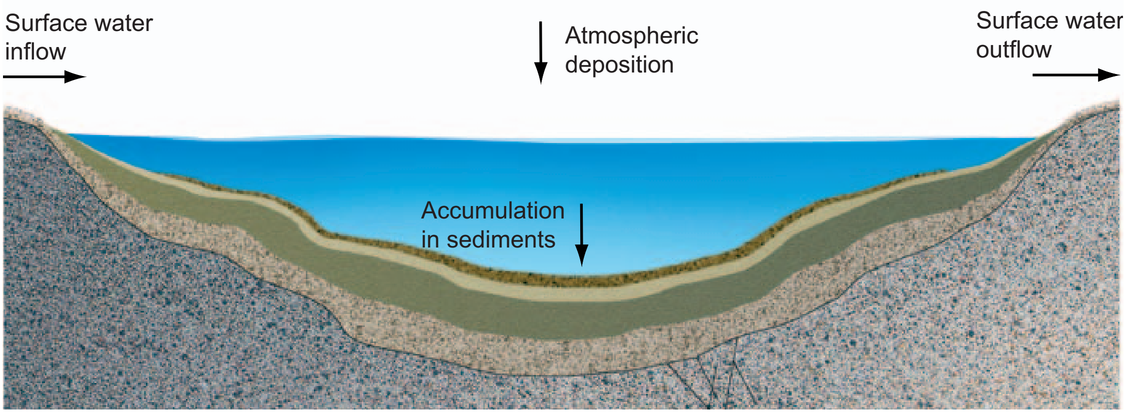

Figure 7-1. *Element fluxes considered in the mass balances.*

may be of importance are volatile elements such as iodine and mercury. We have no site data for estimating atmospheric exchange of other elements than carbon, but we assume that for most other elements this flux is negligible. The reason for not including the outflux via bird consumption is that this process is of minor importance for carbon (Section 5.3) and can therefore also be neglected for other elements. The term long-term accumulation of elements in the sediments has been included to emphasize that this is the net result of sedimentation and resuspension/dissolution processes.

In this report, mass balances have been set up for five lakes in the Forsmark area, situated in the catchment "Forsmark 2": Eckarfjärden, Gällsboträsket, Bolundsfjärden, Puttan and Norra Bassängen (see Appendix 1). Of these lakes, Eckarfjärden and Bolundsfjärden are regarded as larger lakes, while the other three are smaller (like Labboträsket and Gunnarsbo-Lillfjärden in Chapter 5). The fluxes of elements among these five lakes illustrate the downstream transport of elements through the limnic ecosystem in the main part of the Forsmark area. The same catchment contains a couple of smaller ponds. They are not connected with the other limnic environments via streams and have not been included in the calculations since they are small parts of the whole catchment and data are lacking for these objects. The mean values for the five lakes are sometimes used as representative of a mean Forsmark lake to make comparison with e.g. Laxemar-Simpevarp easier. In the Laxemar-Simpevarp area, a mass balance has been set up for Frisksjön.

The construction of ecosystem models for other elements than carbon requires more data than are available. Instead, as a complement to the mass balances, the chemical compositions of important components in the lake ecosystem (i.e. biota, sediment, dissolved and particulate fractions in water) have been used to calculate the masses of the elements in each component. The description of elemental pools in the ecosystem components should not be viewed as a variant of the ecosystem models for carbon presented in Chapter 5, since flows between the different functional groups in the food web are not described, nor do we care about different habitats in the lake ecosystem. However, the description is a useful tool for understanding the distribution of elements in the ecosystem.

The ecosystem was divided into a biotic and an abiotic component, when the former was divided into primary producers and consumers. Primary producers include phytoplankton and benthic primary producers (including benthic macrophytes, macroalgae and microphytobenthos). Consumers include bacterioplankton, zooplankton, benthic bacteria, benthic fauna (herbivores, filter feeders, detritivores, carnivores and omnivores) and fish (zooplanktivorous, benthivorous and piscivorous). Abiotic components for which the chemical composition was estimated include the dissolved and particulate phases of the lake water, as well as the lake sediment. In order to differentiate an oxygenated upper sediment layer, the first centimetre of the sediment has been recognized as a separate component in lakes that lack a microbial mat. For the other lakes, this oxygenated layer is part of the microbial mat and the underlying sediment is assumed to be anoxic. This is supported by observations of purple sulphur bacteria in the microbial mat from lakes in the area (see Section 3.6 and 4.6 for further information about the oxygenated layer). The anoxic sediment layer (denoted deeper sediment) is thus the largest sediment component, and for the lakes with a microbial mat the only sediment component that is recognized.

7.1.1 Elements considered in the evaluation

Chemical elements can be divided according to physical and chemical characters into metalloids, metals, non-metals, lanthanides and actinides, and these groups have been used in the illustration of elements in this report. The following 64 elements were sampled in the site investigations and are considered in this chapter.

Metals: Ag, Al, Ba, Be,Ca, Cd, Cs, Co, Cr, Cu, Fe, Ga, Hf, Hg, K, Li, Mg, Mn, Mo, Na, Nb, Ni, Pb, Rb, Sc, Sn, Sr, Ta Ti, Tl, V, W, Y, Zn, Zr

Non-metalls: Br, C, Cl, F, I, N, P, S

Metalloids: As, B, Sb, Se, Si

Lanthanides: Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Yb

Actinides: Th, U

A detailed description is given for four of the 64 described elements: phosphorus, iodine, thorium and uranium. Phosphorus has been chosen since this is an important element for biota that is often a limiting factor in lakes, and the body of data available on this element is larger than for all other elements (except for carbon, which is dealt with in Chapter 5, and nitrogen, for which an equal amount of data is available). The other three elements have been selected since they represent elements with different sorption properties in deposits. Iodine is representative of elements that are very mobile in the environment. The sorption coefficient of iodine, K_ds, tabulated in /Karlsson and Bergström 2002/ varies from 0.03 m^3 kg^{-1} (organic soil) to 0.3 m^3 kg^{-1} (soil and suspended matter in lakes and brackish environments). Thorium represents almost immobile elements, and the K_ds tabulated in /Karlsson and Bergström 2002/ varies from 10 m^3 kg^{-1} (soil) to 100 m^3 kg^{-1} (suspended matter in lakes and brackish environments). Uranium is representative of elements with sorption properties somewhere in between and the K_ds tabulated in /Karlsson and Bergström 2002/ varies from 0.1 m^3 kg^{-1} (soil) to 10 m^3 kg^{-1} (suspended matter in lakes and brackish environments). Uranium and thorium have no known biological role, while iodine appears to be a trace element essential to flora and fauna.

7.2 Model parameterization

7.2.1 Chemical composition of biotic and abiotic components

Forsmark

The chemical composition of the **dissolved** water phase in Bolundsfjärden, Eckarfjärden and Norra bassängen has been measured in the site investigation and data from 2004-06-01 to 2006-05-31 were used in this evaluation (Appendix 7, data from SICADA[15], October 2006). Chemistry data from Puttan and Gällsboträsket are lacking. For the former, data from Norra Bassängen was used instead, and for Gällsboträsket chemistry data from the Bolundsskogen station (stream water downstream of the lake) were used. When data from Bolundsskogen were missing, data from Bolundsfjärden (which is the closest downstream lake) were used instead. Long-term measurements are lacking for some elements (Ag, B, Be, Ga, Nb, Se, Sn, Ta, Ti, W), so data from one occasion in April 2008 were used (Appendix 7) /Engdahl et al. 2008/. These data includes site specific data for Bolundsfjärden and Eckarfjärden whereas in the case of Gällsboträsket, Norra bassängen and Puttan a mean from Eckarfjärden, Bolundsfjärden and Labboträsket was used. In the case of Ag, Sn, and Ta, concentrations were below detection limit and half the detection limit was used as an estimate.

Data on the **particulate** fractions of the macronutrients carbon, nitrogen and phosphorus are also available for the time period 2004-06-01 to 2006-05-31 (SICADA[16], October 2006). For other elements, one measurement was performed in the spring of 2008 to estimate the size of the particulate fraction (Appendix 8) /Engdahl et al. 2008/. Bolundsfjärden, Eckarfjärden and Labboträsket were sampled in the latter investigation. In the mass balances, data from Bolundsfjärden were also used for Puttan and Norra Bassängen. The mean particulate concentrations for the three investigated lakes were used for Gällsboträsket. Values for Au, In, Ir, Os, Pd, Pt, Rh and Ru were below the detection limit, and half the detection limit was used as an estimate in the model.

The chemical composition of lake **sediments** in two Forsmark lakes, Eckarfjärden and Stocksjön, was derived from Appendix 1 in /Hannu and Karlsson 2006/ and from Appendix 1 in /Strömgren and Brunberg 2006/. The available samples were divided into three deposit layers: gyttja, clay gyttja and clay. As described earlier, the first (upper) centimetre of the sediment (gyttja layer) was recognized as a separate component in the lakes that lack a microbial mat (Gällsboträsket), in order to differentiate a biologically active upper sediment layer. The deeper sediment component consists of the rest of the gyttja layer together with the clay gyttja and clay. For the lakes with a microbial mat, deeper sediment is the only sediment layer as a microbial mat belongs to the biotic component (microphytobenthos and benthic bacteria). The sand layer that is often present between the clay gyttja and clay layers has been omitted since it is often thin and has a much lower weathering capacity compared to e.g. clay. No chemical data concerning the chemical composition of sand in sediments are available from the Forsmark area.

[15,16] SKBs database SICADA, access might be given on request.

The concentration of different elements in sediment samples has been correlated to the carbon content, measured in the same samples /Hannu and Karlsson 2006/. The carbon contents established in /Hannu and Karlsson 2006/ differ slightly from another study by /Hedenström and Risberg 2003/, e.g. 35% instead of 27% in gyttja and 9% instead of 8% in clay gyttja-gyttja clay (see Section 3.6). The differences are small and may be the result of few replicates. The carbon and water contents of the different sediment layers in Eckarfjärden and the elemental contents from Eckarfjärden were therefore used for all lakes in the area, despite the differences presented above. The only lake-specific data used for other lakes was the thickness of each sediment layer (Table 3-10) and the lake area /Hedenström 2004, Brunberg et al. 2004a/. For nitrogen, data on the concentration in the "clay" was lacking; instead, concentrations in the clay gyttja were used for this layer.

Data on the chemical composition of the limnic **biota** from Forsmark is mainly derived from /Hannu and Karlsson 2006/ and /Kumblad and Bradshaw 2008/. The former study presents site-specific chemical data for the microphytobenthos (microbial mat), macroalgae (benthic submerged vegetation), benthic fauna (only filter feeders) and planktivorous, benthivorous and piscivorous fish (further described in Section 3.10). For the chemical composition of the microphytobenthos, a combination of the data presented for the microbial mat in /Hannu and Karlsson 2006/ (Bolundsfjärden) and in /Strömgren and Brunberg 2006/ (Stocksjön) were used (average values when data for the same element is available for both datasets). For phytoplankton, zooplankton and herbivorous, detritivorous and carnivorous benthic fauna, data were taken from /Kumblad and Bradshaw 2008/. This study aimed to characterize the brackish water ecosystem just outside the two islands Stor-Tixlan and Lill-Tixlan within the Forsmark regional model area. The use of data from a brackish ecosystem in this evaluation may introduce some uncertainty, but in the absence of site-specific limnic data we chose to use this site-specific data set. It contains an extensive chemical characterization (48 elements) for a number of functional groups sampled in the same area at the same time. Data for omnivorous benthic fauna were calculated as a mean of all analyzed species of benthic fauna. Concentrations of 15 elements (Ag, B, Be, Ga, Hf, La, Nb, Sb, Sc, Sn, Sr, Ta, Ti, W and Y) in benthic herbivores, benthic detrivores and benthic carnivores were lacking, but were assumed to be identical to the chemical composition of benthic filter feeders /Hannu and Karlsson 2006/.

Site-specific chemical data are lacking for bacterioplankton, but phosphorus, nitrogen and sulphur content in bacterioplankton have been estimated using conversion factors for brackish and freshwater aquatic bacteria (Baltic Sea and Norwegian lake) from the literature /Fagerbakke et al. 1996/. Site-specific data are also lacking for benthic bacteria, and conversion factors from carbon to phosphorus and nitrogen for benthic bacteria from /Kautsky 1995/ are used. The C/P ratio used for bacterioplankton and benthic bacteria is of the same order of magnitude as that reported for Microcystis-associated bacteria in Lake Vallentunasjön (north of Stockholm) /Brunberg 1995/. The sulphur content of benthic bacteria was assumed to be equal to the sulphur content of bacterioplankton reported by /Fagerbakke et al. 1996/. For all other elements, bacterioplankton and benthic bacteria were not included.

To estimate the total pools of different elements in biotic components, we assumed that there is a constant relation between carbon content and the content of any other element. Accordingly, we calculated the element per carbon ratio for the biota samples available in /Hannu and Karlsson 2006, Kumblad and Bradshaw 2008/. For each lake, the element per carbon ratio was then multiplied by the total carbon pool in the biotic component, and finally the estimates for the different biotic components were summarized to estimate the total biotic pool of each element. No carbon content was reported for the microphytobenthos from Stocksjön /Strömgren and Brunberg 2006/. Instead, it was assumed that the carbon content of microphytobenthos was the same as in the microbial mat from Eckarfjärden /Hannu and Karlsson 2006/. The carbon pools for different biotic components (functional groups) in the five lakes were taken from the carbon ecosystem models described in Chapter 5.

Laxemar-Simpevarp

The chemical composition of the **dissolved** water phase has been measured in the site investigation and data was taken from the time period 2002-11-20 to 2007-07-24 (SICADA[17], October 2007).

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[17] SKBs database SICADA, access might be given on request.

Long-term measurements are lacking for some elements (Ag, B, Be, Ga, Nb, Se, Sn, Ta, Ti, W), so data from one occasion in April 2008 were used /Engdahl et al. 2008/.

In the case of the macronutrients carbon, nitrogen and phosphorus, the **particulate** fractions of the elements in lake water have also been measured in the site investigation during the period 2002-11-20 to 2007-07-24 (SICADA[18], October 2007). For all other elements, the particulate fraction was analyzed in Frisksjön as suspended material on one occasion in April 2008. For Au, In, Ir, Os Pd, Pt, Rh and Ru concentrations were below detection limit and half the detection limits were used as estimates of the concentration of these elements. The detection limit was not specified for Re, which resulted in negative concentration when the filter were subtracted in the analyses, so the concentration was set to 0.

The chemical composition of lake **sediments** from Frisksjön down to a depth of 4.4 m was taken from Appendix 2 in /Engdahl et al. 2006/. In the top 10 cm, layers were analyzed every two centimetres, after which a 2–3 cm layer was analyzed at depths of 0.25, 0.5, 1, 2, 3, 4 and 4.4 metres. There was a clear difference in chemical composition between sediments above and below a depth of 1.97 m, indicating the transition from marine to limnic conditions. In calculating the pools of elements in the sediment, the first centimetre of the sediment (gyttja layer) was recognized as a separate component in order to differentiate a biologically active upper sediment layer. Due to the different chemistry in the upper and lower sediments, the remaining deeper sediments were calculated as separate components, one from 0.01 to 1.97 m and one from 1.97 to 10 m. Although sediment depth in Frisksjön is estimated to be 10 m (Section 3.6), the chemical composition is only available for the sediment down to a depth of 4.4 m. For the remaining sediment, the chemical composition was assumed to be the mean from the sediment layer 1.97–4 m.

As with the Forsmark lakes, the concentration of different elements in the sediments has been correlated to the content of carbon measured on the same sample at the same time /Engdahl et al. 2006/. This carbon content differs somewhat from other studies, e.g. 11–12% instead of 20% (Section 4.6). However, this may be due to few replicates in the studies, and as we have no further information regarding which dataset is correct, the data set from /Engdahl et al. 2006/ that includes many elements has been used.

Site-specific data on the chemical composition of limnic **biota** is available for aquatic vegetation (roots/rhizomes and aboveground parts of water lily), benthic fauna (only filter feeders), and for benthivorous and piscivorous fish /Engdahl et al. 2006/. The same non-site specific data as were used for the Forsmark lakes have also been used in Laxemar-Simpevarp. For phytoplankton, zooplankton and herbivorous, detritivorous and carnivorous benthic fauna, the chemical composition was taken from /Kumblad and Bradshaw 2008/. The chemical composition of benthic herbivores, detrivores and carnivores with regard to 15 elements (Ag, B, Be, Ga, Hf, La, Nb, Sb, Sc, Sn, Sr, Ta, Ti, W and Y) was assumed to be identical to the chemical composition of benthic filter feeders /Engdahl et al. 2006/. For bacterioplankton conversion factors from the literature (Baltic Sea and Norwegian lake /Fagerbakke et al. 1996/) were used for converting from carbon to phosphorus, nitrogen and sulphur. Conversion factors from carbon to phosphorus and nitrogen from the literature were also used for benthic bacteria /Kautsky 1995/. The sulphur content of benthic bacteria was assumed to be equal to the sulphur content of bacterioplankton reported by /Fagerbakke et al. 1996/.

The total biotic pools of elements in Frisksjön were calculated in the same way as the elemental pools in Forsmark (for further explanation, see above).

7.2.2 Mass balances

Forsmark

The transport of major elements in surface water has been estimated from simultaneous measurements of concentrations and discharge in streams (Appendix F in /Tröjbom et al. 2007/). These values include water in- (TX_{IN}) and outflow (TX_{OUT}) to/from lakes via in/outlets as well as diffusive in- and outflow of elements directly to the lake from the catchment as well as via groundwater. The transport of trace elements has been calculated by correlation of trace elements to the transport of major elements /Tröjbom et al. 2007/.

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[18] SKBs database SICADA, access might be given on request.

The contribution to the total influx of elements to lakes via wet deposition on the lake surface (TX_{DEP}) has been estimated using site-specific data on the chemical composition of precipitation from two sampling stations in the Forsmark area /Tröjbom and Söderbäck 2006b/ together with site-specific annual precipitation (calculated as an annual mean from two years: 2004 and 2005) /Johansson et al. 2008/. Site-specific precipitation data are only available for ten elements (P, Al, Fe, Na, K, Ca, Mg, Cl, DOC, SO_4^{2-}). Bromine, iodine and silicon were analysed but below detection limit and for these elements, half the detection limit was used as an estimate of concentration in precipitation. For iron, manganese, silicon and strontium, data on chemical composition in precipitation in Laxemar-Simpevarp were used. No site-specific data on deposition are available for uranium and thorium, but deposition has been assumed to equal estimates of atmospheric deposition during the winter period in a deciduous forest in southern Sweden /Tyler and Olsson 2006/. For nitrogen, concentrations in precipitation measured by /Pihl Karlsson et al. 2003/ (Jädraås station) were used for Forsmark. For other elements this influx has not been included in the mass balance.

The accumulation of elements in lake sediments functions as a withdrawal of elements from the lake water. This outflux has been estimated using the average elemental composition of the gyttja layer in Eckarfjärden and Stocksjön (Appendix 1 in /Hannu and Karlsson 2006/, Appendix 1 in /Strömgren and Brunberg 2006/), the estimated dry weight content of the gyttja layer in the lake (Section 3.6), the long-term accumulation rate estimated for Eckarfjärden (Section 4.4 in /Hedenström and Risberg 2003/) and the area for sediment accumulation in the lake. The latter is assumed to be the whole lake area excluding the reed belts.

Laxemar-Simpevarp

The transport of major elements in surface water to/from Frisksjön has been estimated from simultaneous measurements of concentrations and discharge in streams (Appendix C in /Tröjbom et al. 2008/). These values include water in- (TX_{IN}) and outflow (TX_{OUT}) to/from lakes via in/outlets as well as diffusive in- and outflow of elements directly to the lake from the catchment as well as via groundwater. The transport of minor elements has been calculated by correlation of the minor elements to the flows of major elements /Tröjbom et al. 2008/.

When available, TX_{DEP} has been estimated using site-specific data on the chemical composition of precipitation from two sampling stations in the Laxemar-Simpevarp area (SICADA[19], October 2007, ID code PSM002170 and PSM001516, the number of observations varies for different elements: n=29-105, Sep 2002–Nov 2007), together with site-specific annual precipitation (600 mm, calculated as an annual mean from the years 2005 and 2007 and the two stations Plittorp and Äspö) /Werner et al. 2008/. Site-specific data on wet deposition on the lake surface (TX_{DEP}) is available for eleven elements (Br, Na, K, Ca, Mg, Si, Fe, Mn, Sr, Cl, SO_4^{2-}). Data on phosphorus concentrations in precipitation have been taken from /Knape 2001/, where total phosphorus concentrations measured in precipitation at Äspö Island during the period 1997–1999 are presented. Data on the chemical composition of precipitation in Forsmark was used for aluminum. No site-specific data on deposition are available for uranium and thorium, but deposition has been assumed to equal estimates of atmospheric deposition during the winter period in a deciduous forest in southern Sweden /Tyler and Olsson 2006/. For carbon and nitrogen, concentrations in precipitation measured by /Pihl Karlsson et al. 2008/ were used (Rockneby station in Kalmar County). For other elements this flux has not been included in the mass balance.

The accumulation of elements in lake sediments has been estimated using the average elemental composition of the gyttja layer in Frisksjön (Appendix 2 in /Engdahl et al. 2006/), the estimated amount dry weight content of the gyttja layer in the lake (Section 4.6), the long-term accumulation rate estimated for Frisksjön /Sternbeck et al. 2006/ and the area for sediment accumulation in the lake. The latter is assumed to be the whole lake area excluding Littoral I (the reed belts).

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[19] SKBs database SICADA, access might be given on request.

7.3 Evaluation of elemental pools and fluxes for a number of elements in Forsmark

This section contains the main results of the mass balances for a number of elements in Forsmark and pools and mass fluxes are presented in Section 7.3.1 . Detailed results for phosphorus, iodine, thorium and uranium for the five lakes Bolundsfjärden, Eckarfjärden, Gällsboträsket, Puttan and Norra bassängen are presented in Section 7.3.2 and 7.3.3. Detailed results for separate elements in the five lakes are found in Appendices 11 and 12.

7.3.1 Chemical composition of different ecosystem components

The most abundant element in the Forsmark lakes (i.e. in all components, dissolved, particulate, biotic, and sediment, hydrogen and oxygen excluded) is silicon (41%), followed by carbon (17%), aluminium (13%), iron (8%) and calcium (8%) (Figure 7-2). The abiotic component has exactly the same distribution of elements, which is expected as the abiotic component constitutes 99.95% of total mass of investigated elements in the average lake. Moreover, the sediment in the average lake constitutes 99.7% of the total mass of investigated elements, which means that the sediment has the same distribution of elements as the total lake ecosystem (Figure 7-3).

In the abiotic components in lake water, elements are mainly present in the dissolved component, and amounts in the particulate component are considerably smaller (Figure 7-4). Only lanthanum and phosphorus are almost equally abundant in the particulate and the dissolved components. The dissolved and particulate components differ from each other in elemental composition: the dissolved component is dominated by chlorine, sodium, calcium and carbon (Figure 7-5), illustrating the dominance of the major ions in the water phase, while the particulate component is dominated by carbon, which comprises 72% of the particulate matter (Figure 7-6). The dissolved component differs somewhat among the 5 investigated lakes. In four of the lakes, calcium is more abundant than sodium in the dissolved component. In contrast, in Bolundsfjärden, the sodium amounts is much higher than the calcium amount. The high sodium amounts in Bolundsfjärden is probably due to occasional salt-water intrusion. Nitrogen, calcium, silicon and sulphur contribute between 2 and 9% each to the particulate component in the average lake, while all other elements make minor contributions to the particulate component.

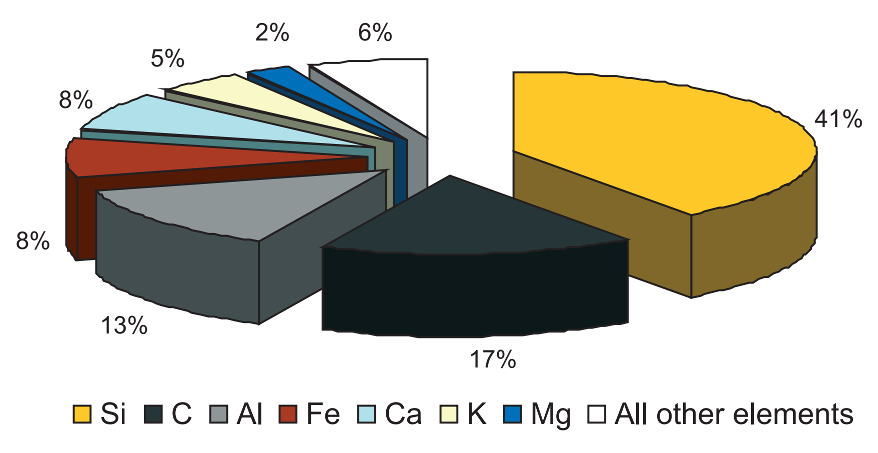

Figure 7-2. *Distribution of elements (% of total investigated elements, based on mass) in the average lake (in all ecosystem components: dissolved, particulate, biotic and sediment). Note that not all elements are analyzed and that the elements of which water is composed, oxygen and hydrogen, are not included.*

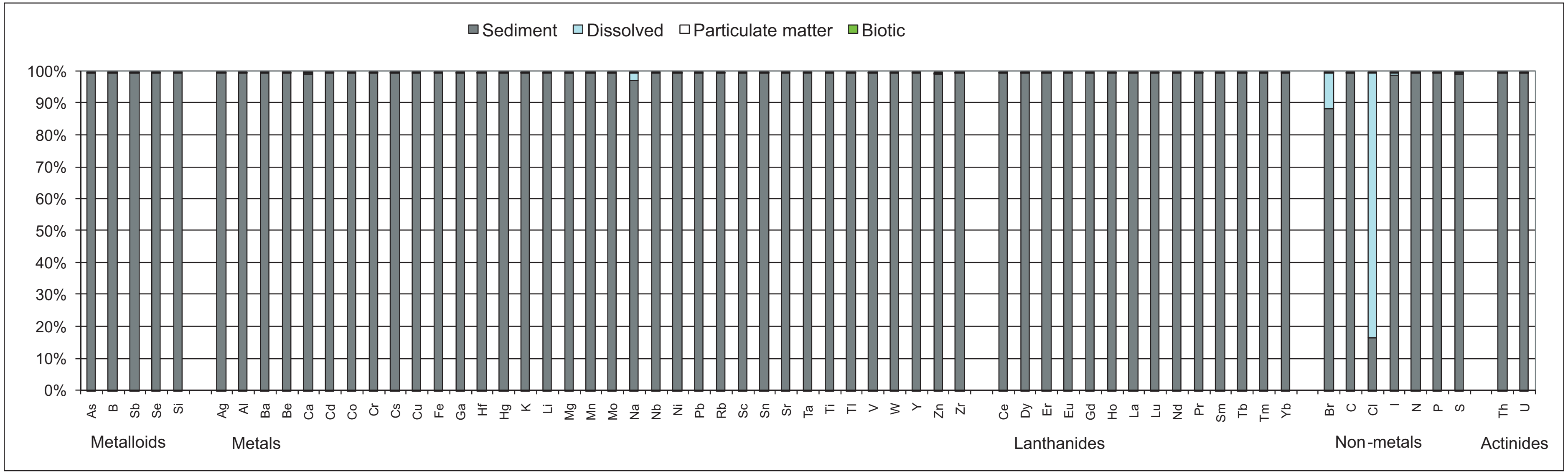

Figure 7-3. *Distribution of analyzed elements among the different components of the ecosystem in the mean lake in Forsmark: sediment (black), dissolved in water (blue), particulate (white) and biotic (green). Sediment is totally dominant and the biotic and particulate fractions are not visible in this figure.*

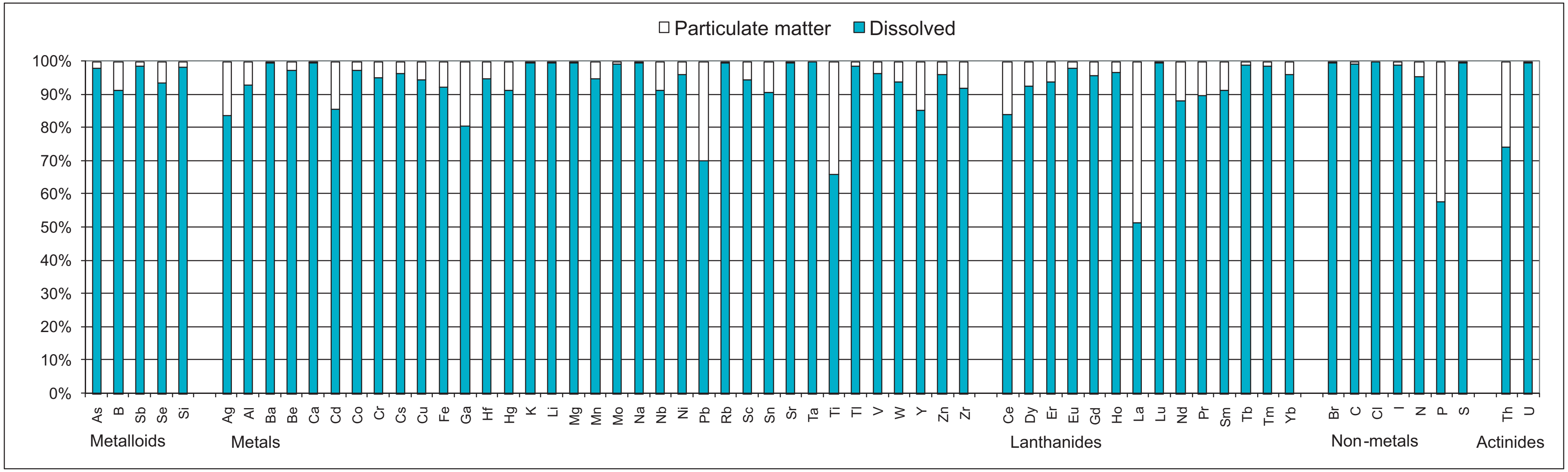

Figure 7-4. *Distribution of analyzed elements between the dissolved and particulate components in lake water in the average lake in Forsmark.*

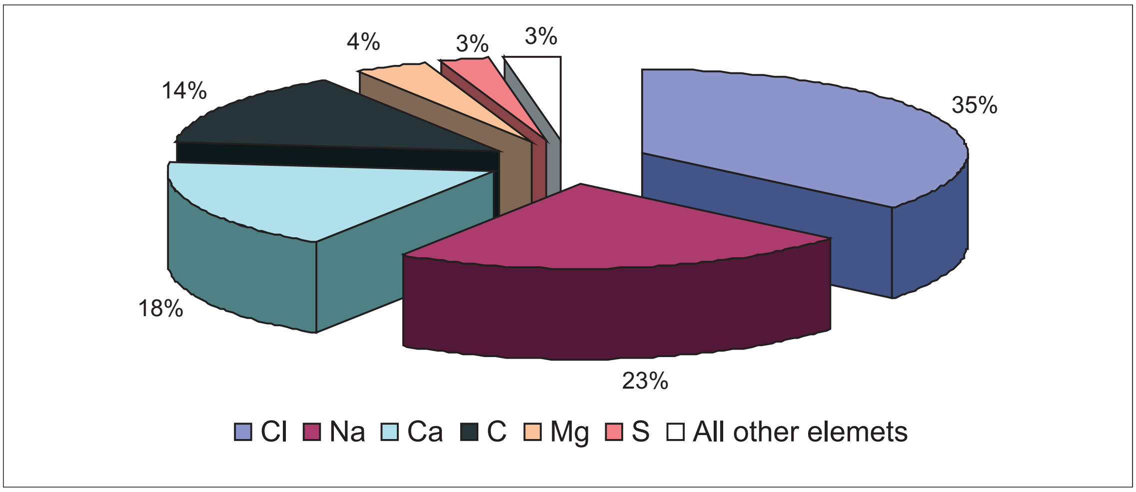

***Figure 7-5.** Distribution of elements (% of total investigated elements, based on mass) in the dissolved component in the average lake in Forsmark. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included.*

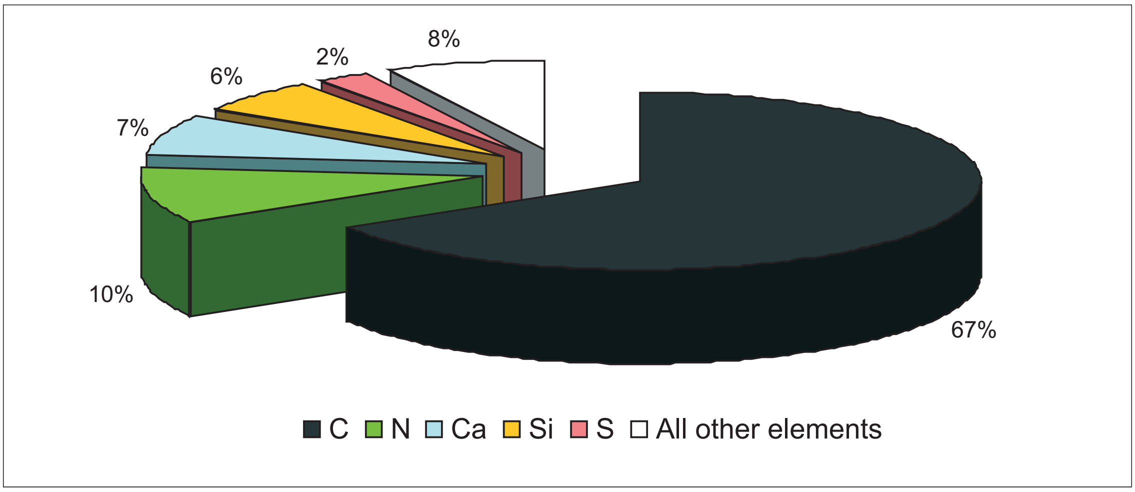

***Figure 7-6.** Distribution of elements (% of total investigated elements, based on mass) in the particulate component in the average lake in Forsmark. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included.*

The elemental composition of the biotic component differs from that of the total abiotic component, but somewhat resembles that of the particulate component. The biotic component is dominated by carbon (57% of total) and calcium (33% of total). Nitrogen, zinc and silicon comprise between 2 and 4% each of total mass of the biotic component, while all other elements comprise smaller fractions (Figure 7-7).

Within the biotic component, almost all the elements are most abundant in benthic primary producers (Figure 7-8). This is especially true of the lanthanides, which occur almost exclusively in the benthic primary producers. This may be accurate, but it may also be an artefact due to missing data on the chemical composition of bacteria. Data on the chemical composition of all functional groups except bacterioplankton and benthic bacteria are available for most elements (Appendix 6), but the composition of all functional groups is available only for phosphorus, nitrogen, carbon and sulphur. Bacteria are known to have a very high phosphorus content /Wetzel 2001/. Accordingly, 70% of all phosphorus in the biota is found in bacteria (average lake). Bacteria also contain considerable amounts of nitrogen, sulphur and carbon (34, 16 and 12% of the total biotic mass of each element in

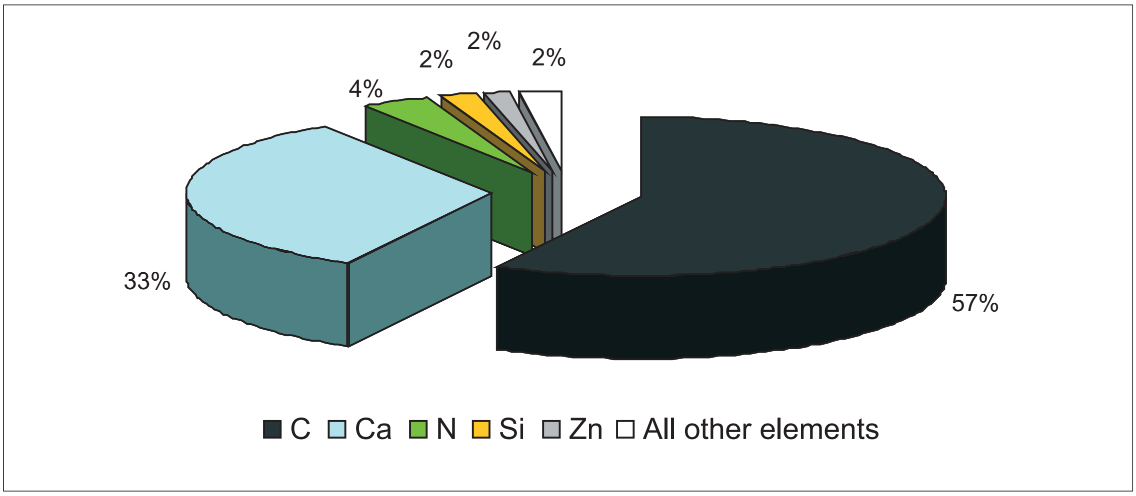

***Figure 7-7.** Distribution of elements (% of total investigated elements, based on mass) in the biotic component in the mean lake in Forsmark. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included.*

the average lake). Thus, most elements are probably present in consumers to a considerably larger degree than shown in Figure 7-8. Some elements are most common in consumers even without the contribution of bacteria: a significant fraction of mercury, potassium, sodium and bromine is found in the analyzed groups of consumers. Mercury, which is an element known for biomagnification, shows the highest concentration in fish. Potassium, rubidium and zinc are also present in large amounts in fish. For some unknown reason, bromine is found mainly in zooplankton, and the same pattern is seen in Frisksjön in Laxemar-Simpevarp and in the marine environment /Wijnblad et al. 2008/. The concentration of almost 30 of the analyzed elements in fish is below the detection limit of the method, and it is evident that the concentrations of most trace elements in fish are small.

7.3.2 Mass balances

Data to estimate all of the four major fluxes (inflow through water, outflow through water, atmospheric deposition and accumulation in sediment) are available for 16 elements (C, Ca, Cl, Fe, I, K, Mg, Mn, N, Na, P, S, Si, Sr, Th, U). However, for another 31 elements the only flux missing is atmospheric deposition. For phosphorus this flux is large for some of the lakes (31, 43, and 45% of total influx in Bolundsfjärden, Eckarfjärden and Puttan, respectively), while for the other 14 elements where all fluxes were measured, atmospheric deposition constitutes a minor fraction of total influx (mean value for the Forsmark lakes 1.7%, min. 0.01% max. 18% of total influx). Due to the small share represented by atmospheric influx for most elements, the mass balances for elements where data on atmospheric deposition are lacking are also discussed in this section. A summary of the estimated elemental fluxes for analyzed elements is given in Appendix 12.

In the average Forsmark lake, the inflow via water is the most important influx for all investigated elements. The most important outflux differs somewhat between elements. For metalloids, metals, and non-metals, outflow via water is the most important outflux, whereas for lanthanides the most important outflux is accumulation in sediments (Figure 7-9). There are some differences among the five studied lakes in the relative importance of different fluxes. In Bolundsfjärden, Eckarfjärden and Puttan, the influx of phosphorus, iron and manganese via atmospheric deposition is relatively large compared to the inflow via water. In the other two lakes, Gällsboträsket and Norra Bassängen, atmospheric influx of phosphorus, iron and manganese is small. This is an effect of the lake area and the position of the lake within the catchment (i.e. the size of the catchment area). Eckarfjärden and Bolundsfjärden have relatively large atmospheric influx due to their large lake area, whereas the smaller Puttan has a relatively large share of atmospheric deposition due to low inflow via water. The importance of different outfluxes differs among the lakes. In Gällsboträsket and Norra Bassängen, the outflow via water dominates for almost all elements, while in Bolundsfjärden, Eckarfjärden and Puttan, accumulation in sediment is the dominating outflux for many elements.

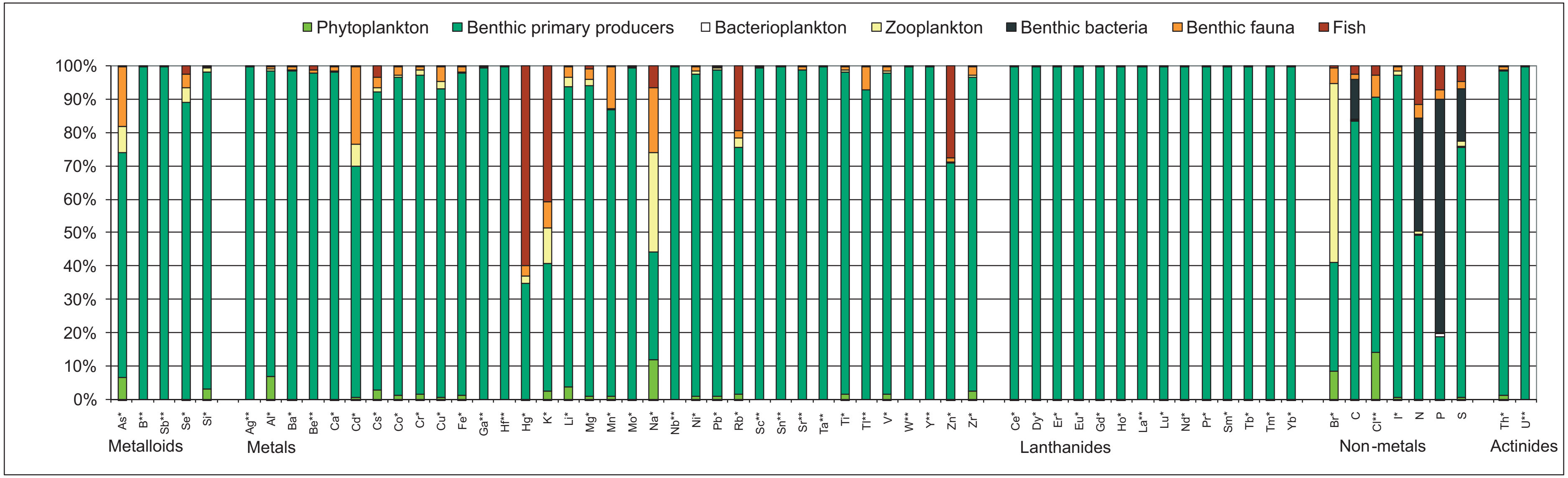

Figure 7-8. *Distribution of a number of elements among the biotic components of the ecosystem in the average lake in Forsmark. * indicates that data for bacterioplankton and benthic bacteria are missing. ** indicates that data are missing for one or more other groups besides bacteria .*

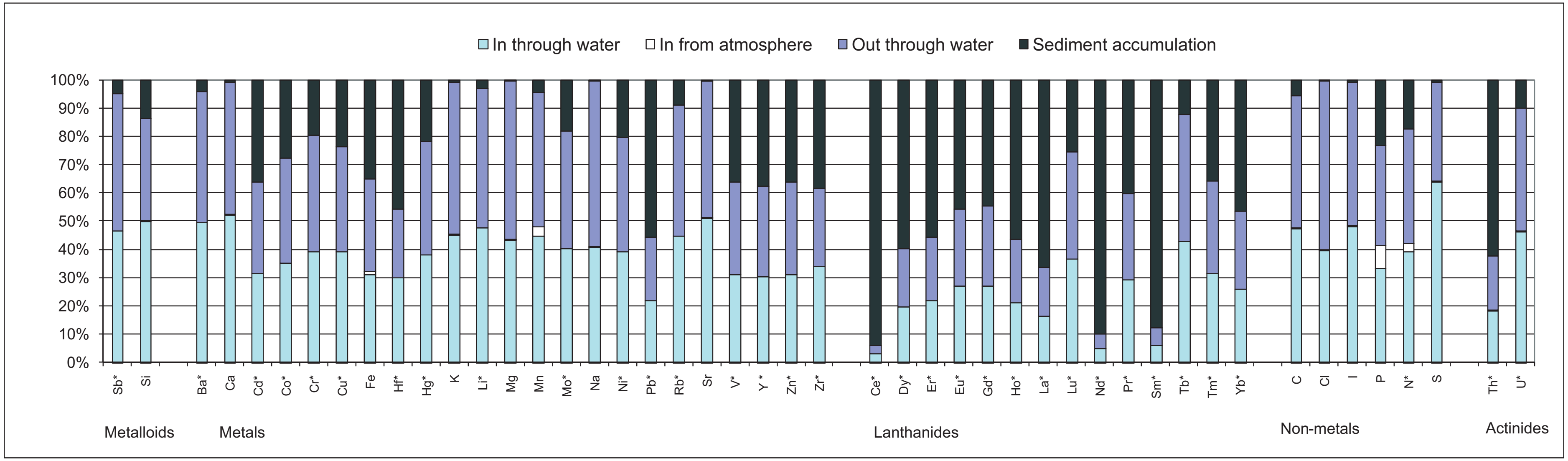

Figure 7-9. *Relative magnitude of different in- and outfluxes for a number of elements in the average lake in Forsmark. Elements included are those where all fluxes were determined or were only atmospheric deposition was lacking (indicated by *). All fluxes are estimated separately, i.e. sediment accumulation is estimated from sediment cores, in- and outflows are estimated from concentrations in inlets and outlets, and atmospheric deposition is estimated from concentrations in precipitation. The uncertainties in the estimated flows can lead to imbalance in the mass balances, e.g. higher outfluxes than influxes to the lake, which is the case for most lanthanides.*

Lake Puttan shows that in addition to lake size, the position of the lake within the catchment (i.e. the size of the catchment area) also influences the functioning of the lake. Properties of the elements also influence the flow pattern of the elements, and iodine, uranium and thorium are examples of this (further discussed in Section 7.3.4).

The most and least abundant elements in the fluxes (based on mass) are shown in Table 7-1. The largest sediment accumulation rates are seen for elements common in biota (carbon, calcium, silicon, nitrogen, sulphur and iron), whereas mercury and lanthanides show the lowest accumulation rates in accordance with their generally low abundance in the landscape. Among the 16 elements for which atmospheric deposition is available, some ions common in marine environments (chlorine, sodium, and sulphur) dominate along with carbon and nitrogen. The inflow as well as outflow via water is dominated by the same elements: carbon, chlorine, calcium, sodium and sulphur. The least common elements in inflow as well as outflow via water are mercury and some lanthanides.

The mass balances are associated with some uncertainties, and the mass balances are well balanced for only 14 elements (influxes vary between 75% and 110% of outfluxes). The mass balances for the lanthanides appear to be very unbalanced, with higher outfluxes than influxes (cf. /Tröjbom and Grolander 2010/). Confidence in the estimates of inflow and outflow via water is relatively high, whereas data on atmospheric deposition is lacking for many elements and the estimate of sediment accumulation is rather uncertain (further discussed in Section 7.6).

7.3.3 Detailed description of phosphorus pools and mass balances

Pools

The distribution of phosphorus between different ecosystem components is similar in the five lakes Bolundsfjärden, Eckarfjärden, Gällsboträsket, Puttan and Norra Bassängen (Table 7-2). The sediment contains by far the largest phosphorus pool, containing between 95 and 99.8% of total phosphorus in the lakes. The second largest pool is consumers followed by producers. Phosphorus deviates from most other elements in that primary producers usually contain most of the biotic pool of an element (Figure 7-8). However, this result is expected and in accordance with the literature since the phosphorus content of bacteria is high /Wetzel 2001/.

The distribution of phosphorus between the particulate and dissolved components is similar in the five lakes. In contrast to most other elements, a relatively large share of the abiotic phosphorus in water is present in the particulate component (Figure 7-4). The main reason for this is that inorganic phosphorus is often limiting for primary production and bacterial secondary production. Therefore, phosphorus available in the dissolved component is rapidly taken up by biota, and the concentrations of dissolved phosphorus remain low.

Although the distribution of phosphorus in the lake ecosystem shows a strong focus to the sediments in all five lakes, the phosphorus amount per unit area in the sediments differs among the lakes. This is a direct result of the sediment thickness: Gällsboträsket and Eckarfjärden are among the oldest lakes in the Forsmark area with thick sediment layers and high amounts of phosphorus bound in the sediments, whereas Norra Bassängen is one of the youngest lakes with a thin sediment layer and lower amount of phosphorus. Moreover, Norra Bassängen has been situated in an exposed wind direction before isolation from the Baltic Sea, resulting in very low sediment accumulation during the marine stage (see Chapter 8).

Table 7-1. Elements which show the largest and smallest mass fluxes (g y^{-1}) for each of the major in- and outfluxes in lakes in the Forsmark area. For example, the element with the highest sediment accumulation is carbon, followed by calcium and silicon, and the element least accumulated in the sediments is mercury. The sizes of the different fluxes are found in Appendix 12.

Flux	Ranking of elements with highest mass flux	Ranking of elements with lowest mass flux
Accumulation in sediment	C > Ca > Si > N > S > Fe	Tb > Ta > Lu > Tm > Hg
Atmospheric deposition	C > Cl > N > Na > S > Ca > K	Sr > I > U > Al > Th
Inflow via water	C > Ca > Cl > Na > S > Mg	Ho > Tm, Eu > Sm > Hg
Outflow via water	C > Cl > Ca > Na > S > Mg	Ho, Tm, Eu, Sm > Hg

Table 7-2. Absolute and relative sizes of phosphorus pools and fluxes in five lakes in the catchment Forsmark 2. (g P and % of total mass in the lake i.e. in all components of the system) (% of total in- or outflux). The last three rows show the net balance for each lake (as g P y^{-1} and %, respectively).

	Bolundsfjärden	Eckarfjärden	Gällsboträsket	Norra Bassängen	Puttan	Mean values, Forsmark Lake
Pools, g P (% of total P in the lake components)						
Producers	2×10^4 (0.1)	1×10^4 (0.01)	4×10^2 (0.01)	2×10^3 (0.9)	1×10^3 (0.2)	7×10^3 (0.04)
Consumers	1×10^5 (0.5)	5×10^4 (0.01)	2×10^3 (0.1)	7×10^3 (3.7)	6×10^3 (0.8)	3×10^4 (0.2)
Particulate phase of water	2×10^3 (0.01)	1×10^3 (0.001)	1×10^2 (0.004)	2×10^2 (0.1)	2×10^2 (0.02)	9×10^2 (0.003)
Dissolved phase of water	3×10^3 (0.01)	1×10^3 (0.002)	3×10^2 (0.01)	2×10^2 (0.1)	2×10^2 (0.03)	9×10^2 (0.004)
Upper sediment layer*	–	–	5×10^3 (0.1)	–	–	–
Deeper sediment layer	2×10^7 (99.4)	8×10^7 (99.9)	4×10^6 (99.8)	2×10^5 (95.3)	8×10^5 (98.96)	2×10^7 (99.8)
Fluxes, g P $year^{-1}$ (% of total influx/outflux)						
Inflow via water	1×10^4 (69)	3×10^3 (57)	5×10^3 (98)	1×10^4 (97)	4×10^2 (55)	6×10^3 (70)
Influx from air	5×10^3 (31)	2×10^3 (43)	1×10^2 (2)	4×10^2 (3)	3×10^2 (45)	2×10^3 (30)
Outflow via water	1×10^4 (48)	3×10^3 (32)	5×10^3 (94)	1×10^4 (93)	4×10^2 (31)	7×10^3 (60)
Net sediment accumulation	1×10^4 (52)	7×10^3 (68)	3×10^2 (6)	1×10^3 (7)	9×10^2 (69)	5×10^3 (40)
Net balance (g P $year^{-1}$)	**-1×10^4**	**-4×10^3**	**-2×10^2**	**-8×10^2**	**-6×10^2**	**-2×10^3**
Net balance (% of total influx)	**–71**	**–80**	**–5**	**–6**	**–85**	**–23**
Net balance (% of total outflux)	**–44**	**–44**	**–5**	**–5**	**–46**	**–19**

* An upper 1 cm sediment layer is only differentiated for Gällsboträsket, which lacks a microbial mat. This layer represents the oxygenated upper layer. In the other lakes, this layer is part of the microbial mat (layer consisting of microphytobenthos and benthic bacteria), which is part of the "producers" component.

The upper centimetre of the sediment is recognized as a separate component in Gällsboträsket (which lacks microphytobenthos) in order to differentiate a biologically active upper sediment layer. The deeper sediment component consists of the rest of the sediment. For the lakes with microphytobenthos, deeper sediment is the only sediment layer as the microphytobenthos belongs to the biotic component.

Mass balances

The most important flux differs among the lakes (Table 7-2). Inflow via water dominated in all lakes. However, for Bolundsfjärden, Eckarfjärden and Puttan, the influx via atmospheric deposition comprise a relatively large part of the total influx (31–45% of total influxes). In Gällsboträsket and Norra Bassängen, on the other hand, inflow via water totally dominates, comprising 95–96% of total phosphorus influx to the lakes. This is an effect of lake size and position in the catchment. In terms of quantity, inflow via water is largest in Bolundsfjärden and Norra Bassängen, which are situated the furthest downstream in the catchment. The amounts of phosphorus reaching the two lakes are of the same magnitude, but the proportion of this influx to the total influx is smaller for Bolundsfjärden because of the larger lake size and thereby larger amounts added via atmospheric deposition.

Outflux of phosphorus via accumulation in sediment is of the same magnitude as outflow via water for Bolundsfjärden, Eckarfjärden and Puttan. For Gällsboträsket and Norra Bassängen, outflow via water dominates. Although accumulation in sediment is the largest outflux from Puttan, the total accumulated amount is small compared to the amounts accumulated in the two larger lakes. The largest sediment accumulation is found in the larger lakes Bolundsfjärden and Eckarfjärden. Lakes of this type (oligotrophic hardwater lakes) are expected to function as phosphorus sinks, as co-precipitation of phosphorus and calcium from the water phase to the sediment is assumed to take place /Brunberg and Blomqvist 2000/. The large pool of phosphorus in lake sediments also indicates that this is the case.

In Bolundsfjärden, Eckarfjärden and Puttan, the annual influx of phosphorus is lower than the estimated size of the total biotic phosphorus pools in the lakes, whereas in Gällsboträsket and Norra Bassängen the biotic pools are smaller than the annual influx of phosphorus. The estimated pools and flows of phosphorus in Bolundsfjärden and Gällsboträsket are presented in Figure 7-10. Bolundsfjärden is one of the larger lakes in the area, whereas Gällsboträsket is one of the smaller.

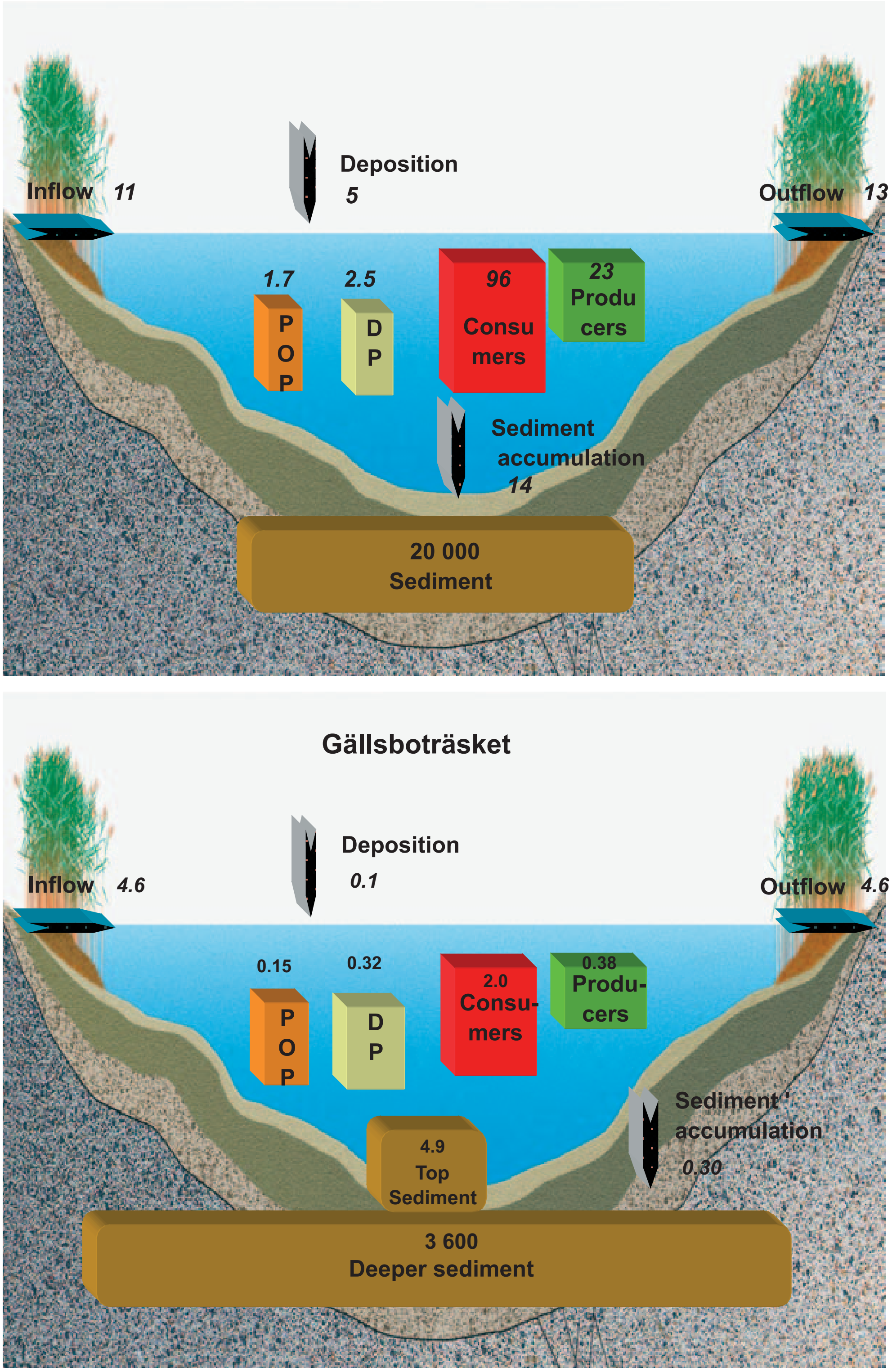

***Figure 7-10.** Phosphorus pools (kg P) and fluxes (kg P per year) in Bolundsfjärden (above) and Gällsboträsket (below). Note that the sediment pools are scaled differently than the other pools in order to fit all pools in the same picture.*

The total phosphorus pool in the lakes is relatively large compared to annual influxes and outfluxes. Accordingly, the phosphorus dynamics in these lakes might be dependent on internal circulation to a large degree. However, as no ecosystem budget for phosphorus has been calculated, we cannot determine the internal circulation, and the influx may be crucial for the functioning of the lake ecosystem. Sediment accumulation appears to be an important process in the phosphorus dynamics, and sediment is by far the largest phosphorus pool in the lakes.

The mass balances are somewhat unbalanced, with higher outfluxes than influxes for all lakes. The largest deficit is seen for Puttan (85% of total influx and 46% of total influx), Bolundsfjärden (71% of total influx and 44% of total outflux) and Eckarfjärden (80% of total influx and 44% of total outflux), whereas the mass balances for Gällsboträsket and Norra Bassängen show good agreement (only c. 5% deficit). The flux associated with largest uncertainties is sediment accumulation. Calculating sediment accumulation as the difference between the other in- and outfluxes in the mass balance indicates a rate about half of our estimates using phosphorus data from lake sediments. This is a realistic result as sediment accumulation can be expected to vary over time, and the estimates from lake sediments are long-term estimates.

7.3.4 Detailed description of pools and mass balances of iodine, uranium and thorium

As described in Section 7.1.1, iodine, uranium and thorium are elements with different sorption properties. Iodine is very mobile, thorium almost immobile, and uranium possess properties somewhere in between iodine and thorium. A description of the pools and mass balances for these elements in the five lakes Bolundsfjärden, Eckarfjärden, Gällsboträsket, Norra Bassängen and Puttan follows below in order to show how the different sorption properties influence the flow pattern of elements in lake ecosystems.

Pools

Iodine, thorium and uranium are all strongly concentrated in the abiotic pool, and particularly in the sediments (Tables 7-3, 7-4 and 7-5). This is a direct result of the large amounts of sediments in the lakes. As expected, thorium is the element with highest Kd value and the strongest focus to the sediment, which contains between 99.998 and 99.999% of total thorium in the 5 lakes. Iodine, the element with lowest Kd, is strongly concentrated in the sediments, but the relative amount (95.9 to 99.2% of total iodine in the lakes) is somewhat lower than for thorium. Uranium, with an intermediate Kd value, is concentrated in the sediments with relative amounts in between those of iodine and thorium (99.6–99.97% of total uranium in the five lakes). As in the case of phosphorus, Eckarfjärden and Gällsboträsket have a larger share of total iodine, uranium and thorium in the sediment component than Puttan, Bolundsfjärden and Norra Bassängen. This is a direct result of sediment thickness: Gällsboträsket and Eckarfjärden are among the oldest lakes in the Forsmark area with thick sediment layers leading to higher amounts of iodine, uranium and thorium than in the younger lakes with shallower sediment depths. The second largest pool of iodine and uranium is the pool dissolved in lake water, while for thorium the second largest pool is contained in the biota.

Between 0.7% and 3.5% of total iodine is dissolved in the lake water, whereas the amounts of iodine in the biota are low. The high solubility of iodine leads to only minor amounts of iodine in particulate matter in lake water in all five lakes (below the detection limit in three of the lakes). Data on the iodine content of bacteria are lacking, making it difficult to compare iodine content in producers and consumers. However, the available data indicate that iodine is concentrated in primary producers, as amounts in these are high, whereas amounts in consumers are low. This is in agreement with a study by /Kumblad and Bradshaw 2008/ showing that iodine was abundant in the plant species. Furthermore, /Kumblad and Bradshaw 2008/ state that marine macroalgae have a high ability to fix halide ions, which may be true also for the macroalgae in lakes as the iodine content in these are high. Fish contain very little iodine and all measurements on fish were below the detection limit.

Table 7-3. Iodine amounts (g) and fluxes (g y^{-1}) in five lakes in the catchment Forsmark 2. The last three rows show the net balance for each lake (as g y^{-1} and %, respectively). The particulate pool of iodine is below the detection limit in some lakes, noted as <d.l, and in the calculation of a mean value for iodine the concentrations in these lakes were set at 0.

	Bolunds-fjärden	Eckar-fjärden	Gällsbo-träsket	Norra Bassängen	Puttan	Average Lake
Pools, g iodine (% of total iodine pool in the lakes)						
Producers	266	124	5	21	17	87
Consumers	8	4	0.1	1	1	3
Particulate phase of water	< d.l.	41	0.4	< d.l.	< d.l.	
Dissolved phase of water	2,165	1,305	52	127	170	764
Upper sediment layer*	–	–	56	–	–	11
Deeper sediment layer	165,012	164,285	7,129	3,454	14,241	70,824
Fluxes (g year^{-1})						
Inflow via water	6,987	2,023	2,364	9,009	309	4,138
Influx from air	56	26	2	4	4	18
Outflow via water	8,270	2,023	2,364	9,066	309	4,406
Net sediment accumulation	258	120	6	20	17	84
Net balance (g year^{-1})	**–1,486**	**–94**	**–4**	**–73**	**–13**	**–334**
Net balance (% of total influx)	**–21**	**–5**	**–0.2**	**–1**	**–4**	**–7**
Net balance (% of total outflux)	**–17**	**–4**	**–0.2**	**–1**	**–4**	**–8**

* An upper 1 cm sediment layer is only differentiated for Gällsboträsket, which lacks a microphytobenthos. This layer represents the oxygenated upper layer. In the other lakes, this layer is part of the microbial mat (layer consisting of microphytobenthos), which is part of the "producers" component.

Table 7-4. Uranium amounts (g) and fluxes (g y^{-1}) in five lakes in the catchment Forsmark 2. The last three rows show the net balance for each lake (as g y^{-1} and %, respectively).

	Bolunds-fjärden	Eckar-fjärden	Gällsbo-träsket	Norra Bassän-gen	Puttan	Average lakes
Pools (g U)						
Producers	174	81	1	14	11	56
Consumers	0.2	0.1	0.003	0.01	0.01	0.1
Particulate phase of water	0.6	0.5	0.01	0.03	0.04	0.2
Dissolved phase of water	668	264	18	33	44	205
Upper regolith layer*	–	–	92	–	–	18
Deeper regolith layer	668,840	1,250,267	49,953	12,639	54,469	407,234
Fluxes (g U y^{-1})						
Inflow via water	2,645	977	1,012	2,822	99	1,511
Influx from air	7	3	0.2	1	0.5	2
Outflow via water	2,606	687	959	2,820	68	1,428
Net sediment accumulation	1,017	474	22	80	67	332
Net balance (g U year^{-1})	**–971**	**–180**	**32**	**–77**	**–35**	**–240**
Net balance (% of total influx)	**–37**	**–18**	**3**	**–3**	**–35**	**–16**
Net balance (% of total outflux)	**–27**	**–15**	**3**	**–3**	**–26**	**–14**

* An upper 1 cm sediment layer is only differentiated for Gällsboträsket, which lacksa microphytobenthos. This layer represents the oxygenated upper layer. In the other lakes, this layer is part of the microbial mat (layer consisting of microphytobenthos), which is part of the "producers" component.

Table 7-5. Thorium amounts (g) and fluxes (g y^{-1}) in five lakes in catchment Forsmark 2. The last three rows show the net balance for each lake (as g y^{-1} and %, respectively).

	Bolunds-fjärden	Eckar-fjärden	Gällsbo-träsket	Norra Bassängen	Puttan	Average lake
Pools (g Th)						
Producers	12	6	0,03	1	1	4
Consumers	0.2	0.1	0.003	0.02	0.01	0.01
Particulate phase of water	1	0.5	0.01	0.05	0.07	0.4
Dissolved phase of water	3	2	0.1	0.2	0.2	1.2
Upper sediment layer*	–	–	6	–	–	1
Deeper sediment layer	297,387	1,435,612	68,483	1,682	6,736	361,980
Fluxes (g Th year^{-1})						
Inflow via water	19	6	7	25	1	11
Influx from air	2	1	0.1	0.2	0.2	1
Outflow via water	23	6	7	25	1	12
Net sediment accumulation	120	56	3	9	8	39
Net balance (g Th year^{-1})	**–121**	**–55**	**–3**	**–9**	**–8**	**–39**
Net balance (% of total influx)	**–556**	**–812**	**–38**	**–37**	**–757**	**–320**
Net balance (% of total outflux)	**–89**	**–85**	**–28**	**–27**	**–88**	**–76**

* An upper 1 cm sediment layer is only differentiated for Gällsboträsket, which lacks microphytobenthos. This layer represents the oxygenated upper layer. In the other lakes, this layer is part of the microbial mat (layer consisting of microphytobenthos), which is part of the "producers" component.

Although the dissolved component of uranium is the second largest pool of uranium, this component contains small amounts of total uranium in the lakes, between 0.02% and 0.26%. The biotic pool is even smaller (0.001–0.1% of total uranium) and the particulate pool is negligible (0.00004–0.0001% of total uranium). Data on uranium in phytoplankton, bacterioplankton and benthic bacteria are lacking and it is therefore difficult to make any comparison between uranium content in producers and consumers. Available data indicate that uranium in the biotic pool is concentrated in benthic primary producers and the amounts in benthic fauna and fish are negligible (Figure 7-8).

In the case of thorium, the second largest pool (next to sediment) is contained in biota, with 0.004–0.06% of total thorium in the lakes. The dissolved component contains somewhat smaller amounts of thorium than the biotic component (0.0001–0.01% of total thorium), but approximately 3 times more thorium than the particulate component. As in the case of iodine and uranium, data are not available on the thorium content of bacteria, making it difficult to compare thorium content in producers and consumers. The thorium in the biota (excluding bacteria) is almost exclusively found in benthic primary producers, while the thorium content of the consumers is low. In the study by /Kumblad and Bradshaw 2008/, thorium concentrations were highest in benthic microalgae followed by phytoplankton and plants.

Mass balances

The mass balances of iodine, uranium and thorium show that the most important fluxes differ among the elements due to their sorption properties and mobility in the ecosystem. The distribution of fluxes for iodine (very mobile), uranium (intermediate) and thorium (almost immobile) is shown in Figure 7-11 and Tables 7-3, 7-4 and 7-5. As expected, the outflow via water is much more important for mobile iodine than for uranium (intermediate) and thorium (lowest fluxes). For uranium, outflow via water is the largest outflux, but accumulation in sediments is also an important process. Thorium accumulation in sediments is c. 3 times larger than outflow via water. A detailed description of the mass balances for iodine, thorium and uranium follows below.

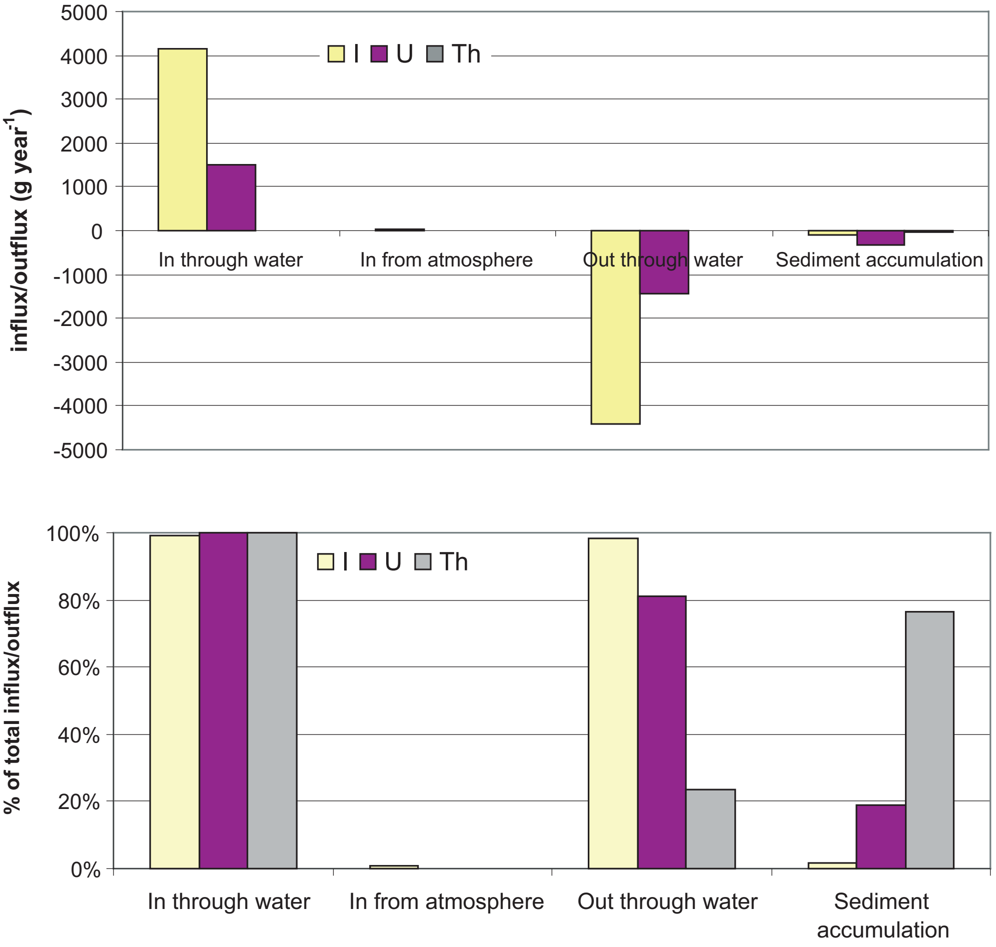

Figure 7-11. *Distribution of fluxes of iodine, uranium and thorium in the average Forsmark lake in weight and in % of influx and % of outflux, respectively.*

Iodine

The influx and outflux of iodine to the lakes are dominated by water in- and outflow. Water inflow constituted between 99 and 100% of the total iodine influx to the five investigated lakes. Likewise, the accumulation of iodine in sediment has little impact on outfluxes and between 94 and 100% of the iodine outflux is composed of outflow through water.

The mass balances for iodine are well balanced. The outfluxes are higher than the influxes, but the differences were small: for Gällsboträsket the iodine deficit is only 0.2% of total influx and outflux, and for Bolundsfjärden with the largest differences the net balance is 17% and 21% of total outfluxes and influxes, respectively. The atmospheric deposition can be considered uncertain as it is estimated as half the detection limit based on a few measurements below detection limit. However, although in the lower range, it is within the reported range of iodine concentrations in rainwater from a study in United Kingdom (range 0.4–5.9 µg L^{-1}) /Sheppard et al. 2002/.

With the exception of the sediments, which to a large degree are assumed not to be utilized by the biotic pool, the pools in the lakes are of the same size or smaller than the fluxes into and out of the five lakes. The largest amounts of iodine in the biotic pool were found in benthic primary producers. As the pools and fluxes are of the same size, it is possible that much of the incoming iodine will be incorporated into the food web.

Uranium

The influx of uranium is strongly dominated by inflow via water and atmospheric deposition comprises at most 0.3% of total influxes in the investigated lakes (Table 7-5). The outflux of uranium is dominated by outflow via water in all lakes (between 50% and 98% of total outflux in the five investigated lakes). Again, uranium fluxes in Norra Bassängen and Gällsboträsket were more dominated by outflow via water compared with the lakes Bolundsfjärden, Eckarfjärden and Puttan, where a relatively large portion of the outflux was through sediment accumulation: 28%, 41% and 50% of total outflux, respectively.

The mass balances for uranium for Gällsboträsket and Norra Bassängen are well balanced, and the net balance differs only by ±3% from the total in- and outfluxes in these lakes. In contrast, the mass balances in Bolundsfjärden, Eckarfjärden, Norra Bassängen and Puttan, are not as well balanced, andthere is a deficit of uranium in the mass balance, equivalent to 18–35% of total influx.

The influx and outflux of uranium are small compared with the total pool of uranium in the lake when the sediment is included. However, large amounts of the sediment can be considered to be unavailable to the biota. The influx is almost 27 times higher than the biotic pool in the average Forsmark lake, and unless there is a rapid recycling of uranium in the biotic pool, much of the uranium influx should pass through the lake without being incorporated in the food web. According to the model there is a relatively large sediment accumulation in some of the lakes that could be a uranium sink. However, the retention of Uranium at a landscape level is low (see /Tröjbom and Grolander 2010/) and it is possible that the relatively high accumulation in some of the lakes are due to uncertainties in the in-data rather than a high accumulation.

Thorium

The influx of thorium is dominated by the inflow via water. Atmospheric deposition is as low as 1% of the total influx in Gällsboträsket and Norra Bassängen but somewhat larger in Bolundsfjärden, Eckarfjärden and Puttan constituting between 11% and 17% of the total influx.

The outflux differs between the lakes. In the smaller lakes Gällsboträsket and Norra Bassängen the outflow via water dominates and comprises 72–73% of the total outflux. In the larger lakes Bolundsfjärden and Eckarfjärden and in Puttan, on the other hand, sediment accumulation is the dominant outflux, constituting 84–91% of the total outflux.

The mass balances for thorium are heavily unbalanced and the outflux exceeds the influx for all five lakes. Norra Bassängen and Gällsboträsket are the best balanced, but still the thorium deficits are 37% and 38% of the total influx for these lakes. The deficit is much higher for the other lakes, varying between 556% and 812% of the total influx. The most uncertain flow in the mass balance is sediment accumulation. The fact that Eckarfjärden, Bolundsfjärden and Puttan, the lakes with high sediment accumulation, have the most unbalanced mass balances indicates that sediment accumulation may be somewhat overestimated. Confidence and uncertainties in the mass balances will be further discussed in Section 7.6.

The influx and outflux of thorium are about 4 times larger than the biotic pool, while the flow is small compared to all pools in the lake. Some of the thorium influx could be incorporated in the food web, and according to the model large amounts are incorporated in the sediment through sediment accumulation.

7.4 Evaluation of elemental pools and fluxes for a number of elements in Laxemar-Simpevarp

The main results of the mass balances for a number of elements in Frisksjön are presented in Section 7.4.1, while more detailed results for phosphorus, iodine, uranium and thorium are presented in Sections 7.4.2 and 7.4.3. Detailed results for separate elements are found in Appendices 11 and 12.

7.4.1 Chemical composition of different ecosystem components

The most common elements in Frisksjön (all components: dissolved, particulate, biotic and sediment) are silicon (38% of total mass of investigated elements) and carbon (37% of total) (Figure 7-12). Other elements that make a substantial contribution to the total mass are sulphur (5%), nitrogen (5%), aluminium (4%), iron (4%), and calcium (2%), while all other elements comprise 1%

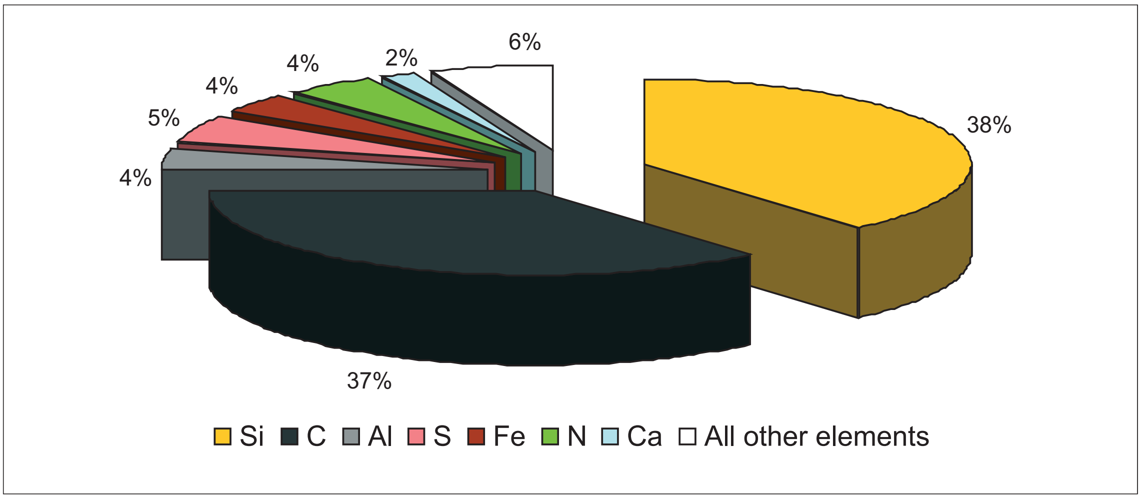

Figure 7-12. Distribution of elements (% of total investigated elements, based on mass) in Frisksjön (in all ecosystem components: dissolved, particulate, biotic and sediment). Note that not all elements are analyzed and that the elements of which water is composed, oxygen and hydrogen, are not included.

or less of the total mass of investigated elements in the lake (hydrogen and oxygen, the elements of which water is composed, are not included in the analysis).

The abiotic component (sediment, dissolved, and particulate) comprises 99.998% of the total mass of investigated elements, and this component accordingly has the same distribution of elements as the total lake ecosystem. All elements are strongly concentrated in the sediment component (Figure 7-13). The sediment constitutes between 97% and 100% of the total abiotic component and has the same distribution and share of major elements as the total distribution of the lake ecosystem. A large portion of the deeper sediment can be assumed to be unavailable for the biotic processes in the lake, and it is therefore of interest to evaluate the distribution of elements in the ecosystem when excluding the deeper sediments. After excluding the deeper sediment, many elements are still concentrated in the top sediment, but there are also some elements (Sb, Ca, Na, Mg, I, Cl, Br, F) that occur mainly in the dissolved phase (Figure 7-14). There are also considerable amounts of some elements in the biotic component, i.e. zinc, phosphorus and nitrogen. These elements are utilized by the biota, and the low amounts of these elements in the dissolved component are probably a result of rapid biotic uptake when the element is available in the water phase. Data on the chemical composition of bacteria are lacking for all elements except carbon, phosphorus, nitrogen and sulphur, so the biotic pool of many elements may be underestimated. Overall, the distribution of all elements is strongly concentrated in the abiotic components (mainly the sediments), and only a minor fraction of the elements is present in the biotic component.

In the abiotic component in lake water, most elements are mainly present in the dissolved component, and amounts in the particulate component are considerably smaller (Figure 7-15). The only exceptions are Si, Ga, Nb, Sn, Ti, Sm and Th, which are more abundant in the particulate than in the dissolved component. The elemental composition of both the dissolved and the particulate components differs from that in the sediments. The dissolved component is dominated by carbon and major ions such as chlorine, sodium and calcium (Figure 7-16), whereas the particulate component is strongly dominated by silicon, which comprises 79% of the total mass (Figure 7-17). The second and third most common elements in the particulate component are carbon and iron. The elemental composition of the particulate component is based on a single sampling occasion in April 2008, and it seems reasonable to assume that the sampling coincided with a diatom bloom. Diatoms are a phytoplankton group that incorporate silicon in their cell surfaces, and diatoms often form blooms in lakes in the early spring during circulation of the water column. Thus, the high content of silicon in the particulate component is probably not representative of the entire year. The relatively high iron content in the particulate component, on the other hand, is probably representative and caused by a high concentration of humic substances in the water.

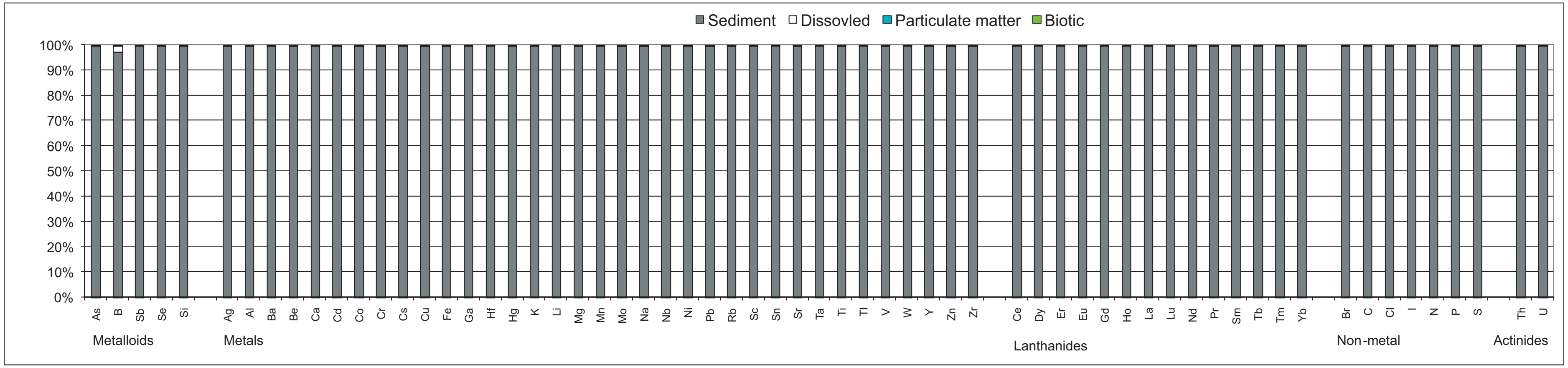

Figure 7-13. *Distribution of analyzed elements among the different components of the ecosystem in Frisksjön: sediment (black), dissolved in water (blue), particulate (white) and biotic (green). Sediment is totally dominant and is the only visible component in the figure.*

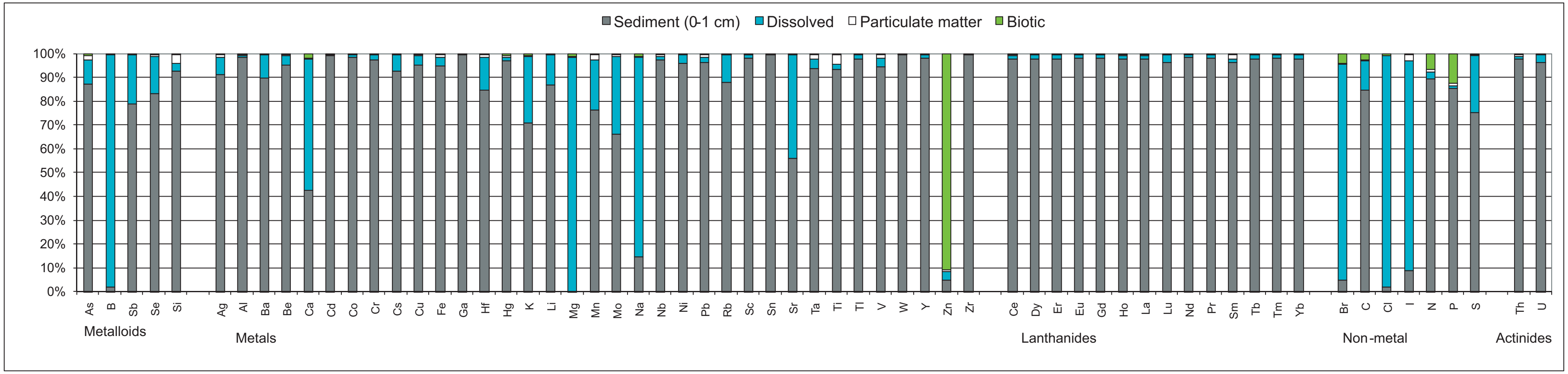

Figure 7-14. *Distribution of elements in percent between biotic, dissolved, top sediment and particulate components in Lake Frisksjön.*

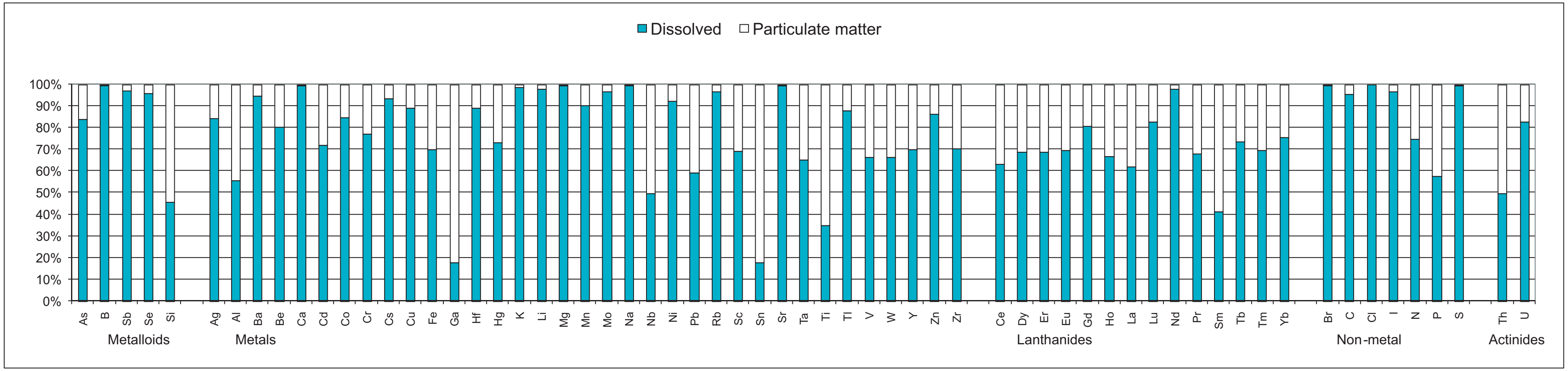

Figure 7-15. *Distribution of elements in percent between the dissolved and particulate components of the water in Frisksjön.*

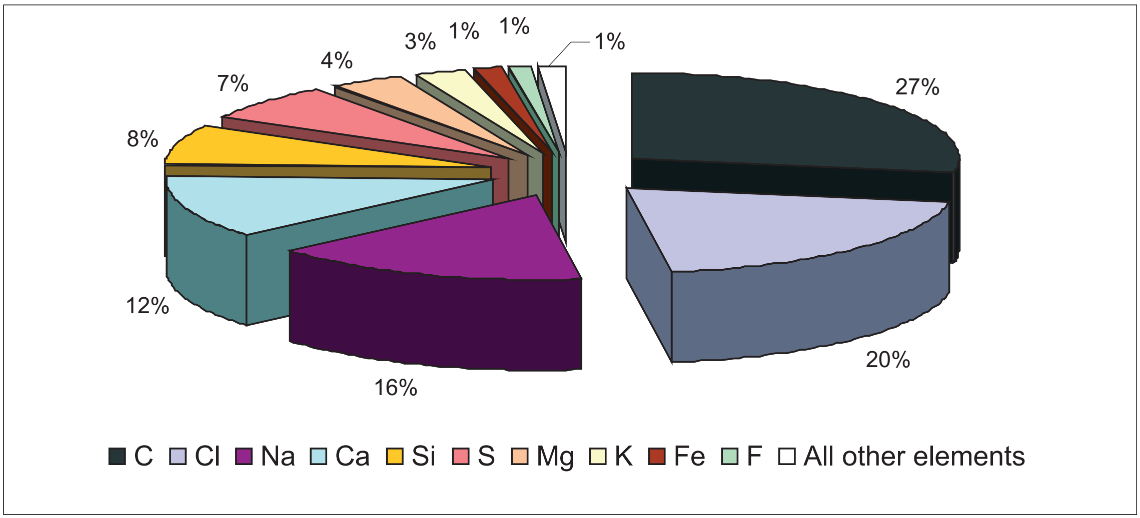

Figure 7-16. *Distribution of elements (% of total investigated elements, based on mass) in the dissolved component in Frisksjön. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included.*

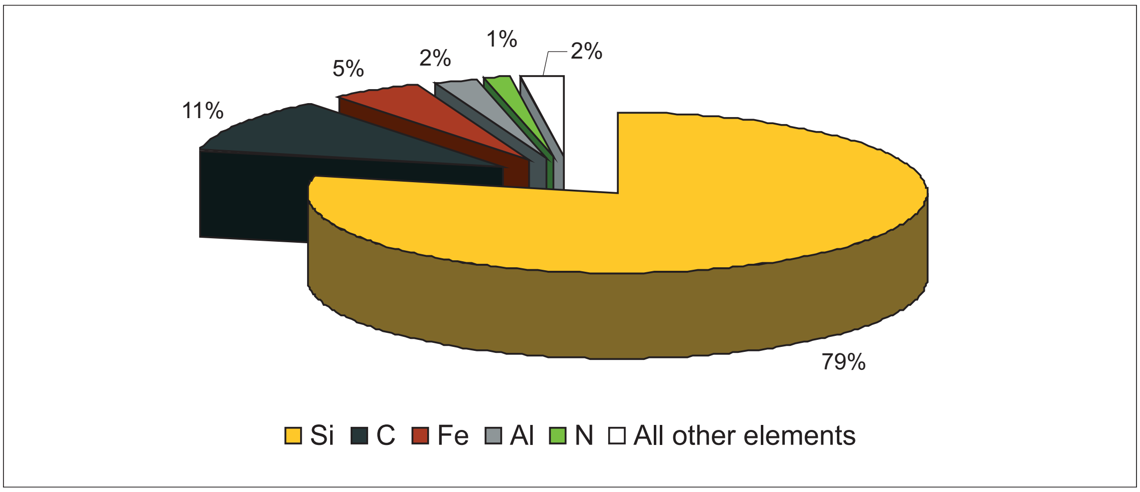

Figure 7-17. *Distribution of elements (% of total investigated elements, based on mass) in the particulate component in Frisksjön. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included. Moreover, this distribution is based on one measurement in April 2008. This may explain the high abundance of silicon as diatoms often form blooms at this time of the year.*

The biotic component, which comprises only 0.002% of total mass in Frisksjön, is dominated by carbon (64% of total biotic component), followed by nitrogen (12% of total biotic component, Figure 7-18). Calcium, silicon, phosphorus, sodium, chlorine and zinc each comprise 2% or more of the total mass of investigated elements in the biotic components, while each of the other elements constitute 1% or less.

Within the biotic components, there is a clear difference in distribution of elements among different functional groups (Figure 7-19). Metals are present in higher proportions in primary producers than lanthanides, which are strongly concentrated in consumers. In all, most elements are concentrated in the consumers, and on average 66% of all elements are present in consumers. Mercury is an element known for biomagnification in nature, so one would expect to find a high share of this element in the top predator fish. This is indeed the case, and 75% of biotic mercury is present in fish (this percentage is probably slightly lower as data for bacteria are lacking). Likewise, zinc and rubidium

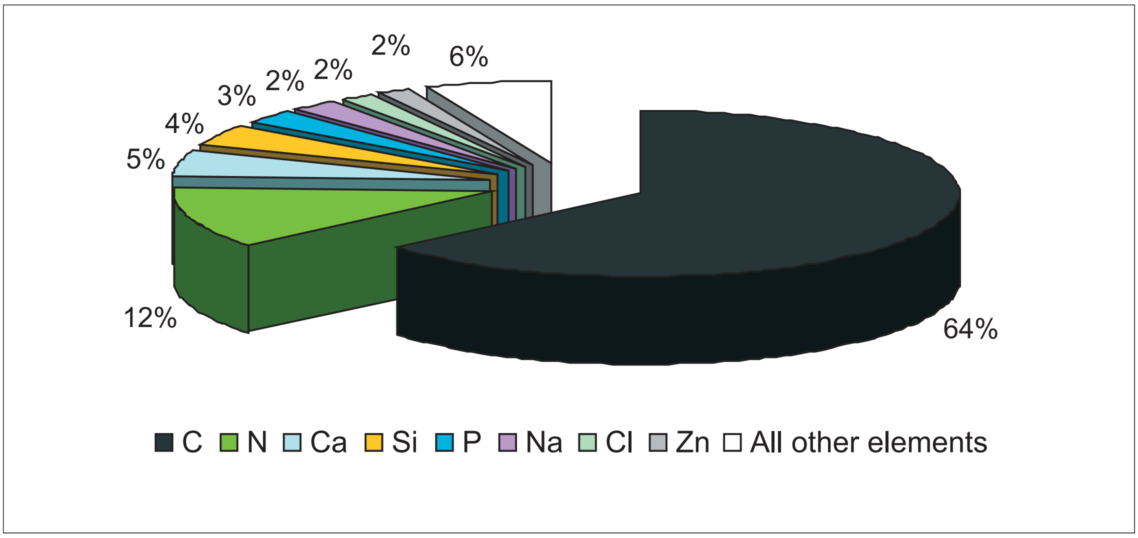

***Figure 7-18.** Distribution of elements (% of total investigated elements, based on mass) in the biotic component in Frisksjön. Note that not all elements are analyzed and the elements of which water is composed, oxygen and hydrogen, are not included. Moreover, data on bacteria are lacking for all elements except carbon, nitrogen, phosphorus and sulphur.*

are strongly concentrated in fish (99% and 60%, respectively, of the total biotic pools). Lanthanides have a strong concentration in zooplankton, while most metals tend to have a higher occurrence in benthic fauna. In addition to the lanthanides, bromine is also strongly concentrated in zooplankton. The reason for the concentration of bromine and lanthanides in zooplankton is unknown, but the concentration of bromine in zooplankton is also seen in the Forsmark lakes and in the marine areas /Wijnbladh et al. 2008/.

Data on the chemical composition of bacteria is lacking for all elements except carbon, phosphorus, nitrogen and sulphur, and this may affect the picture of the distribution of elements in the biotic components. A large portion of the biotic C, N, P and S is present in bacteria (69%, 67%, 88% and 57% of the total biotic mass of each element, respectively), and thus, the concentration of elements in the consumer part of the biotic component may be even larger than suggested by Figure 7-19.

7.4.2 Mass balances

We have data to estimate all 4 fluxes (in- and outflow through water, atmospheric deposition and accumulation in sediment) for 16 elements (Al, C, Ca, Cl, Fe, I, K, Mg, N, Na, P, S, Si, Sr, Th, U). For another 28 elements the only flux missing is deposition from atmosphere. For the 16 elements where data for all fluxes are available, deposition from the atmosphere was most often small. The mass balances for elements where data on atmospheric deposition are lacking are therefore also discussed in this section. A compilation of estimated elemental fluxes is presented in Appendix 12.

For the 16 elements were all fluxes are estimated, the inflow via water is the largest influx and the atmospheric deposition made up 14% or less of total influx (mean 3%, median 1.2% of total influx). It is therefore reasonable to conclude that atmospheric deposition makes a small contribution for most elements. For most elements, sediment accumulation is the dominant outflux. This is particularly true for the lanthanides, where between 75% and 99% of the total outfluxes consist of sediment accumulation (Figure 7-20). The ions Ca, Mg, Na, Cl and S, which have a relatively large share of their total pools in the dissolved component, have outflow via water as the dominant outflux. The dominant outflux is via water for C, Ba and Sr as well, but for all other elements sediment accumulation is the dominant outflux from the system.

Most of the mass balances are not balanced and the outfluxes often exceed the influxes. The mass balances are well balanced for only 7 of the elements (Ca, Cl, I, Mg, Na, S, Sr), with influxes between 81% and 108% of outfluxes. The uncertainties in the mass balances will be further discussed in Section 7.6.

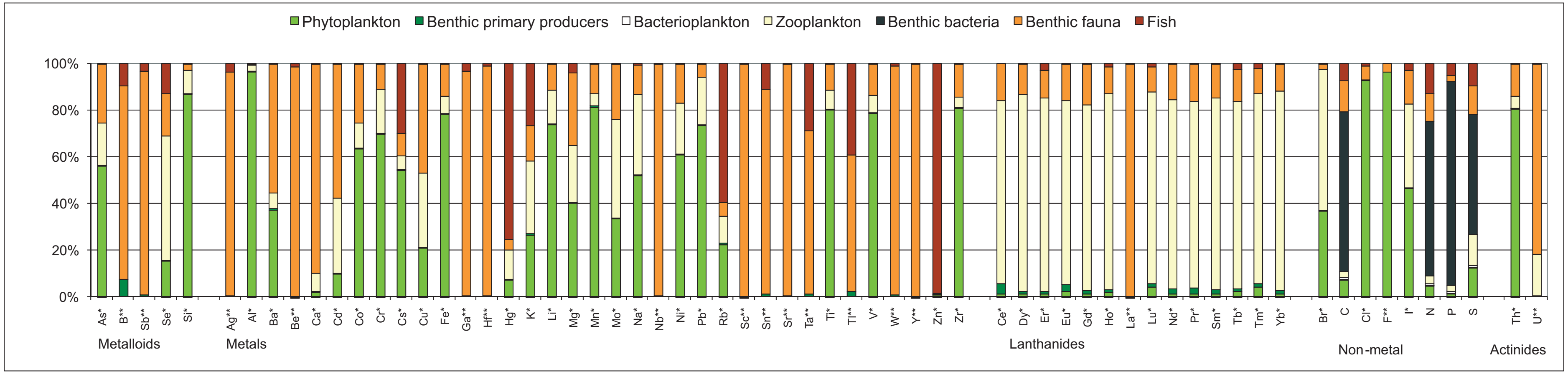

Figure 7-19. *Distribution of a number of elements among the biotic components of the ecosystem in Frisksjön. * indicates missing data for bacterioplankton and benthic bacteria. ** indicates missing data for at least one more functional group in addition to bacterioplankton and benthic bacteria (for further information of missing data see Appendix 6).*

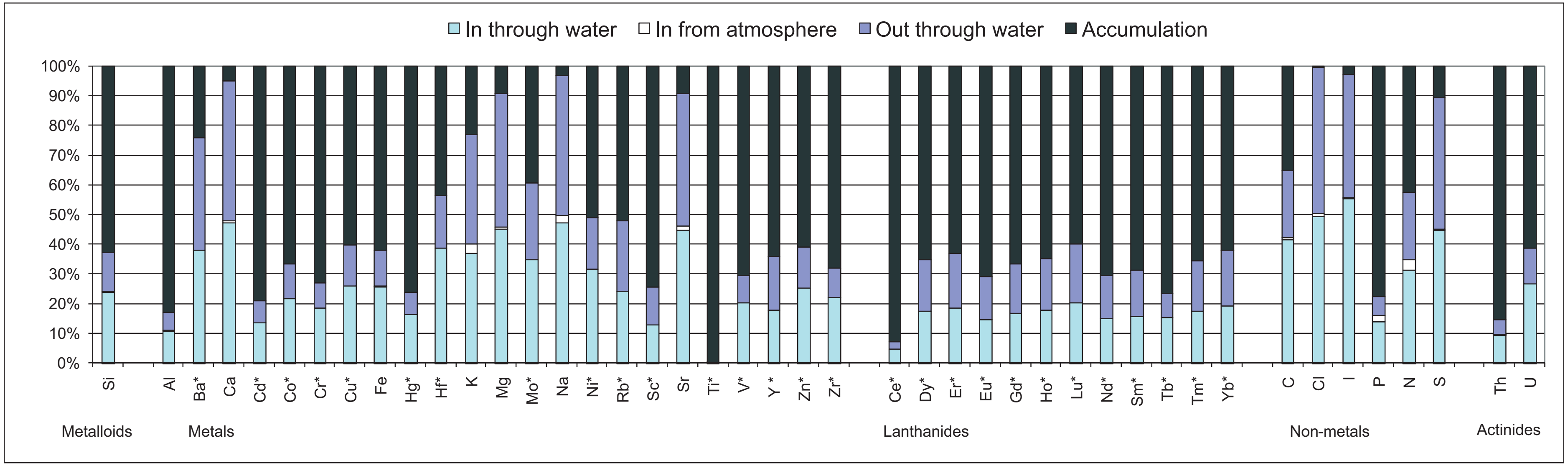

Figure 7-20. *Relative magnitude of different in- and outfluxes for a number of elements in Frisksjön. Elements included are those where all fluxes were determined or where only atmospheric deposition was lacking (indicated by *). All fluxes are estimated separately: sediment accumulation is estimated from sediment cores, in- and outflows are estimated from concentrations in inlets and outlets, and atmospheric deposition is estimated from concentrations in precipitation. The uncertainties in the estimated flows can thereby lead to imbalance in the mass balances, e.g. higher outfluxes than influxes to the lake, which is the case for most lanthanides.*

The most and least common elements in the fluxes (based on mass) are shown in Table 7-6. The most common elements in sediment accumulation were silicon, carbon, iron, aluminium, sulphur and nitrogen. Silicon, carbon and nitrogen are common elements in biota, whereas iron is commonly associated to humic substances. Certain metalloids and metals – silver, mercury tantalum and thallium – have the lowest accumulation rate in sediment in accordance with their uncommonness in nature. Among the 16 elements for which atmospheric deposition has been measured, certain ions (Cl, Na and Ca) dominate together with carbon. Inflow as well as outflow via water is dominated by carbon, sulphur and calcium. The fourth most common element in the inflow is silicon, but this element is found in the sixth place among the elements most common in outflow. This can be explained by high sediment accumulation of silicon, and the lakes can be considered a sink for this element (cf. /Tröjbom et al. 2008/). Mercury is the least common elements in inflow as well as outflow via water.

7.4.3 Detailed description of phosphorus pools and mass balances

Pool

The estimated pools and fluxes of phosphorus in Frisksjön are presented in Figure 7-21 and Table 7-7. The sediment layer is by far the largest phosphorus pool and almost 100% of the total amounts of phosphorus are allocated there. This is expected considering the large amounts of sediments. However, even when the deeper sediment is excluded and only the top centimetre of sediment is included, there is a strong allocation of phosphorus to the sediment pool (c. 90%). The second largest pool of phosphorus is found in the consumers, followed by the dissolved and particulate pools in lake water. Bacteria constitute the major part of the biotic biomass in the lake, so the concentration of biotic phosphorus in consumers is expected, considering the high phosphorus content of bacteria. The phosphorus pool in the primary producers is small.

Mass balance

The influx of phosphorus into Frisksjön is dominated by the inflow via water, which is about one order of magnitude larger than the influx via air (Figure 7-21 and Table 7-7). Outfluxes of phosphorus are clearly dominated by sediment accumulation, which is one order of magnitude higher than the outflow via water. The inflow via water is somewhat higher than the outflow via water, but the difference is not enough to balance the high sediment accumulation. There is a deficit of 8.5×10^4 g P y^{-1} which corresponds to over 400% of the total influx, or 81% of the total outfluxes. Thus, there are large uncertainties in the mass balance, which will be further discussed in Section 7.6.

The phosphorus pool in biota is about twice as large as the annual phosphorus influx, and the phosphorus pool in the top sediment is c. 10 times larger than the annual influxes (inflow and deposition). Thus, the lakes are probably more influenced by internal circulation of phosphorus than phosphorus entering the lake from the catchment. Phosphorus is often a limiting nutrient in lakes, and considering the fact that the biotic pool of phosphorus is larger than the amount of phosphorus entering the lake, it is reasonable to assume that much of the phosphorus influx will be incorporated in the food web.

In conclusion, sedimentation appears to be an important process in the dynamics of phosphorus, and the sediments contain by far the largest phosphorus pool in the lake.

Table 7-6. Most and least common elements in the fluxes to and from Frisksjön, based on amounts (g year^{-1}) of elements that show the highest and lowest mass fluxes (g y^{-1}) for each of the major in- and outfluxes in lakes in Frisksjön. For example, the element with the highest sediment accumulation is silicon, followed by carbon and iron, and the elements least accumulated in the sediments are silver and mercury. The sizes of the different flows are found in Appendix 12.

Flux	Ranking of elements with highes mass flux	Ranking of elements with lowest mass flux
Accumulation in sediment	Si> C > Fe > Al > S > N	Sb > Tl > TA > Hg > Ag
Atmospheric deposition	Cl > C > Na > Ca > N	I > U > Al > Th
Inflow via water	C > S > Ca > Si > Cl > Na	Lu> Tm > Ti > Hg
Outflow via water	C > S > Ca > Cl > Na > Si	Cd > Tb > Ti > Hg

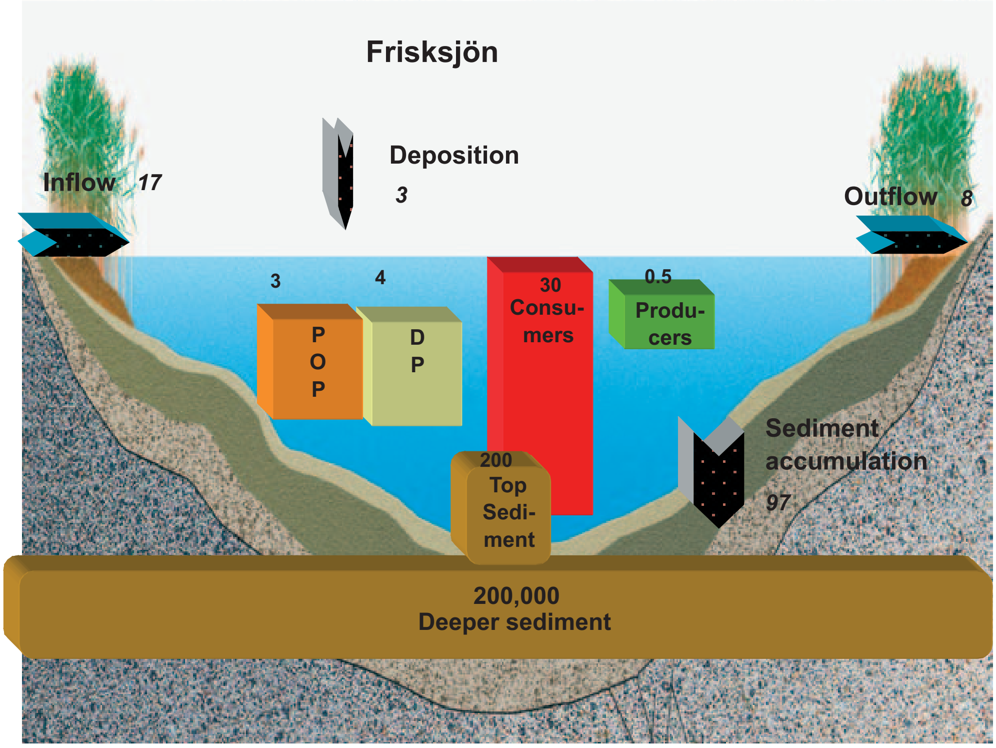

Figure 7-21. *Phosphorus pools (kg P) and fluxes (kg P per year) in Frisksjön). Note that the sediment pools are scaled differently than the other pools in order to fit all pools in the same picture.*

Table 7-7. Amounts (g) and fluxes (g y^{-1}) of phosphorus, iodine, uranium and thorium in Frisksjön. The last three rows show the net balance (as g y^{-1} and % of influx/outflux, respectively).

	Phosphorus	Iodine	Uranium	Thorium
Pools, g (% of total pools)				
Producers	5×10^{2} (0.0002)	5×10^{0} (0.0001)	5×10^{-4} (0.00000003)	4×10^{-1} (0.00005)
Consumers	3×10^{4} (0.02)	6×10^{0} (0.0001)	3×10^{-1} (0.00002)	1×10^{-1} (0.00001)
Particulate phase of water	3×10^{3} (0.001)	2×10^{2} (0.01)	1×10^{1} (0.001)	2×10^{1} (0.002)
Dissolved phase of water	4×10^{3} (0.002)	6×10^{3} (0.1)	7×10^{1} (0.003)	2×10^{1} (0.002)
Upper sediment (0–1 cm)	2×10^{5} (0.10)	6×10^{2} (0.02)	2×10^{3} (0.1)	2×10^{3} (0.2)
Deeper sediment	2×10^{8} (99.9)	4×10^{6} (99.8)	2×10^{6} (99.9)	9×10^{5} (99.8)
Fluxes, g year^{-1}, (% of total influx/outflux)				
Inflow via water	$+2\times10^{4}$ (+86)	4.5×10^{3} (+99.7)	2.5×10^{2} (99)	5×10^{1} (99)
influx from air	$+3\times10^{3}$ (+14)	1.5×10^{1} (+0.3)	2×10^{0} (1)	6×10^{-1} (1)
Outflow via water	-8×10^{3} (–8)	4.5×10^{3} (–95)	2×10^{2} (25)	3×10^{1} (6)
Net sediment accumulation	-1×10^{5} (–92)	3×10^{2} (5)	6.5×10^{2} (75)	5×10^{2} (94)
Net balance (g P year^{-1})	**-9×10^{4}**	**-2×10^{2}**	**–618**	**–445**
Net balance (% of total influx)	**–427**	**–5**	**–246**	**–849**
Net balance (% of total outflux)	**–81**	**–5**	**–71**	**–89**

7.4.4 Pools and mass balances for iodine, thorium and uranium

As described in Section 7.1.1, iodine, uranium and thorium are elements with different sorption properties. Iodine is very mobile, thorium almost immobile, and uranium possess properties somewhere in between iodine and thorium. A description of the pools and mass balances for these elements follows below.

Pools

As in the Forsmark lakes, iodine, uranium and thorium are all strongly concentrated in the sediment pool in Friskjön (Table 7-7). In the biotic pools, most of the elements are concentrated in benthic primary producers. A detailed description of the pools for each of the three elements follows below:

Iodine is strongly concentrated in the sediments (99.8%, Table 7-7). This is due to the very thick layers of sediment. If the deeper sediments are subtracted, the most important pool of iodine is instead the dissolved component (0.1% of total iodine in the lake). This is in accordance with the mobility of iodine in water. The third and fourth largest pools of iodine are the top sediment component followed by the particulate component. The biotic components contain little iodine in comparison with the abiotic components (only 0.0002% of total iodine).

Of the biotic pool, producers and consumers are of equal importance. However, data on iodine in bacteria are lacking, so the consumers may have a higher share of the total iodine than is shown here. In consumers, more iodine is found in zooplankton than benthic fauna. Little iodine is found in fish. In the study by /Kumblad and Bradshaw 2008/ iodine was most abundant in the plant species. They state that marine macroalgae have a high ability to fix halide ions and that many different halogenated compounds have been detected in red and brown algae. In Frisksjön, the biomass of plant species is low and thus it is reasonable that our result indicate a concentration of iodine in consumers.

The largest pool of uranium is deep sediments, where 99.9% (1,990 kg) of total uranium occurs (Table 7-7). The second most abundant pool of uranium is the top 1 centimetre of the sediment (0.1% of total uranium), illustrating the very strong concentration of uranium in the sediments. The dissolved and particulate pools contain much less uranium (0.02% each of total uranium in the lake), and the amounts in biota are almost negligible in comparison with the abiotic pools (0.00006% of total uranium). Data for uranium in bacterioplankton, benthic bacteria and phytoplankton is lacking in the biotic pool. Excluding the microbiota, available data indicate that uranium is concentrated in benthic fauna, whereas concentrations in fish are very low.

Like uranium, thorium is strongly concentrated in the sediments, and 99.8% of the total thorium in the lake is found in the deeper sediments while another 0.2% is found in the upper sediment. The dissolved and particulate fractions contain only 0.002% each of the total thorium, and the thorium content of the biota is negligible. In contrast to iodine and uranium, biotic thorium is more abundant in producers than consumers. The thorium content in biota (excluding bacteria) is concentrated in phytoplankton, where 80% of total biotic thorium occurs. The most important consumers in terms of thorium are benthic fauna, while fish and zooplankton have very low thorium contents. In the study by /Kumblad and Bradshaw 2008/, thorium concentrations were highest in benthic microalgae followed by phytoplankton and plants. Among the animal species analyzed, *Theodoxus fluviatilis* and *Idotea spp* (both benthic grazers) had the highest concentrations. Thus the concentration of thorium in phytoplankton and benthic fauna in this study agrees very well with the study by /Kumblad and Bradshaw 2008/.

Mass balances

Similar to Forsmark, the mass balances of iodine, uranium and thorium show that the most important flows differ among the elements due to their sorption properties and mobility in the ecosystem. The distribution of fluxes for iodine (very mobile), uranium (intermediate) and thorium (almost immobile), are shown in Figure 7-22 and Table 7-7. As expected, the outflow via water is much more important for the mobile iodine than for uranium (intermediate) and thorium (lowest flows).

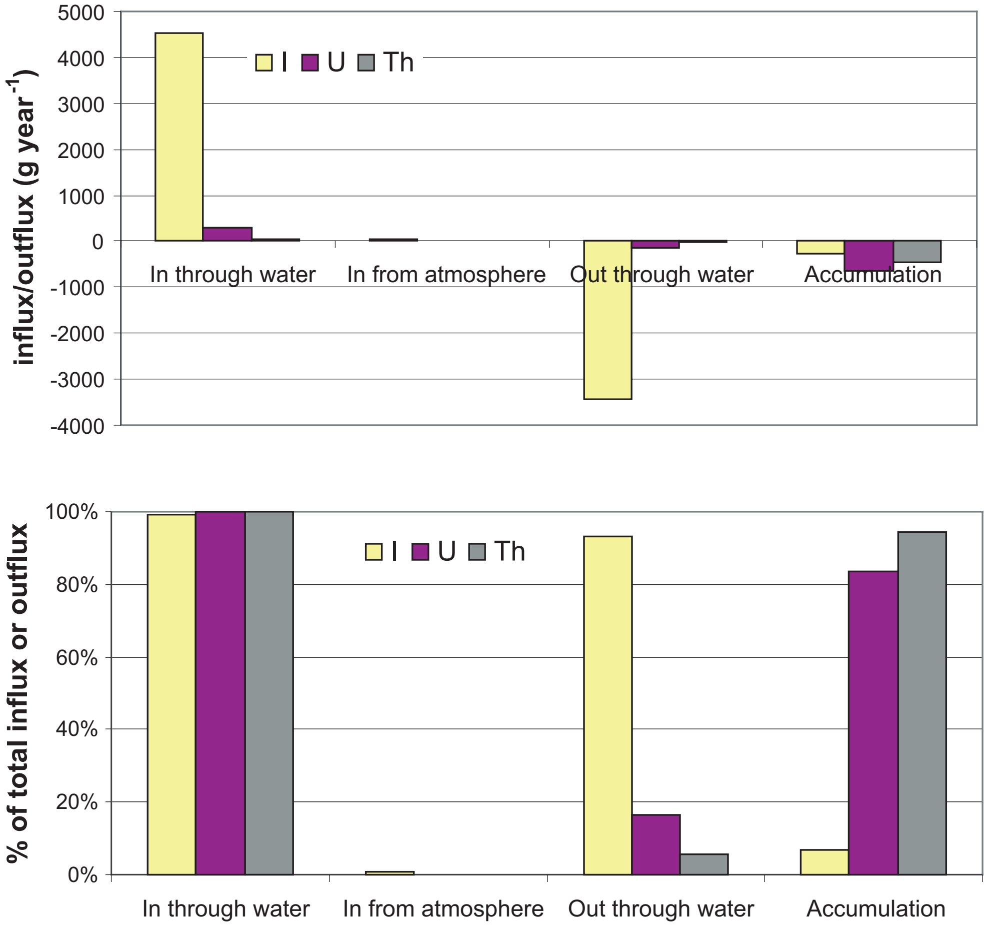

Figure 7-22. *Distribution among fluxes of iodine, uranium and thorium in Frisksjön (% of influx and % of outflux).*

Iodine

As expected, the influx of iodine is dominated by inflow via water and atmospheric deposition makes up small share (0.3%) of total influx. The influx via deposition was always below detection limit in the site measurements but the estimate of half detection limit seem reasonable as it is within the lower range of reported iodine precipitation in an English study /Sheppard et al. 2002/. The calculated sediment accumulation is the largest outflux of iodine from the system. The mass balance of iodine is relatively well balanced.

Influx of iodine is almost twice the size of the biotic pool of iodine. Since iodine plays an active role in biota it is possible that incoming iodine will be incorporated into the food web but the majority of iodine should pass through the lake with the flowing water.

Uranium

The mass balance for uranium indicates that the influx via water dominate the total influx of uranium. The influx of uranium via atmospheric deposition is not site specific, but literature estimates indicate that influx via the atmosphere is negligible in comparison to the inflow via water. The outflux of uranium is dominated by sediment accumulation, which comprises 88% of the total outflux.

The mass balance for uranium is very unbalanced with 618 g lower influx than outflux, equivalent to 246% of the total influx and 71% of the total outflux. The uncertainties in the mass balance will be discussed further in Section 7.6.

The influx of uranium is much larger than the biotic pool, and unless there is a rapid cycling of uranium in biota there is a small probability for uranium entering the lake to be incorporated into the food web. However, there is a large sediment accumulation and large amounts of uranium entering the lake may be bound in the sediment.

Thorium

The mass balance for thorium indicates that inflow totally dominates the total influx of thorium to Frisksjön. The influx of thorium via atmospheric deposition is not site-specific, but literature estimates indicate that the influx via the atmosphere is negligible in comparison to the inflow via water. The inflow via water is almost twice as high as the outflow via the outlet. Nevertheless, the outflux of thorium greatly exceeds the influx due to high accumulation of thorium in the sediments. The mass balance for thorium is not balanced and the outflux exceeds the influx by 445 g (equivalent to 849% of the total influx and 89% of the total outflux). The uncertainties in the mass balance will be further discussed in Section 7.6.

The influx of thorium is much larger than the biotic pool, and unless there is a rapid cycling of thorium in the biota there is a small probability for thorium entering the lake to be incorporated into the food web. However, there is a large sediment accumulation and large amounts of thorium entering the lake may be bound in the sediment.

7.5 Comparison of element pools and fluxes between Forsmark and the Laxemar-Simpevarp lakes

In this section, the lakes in Forsmark and Laxemar-Simpevarp are compared with each other in terms of distribution of elements between different components in the ecosystems. In addition, the main results of the mass balances are compared between the sites. Since these kinds of thorough mass balances are very rare in the literature, the comparison between sites provides some information as to whether the results are representative of Sweden or whether they should be viewed as site-specific.

7.5.1 Pools of elements in different components of the lake ecosystems

Both in Forsmark and Laxemar-Simpevarp, the sediment is the largest component in terms of mass of elements. The sediment therefore has a large impact on the elemental composition in both areas. The relative chemical composition in the Forsmark and Laxemar-Simpevarp lakes is similar, silicon being the most common element, followed by carbon. Carbon, sulphur and nitrogen comprise larger fractions of the sediments in Frisksjön than in the average Forsmark lake, while aluminium, potassium and magnesium contribute more to the total weight of elements in the average Forsmark lake than in Frisksjön.

The dissolved component in both areas is dominated by carbon, iron chlorine, sodium, calcium and manganese, although the order differs somewhat between the sites (Figure 7-5 and 7-13). Contribution of calcium from calcareous soils as well as a more recent emergence from the sea leads to a stronger marine influence (higher concentrations of Ca Cl, K, Mg) in Forsmark compared to Laxemar-Simpevarp.

There are higher concentrations of particulate matter in Frisksjön than in the Forsmark lakes. The particulate component in the water has a somewhat different elemental composition in the two areas. Particulate matter in the Forsmark lakes is strongly dominated by carbon, followed by nitrogen, calcium and silicon (Figure 7-6). In Frisksjön, on the other hand, particulate matter is totally dominated by silicon, followed by carbon and iron (Figure 7-14). The strong dominance of silicon in the particulate pool in Frisksjön is most probably caused by a diatom bloom during sampling. The estimated chemical composition of particulate matter in both areas is based on one sampling in April 2008 and may thus not be representative of the entire year. The only exceptions are carbon, nitrogen and phosphorus, for which long-term measurements are available. The particulate pool in the average Forsmark lake does not show any signs of a diatom bloom, but the elemental composition indicates biotic origin as the carbon to nitrogen ratio is close to the Redfield ratio (7:1 in weight). As discussed in earlier chapters, calcium concentrations are high in Forsmark and iron concentrations are high due to the high humic content of Frisksjön.

The biotic component is much larger in the Forsmark lakes compared to Frisksjön. This is mainly caused by benthic primary producers which weight is several orders of magnitude higher in the Forsmark lakes than in Frisksjön. Accordingly, much of the element pool in Forsmark is focused to benthic primary producers whereas the elements are more evenly distributed between organism groups in Laxemar (see Figures 7-8 and 7-19).

7.5.2 Fluxes of elements

In both areas, the inflow via water is the main influx to the lakes. In Laxemar-Simpevarp the largest outflux of elements is sediment accumulation for most elements and especially the lanthanides. In Forsmark, the most important outflux differs somewhat between elements. For metalloids, metals and non-metals, outflow via water is the most important outflux, while for lanthanides, as in Laxemar-Simpevarp, the most important outflux is accumulation in sediments (Figure 7-9). However, the importance of different outfluxes differs among the lakes in Forsmark. In three of five lakes (Bolundsfjärden, Eckarfjärden and Puttan), accumulation in sediment is the dominant outflux for most elements, while in the other two (Gällsboträsket and Norra Bassängen) outflow via water dominates for almost all elements. It is evident that in Forsmark, lake size and position in the catchments greatly influence the distribution of fluxes.

In addition to lake size and position in catchments, the properties of the elements (e.g. sorption properties) also influence the flow pattern of the elements. In both Forsmark and Laxemar-Simpevarp, outflow via water is much more important for soluble iodine than for uranium (intermediate solubility) and thorium (almost immobile). When it comes to uranium, outflow via water is the largest outflux, but accumulation in sediments is also an important process. Thorium accumulation in sediments is c. 3 and 17 times larger than outflow via water in Forsmark and Laxemar-Simpevarp, respectively.

The elements that account for the largest mass fluxes are similar between the sites. The largest sediment accumulation in mass is accounted for by elements common in biota (carbon, silicon, nitrogen, calcium, iron, sulphur) in both areas but in somewhat different orders. In Forsmark, calcium accumulation in sediments is relatively greater than in Frisksjön, and in Frisksjön the relative importance of iron is greater than in Forsmark. Ions common in the marine area, Na and Cl, show the largest atmospheric deposition in both areas. Carbon, calcium and sulphur show large influxes and outfluxes via water in both areas, although the relative importance of the fluxes is different between the sites.

7.6 Confidence and uncertainties in the mass balance results

The estimates of pools and fluxes of different elements in lakes in the two investigated areas are based on data from extensive site investigations. Generally, the estimated pools and mass balances in the Forsmark lakes can be considered reliable for most elements. In the case of Frisksjön in the Laxemar-Simpevarp area, the estimated pools can be considered relatively reliable, while the estimated flows of elements in the mass balances are associated with more uncertainties. A detailed description of the confidence and uncertainties of the different types of estimates follows below.

7.6.1 Forsmark

Pools

Site-specific measurements are available for all ecosystem components in the Forsmark lakes and confidence in the pool estimates is high. The estimated pools of different elements in particulate matter in lake water, in biota, and in sediments are associated with some uncertainties with regard to absolute numbers, but the orders of magnitude of the estimates are most probably correct. The estimated pools of different elements dissolved in lake water are based on site-specific data from several lakes and several years and can be considered reliable.

Data on the pool of elements dissolved in water are available for 18 sampling sites for the period March 2002–June 2004, and for 9 of these sampling sites for the period July 2004–June 2006 as well, giving these estimates a relatively good resolution in both time and space.

The pools of **particulate** carbon, nitrogen, and phosphorus are available for the same time period and sampling stations as the elements in the dissolved component and can be regarded as reliable estimates with good resolution in time and space. The estimated pools of other elements in particulate matter are, however, based on a single sampling performed in spring 2008. Using the results from this sampling to estimate the mean annual pool of different elements in particulate matter naturally entails relatively high uncertainty in the estimates. Moreover, the particulate fraction also includes the living biota. No estimate of living biota was made at the same occasion as suspended material and the living biota has not been subtracted from the particulate component in the result and thus the particulate fraction may be somewhat overestimated. However, as the data are site-specific they provide high confidence in the order of magnitude of the pools of elements in the particulate component.

The largest uncertainty in pools of elements in the **biotic component** stems from the lack of data on the chemical composition of bacteria for all elements except phosphorus, nitrogen, sulphur and carbon. This of course leads to uncertainties in the distribution of the elements within the biotic component. A relatively large share of biotic carbon, nitrogen, phosphorus and sulphur is present in bacteria. This is particularly true of phosphorus, as phosphorus concentrations in bacteria are higher than in other organisms. The concentrations of most elements in bacteria will probably be proportionate to the concentration of carbon, sulphur and nitrogen, but the possibility cannot be excluded that some trace elements will, like phosphorus, be highly concentrated in bacteria. Either way, it is clear that most elements are probably present in consumers to a considerably greater degree than presented. In the case of other organisms, the elemental composition data for biotic pools is a reliable estimate, since it is mainly site-specific. There are relatively few replicates, which causes some uncertainties, but the available replicates show low variation for most functional groups. Biomass data and chemical composition are used to estimate the pools of different elements. Although small, uncertainties are of course also associated with the biomass data (further discussed in Section 5.6.1).

The pools of elements in the **sediment component** are highly dependent on the estimated sediment volume. The volumes are based on average values of layer thickness from lake-specific stratigraphical data measured in field. The representativity of these average values is dependent on the number of sampling points used and their spatial resolution. The number of sampling points in each lake was adjusted to the size of the lake basin (fewer points in smaller lakes, see /Hedenström 2004/). In the calculation of average sediment thickness, data points lacking organic sediments were excluded, probably resulting in overestimated sediment volumes. On the other hand, the sampler used in the investigations does not sample the top sediment, leading to underestimation of sediment volumes. Another way to estimate the volume of sediment layers is to use the geometrical regolith depth model (RDM) constructed for the Forsmark area /Hedenström et al. 2008/. The RDM presents sub-models for the lake sediments in eight lakes. The sub-models give the geometry of the gyttja layer and clay layer separately so the volume of each of these layers can be calculated. In general, the model predicts smaller sediment volumes than our calculations above. The largest difference is for the clay layer in Gällsboträsket, which is about 5 times larger in our calculations. This is equivalent to a difference in layer thickness of c. 0.55 m. In a few cases the RDM predicts larger sediment volumes, for example the gyttja layer in Eckarfjärden which is c. 10% larger than in our calculations. This is equivalent to a difference in layer thickness of c. 15 cm. Since the model also includes Littoral I, which in this report has been considered to be a wetland, we have used the average values. It is difficult to decide which of the two methods gives the most realistic sediment volumes. In conclusion, the absolute numbers for element concentration in lake sediments may be incorrect, and the estimate of this pool of elements is one of the most uncertain in the model. Nevertheless, regardless of which sediment depth is used, the order of magnitude of the sediment pool will be the same and the total dominance in the lake ecosystem of elemental pools contained in the sediment is most certainly accurate.

The elemental composition data for sediment is also site-specific with data from two lakes (Eckarfjärden and Stocksjön). The different sediment layers are represented by different numbers of observations, so the reliability of the estimates differs between the different layers: the clay gyttja layer is represented by only one sample from each lake, while the clay layer is represented by one sample from Stocksjön and 3 samples from Eckarfjärden. The number of samples for the gyttja layer is greater: 5 samples from Eckarfjärden and 9 samples from Stocksjön. In the model, it was assumed that the chemical composition of different sediment layers does not differ between lakes. Instead, a mean value of the different samples from the same sediment layer was calculated and used as a representative value for that sediment type in the area. A simple comparison of the chemical composition of the sediments from the two lakes (Stocksjön and Eckarfjärden) has been performed. The concentrations of different elements in a specific sediment layer are higher in Eckarfjärden for some elements and lower for others. However, differences between the lakes are always smaller or of the same order of magnitude as the in-lake variations. Thereby, it seems reasonable to use the same data on chemical composition of sediments for all the lakes in the area.

Mass balances

Mass balances for a large number of elements have been constructed for five lakes in Forsmark. Only about half of the mass balances for the average lake were well balanced. Generally, the mass balances for the smaller lakes Gällsboträsket and Norra Bassängen are well balanced, while those for Bolundsfjärden, Eckarfjärden and Puttan are less well balanced for many elements. This is most probably due to uncertainties in estimated sediment accumulation. In Gällsboträsket and Norra Bassängen, sediment accumulation is small compared to in- and outflow via water, so this will not greatly affect the mass balance. In the other three lakes, sediment accumulation is larger than outflow via water for many elements. An incorrect estimate of sediment accumulation in these lakes should have a significant influence on the total mass balance. The most reliable flow estimates in the mass balance are the in- and outflow of elements via water. Atmospheric deposition is lacking for many elements, but for those elements where atmospheric deposition is available the estimated annual deposition is of little importance for the mass balance.

The most reliable estimates of elemental fluxes are for flows into and out of the lakes via water, as they are based on a large quantity of measured data from different parts of the catchment and therefore have a better spatial resolution than the other fluxes (atmospheric deposition and accumulation in sediments, see below). They are also based on longer time series of data (c. 5 years), resulting in more representative values over a longer time period. There was a mismatch among the discharge and chemistry stations with respect to time periods, sampling interval and spatial coverage of the stations, similar to that described for the carbon mass balance. Accordingly, there was a need for extrapolation in time and space in order to make transport estimates possible. This transformation is further discussed in Section 5.2.1.

The site-specific data on atmospheric deposition include only a few elements and is therefore lacking for many elements. For most elements this flux is small and probably does not alter the mass balance in any significant way. However, in the case of the lanthanides atmospheric deposition has not been estimated for a single element. Although less likely, we cannot exclude the possibility that atmospheric deposition is high for these group of elements. For elements where site-specific measurements of atmospheric deposition are available, the estimates of this flux can be considered reliable. The estimate of annual mean chemical composition of precipitation is based on sampling during more than one year, and thus the results should be relatively representative.

The estimates of sediment accumulation of elements are dependent on lake size, since the estimates are based on the assumption of the same (constant) area-specific accumulation rate in all lakes, independent of lake size or age. Moreover, estimated sediment accumulation is dependent on the element content of the sediments, which is based on data from one sampling point each in two lakes (Eckarfjärden and Stocksjön). Accordingly, element accumulation in sediments must be considered to be the least certain part of the mass balances, although the concentrations for each sediment layer are based on more than 1 sample (gyttja layer n=14, clay gyttja n=2, clay n=4).

7.6.2 Laxemar-Simpevarp

Pools

Site-specific measurements are available for all ecosystem components in Frisksjön, and there is high confidence in the pool estimates. The estimated pools of elements in particulate matter in water, in biota, and in sediments are associated with some uncertainties regarding the absolute numbers, but the orders of magnitude of the estimates are probably correct. The estimated pools of elements in the dissolved component are based on site-specific data from several years and can be considered reliable.

Site-specific data for most elements in the dissolved component are available for the period November 2002–July 2007, giving these estimates a relatively good resolution both in time and space. For some elements (Ag, B, Be, Ga, Nb, Se, Sn, Ta, Ti, W) data are only available from a single occasion and thus the estimates of these pools are more uncertain, although the site-specific data provide confidence in the order of magnitude of element pools.

The pools of **particulate** carbon, nitrogen, and phosphorus are available for the same time period and sampling stations as the elements in the dissolved component and can be regarded as reliable estimates with good resolution in time and space. The estimated pools of other elements in the particulate component are, however, based on a single sampling performed in spring 2008. Using the results from this sampling to estimate the mean annual pool of different elements in particulate matter naturally entails relatively high uncertainty in the estimates. Moreover, the particulate fraction also includes the living biota. No estimate of living biota was made at the same occasion as suspended material and the living biota has not been subtracted from the particulate component in the result and thus the particulate fraction may be somewhat overestimated. However, as the data are site-specific they provide high confidence in the order of magnitude of the pools of element in the particulate component.

As in Forsmark, the largest uncertainty in the pools of elements in the **biotic component** in Laxemar-Simpevarp is the lack of data on the chemical composition of bacteria for all elements except phosphorus, nitrogen, sulphur and carbon (further discussed in Section 7.6.1). For other organisms, the estimated pools of elements are reliable, since they are mainly based on site-specific measurements. There are relatively few replicates, which imply some uncertainty, but the available replicates show small differences for most elements. Biomass data and chemical composition are used to estimate the pools of different elements. Uncertainties in these estimates are of course also associated with the biomass data, but for most organisms these can be considered small (further discussed in Section 5.6.2).

The pools of elements in the **sediment component** are highly dependent on the estimated sediment volume. The sediment depth has been measured in field, but the number of replicates is limited. However, although the number of replicates is few, there is no doubt that the sediment pool is large and that the order of magnitude of the sediment volume should be correct. In addition to sediment volume, there are uncertainties associated with the sediment component since data on the chemical composition of the sediments are available only for the upper 4.4 m. For the remaining 5.6 meters, chemical composition was assumed to be identical to the layer 1.97–4 metres. This assumption is based on the fact that sediment layers in the upper 1.97 metres had a similar chemical composition and sediment layers between 1.97 and 4.4 metres had a similar chemical composition. Although the sediment pool is the most uncertain of the pools, we conclude that regardless of which sediment depth and chemical composition are used, the order of magnitude of the sediment pool will be the same and its dominance in the lake ecosystem is most certainly accurate.

Mass balances

Mass balances for a large number of elements have been constructed for Frisksjön in Laxemar-Simpevarp. Most mass balances are not well balanced, and most often the outfluxes exceed the influxes. There are relatively large uncertainties associated with sediment accumulation as well as in- and outflow via water. The in- and outfluxes are estimated from site-specific measurements and should be of the right order of magnitude, but the absolute numbers are more uncertain. The mass balances could easily be brought into balance by making adjustments in one or several of the flows. However, it is not possible to determine which of the flows are inaccurate in the unbalanced mass balances, as all flows are associated with uncertainties. A description of the confidence and uncertainties of separate flows follows below.

As discussed in Section 5.6.2, in- and outflows to/from the lake via water are extrapolated from measurements in the Laxemar-Simpevarp area and are not site-specific data for Frisksjön. This of course makes the estimates uncertain, although they should be of the right order of magnitude.

The site-specific data on atmospheric deposition include only a few elements and is therefore lacking for many elements. For most elements (except phosphorus) this flux was small and probably does not alter the mass balance to any significant degree. However, in the case of the lanthanides atmospheric deposition has not been estimated for a single element. Although less likely, we cannot exclude the possibility that atmospheric deposition is high for these group of elements. For elements where site-specific measurements of atmospheric deposition are available, the estimates of this flux can be considered reliable. The estimate of the annual mean chemical composition of precipitation is based on sampling during more than one year, so the results should be relatively representative.

The estimate of sediment accumulation is high and may be somewhat overestimated. As discussed in Section 5.6.2, the water-rich top of the sediments is not included, which may lead to overestimation of the sediment accumulation of carbon and other elements. On the other hand, high concentrations of inorganic nutrients, and substantial reed production in areas surrounding the lake, may contribute to large sediment accumulation. Judging from the unbalance in the models and the fact that outfluxes exceed influxes, it is reasonable to assume that sediment accumulation is overestimated. It is difficult to determine by how much, but the order of magnitude of the estimated sediment accumulation is probably correct.

8 Long-term development of lakes and streams

The long-term development of the limnic systems in Forsmark is considered to be driven mainly by three factors: 1) shoreline displacement, 2) successional processes (transforming lakes to terrestrial areas) and 3) climate change. The aim of this chapter is to describe these processes, the historical development of limnic systems at Forsmark and Laxemar-Simpevarp, and the potential future development of the limnic systems at Forsmark. Knowledge of historical development serves as a basis for the discussion for future development of the limnic systems in Forsmark. The description of future development aims at evaluating the possible effects of future climate change on important processes used in the radionuclide model, i.e. discussions concerning ecosystem properties in this chapter relate mainly to processes of potential importance for the distribution of radionuclides in the limnic ecosystem.

Lake basins may be formed in many different ways, often related to catastrophic events in earth's history. Lakes appear wherever a threshold that obstructs the passage of runoff water is formed. /Hutchinson 1975/ defined eleven main classes and characterized 76 sub-classes of lake basins, based on the processes involved in their formation. Lake basins found in Sweden include e.g. tectonic basins, basins formed by glacial activity, by fluvial action and by meteorite impact, as well as man-made dams. The most common types of lake basins in Sweden are those that have been formed directly or indirectly by glacial activities during and after the Pleistocene glaciations. New lakes are still continuously being formed along the coast as the land rises from the depression that occurred during the last glacial period. This is the case in both the Forsmark and the Laxemar-Simpevarp areas.

Land rebound (isostacy) following deglaciation of the late Pleistocene ice sheets cause shoreline regression and constantly emerging coastal land and new lakes along the east-central Swedish coast today. New emerging land creates a landscape of different ages and different stages of maturity as a function of altitude. Higher parts in the landscape are relatively older and have undergone a longer time of transforming processes like for example chemical weathering or peat accumulation in wetlands. Because both Forsmark and Laxemar-Simpevarp areas have relatively subdued topography, landscape maturity almost appears to be dependent on distance to the present coast, with the oldest parts most distant to the sea. With this simplification in mind, the present landscape can be described as showing special gradients of maturity from cost to inland. This concept of landscape having different age (as a function of altitude) is important for the following description of landscape development. This is mainly because objects of different maturity, and therefore different characteristic, co-exist juxtaposed in the landscape.

The time perspective considered covers a glacial cycle estimated to be 120,000 years. The radionuclide model used in the safety assessment (Chapter 10) attempts to describe the dose to humans during a glacial cycle, i.e. under varying climatic conditions. The model follows a reconstruction of temperature conditions for the last glacial cycle, the Weichselian. The model starting point is at the end of last glacial cycle, corresponding to the situation 8,800 years BC when both Forsmark and Laxemar-Simpevarp were deglaciated. Over a glacial cycle, the area will undergo a wide range of environmental conditions including temperate, periglacial and glacial conditions in addition to a submerged stage where the areas of interest are below sea level. Moreover, the effect of global warming on ecosystems has been widely discussed in literature in recent years, and this may influence the succession and functioning of the ecosystems and is therefore included in the discussion and as a climate case in the safety assessment (**Climate report**).

It should be noted that a descriptions of future development of the area in the following text are based on existing knowledge of the past, known processes, such as shoreline displacement, and knowledge of the current situation, such as existing ecosystems, climate, and geometry. All these descriptions have their uncertainties. Moreover, the future development may be different than expected based solely on history. Thus, the descriptions presented here are potential future cases that are logically coherent, but the temporal and spatial extent of various climatic conditions is uncertain due to limitations in underlying data and conceptual models.

8.1 Shoreline displacement

A major crustal phenomenon that has affected and continues to affect northern Europe, following the melting of the Weichselian ice sheet is the interaction between isostatic recovery on the one hand and eustatic sea level variations on the other.

Isostatic recovery is an ongoing process and is an effect of the unloading of the Weichselian ice (the last glacial period in northern Europe, occurring approximately 115,000–10,000 years before present). In northern Sweden, the heavy continental ice load depressed the Earth's crust by as much as 650 m below its present elevation in around 18,000 BC /Påsse and Andersson 2005/. As soon as the pressure started to decrease due to thinner ice cover, the crust started to rebound (isostatic land uplift). This uplift started before the final deglaciation and is still an ongoing 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 former shoreline is situated at different elevations in different parts of Sweden, depending on how much the crust was depressed and the level of the global sea level at the time of deglaciation. The highest levels, nearly 300 metres above sea level (m.a.s.l.), are found along the coast of northern Sweden, and decrease to levels less than 20 m.a.s.l. in southernmost Sweden. The rate of isostatic recovery has decreased significantly since the deglaciation and has during the last 100 years been about 6 mm per year in Forsmark and 1 mm per year in Simpevarp /Ekman 1996/.

In addition to isostatic rebound, the eustatic level is dependent on the amount of water in the world's oceans, which changes depending on the amount of water bound in the world's glaciers and ice sheets. During the latest glaciation, the global sea level was in the order of 120 m lower than at present, due to the large amounts of water stored in ice /Fairbanks 1989/.

As a result of an overall regressive shoreline displacement, the sea bottom is uplifted and transformed into new terrestrial areas or to freshwater lakes. In coastal areas such as Forsmark and Laxemar-Simpevarp, shoreline displacement has strongly influenced ecosystem development and is still causing continuous changes in the environment. Both areas are situated below the highest coastline. Thus, the post-glacial development of Forsmark in particular is determined mainly by the development of the Baltic basin and by shoreline displacement. The estimated rate of historical and future shoreline displacement in Forsmark is shown in Figure 8-1. Climate change may alter the sea level and thereby the timing when land rises above the sea /Lindborg 2010/.

Shoreline displacement cause new land to emerge from the sea. Thereby lakes and streams become situated further away from the coast. Successional processes will alter the distribution of sea, lakes and land. This is further described in the following sections.

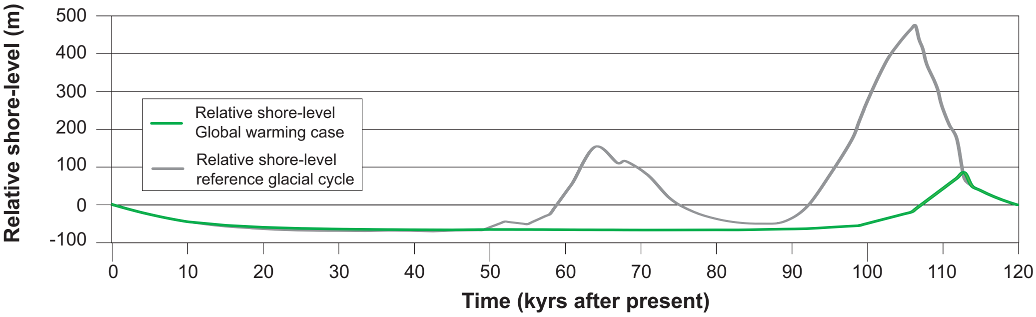

Figure 8-1. Shore-level evolution at Forsmark for the reference glacial cycle (grey) and the global warming climate case (green). Negative numbers indicate that the area is situated above the contemporary sea-level.

8.2 Successional processes

Succession is a directional change of ecosystem structure and functioning that may occur over time scales from decades to millennia. Succession may be a result of new land or lakes emerging (primary succession) or of disturbance such as after a clear-cut (secondary succession). The vegetational development and the species community at any given time are limited by the availability of dispersal propagules and the local abiotic conditions (e.g. / Rydin and Borgegård 1991/). In the investigated coastal areas, shoreline displacement continuously transforms the near-shore sea bottom to new terrestrial areas or to freshwater lakes. The subsequent development of these terrestrial areas and lakes may follow different trajectories depending on factors such as fetch during the shallow marine stage, slope and surrounding topography. A schematic illustration of some of the main trajectories is shown in Figure 8-2, where the sea bottom is the starting point and the endpoint is an inland bog or a forest.

The starting conditions for ecosystem succession from the original sea bottom in a coastal area are strongly dependent on the topographical conditions, where low points in the bottoms accumulate sediments (accumulation bottoms) to a higher degree than higher located bottoms (transport bottoms). This difference becomes even more pronounced in near-coast locations, where the bottoms of sheltered bays accumulate organic and fine-grained inorganic material, while the finer fractions are washed out from more wave-exposed shorelines with a large fetch.

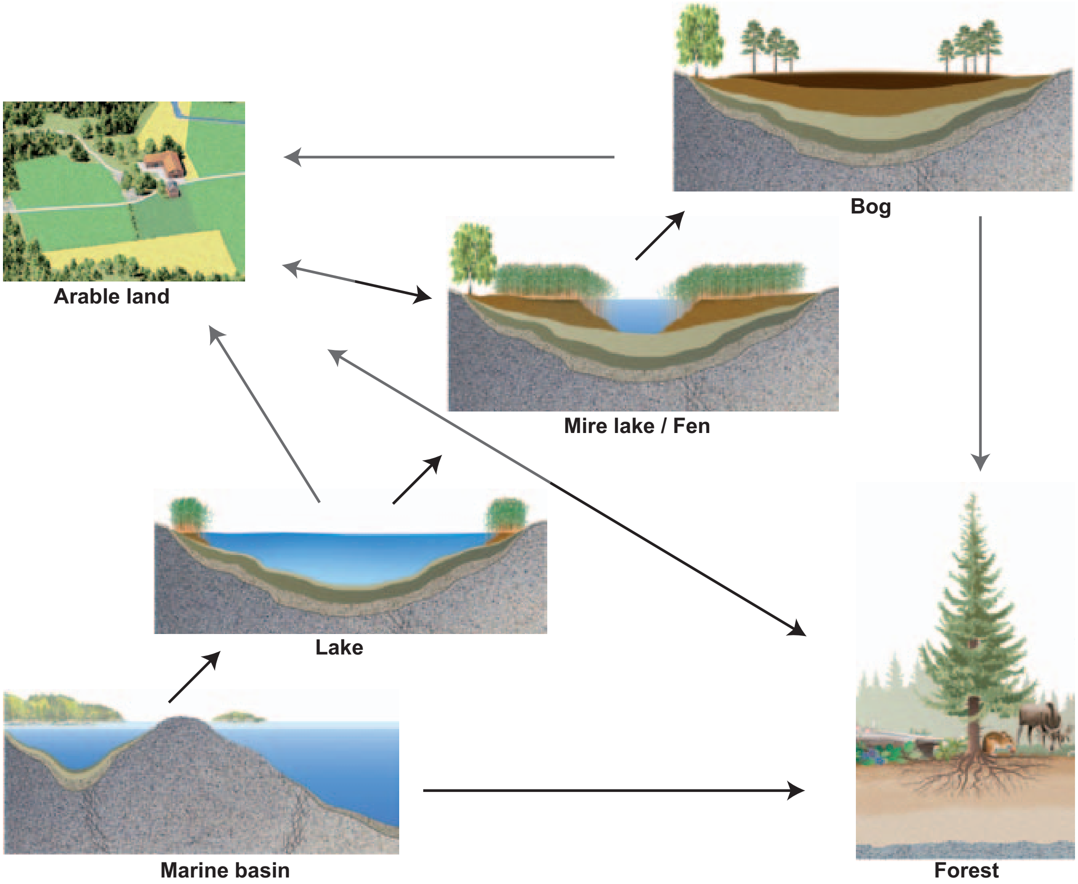

Figure 8-2. *Schematic illustration of the major ecosystems that may be found at different stages of succession, where the original sea bottom is slowly transformed into land due to shoreline displacement. Black arrows indicate natural succession, while grey arrows indicate human-induced changes to create new agriculture land or improve the forest. Agriculture land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and used as agriculture land.*

During the process of shoreline displacement, a sea bay may either be isolated from the sea at an early stage and thereafter gradually be transformed into a lake as the water becomes less saline, or it may remain as a bay until shoreline displacement transforms it into a wetland. The Baltic Sea shore can be divided into four different types: rocky shores, shores with wave-washed till, sandy shores and shores with fine sediments. Wave-exposed shores will undergo a relocation of previously accumulated sediments, and these shores will emerge as wave-washed till, where the grain size of the remaining sediments is a function of the fetch at the specific shore.

Shores with wave-washed till are the most common kind in the Forsmark area, but rocky shores and shores with fine sediments can also be found. In the Laxemar-Simpevarp area, rocky shores are the most common type followed by shores with wave-washed till and shores with fine sediments. These shores later become forests (see below). In coastal basins that will later develop into lakes, there is a threshold in the mouth of the basin towards the open sea. This threshold allows fine material to accumulate in the deeper parts of the basin. Provided that the water depth is less than 2–3 m, different macrophyte species (e.g. *Chara* sp.) colonize the illuminated sediments. Along the shores, *Phragmites australis* and other aquatic vascular plants colonize the system, and a wind-sheltered littoral zone develops. In both these habitats, colonization by plants reduces the water currents, resulting in increased sedimentation and accelerated terrestrialization of the bay. When the threshold rises above sea level, inflow of fresh surface water and groundwater slowly changes the system from a brackish to a freshwater stage (Figure 8-3).

All present-day lakes in the investigation areas originated from depressions in the bottom of the coastal system, and where shoreline displacement is regressive new freshwater lake basins are continuously being formed along the coast of the Baltic Sea. Lakes in Uppland County formed by shore-line displacement can be divided into three different categories: oligotrophic hardwater lakes, dystrophic lakes and eutrophic lakes. The specific succcesion of these lake types are further described below. Independent on category, all lake ecosystem gradually matures in an ontogenetic process, which includes subsequent sedimentation and deposition of allochthonous (transported from the surrounding catchment area) as well as autochthonous (originating from/produced within the lake) substances. Hence, the ultimate, inevitable fate of all lakes is infilling and transformation to either a wetland or a drier land area, the final result depending on local hydrological and climatic

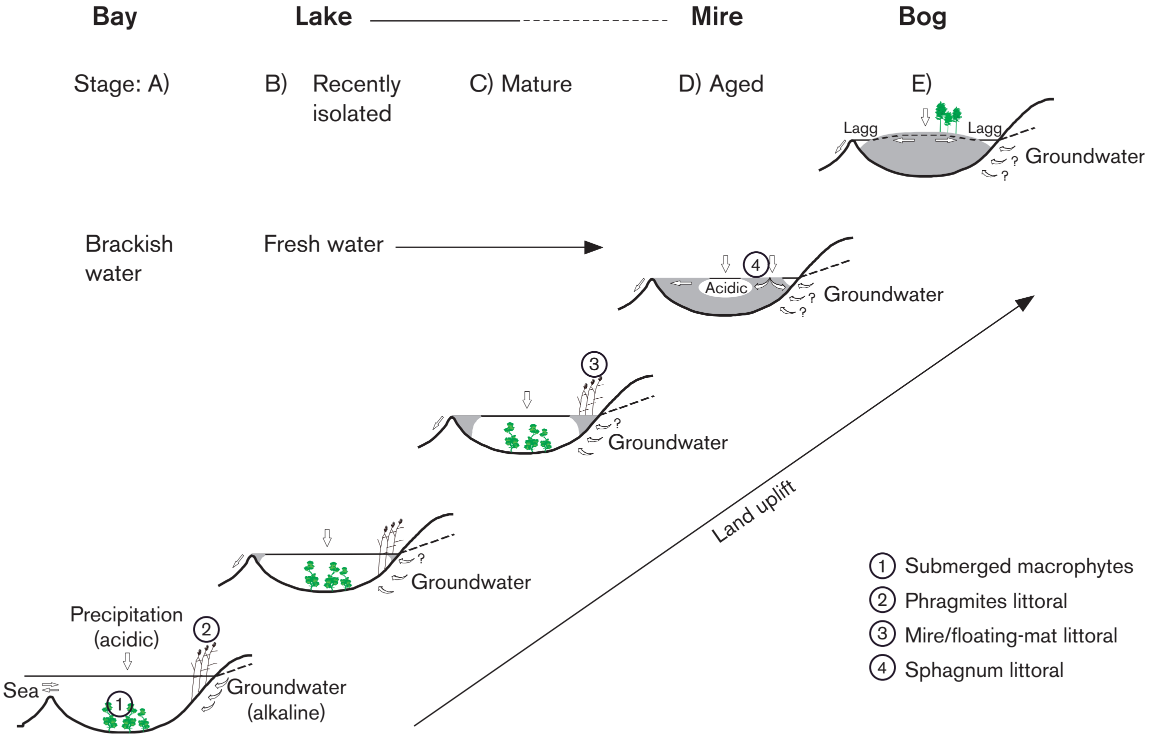

Figure 8-3. *Schematic description of the ontogeny of a closed-off bay of the sea to a mire. The figures represent different important components of the ecosystem. Modified from /Brunberg and Blomqvist 2000/.*

conditions. A common pattern for this ontogeny is the progressive development of more and more eutrophic (nutrient-rich) conditions as lake depth and volume decrease /Wetzel 2001/. In later stages, aquatic macrophytes speed up the process by colonizing large areas of the shallow sediments, and finally more terrestrial plant communities can colonize and grow there. Accordingly, the peat layers developed during this ontogenetic process follow a certain bottom-up order with a more limnic character at the bottom with *Phragmites* peat, followed by *Equisetum* and then sedge-fen peat, usually overgrown by bog peat /Sjörs 1983/. However, various environmental conditions may alter this general ontogenetic pattern, and there are examples of lake ontogeny that include a transition to more oligotrophic (nutrient-poor) conditions /Engstrom et al. 2000/, as well as to more dystrophic (low pH, brown-water) conditions /Brunberg et al. 2002, Brunberg and Blomqvist 2003/(see below).

Dystrophic conditions are typical of small forest lakes in large areas of Sweden. These lakes are characterized by a high input of allochthonous carbon from the drainage area and often by a short water turnover (retention) time /Brunberg and Blomqvist 2000/. The development into dystrophic conditions starts with colonization by *Sphagnum* mosses in areas with macrophytes in the sheltered littoral. As the growth of *Sphagnum* proceeds in an outward direction and organic accumulation underneath these plants increases, a mire/floating-mat littoral zone is gradually developed. This mire-littoral is important as it may alter the groundwater flow and/or the chemistry of the inflowing groundwater and turn the system increasingly acidic. Thus, the invasion of the sheltered littoral by *Sphagnum* should, at least theoretically, have a profound effect on the functioning of the lake ecosystem. In a later stage of succession, the accumulation of organic detritus in the lake basin completely covers the previously illuminated benthic area. At this stage, the *Sphagnum* littoral alone dominates the metabolism of the system, as most of the previously benthic habitat has been lost through accumulation of peat. The whole ecosystem, the mire-littoral as well as the open water, is now acidic. The area of open water is continuously reduced due to expansion of the floating mats. The floating mats fill in the lake from the top, which means that bog-like peat can be deposited directly on the lake bottom (with some mud layer in between), as the weight of the growing peat pushes the lower parts downwards /Sjörs 1983/. The final stage of this ontogenetic process is the raised bog ecosystem (Figure 8-2 and 8-3).

8.2.1 Successional processes in lakes in the Forsmark area

Ontogeny of oligotrophic hardwater lakes

All lakes existing in the Forsmark investigation area today (see Figure 3-1), as well as a number of previously small and shallow lakes which over time have been transformed into wetlands due to the ontogenetic process, can be classified as oligotrophic hardwater lakes. Due to both chemical and biological processes in the lake water, the amount of nutrients available in the lakes is effectively reduced by co-precipitation together with calcium-rich particulate matter. Because of this, the phosphorus concentration in lakes and streams is generally low. The nitrogen concentration, on the other hand, tends to be high, or even very high, due to a combination of high input and low biotic utilization /Brunberg and Blomqvist 1999, 2000/. These conditions, together with shallow lake depths, give rise to the unique type of lake found in the Forsmark area, the oligotrophic hardwater lake (further described in Chapter 3).

As described above, all lakes can in the long-term be regarded as temporary since they will eventually be filled up and transformed into either wetland or drier land area. However, provided that the lake is deep enough, the oligotrophic hardwater stage may also be of a temporary nature. /Brunberg et al. 2002/ proposed that light conditions at the sediment surface may have a major influence on nutrient conditions in this type of lake. If during the ontogenetic process the lake water turns more brownish, reduced benthic photosynthesis may contribute to a transition from an oligotrophic hardwater stage into a more eutrophic stage. Moreover, it is only the minerogenic Quaternary deposits, such as glacial till and glacial clay, and not the bedrock, that contain carbonates and coupled anions, and these sources will therefore be depleted with time (most likely within 1,000 to 10,000 years cf. /Tröjbom and Grolander 2010/). The system will reach a point when precipitation of $CaCO_3$ from the lake water will no longer take place. At that point, there will be no co-precipitation of important plant micronutrients (e.g. phosphorus) or essential trace elements (e.g. iron, manganese). Instead, these elements, and especially phosphorus, will contribute to the production of organisms in the lake system and there will be a rapid change towards more eutrophic conditions. This change will in turn lead to increased amounts of sedimenting organic matter (i.e. increased infilling), increased decomposition rates, at least until anoxic conditions are reached, and enhanced nutrient recycling /Brunberg and Blomqvist 2000/.

Ontogeny of brown-water lakes in the region

Today there are no brown-water lakes in the Forsmark area. However, investigations of lakes in the nearby catchment Forsmarksån /Brunberg and Blomqvist 2000, 2003/ showed that lakes in the vicinity of the Forsmark area may develop into brown-water lakes after passing through an oligotrophic hardwater stage, but may also form brown-water lakes directly after isolation. From an ontogenetic point of view, the catchment of the Forsmarksån River, and thereby also its lakes, may be divided into two parts with differing ontogeny: the areas upstream and downstream of the 13 m high waterfalls at Lövstabruk /Brunberg and Blomqvist 2000/.

Palaeoecological studies by Tord Ingemar et al. (referenced in /Brunberg and Blomqvist 1998/) show that the upstream Lake Vikasjön passed through an oligotrophic hardwater stage after its isolation from the Baltic Sea, a period when “cyanophycée-gyttja” was formed. This corresponds to the present situation in the oligotrophic hardwater lakes along the coast, e.g. Lakes Eckarfjärden and Bolundsfjärden in the regional model area. In Lake Vikasjön, this stage lasted for about 1,000 years, and was followed by a period of 1,000–2,000 years when the lake sub-basins were gradually isolated from each other and partly transformed into mires. The sediments in the remaining lake basins then switched to “dy” sediments, i.e. lake sediments mainly consisting of humic compounds, transported to the lake from the terrestrial surroundings.

The lakes situated below the 13 m fall in Lövstabruk have a different history. Due to the substantial difference in the topography, they were isolated from the Baltic Sea at least 2,000–2,500 years later than the upstream lakes. At that time, the upstream lakes had passed the oligotrophic hardwater stage, and were already more or less brown-water systems. The inflowing water from the upstream areas to the newly formed lakes was thus brownish and less alkaline. This water from the main river constituted a major component of the inflowing water to the newly formed lake basins. The large flow of water dominated, and still dominates, the hydrology of the systems, thus diluting and washing out the contributions from the land areas in the close vicinity of the newly formed lakes. Consequently, no oligotrophic hardwater stage occurred in the chain of lakes situated along the main river below Lövstabruk. Instead, they developed into brown-water flow-through lakes more or less directly after isolation /Brunberg and Blomqvist 2000/. Brown-water lakes in the region today are further described in Section 3.12.1.

Ontogeny of deep eutrophic lakes in the region

There are no deep eutrophic lakes in the Forsmark area today, but the deepest parts of Öresundsgrepen will in the future develop into a number of deep lakes which will differ considerably from the present-day lakes in the Forsmark area (cf. Table 5-1 in /Kautsky 2001/). There are a few deep lakes in the region, and the ontogeny of two deep lakes in the vicinity of the Forsmark area, Lake Erken and Lake Limmaren, was assessed by /Brunberg and Blomqvist 2000/. Both of these lakes are relatively eutrophic today. In investigations of sediments from Lake Limmaren, /Brunberg et al. 2002/ found no signs of changing trophic status after isolation from the Baltic Sea, despite the fact that the surroundings of the lakes, like those of the Forsmark lakes, have calcareous soils. It seems likely that neither Lake Erken nor Lake Limmaren have passed an oligotrophic hardwater stage, the main reason probably being that, due to their larger depths, dark conditions prevail at the sediment surface. Thus, benthic photosynthesis is limited and pelagic photosynthesis dominates instead /Brunberg et al. 2002/.

In Lake Erken, the accumulation of sediments in the deepest parts of the basin is at most 1 m over the 2,500 years that have passed since the lake was isolated from the Baltic Sea. Assuming the same rate of sediment deposition, the accumulation of sediments during the next 10,000 years would be 4 m. The accumulation of sediments in other parts of the lake would be considerably less. Thus, even 10,000 years from now, Lake Erken will be a large and, for the region, relatively deep lake (maximum depth c. 16 m).

The situation in Lake Limmaren is different. Firstly, the sedimentation rate over the last 1,000 years has been considerably higher than that in Lake Erken, with an accumulation of some 1.4 m of sediment in the deepest part of the lake /Bergström 2001/. Secondly, Lake Limmaren is much shallower than Lake Erken. Considering these factors, it seems reasonable to conclude that the Lake Limmaren basin will be completely filled with sediments 5,000 to 10,000 years from now. An initial transition to reed-marsh seems very likely, but whether this state will be a mire or a wetland forest (dominated by alders) is highly uncertain.

Based on knowledge from present deep lakes in Upland, one may assume that it is likely that deep lakes that form in the Forsmark region will be more eutrophic than the oligotrophic hardwater lakes. They will probably have similar nutrient status their entire life span and are becoming shallower with time but the speed of lake infilling may differ between individual lakes due to e.g. lake morphometry and catchment characteristics. Deep eutrophic lakes in the region today are further described in Section 3.12.1.

8.3 Climate change

By taking the succession into account, it is possible to cover potential changes in ecosystem properties at the site at present temperature conditions. However, a changing climate adds further variation to the existing span of ecosystem properties, representing the different successional stages occurring at the site. In order for the safety assessment to cover a period of 120,000 years, a broader approach must be taken to cover the full extent of different climate stages. Below is a description of the different climates Forsmark will undergo over the modelled time span, along with a discussion of the effect of changing temperatures on the functioning of the limnic ecosystem.

8.3.1 Climate cases

In In SR-Site, six different climate cases are described for the future evolution of Forsmark, see the **Climate report**. Two of these will be discussed below: the reference evolution and a global warming case, which together cover the full range of potential effects associated with surface ecosystems. In both cases the site is subjected to a number of different climate conditions, or climate domains, it may be covered by an ice sheet, be submerged, or have permafrost or temperate climate conditions (as today), see Figure 8-4. These domains are defined by how different surface processes are affected by the climate conditions. In the following sections, descriptions of the possible effects of increased temperature on abiotic and biotic parameters in limnic systems at different climate conditions are provided.

Reference case

In the reference evolution case, the succession of climate domains follows a reconstruction of environmental conditions of the last glacial cycle /**Climate report**/. The deglaciation is followed by a period where the area is submerged by water (neither of these events is seen in Figure 8-4). After that, temperate climate conditions prevail for about 8,000 years. Climate conditions within the temperate climate domain may be colder, warmer, wetter or drier than today's climate. After the initial temperate period, the first short period of permafrost conditions ensues. Subsequently, the periods with temperate climate conditions are replaced by progressively longer periods of permafrost conditions, before the first phase of ice sheet coverage, at around 60,000 years into the reference evolution. The glacial conditions are replaced by submerged conditions, followed by a period dominated by permafrost conditions. After that, the main phase of ice sheet coverage ensues, starting about 90,000 years into the evolution. At the end of this glacial cycle, the site is again deglaciated, around 120,000 AD, see the **Climate report**.

Global warming case

In addition to the reference evolution, a global warming case has been constructed, starting with a prolonged initial temperate period that prevails for about 60,000 years before the first period with permafrost conditions. After that the same sequence of events occurs as in the reference evolution /**Climate report**/.

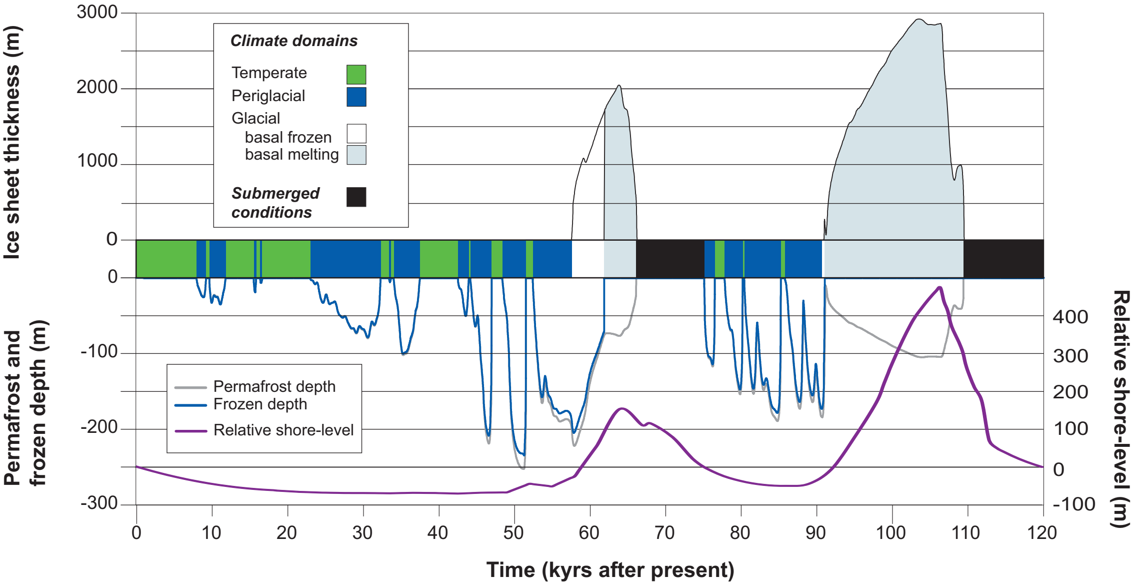

Figure 8-4. *Duration of climate domains at Forsmark, expressed as a percentage of the total time for the reference case evolution. The bars below the pie charts show the development of climate-related conditions for the reference evolution as a time series of climate domains and submerged periods. Figure from the* ***Climate report****.*

Global warming may of course, in addition to prolonging the periods of temperate conditions, alter the temperature to conditions significantly warmer than today. A growing body of evidence suggests significant effects on the species composition, phenology and functioning of lake ecosystems following temperature changes (e.g. /Adrian et al. 2006, Meerhoff et al. 2007, Smith et al. 2008, Moss et al. 2009, George 2010 and references therein/). However, the response of a certain limnic ecosystem to climate change is dependent on many factors, such as catchment characteristics, geographic position, morphometry, nutrient conditions, etc. Since lakes respond individually to climate change it is difficult to predict the effect of global warming on specific lake ecosystem /Blenckner 2005/. Therefore, any changes in limnic parameters in modelling due to increased temperature would be associated with large uncertainties. Instead of changing parameters in the SR-Site modelling, it has been assumed that increased temperature prolongs the temperate period by about 50,000 years. This is assumed to be a good estimate, since event though green house gases may increase temperature the climate will remain temperate, i.e. there will not be tropical conditions in Sweden. Thus, the entire temperate period of 60,000 years may include both warmer and colder periods than at present.

8.3.2 Climate conditions during different climate domains

As stated above, it is assumed that the Forsmark area will undergo three different climate domains in the next 120,000 years, in addition to a state where all objects in the area are submerged. It is not possible to predict the climate evolution in detail in a 120,000 year time perspective. However, the extremes within which the climate of Sweden may vary can be estimated with reasonable confidence. By selecting appropriate time periods from the last glacial-interglacial cycle, periods with extreme climate conditions were used to quantify extreme temperatures, precipitation, runoff and evaporation, including their annual variation /Kjellström et al. 2009/. This was done with climate models, where the setup of forcing conditions for the model simulations was based on the selected separate periods during the Weichselian, the Holocene (i.e. the present interglacial starting about 10,000 before present) and a future hypothetical case with higher levels of greenhouse gases in the atmosphere than today. Steady-state simulations of equilibrium climates for the different periods were then compared to the pre-industrial climate and the "recent past" climate representing the period 1961–2000. This recent past is assumed to illustrate the temperate domain.

In addition to the temperate domain, three different climate conditions were studied and compared with the recent past by /Kjellström et al. 2009/. Thus, four different climate conditions are considered for the future:

1. Temperate domain – present conditions – a period corresponding to "recent past" climate representative of the present temperate climate.
2. Temperate domain – Global warming conditions– in addition to prolonging the temperate domain (discussed in 8.3.1), global warming will also give rise to a period of a few thousand years into the future with increased greenhouse gas concentrations and enhanced temperature. This period represents the climate during this shorter period with increased temperature.
3. Periglacial domain– a period corresponding to the conditions at 44,000 before present during Marine Isotope Stage 3 i.e. representing permafrost conditions.
4. Glacial domain – a period corresponding to the conditions at 21,000 before present during the Last Glacial Maximum, i.e. representing the glacial domain.

Temperate domain – present conditions

The climate in the recent past is used as an estimate of temperate conditions (Table 8-1).The temperate domain is assumed to resemble present-day conditions, although the climate may be warmer, colder, dryer or wetter than today. The deviations from present conditions are assumed to be small in comparison to differences between changing climate domains, and present-day conditions are assumed to be relevant to use for estimation of biological parameters in the limnic habitat in future temperate periods.

Temperate domain – global warming conditions

The estimated seasonal mean temperature was up to 5°C warmer in summer and up to 7.5°C warmer in winter over Scandinavia in the warm case as compared with the simulation of the recent past. Seasonal mean summer temperatures in Sweden vary from 12 to 18°C, while winter temperatures vary from 0 to 6°C. The annual mean temperatures for Forsmark and Laxemar-Simpevarp in a potential warm case are presented in Table 8-1 /Kjellström et al. 2009/. The simulated climate of the warm case clearly resembles many of the scenarios for the 21st century from the climate model intercomparison project (CMIP3) as presented by the Intergovernmental Panel on Climate Change /Meehl et al. 2007/. The uncertainties related to the future forcing in the warm case are great, and the possibility of either lower or higher greenhouse gas concentrations than the ones used cannot be ruled out. Differences between the modelled mean annual temperature and precipitation and the recent past are presented in Table 8-2 for Forsmark and Laxemar-Simpevarp.

Table 8-1. 50-year averages of annual mean temperature (T), precipitation (PR) and runoff (R) for Forsmark and Oskarshamn (equivalent to Laxemar-Simpevarp) in the regional climate model simulations /Kjellström et al. 2009/. Runoff is not given for the glacial case. The standard deviation /using nine grid boxes in the model closest to the location) is shown in parentheses.

Simulation	T (°C)	PR (mm/year)	R (mm/year)
Forsmark			
Global Warming	8.0 (0.3)	852 (66)	249 (102)
Temperate (recent past)	4.7 (0.6)	666 (93)	175 (113)
Permafrost	–7.8 (0.9)	438 (53)	170 (40)
Last glacial maximum	–20.3 (1.0)	564 (161)	–
Oskarshamn			
Global Warming	9.2 (0.5)	929 (196)	283 (168)
Temperate (recent past)	6.2 (0.3)	806 (192)	242 (158)
Permafrost	–3.2 (0.5)	582 (117)	218 (80)
Last glacial maximum	–13.2 (1.0)	581 (71)	–

Table 8-2. Summary of results as the difference between the temperate domain (recent past, measured in 1961–2000) and the modelled annual mean temperature (∆T) and precipitation (∆PR) for the different climate domains at Forsmark and Oskarshamn (equivalent to Laxemar-Simpevarp). The change in the global annual mean temperature (∆T_{agm}) is taken from a global model. Data are further described in /Kjellström et al. 2009/.

Simulation	Global annual mean (CCSM3)	Annual means for three sites in Fennoscandia			
	Global	Forsmark		Oskarshamn	
	∆T_{agm} (°C)	∆T (°C)	∆ PR (%)	∆T (°C)	∆PR (%)
Global Warming	+2.1	+3.6	+21	+3.2	+12
Temperate (recent past)	0	0	0	0	0
Permafrost	–5.6	–12.5	–34	–9.4	–29
Last glacial maximum	–6.9	–25.0	–15	–19.3	–33

Although surface water may increase less than the atmosphere, it is clear that increased air temperature also leads to increased water temperature (e.g. /DeStasio et al. 1996, Wilhelm and Adrian 2008/). In addition, runoff is assumed to increase by about 20% in the global warming case. Increased runoff and altered runoff pattern may influence nutrient concentrations and the amount of flooding around the shores of lakes and streams. The effects of increased temperature and runoff on abiotic and biotic factors in lakes are further discussed in Section 8.3.3.

Periglacial domain

In the periglacial domain, permafrost prevails. The definition of permafrost applies to the land ecosystem, i.e. the soil is at or below the freezing point of water (0°C) for two or more years. The uppermost permafrost in a terrestrial ecosystem is a thin active layer that seasonally thaws during the summer. The permafrost domain in limnic ecosystems means an environment with lower water temperature and only a short ice-free season. Permafrost is assumed to occur both in the reference case and in the global warming case, but at different times (see 8.3.1 above). In the periglacial period, Forsmark and Laxemar-Simpevarp are in distal position to the ice sheet margin (Forsmark about 100 km, Laxemar-Simpevarp > 200 km). A mean annual ground temperature between –5 and –2°C is defined as the boundary for discontinuous permafrost (50–90% of landscape covered by permafrost) and –5°C and colder as the boundary for continuous permafrost (90–100%) /Heginbottom et al. 1995/. For the modelled periglacial period in Forsmark and Laxemar-Simpevarp, the annual mean temperature is about –9°C and –5°C, respectively. According to /Heginbottom et al. 1995/, these low temperatures indicate that climate conditions are favourable for continuous permafrost (covering more than 90% of the landscape). Precipitation is low at both sites compared with the glacial climate (Table 8-1). Precipitation is also low compared with precipitation in the recent past. However, due to decreased evaporation under permafrost conditions, runoff is similar to runoff in the recent past. The cold and dry climate with partially snow-free conditions suggests conditions that are favourable for development of permafrost at both sites.

The colder climate will have an impact on water temperature and the length of the period with ice coverage. Permafrost will also have implications for the runoff of nutrients and ions to the streams and lakes. During periods of permafrost, the speed of biogeochemical processes will slow down, which may lead to reduced weathering and ion concentrations. The effects of colder temperature and altered runoff pattern on abiotic and biotic parameters in lakes are further discussed in Section 8.3.3.

The glacial domain

Essentially, the glacial domain means that the areas of Forsmark and Laxemar-Simpevarp are covered by an ice sheet. It is therefore assumed that no terrestrial vegetation is present. Although lake may be present below the ice, low temperature and low productivity leads to no fish populations in these permanently ice-covered lakes, and these lakes cannot be utilized as a food source for humans. Thus, the lakes are not further investigated from a safety assessment view, since they do not contribute to the transfer of radionuclides to humans.

8.3.3 Ecosystem functioning in different climate domains

The effect of global warming has been widely discussed in the literature in recent years. In the time span covered by the safety assessment, permafrost will most certainly have more drastic effects on ecosystem functioning than warming due to greenhouse gases. The effects of both warmer and colder climate may be somewhat more modest in aquatic systems than in terrestrial areas, due to the heat storage properties of water, which dampen temperature fluctuations. On the other hand, lakes are proposed to serve as sentinels of climate change due to their rapid and observable responses to climate change (e.g. /Adrian et al. 2009/).

There is a variety of means by which climate can affect limnic biota, directly or indirectly. Examples of the former include temperature, which affects the metabolism. Indirect means by which climate can affect biota are those climate processes that affect abiotic conditions such as runoff, nutrient levels and surface mixed layer depth, which in turn influence biotic processes. Climate changes can also have profound effects on food web interactions and may change the system from top-down controlled (i.e. predators control the biota in lower trophic levels) to bottom-up controlled (production at the base of the food web determines the growth of top consumers) or vice versa (e.g. /Huber et al. 2008/).

In order to predict potential future changes in ecosystem properties, sediment records and site development data can be used together with studies from other limnic systems in the world exhibiting relevant climate conditions. However, there are uncertainties also with these comparisons. The average global temperature has varied between c. 4 and 7°C since the last glacial maximum. Although periods of warming has occurred repeatedly since the last glacial maximum, a future global warming due to human activities is predicted to occur at a rate of about 10 times faster than during any previous period of warming /Jansen et al. 2007/. Such a rapid warming may imply that changes in ecosystem may not be identical between past and recent warming periods. Sediment records in lakes can be used to predict biotic communities during other climate regimes (e.g. /Helmens 2009/). The rapid warming due to global warming may result in other species composition than predicted from sediment record due to insufficient time for species to colonise or adapt to new temperatures. Likewise, studies from other limnic systems in the world exhibiting warmer climate may not be comparable to Forsmark if the temperature increase is too fast for species to adapt. Moreover, nutrient and chemistry conditions may have an equally large influence on biota as temperature and may therefore also interfere with the comparison with other climate domains.

Most of the ecologically important factors (e.g. temperature, availability of nutrients, wind, storms, mixing, length of ice season etc) are affected by climate changes. However, the response to climate changes are often case specific and are dependent on lake or catchment characteristics, lake morphometry, retention time, nutrient status /Smith et al. 2008 and references therein, George 2010 and references therein/. For example, modelling of phosphorus dynamics at increased temperatures indicated large sensitivity to climate change in a lake with long retention time whereas in lakes with short retention time (less than 1 year) phosphorus dynamics varied little with temperature /Malmaeus et al. 2006/. /Blenckner 2005/ has presented a model with a landscape filter (comprising geopgraphical location, catchment characteristics lake morphometry) and an internal lake filter (comprising lake history, and biotic/abiotic interaction). /Blenckner 2005/ concluded that including landscape factors help explain the possible outcome of climate changes.

In the following text, the focus is on climate change in the landscape Forsmark, i.e. although lakes from other temperate areas may be used for comparison, the effect on Forsmark lakes are in focus. The expected effect on abiotic and biotic parameters in different climate domains compared to present (temperate) are summarised in Table 8-3 and discussed in the following sections. Since the uncertainties in future landscape development are large it is undoable to specify change in exact numbers, instead direction of response to a different climate are described.

Temperate domain – present conditions

Temperate domain is assumed to be dominated by a period resembling recent past which is thoroughly described for Forsmark in Chapter 3 and 5. Temperate conditions may also include global warming, i.e. a situation with warmer and wetter conditions than at present. This situation is described as a special case below.

Table 8-3. Expected parameter values at different climate domains compared to present (temperate). Values in brackets represent expected range. * Represent median value in present day lakes and values in brackets are the range measured in the present lakes (see Chapter 3). ** Ranges are taken from values in the literature (se Chapter 3). * Values are calculated for Lakes Bolundsfjärden and Eckarfjärden in Forsmark (see Chapter 5). For references and discussion on expected parameter values see text.**

Parameter	Temperate	Global warming	Periglacial
Abiotic parameters			
Period with ice coverage (days)	141* (98–143)	1–2 months shorter	Several months longer
Nitrogen concentrations (mg L^{-1})	0.99* (0.33–3.7)	Similar to present or higher	Probably lower
Phosphorus concentrations (mg L^{-1})	0.01* (0.004–0.04)	Similar to present or higher	Probably lower
DOC concentrations (mg L^{-1})	17* (4.2–33)	Probably similar to present	Probably lower
Particulate matter (kg dw m^{-3})	0.0011*	Probably higher	Probably lower
Periods with anoxia	Only in very shallow lakes	Lower risk of anoxia in winter, higher risk in summer	Probably in winter in shallow lakes
Biotic parameters			
Phytoplankton biomass (g C m^{-3})	0.04* (0.02–0.06)	Similar to present, higher or lower	Similar to present
Microphytobenthos biomass (g C m^{-2})	3.8* (2.8–5.8)	Similar to present, higher or lower	Similar to present
Benthic macroalgae and macrophytes (g C m^{-2})	22* (11–134**)	Similar to present, higher or lower	Similar to present
Bacterioplankton biomass (g C m^{-3})*	0.05*	Similar to present, higher or lower	Similar to present
Benthic bacterial biomass (g C m^{-2})	3.7* (3.0–4.2)	Similar to present, higher or lower	Similar to present
Zooplankton biomass (g C m^{-3})	0.06* (0.02–2.3**)	Similar to present, higher or lower	Similar to present
Fish biomass (g C m^{-2})	1.0* (0.5–1.6)	Similar to present, higher or lower	Lower
Benthic fauna biomass (g C m^{-2})	1.6* (0.24–5.0)	Similar to present, higher or lower	Similar to present
Pelagic Primary production (g C m^{-2} y^{-1})	16* (10–19)	Similar to present, higher or lower but probably higher	Probably lower
Benthic primary production by macroalgae (g C m^{-2} y^{-1})	87*	Similar to present, higher or lower but probably lower	Similar to present or lower
Benthic primary production by microphytobenthos (g C m^{-2} y^{-1})	56* (34–77)	Similar to present, higher or lower but probably lower	Similar to present or lower
Pelagic respiration (at 1 m depth, g C m^{-2} y^{-1})	74***	Higher	Lower
Benthic respiration (g C m^{-2} y^{-1})	73***	Higher	Lower
Net ecosystem productivity*** (calculated for respiration and primary production at 1 m depth, g C m^{-2} y^{-1})	11–15***	Probably lower	Similar to present, higher or lower

Temperate domain – global warming

As discussed in previous section (8.3.2), during a global warming case in a temperate climate domain the annual mean temperature is assumed to increase along with precipitation and runoff. The direction of the effects on abiotic factors are relatively easily to foresee and some abiotic parameters that are likely to be affected include: period with ice coverage, nutrient concentrations, particulate matter concentrations, and dissolved organic carbon and oxygen conditions. Biotic parameters are also likely to be affected but the effects are more complex due to the multiple interactions in ecosystems. As an example although a warmer climate is assumed to increase primary production in most lakes there are also examples of decreased primary production at warmer climate /O'Reilly 2003/. Thus, although response of global warming is relatively easily to foresee in terrestrial ecosystems the effects on lake ecosystems is less clear /Blenckner 2005/. Biotic factors may be affected either directly through increased temperature or indirectly due to altered abiotic conditions. Predictions of expected values of abiotic and biotic parameters compared to present (temperate) conditions are discussed below and summarised in Figure 8-5 and Table 8-3.

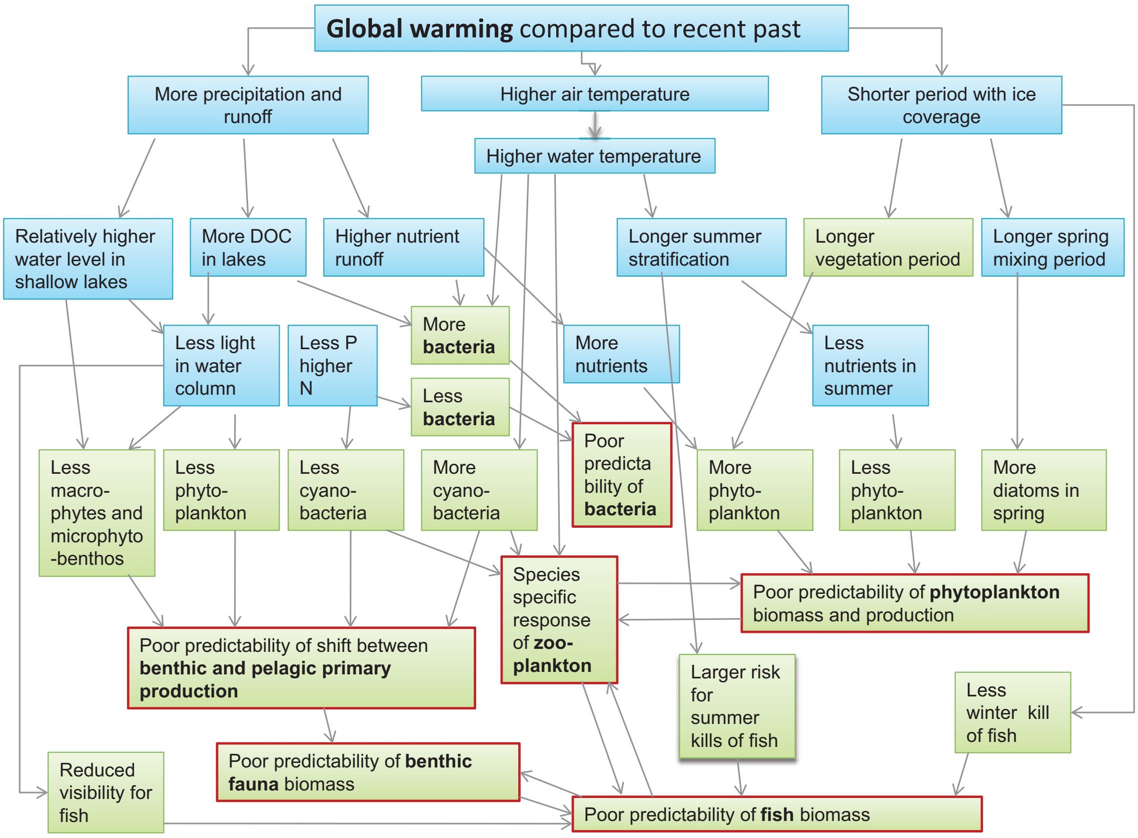

Figure 8-5. *Major effects of global warming on aquatic ecosystems compared to present situation in temperate regions. Note that although effect on abiotic factors (blue boxes) are determined with relatively high confidence, the effect on biotic parameters (green boxes) are less confident due to many interactions in the ecosystem between abiotic and biotic parameters as well as between different biotic components. Modified after /Smith et al. 2008/.*

Abiotic conditions

The period of ice coverage in the present-day Forsmark lakes range between 98 and 143 days. Even though water temperature is expected to increase less than air temperature, an increased air temperature will lead to longer stratification period in summer and shorter periods with ice coverage in lakes (e.g. /DeStasio et al. 1996, Weyhenmeyer et al. 1999, Smith et al. 2008, Livingstone and Adrian 2009/. Modelling studies have simulated a shortened ice period of 1–2 months in the Nordic areas by the year 2070 /Smith et al. 2008/. Since the temperature in winter in the global warming scenario will range between 0 and 6°C, it will likely be at most short periods of ice coverage interrupted by open water periods (see e.g. /Livingstone and Adrian 2009/). This also has implications for other abiotic and biotic parameters in the lakes, such as mixing, light conditions, biomass and production.

Runoff is modelled to increase which will influence nutrient concentrations both by altered input but also by altered retention time in lakes. However, although runoff in terms of water quantity increases by about 17–40% (see Section 8.3.2 above), it is not certain that nutrient runoff will increase proportionately since nutrient runoff is influenced by accumulation and decomposition on land, weathering etc. Processes within the lake such as mixing and anoxia may influence the future nutrient concentrations in the water column. Most deep lakes are stratified in summer and altered temperatures may affect period and frequency of mixing which in turn affect nutrient concentrations. Occasions and magnitude of nutrient pulses may differ, and /Wilhelm and Adrian 2008/ state that the frequency and magnitude of nutrient pulses are likely to increase in the future due to increased severity of anoxia in stratified lakes. It is possible that quotas between different nutrients (e.g. N/P-quota) will be altered due to different retention and release due to global warming which may have a profound effect on species distribution in aquatic habitats /Smith et al. 2008/. In the recent studies concerning global warming there are examples of increased phosphorus concentrations due to increased mixing and shorter ice coverage, but there are also examples of reduced phosphorus concentrations during mixing /Blenckner 2005 and references therein/. The response of individual lakes is thus difficult to predict based solely on the literature, although it is likely that increased temperatures will increase anoxia during stratification, which in turn affects the release of phosphorus from sediment to water /Blenckner 2005/. In lakes with long retention time (several years) an increased input from runoff are likely to increase nutrient concentrations whereas in lakes with short retention time, increased runoff may lead to lower nutrient concentrations if phosphorus released from sediments are flushed out when retention time decreases /Smith et al. 2008/. Thus, nutrient conditions following global warming are determined by catchment characteristics, runoff and internal lake factors such as anoxia and nutrients stored in the sediments. In Forsmark, both lakes with long retention time and short retention time are present and thus the response of climate on nutrients is difficult to foresee. However, considering the low concentrations of phosphorus at present it is likely that concentrations will remain similar or increase.

The concentration of dissolved organic carbon (DOC) is important for bacterial growth. There has been an increase of DOC in surface waters in the last decades, which has been suggested to have been caused by either global warming, nitrogen deposition or changes in land use. In most lakes dissolved organic carbon (DOC) are expected to increase due to global warming but impact of climate factors on DOC are complex and includes combined effect of temperature, precipitation, decomposition, solubility , hydrological transport, land-use and acid depositions, and depending on climate scenario and catchment characteristics DOC concentrations could remain similar to present /Sobek et al. 2003, Sobek et al. 2007, Smith et al. 2008, Jennings et al. 2010, Naden et al. 2010/. A higher temperature could lead to increased primary production in terrestrial areas, and although this leads to higher humus production, a higher mineralization rate may cause lower amounts of DOC to be exported to lakes and streams /Clair and Ehrman 1996/. At present DOC concentrations are very high in the Forsmark lakes which may be caused by internal release of DOC from primary producers. Therefore if DOC input from the catchment increase there will likely be a decrease in internal DOC production (shading of primary producers by humic DOC reduces primary production) although the DOC concentrations will probably remain similar to present at global warming conditions.

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

There may be a shift in occurrence of anoxia from winter to summer. At present, anoxia occurs in the very shallow lakes in Forsmark during winter. Shortened period with ice coverage reduces the risk for anoxia in winter. On the other hand, increased production in summer can lead to increased amounts of degradable matter, resulting in increased respiration and increased anoxia during summer stratification (when the water column is divided into an upper and a lower layer that are not mixed with each other). An example of the latter situation is the German Lake Müggellsee where anoxia increased during summers with increased temperatures /Wilhelm and Adrian 2008/. Present-day Forsmark lakes are shallow without strong stratification and in these lakes there will probably not be anoxic conditions during summer. In some of the future deeper lakes, on the other hand, anoxia may occur during summer.

Biomass and production of primary producers

The higher water temperature and shorter periods of ice coverage lead to a longer vegetation period for primary producers. However, although primary producers are affected by temperature they are most often limited by light conditions and nutrients /Gyllström 2005, Wilhelm and Adrian 2008/. As nutrients are assumed to increase in a global warming period there is a large probability that **phytoplankton** biomass and production increases. However, although increased nutrient inputs to water may lead to higher primary production in the water column, there may be a subsequent decrease in benthic primary production since phytoplankton reduces light availability for **benthic algae** /Vadeboncoeur et al. 2003/. There are examples of lakes with switching stable states between macrophytes dominated and phytoplankton dominated states of shallow lakes. Although climate may be a large contributor of this shift, climate alone cannot explain shift but there are other factors influencing as well /Hargeby et al. 2004, Hargeby et al. 2007, Van Geest 2007/. Most lakes showing shift between macrophyte and phytoplankton dominance are rather nutrient rich and /Andersson and Brunberg 2006b/ showed that increased nutrient inputs to one of the Forsmark lakes did not favour phytoplankton biomass and production. The lack of response by phytoplankton to increased nutrient conditions may have been due to efficient competition for nutrients by microphytobenthos and bacteria or by allelophatic toxins that may be formed by benthic algae /Faust 1995, Mez et al. 1998, Berger and Schagerl 2003/. In addition, there are also examples of increased nutrient turnover rates at higher temperatures which may enhance benthic algal biomass /Havens et al. 2001/. Thus, if nutrient increases due to increased temperature are moderate, biomass and production of microphytobenthos will probably remain similar to what they are at present, whereas if the nutrient increase is large there will probably be an increase in phytoplankton biomass and decrease in microphytobenthos benthic macrophytes and macroalgae. Thus, although warmer climate may increase pelagic production there may be a subsequent decrease in benthic production and total lake primary production may remain similar to present.

In addition to altering the proportion between benthic and pelagic production, increased temperatures and nutrient may lead to a shift in species composition of phytoplankton. Many studies suggest that the proportion of cyanobacteria in phytoplankton communities will increase with increased temperature and there will be an increased risk of algal blooms /Smith et al. 2008, Wagner and Adrian 2009/. As cyanobacteria are a less favourable food source for consumers, this may have an effect on the entire food web and utilisation of the lakes by humans. However, if nutrient composition is altered with respect to more nitrogen and less phosphorus (see abiotic factors above), other species than cyanobacteria will most probably be favoured.

The seasonal timing of biotic maximums such as the spring bloom of diatoms has been shown to be altered by global warming /Blenckner et al. 2007/. In shallow lakes, the effects of winter climate on phytoplankton are short-lived and are soon taken over by prevailing weather and biotic interactions /Adrian et al. 1999/. In deep lakes however, the winter climate signal can persist until late summer /Gerten and Adrian 2001/.

Biomass and production of consumers

Bacteria will be affected by global warming conditions but is seems that the indirect effects such as nutrient concentrations and DOC have a larger impact on bacterial respiration than the actual temperature /Cimbleris and Kalff 1998, Sobek et al. 2003, Smith and Prarie 2004, Sobek et al. 2005, Hall and Cotner 2007/. Bacterial biomass has been shown to be correlated to DOC concentrations (e.g. /Tranvik 1988/) but DOC concentrations are already high in the Forsmark lakes and it is likely that bacteria are limited by other nutrients than DOC such as low phosphorus concentration /Andersson and Brunberg 2006b/. Bacterial respiration may increase as a response of increased nutrient concentrations and higher temperature at global warming conditions. However, many bacterial strains have large plasticity, especially in temperate regions were bacterial communities experience large temperature variation over the year /Smith et al. 2008/. It is therefore difficult to predict the effect of a few degrees warming on bacterial respiration.

Zooplankton can tolerate high summer temperatures but small increases in winter temperatures can strongly influence zooplankton dynamics /Smith et al. 2008/. In addition to temperature, global warming conditions can indirectly affect zooplankton by food web interactions and important factors include biomasses and composition of phytoplankton and biomass of zooplankton eating fish (Figure 8-5). Zooplankton biomass has been shown to be negatively correlated with temperature /Gyllström et al. 2005/ which may be caused by increased grazing by fish or by reduced food quality if larger proportion of phytoplankton are composed of cyanobacteria. On the other hand, zooplankton metabolism has been shown to co-vary with primary production /Wetzel 2001 and references therein/, and the amount of zooplankton has been shown to be correlated with phosphorus concentrations /Gyllström et al. 2005/, so the net effect on the zooplankton community is most likely specific for each lake.

The biomass of **benthic macrofauna** is rather low in the Forsmark lakes. This is probably a result of the soft microbial mats in the lakes. The biomass of benthic fauna under present conditions is somewhat low compared with that in the *Chara*-lake Krankesjön in southern Sweden /Hargeby et al. 1994/, which may suggest that biomass and production increase with temperature. On the other hand, the benthic fauna biomass is similar to that of a *Potamogeton* population in southern Sweden /Hargeby et al. 1994/, indicating that other factors than temperature is important. Biomass of benthic fauna has been shown to correlate with the biomass of benthic algae /van den Berg et al. 1997/. Thus, the biomass and production of benthic fauna probably follow the same pattern as macroalgae biomass and production. As discussed above, there may be either an increase or a decrease in macroalgal biomass in response to global warming (Figure 8-5).

Warmer temperatures affect the **fish** (both by affecting growth but also by affecting species distribution), which in turn can affect the entire food web via cascading effects /Blenckner 2005 and references therein/ (Figure 8-5). Warmer temperatures often lead to earlier spawning, increased survival of the young of the year, which increases the grazing pressure on zooplankton /Smith et al. 2008/. Fish biomass has been shown to be positively correlated with temperature, and nutrient concentrations /Hanson and Leggett 1982, Jeppesen et al. 1999, Gyllström 2005/. On the other hand, /Karlsson et al. 2009/ showed that for oligotrophic and mesotrophic lakes in Sweden and Finland, fish biomass and yield were negatively correlated with phosphorus concentration, i.e. the opposite of what previous studies had found. They are a result of increased concentrations of nutrients and that organic matter reduce light conditions in the benthic habitat and thereby reduce the food available to fish from the benthic pathway. In addition, previous correlations between phosphorus and production includes very high phosphorus concentration up to 500 µg L^{-1} whereas the study by /Karlsson et al. 2009/ includes lakes with phosphorus concentration up to 30 µg L^{-1} (i.e. more similar to concentrations found in Forsmark lake water, see Chapter 3).Thus, one possible outcome of increased phosphorus concentrations is reduced fish production in Forsmark lakes. However, the interpretation of response of fish to global warming is even more complex due to possible changes in oxygen conditions and macrophyte communities, which serve as nurseries for young fish (Figure 8-5). Warmer temperatures may lead to anoxia during summer leading to fish kill and reduced fish biomasses. On the other hand, shortened period of ice coverage may reduce winter fish kill leading to higher biomasses of fish.

Net ecosystem production

Increased nutrient load may or may not lead to a higher primary production since as discussed above; increased nutrients may also lead to reduced light conditions in the benthic habitat. However, the earlier ice breakup and thereby a longer growing season most probably leads to a somewhat higher annual primary production. However, respiration is also positively correlated to temperature and a higher mineralisation of allochtonous carbon is expected following a global warming (e.g. /Gudasz et al. 2010/. Thus, the net ecosystem production will probably remain similar to the present or decrease due to increased respiration at higher temperatures. Respiration is temperature-dependent, and an increased temperature is assumed to lead to increased respiration in the pelagic community. However, /Hall and Cotner 2007/ state that these short-term studies are difficult to apply to a long-term perspective such as a global warming case. Most lakes in Scandinavia and world wide are net heterotrophic, i.e. have a negative net ecosystem production, are dependent on allochthonous material from the catchment and are dominated by respiration (e.g. /del Giorgio et al. 1997b, Sobek et al. 2003, Kortelainen et al. 2006/). /Sobek et al. 2003/ showed that net heterotrophy occurred in all lakes investigated by them (n=33) from southern to northern Sweden regardless of temperature. Instead of temperature, bacterial respiration was more dependent on DOC concentrations in the system. Higher runoff of humic DOC and nutrients in winter, combined with higher winter temperatures favour heterotrophic organisms since the latter are not as light-dependent as the primary producers. In the Forsmark lakes, an increased nutrient input probably do not lead to more autotrophic systems, as increased nutrient concentrations most certainly also result in less light reaching the benthic, highly productive part of the system. Thus, if the NEP are altered in the Forsmark lakes due to global warming condition it is likely that it decrease as a response to decreased benthic primary production and a somewhat increased respiration due to higher temperatures.

Periglacial domain

As discussed above (8.3.2), the annual mean temperature is assumed to decrease by about 13°C in a periglacial domain. In addition to existing lakes at temperate conditions there will be thermokarst lakes (thaw lakes) at periglacial conditions. Thermokarst lakes form by thawing permafrost and subsequent contraction and slumping of soils. Thermokarst lakes are discussed in a separate paragraph below whereas effects on abiotic and biotic conditions in existing lakes are treated separately. A large difference in periglacial lakes compared to the present lakes is that there will be no reed surrounding the lakes. The reed belt surrounding lakes may be important for the functioning of lakes both structuring the composition of water entering the lake from the sub-catchment and the reed belts in the littoral may function as sheltered breeding areas for aquatic organisms. In periglacial regions, instead of reed, lakes are surrounded by heat land vegetation (Figure 8-6).

Polar regions of today may be used to predict conditions in Forsmark at periglacial conditions. Greenland experience a wide range in temperature and northern part of Greenland have perennially ice covered lakes whereas lakes in southern Greenland have open water for 6 months of the year. Thus Greenland may be used to compare how ecosystem changes towards colder climate. However, one has to remember that Greenland experience a wide range of nutrient and salinity concentrations which may influence the lakes in addition to the climate variation. SKB personal involved in SR-Site has visited an area of Greenland, Kangerluusuaq, in order to gather information of surface systems at periglacial areas. Photos in the following sections are from these field visits.

The effects of periglacial climate on abiotic factors within the lakes are relatively easily to foresee and some abiotic parameters that are likely to be affected include: period with ice coverage, solar insolation, mixing, nutrient concentrations, particulate matter concentrations, and dissolved organic carbon and oxygen conditions. Biotic factors may be affected either directly through lower temperature or indirectly due to altered abiotic conditions. Predictions of expected values of abiotic and biotic parameters compared to present (temperate) conditions are discussed below and summarised in Figure 8-7 and Table 8-3.

Figure 8-6. *A Greenland lake surrounded by heat land vegetation. This is as an example of possible lake surrounding in Forsmark at periglacial conditions.*

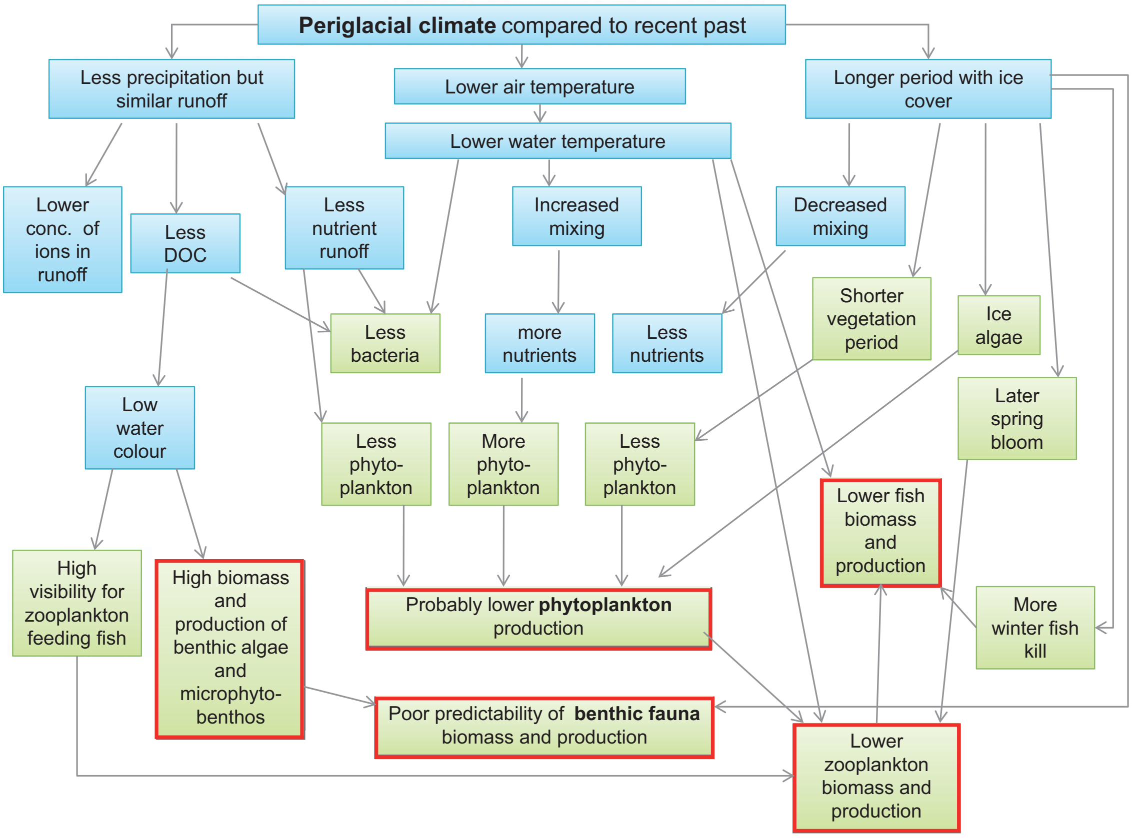

Figure 8-7. *Expected effect of a periglacial climate on the Forsmark lakes compared to present temperate conditions. Note that although effect on abiotic factors (blue boxes) are determined with relatively high confidence, the effect on biotic parameters (green boxes) are less confident due to many interactions in the ecosystem between abiotic and biotic parameters as well as between different biotic components.*

Thermokarst lakes

As stated above thermokarst lakes are formed by thawing permafrost and therefore do not have connection to groundwater flow. In aspect of radionuclide transport from a deep repository they are therefore not important since there are no connections to the flow from the repository. However, from an ecological point of view they may be important for the landscape as they may be hotspots of biological activity in tundra regions with abundant microbial activity, primary production benthic communities and birds. At present, thermokarst lakes are the most abundant aquatic ecosystems in the Arctic and for example in Yukon river delta in Alaska there are 200,000 thaw lakes and ponds /Maciolek 1989/. Thermokarst lakes are often small and shallow although depth may increase with time (Figure 8-8). Examples of thaw lakes in Alaska show that they were frozen solid for all but three months of the year. Still production of benthic primary producers and sedges in summer was high. Grazers on the other hand were of little importance /Vincent et al. 2008/. However, since the lakes are of little importance for radionuclide transport or human food gathering (there are no fish or crayfish) these lakes are not further described here.

Abiotic conditions

In a colder climate the period with ice coverage will be longer than at present. Greenland lakes experience a range of ice coverage between the entire year and 6 months /Vincent et al. 2008/. It is likely that the Forsmark lakes will be somewhere in-between this range at a periglacial climate. A thicker ice sheet allows for less light penetration, affecting the primary producers beneath the ice as well as affecting mixing and transport of nutrients.

Figure 8-8. *Small shallow thermokarst lakes in Greenland. These kinds of lakes may form in Forsmark during periglacial conditions in the future.*

Mixing is prevented for a longer time in winter due to a longer period with ice coverage. In summer, periglacial lakes may have a longer period of mixing than at present if the temperature remains close to 4°C. In the Arctic, there are examples of lakes with summer stratification i.e. no mixing, lakes with mixing the entire open water season, and lakes that are polymictic, i.e. stratified for short periods interrupted by mixing (occurs when the temperatures rise only slightly above 4 °C) /Vincent et al. 2008/.

The magnitude of water runoff will most likely be similar to present-day conditions (see Section 8.3.2), but nutrient concentrations may be lower due to shorter runoff season. The exact nutrient runoff is difficult to estimate since the nutrient concentrations in runoff are influenced by e.g. accumulation and decomposition on land. It is likely that less weathering during periglacial conditions will lead to less ions in runoff /Vincent et al. 2008/. In addition to runoff, nutrient concentrations in lakes are affected by internal lake turnover and accumulation in sediments. Anoxia in sediments releases phosphorus and there may be a larger release of phosphorus during winter which then increases nutrients in the beginning of the growing season. On the other hand, ice cover prevents mixing for large parts of the year which may lead to less transport of nutrients form sediments to the water column /Vincent et al. 2008/.

The concentrations of DOC are very high in present day lakes and will likely decrease during periglacial conditions. There are a wide range of DOC concentrations in lakes in the Arctic region today (1–18 mg DOC L^{-1}) but most lakes in tundra zone contain less DOC than lakes in the temperate region /Hobbie and Laybourn-Parry 2008, Lyons and Finlay 2008/. Decreased primary production in terrestrial areas leads to lower humus production which may cause lower amounts of DOC to be exported to lakes and streams. At present, much of the DOC in the Forsmark lakes are supposed to be produced within the lakes as primary producers release DOC exudates during photosynthesis (see Chapter 3) but also this source may decrease if there are lower annual primary production.

The concentrations of particulate matter will probably be lower in periglacial conditions than at present condition. Periglacial lakes in the world today often have few particles in the water. The Forsmark lakes today are clearwater lakes and have relatively low concentrations of particulate matter. Runoff in the future will be similar to the present runoff, but as the ground will be frozen it is likely that fewer particles will be transported to the limnic systems and the concentration of suspended particles may decrease.

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

Biomass and production of primary producers

Lakes in colder regions do not necessary have lower biomasses and production of **phytoplankton** compared to warmer lakes. Although ice limits light insolation in Arctic lakes during large part of the year production is often lower in late summer than in early summer probably due to limitation of nutrients /Vincent et al. 2008 and reference therein/. Phytoplankton biomass in areas with permafrost today is similar to the Forsmark phytoplankton biomass. Chlorophyll *a* (chl *a*) concentrations in some 240 Arctic lakes (Canadian, western North American, Greenland and European) ranged between undetectable (0) and 148 µg chl *a* L^{-1} (e.g. /Lizotte 2008 and references therein, Vincent et al. 2008/). Most lakes, however, were in the lower part of this range, often below 2 µg chl *a* L^{-1}. In Forsmark, chl *a* ranges from below the detection limit to maximum values of 16 µg chl *a* L^{-1}, with most lakes having mean values between 1 and 2 µg chl *a* L^{-1}. Thus the phytoplankton biomass is low in both periglacial conditions and under present conditions in Forsmark, and it is likely that the biomass will be similar under temperate and periglacial conditions. Annual production by phytoplankton in Arctic lakes ranges from 0.3 to 15.9 g C m^{-2} /Lizotte 2008/. This is somewhat lower than reported for the Forsmark lakes today: 25 gC m^{-2} y^{-1}. The phytoplankton biomass in Forsmark will probably remain similar to present-day conditions under periglacial conditions, whereas primary production may decrease somewhat due to a shorter growing season.

Since the water in the lakes during periglacial conditions are assumed to be clear (low amounts of DOC and particulate matter) it is likely that the biota will continue to be concentrated to the benthic communities in Forsmark lakes also at periglacial conditions. In Forsmark, thick microbial mats (c. 10 cm) consisting of cyanobacteria are found in the benthic habitat although this kind is very uncommon in temperate regions. In Polar Regions, microbial mats and moss mats several decimetres thick have been noted in the benthic habitats of lakes (e.g. /Imura et al. 1999, Quesada et al. 2008/) (Figure 8-9). Therefore, there is no reason to assume drastically different biomasses in permafrost lakes. Benthic microbial mats may flourish in a number of physically stressed systems including nutrient deplete, hyper-saline, calcified, high irradiance, tropical and polar systems /Paerl et al. 2000/ and thus production may be high at periglacial conditions. Primary production in microbial mats in the Polar Regions is typically within the range 10–100 mgC $m^{-2}h^{-1}$ /Quesada et al. 2008/. In Forsmark, primary production by microphytobenthos ranges between 0 and 144 mgC $m^{-2}h^{-1}$ /Andersson and Brunberg 2006a/ and is thus also similar to that in polar regions. The biomass of **macroalgae and macrophytes** may be just as high under permafrost conditions as in present-day lakes as exemplified by Figure 8-9 showing vegetation in periglacial lakes in Greenland. The growing season may influence the annual production of microbial mats and macroalgae, so that in permafrost regions the relatively shorter growing season could lead to lower primary production. On the other hand, most macrophytes are annual and examples of high production in Greenland lakes indicate that benthic primary production could remain similar to present in Forsmark lakes during periglacial conditions.

Biomass and production of consumers

Most organisms in the polar regions today seem to be cold tolerant rather than cold adapted, resulting in lower growth and metabolism at the low temperatures in polar regions /Vincent et al. 2008/.

Bacterial respiration is temperature-dependent, and it is likely that bacterial biomass and respiration will be lower under periglacial conditions compared with the recent past. However, bacterial biomass has been shown to be mainly dependent on the amount of DOC /Sobek et al. 2003/. Lakes in tundra zone often contain less DOC than lakes in temperate region (see abiotic factors above) and therefore, it is possible that in addition to effects of lower temperature, bacterial respiration may decrease due to lower substrate availability.

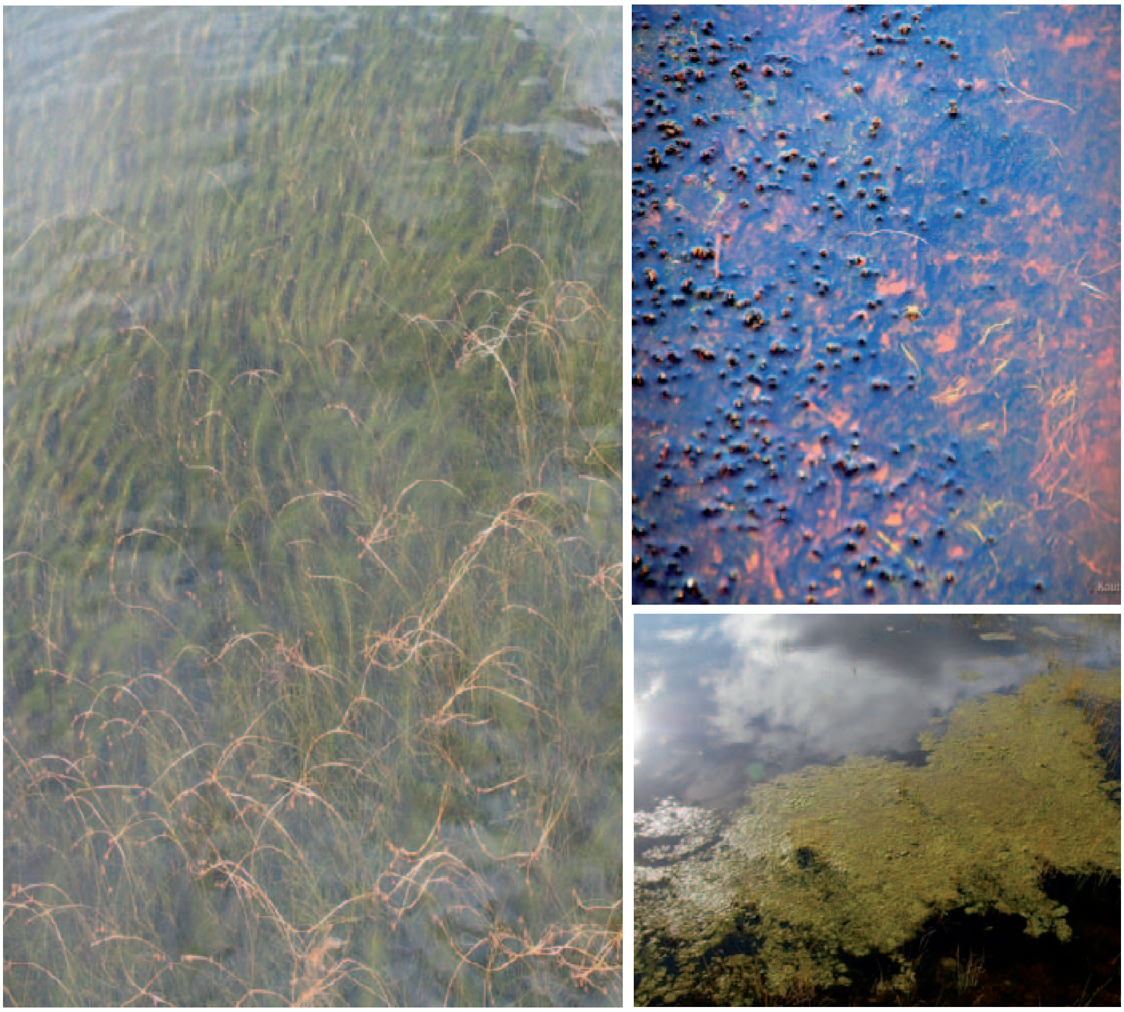

Figure 8-9. *Vegetation found in Greenland lakes as examples of vegetation found in lakes in periglacial conditions. "Axslinga" forms tick vegetation on the bottom of a Greenland lake (left) similar to the Chara beds in present Forsmark lakes. Thick mats of brown mosses cover some of the Greenland lakes (upper right) and in calm areas floating vegetation may form (bottom right).*

Cold climate may reduce the fish biomass, which could favour the zooplankton biomass. On the other hand, the growth season of phytoplankton will be shorter and thereby limit the food for zooplankton. Invertebrates (zooplankton and benthic fauna) in Arctic areas are adapted to cold temperatures and some are as abundant as in temperate regions /Rautio et al. 2008/. Small zooplankton seem to be more dependent on trophic status than temperature and ciliates are composed of the same species in temperate as periglacial lakes as long as nutrient status is similar /Hobbie and Layborn-Parry 2008/. Respiration is probably slower, due to a lower temperature. Both zooplankton and benthic fauna are likely to be sustained by the production by benthic primary producers in shallow periglacial lakes /Rautio et al. 2008/. Examples of zooplankton species in periglacial conditions are copepods, cladocerans, rotifers, ciliates and mysids. Examples of benthic fauna species found at periglacial conditions are oligochaetes and Tadpole shrimp (see Figure 8-10). The clear water in periglacial lakes enhance foraging success by fish which may control zooplankton biomass /Cristoffersen et al. 2008/. Biomass of zooplankton is already low in Forsmark lakes and it is reasonable to assume that biomass will remain similar also in periglacial conditions.

Figure 8-10. Examples of benthic fauna (Chironomidae and adpole Schrimp) found in Greenland lakes, thus possible benthic fauna also in future periglacial Forsmark lakes.

To survive in periglacial lakes fish has to be adapted to low temperatures and low productivity /Power et al. 2008/. Fish in periglacial habitats are often dependent on benthic food web as the pelagic production does not provide enough energy /Vincent et al. 2008/. The benthic food web is a assumed to be a major contributor to fish also in present Forsmark lakes but biomass and production is assumed to be higher in the temperate regions. Catches in northern Swedish mountain lakes are about 2 kg ha^{-1} y^{-1} /Alanärä and Näslund 1995/. Although nutrient conditions may be different in Uppland compared with northern Sweden, the cold climate will most certainly influence the production of fish, and the figure from Swedish mountain lakes is assumed to be a reasonable estimate of the future fish biomass under periglacial conditions. Although fish are present in colder regions, species diversity is smaller and there will be fewer species in the periglacial climate domain than in present-day lakes /Power et al. 2008/.

Net ecosystem production (NEP)

Generally, annual productivity in Arctic freshwater systems are low because of short growing season, low temperatures and low nutrient input /Lyons and Finlay 2008/. It is likely that primary production during periglacial climate conditions will be lower than at temperate climate due to a shorter growing season. Also respiration will be lower due to lower temperatures and lower DOC availability for bacteria, and NEP may be similar to NEP in present temperate lakes. However, present Arctic freshwaters are almost always net heterotrophic /Lyons and Finlay 2008/. In Antarctic lakes, microbial mat communities have been found to be net autotrophic (e.g. /Hawes et al. 2001/), whereas in Arctic communities they have more diverse food webs and more consumers, which means that respiration may be higher in these systems. Thus, it is possible that the Forsmark lakes will remain net autotrophic during periglacial conditions but it is also possible that they turn net heterotrophic, i.e. having a negative NEP.

Streams

Streams are likely to be affected by a periglacial climate by temperature, altered runoff pattern, and altered nutrient concentrations in the runoff. In small head water streams water freeze from top to bottom in Artic areas whereas larger streams have perennial discharge. Biota will likely be dominated by cold tolerant species. Fish in the Arctic streams may over-winter in lakes /McKnight et al. 2008/, so streams may host fish populations although freezing in winter. In small streams that freeze only insects capable of surviving encased in ice are found /Rautio et al. 2008 and references therein/. In larger streams benthic fauna may migrate to deeper waters in winter. Insect diverity in small Arctic streams are low and are heavily dominated by coldwater chironomids (see Figure 8-10) (e.g./Rautio et al. 2008 and references therein/).

Glacial domain

As discussed above (8.3.2), the annual mean temperature is assumed to decrease by about 25°C in a glacial domain and lakes will be covered by ice the entire year. Although lake may be present below the ice, there are no fish populations in these permanently ice-covered lakes, and these lakes cannot be utilized as a food source for humans. Thus, the lakes are not useful to investigate from a safety assessment view, since they do not contribute to the transfer of radionuclides to human. However, it is clear that both primary production and respiration is heavily reduced in these lakes compared to present lakes at temperate climate conditions.

8.3.4 Transitions between different climate domains

Transitions between different ecosystems due to a changing climate may lead to other responses that are difficult to predict. The recent debate concerning effects of global warming has generated literature describing mostly short-term responses to temperature increases spanning over a few degrees. Reviews, e.g. for temperate and boreal forests /Hyvönen et al. 2007/ and peatlands /Limpens et al. 2008/, have shown that single-factor responses can be misleading due to the large number of interactions between different factors and feedbacks. From the perspective of a safety assessment, the most critical scenario is if large reservoirs e.g. of organic matter/biomass, were suddenly released during a short period as a consequence of a transition between two climate domains. This can deplete the oxygen in shallow lakes and strongly affect the entire ecosystem /Lyons and Finlay 2008/. Large flushes may also lead to flooding /Vincent et al. 2008/ which may affect the transport of nutrients between the terrestrial areas surrounding lakes and the lakes themselves.

Release of matter could be accumulated again and reach even higher concentrations compared to original position. If no secondary accumulation occurs or is less than the initial accumulation, the release would eventually only lead to dispersal and dilution of the radionuclides. Transitions between climate domains (as defined above) is generally a slow process spanning thousands of years, but there may be cases where sudden changes could occur as a response to long-term changes reaching a threshold. However, the extent and magnitude of such potential sudden changes as an effect of climate change must still be regarded as an poorly known issue. From the perspective of dose calculations extending over the lifetimes of different taxa, it may therefore be relevant to refer to literature from which it may be possible to infer ecological consequences from minor temperature changes, e.g. global warming or present-day temperature gradients.

8.4 Historical development

8.4.1 The Forsmark area

When the latest deglaciation occurred in Forsmark in approximately 8800 BC, the closest shore was situated about 80 km to the west of Forsmark. At that time, the Forsmark area was situated 150 m beneath the surface of the Yoldia Sea (Section 4.3.4 in /Söderbäck 2008/). Since most of the Forsmark regional model area was covered by water until about 2,500 years ago, the postglacial development of the area is determined mainly by the development of the Baltic basin and by shoreline displacement.

At around 500 BC, a few scattered islands situated in the western part of the regional model area were the first land areas to emerge from the brackish water of the Bothnian Sea (Figure 8-11). The surface of these first islands was covered by sandy till and exposed bedrock, which is similar to the present-day situation on the islands outside Forsmark. Palaeo-ecological studies from the Florarna mire complex, situated c. 30 km west of the regional model area, indicate a local humid and cold climate at approximately this time /Ingmar 1963/.

At 0 BC, the Bothnian Sea still covered the Forsmark candidate area, whereas the islands in the western part of the regional model area had expanded in size (Figure 8-11). Land areas currently covered with peat had emerged. These newly isolated basins were small shallow freshwater lakes/ponds, similar to the near-shore lakes that can be found in the area today. The apparent isolation of Lake Bruksdammen in the western part of the area around 0 BC is an artefact caused by the use of today’s lake thresholds when constructing the map. The lake was probably created by man in the 17th century by damming the river Forsmarksån /Brunberg and Blomqvist 1998/.

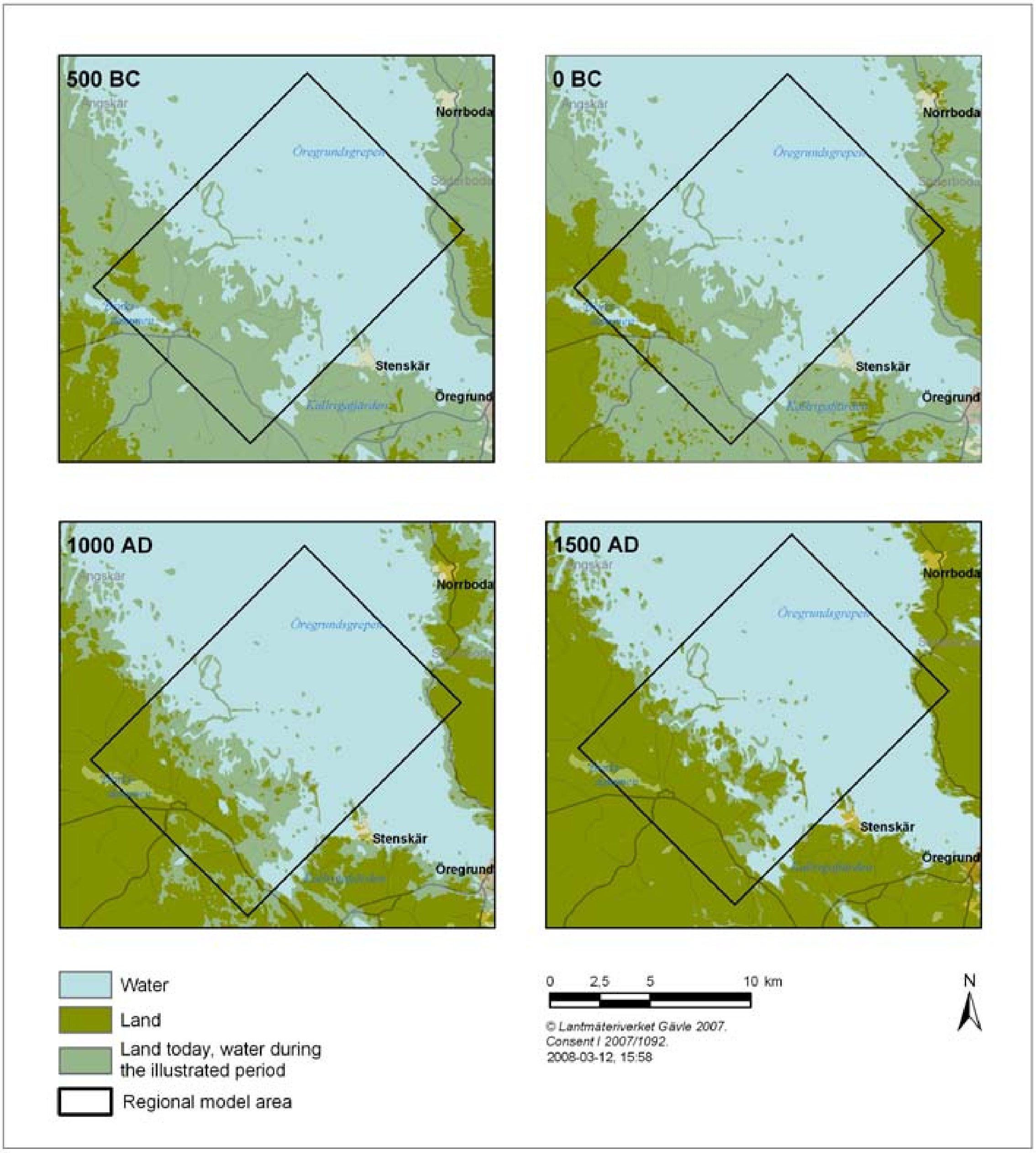

Figure 8-11. *The distribution of land and sea in the Forsmark area at 500 BC, 0 BC, 1000 AD and 1500 AD.*

At 1000 AD, the mainland had expanded further in the south-western part of the area (Figure 8-11). The isolation process of the Lake Eckarfjärden basin was initiated, but the bay still had an open connection with the Baltic in the northern part (cf. /Hedenström and Risberg 2003/). The area west of Eckarfjärden currently occupied by the Stenrösmossen mire had emerged, and a short lake phase was succeeded by invasion of reed (cf. /Fredriksson D 2004/). The Börstilåsen esker and the most elevated areas at Storskäret constituted some small islands in the east, exposed to waves and erosion.

At 1500 AD, a considerable part of the regional model area had emerged from the Baltic and several freshwater lakes were isolated, e.g. Eckarfjärden and Gällsboträsket (Figure 8-11). A shallow strait connected the bays that today are Bolundsfjärden and Fiskarfjärden. The northern part of this archipelago was heavily exposed to wave action, whereas the southern part was relatively protected. The area covered by clayey till at Storskäret formed a large island, partly protected from wave exposure by the Börstilåsen esker. A hundred years later, the strait between Bolundsfjärden and Fiskarfjärden had been cut off, and there were two bays with different conditions. At about 1650 AD, most of the candidate area was situated above sea level.

/Brydsten 2006/ used the lake elevation today, together with the shoreline equation model by /Påsse 2001/, and estimated the sedimentation rate to model the isolation time and the duration of the lake phase for the lakes in the Forsmark area. The oldest of the present-day lakes in the area emerged from the Baltic Sea around 1100 AD (Table 8-4), As described above, all lakes can in the long-term be regarded as temporary since they will eventually be filled up and transformed into either wetland or drier land area. Due to the shallow depths of both previous and present-day lakes in the Forsmark area, it is unlikely that they reached or will reach a stage of increasing eutrophication before they are completely filled with material. Instead, a likely ontogeny of the shallow hardwater lakes in Forsmark is growth of reed around the lakes and a succession towards a reed swamp, a fen and finally a bog ecosystem. This idea is supported by the fact that mires (fens) constitute a large part of the Forsmark area today (10–20% of the area in the three major catchments). It is also supported by the fact that the riparian zone of most existing oligotrophic hardwater lakes in the area is dominated by mires. Interestingly, this was also supported by a vascular plant inventory of different mire types /Göthberg and Wahlman 2006/, where the number of indicator species for bog increased with the height above sea level (Section 4.1.1 in /Löfgren 2010/). In Table 8-4, time at conversion to mire for present day lakes are presented.

8.4.2 The Laxemar-Simpevarp area

The latest deglaciation in the Laxemar-Simpevarp area occurred around 16,000 BC, and the highest shoreline in the region is located c. 100 m above the present-day sea level. Thus, the whole Simpevarp regional model area is situated below the highest shoreline, since the highest point in the area is situated c. 50 m above the present-day sea level. The sea level dropped fast during the end of the Baltic Ice Lake, from c. 66 metres above the present-day sea level (m.a.s.l.) around 10,000 BC to less than 20 m.a.s.l. just over 1,000 years later (Figure 4-28 in /Söderbäck 2008/). Accordingly, the first islands in the area emerged from the sea around 9400 BC.

Table 8-4. Time of isolation from the Baltic Sea and estimated time of transformation to wetland for existing lakes in the Forsmark area (modified from Table 3-1 in /Brydsten 2006/). For identification of catchments and sub-catchments, see /Brunberg et al. 2004a/.

Catchment	Sub-catchment	Lake	Lake isolation time (Year AD)	Time at conversion to wetland (Year AD)
Forsmark 1	1:3–4	Labboträsket	1400	2200
	1:1–4	Gunnarsbo-Lillfjärden	1700	2900
Forsmark 2	2:8	Gunnarsboträsket	1100	2900
	2:10	Eckarfjärden	1200	7100
	2:9–10	Stocksjön	1500	2400
	2:7	Kungsträsket	1600	2200
	2:8	Gällsboträsket	1700	2500
	2:5	Fräkengropen	1800	2200
	2:6	Vambördsfjärden	1800	3000
	2:4–5	Graven	1900	2500
	2:11	Puttan	1900	3200
	2:1–10	Norra Bassängen	1900	3400
	2:3–10	Bolundsfjärden	1900	7600
Forsmark 3	3:1	Tallsundet	2000	2600
Forsmark 4	4:2	Lillfjärden	2000	3700
Forsmark 5	5:1	Bredviken	2000	5900
Forsmark 6	6:1	Simpviken	2000	2200
Forsmark 7	7:2–4	Märrbadet	2000	2300
Forsmark 8	8:1	Fiskarfjärden	1900	7600

The Yoldia Sea stage (9500–8800 BC) was characterized by regressive shoreline displacement, whereas the onset of the Ancylus Lake stage around 8700 BC was characterized by a transgression with a total amplitude of c. 11 m. Figure 8-12 shows the former shoreline in the Simpevarp regional model area at four different occasions during the Holocene. At around 8000 BC, i.e. in the middle of the lacustrine Ancylus Lake stage, the shoreline was situated just over 20 m.a.s.l., which means that the western part of the Simpevarp regional model area was dry. Between 8000 BC and 5000 BC, i.e. the first part of the Littorina Sea stage, shoreline displacement was mostly regressive, although there are indications of several minor transgressions during that period (Section 4.4 in /Söderbäck 2008/). At 5000 BC, when the shoreline was situated c. 15 m.a.s.l., the central parts of the regional model area were dry, but the fissure valleys still constituted long and narrow coastal bays which intersected the area. At 2000 BC, most of today's terrestrial areas had emerged from the sea and the coastal bays were considerably reduced in size. From 0 BC and onwards, the sea level has dropped c. 3 m, but this has resulted in only minor changes in the distribution of land and sea in the regional model area.

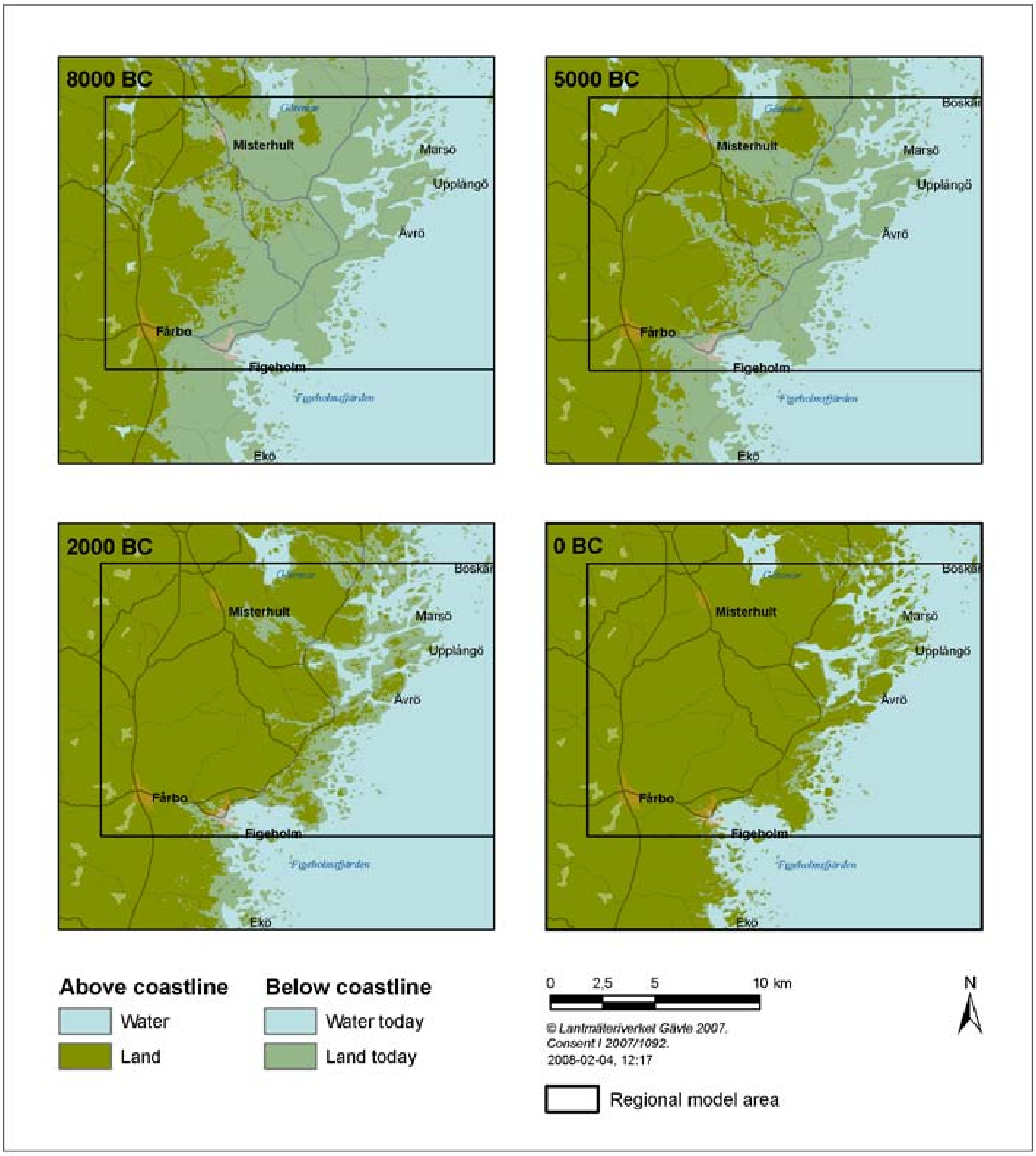

Figure 8-12. *The distribution of land and sea in the Laxemar-Simpevarp area at 8000 BC, 5000 BC, 2000 BC and 0 BC.*

Long-term development of lakes in the Laxemar-Simpevarp area

Only five lakes are situated completely within the Simpevarp regional model area today. All of these lakes are relatively small, shallow, and characterized by more or less dystrophic conditions (cf. /Tröjbom and Söderbäck 2006a/). The ontogeny of these lakes has not been examined explicitly, but there are no reasons to suggest any major differences from the general ontogeny of dystrophic lakes outlined in Section 8.1 above. The higher situated lakes, e.g. Jämsen and Plittorpsgöl, were isolated from the Baltic Sea early during the Holocene (both these lakes were isolated around 8200 BC). The near-shore Frisksjön is today situated at 1.3 m.a.s.l., indicating that the lake was isolated from the Baltic Sea at 1200 AD. However, the lake threshold has been lowered by man in recent centuries, and the lowering is probably larger than 1 m. This means that Frisksjön was isolated from the Baltic Sea much earlier, possibly before 0 BC/AD. Moreover, there is at least one previously shallow lake in the area (Gäster) which has been totally drained in recent centuries in order to gain new agriculture land (Appendix 1 in /Nyborg et al. 2004/), further discussed in Section 4.11.1.

The considerably larger and deeper Götemar (surface area 3.0 km^2, max. depth 18 m) is situated just north of, and partly within, the regional model area, at an elevation of 1 m above the present-day sea level. According to the shoreline displacement model /Påsse 2001/ it was isolated from the Baltic Sea around 1200 AD. Götemar is characterized by oligotrophic, clear-water conditions /Tröjbom and Söderbäck 2006a/. There are no investigations of sediment accumulation from Götemar, but considering the relative nutrient-poor conditions and large depth it seems reasonable to suggest that the lake will remain large and deep for many millennia to come (cf. Erken in the Forsmark region, Section 8.2.1). The currently relatively deep coastal basins north of Äspö (Granholmsfjärden and Kalvholmsfjärden) are expected to be isolated from the sea around 4000 AD (Section 4.1.6 in /SKB 2006b/). Eventually developed into freshwater lakes, they will probably be more similar to the oligotrophic clear-water Götemar than to the small dystrophic lakes in the area.

8.5 Future development of limnic systems in the Forsmark area

8.5.1 Future lakes

As stated in previous sections, new lakes will be formed in Forsmark due to the ongoing shoreline displacement. By modelling of future shoreline displacement and using digital elevation model, regolith models, hydrological model, properties of the future lakes and streams can be predicted. Several of these new lakes will be larger and deeper than present-day lakes. The lakes will have similar setting (surrounding topography and distance to the sea) as present-day lakes and may therefore have many similarities to the limnic system of Forsmark today. However, there will also be differences between the lakes due to differences in sizes of catchments, lake depths and lake areas. The lake basins formed will eventually be filled with lake sediment and wetlands will encroach until the only limnic systems that remains are streams. Figure 8-13 shows the landscape at different future time steps and Figure 8-14 show lakes that will form in the model area. Only lakes that are important for transport and accumulation of radionuclides are considered in the description of future limnic ecosystems.

In the Forsmark area, some of the lakes that will emerge due to shoreline displacement will not receive radionuclides from a deep repository. This section focuses on lakes that are either hit by “radionuclide release” (primary basins) or a basin that are receiving surface water from a primary basin but not hit by “radionuclide release”. Basins without any radionuclide release and that are placed upstream primary basins (tertiary basins) are merged into the primary basins The modelling of future landscape and division of future lake basins in the landscape are thoroughly described in /Lindborg 2010/. During periglacial conditions, thermokarst lakes may form. These lakes are formed in depressions by melt-water from thawing permafrost and are often small and shallow (see Section 8.3.3). Since thermokarst lakes are formed of melt-water they have no connection with talliks and groundwater and are thus not reached by radionuclides from a deep repository. Therefore this kind of lakes is not further discussed in the section below as this report focuses on lakes and streams important for radionuclide transport and accumulation.

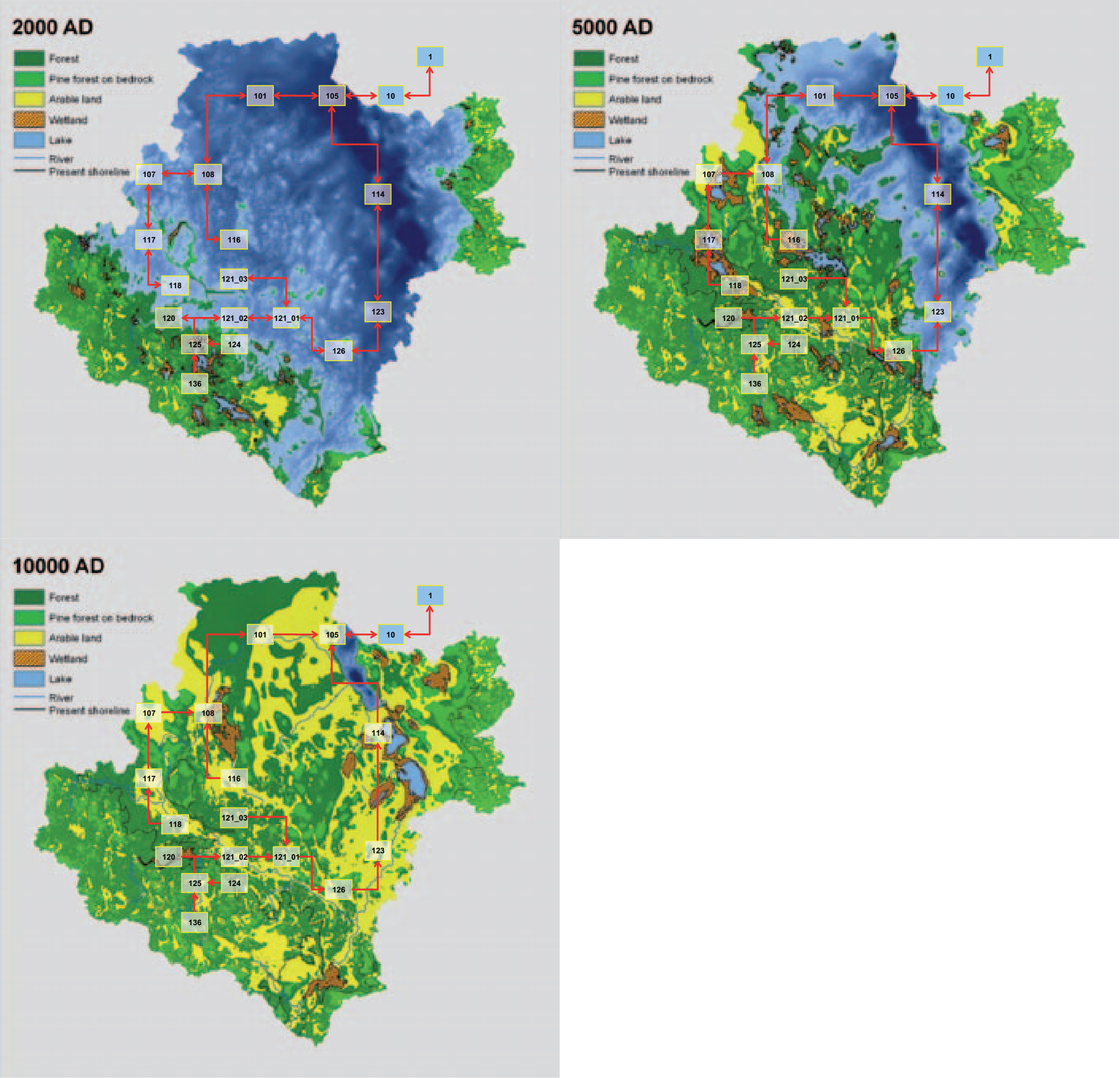

Figure 8-13. The landscape model displayed on the landscape development model at three different time steps (2000, 5000 and 10,000 AD). The boxes shows biosphere objects (with id numbers) at their approximate locations in the landscape and red arrows indicate the surface water flow paths connecting the objects. The blue boxes represent the combined objects of Öregrundsgrepen (object 10), see text, and the model area outlet, the Baltic Sea (object 1).

In the modelling of the landscape, Forsmark is modelled for a period equivalent to an interglacial with starting point at the withdrawal of ice (corresponding to –9500 AD) until the start of the next glacial period (120,000 AD) (see /Lindborg 2010/ for a thorough description of the landscape modelling). However, at c. 36,000 AD all lakes in the landscape are filled in and the only limnic ecosystems remaining are streams passing through wetlands. The first lakes in the modelled area to be isolated from the marine area were isolated around 1900 AD, corresponding to the existing lakes Bolundsfjärden, Norra Bassängen and Puttan). The last modelled lake will be isolated around 11,200 AD (Table 8-5). The lakes are gradually transformed to wetlands and Table 8-5 shows the isolation and terrestrialisation of all future lake objects in Forsmark. When the lakes are fully transformed to wetlands a stream passing through the wetland is assumed to be present in most objects. That is the remaining limnic system in the Forsmark landscape.

The initial depths of the lakes at the time of isolation from the marine basins are shown in Table 8-6. All existing lakes in Forsmark are, and most of the future lakes will be shallow. The depth of lake may play a crucial role of the functioning of the lakes by affecting mixing, stratification, light conditions, nutrient conditions, oxygen conditions etc. These factors in turn affect primary production and

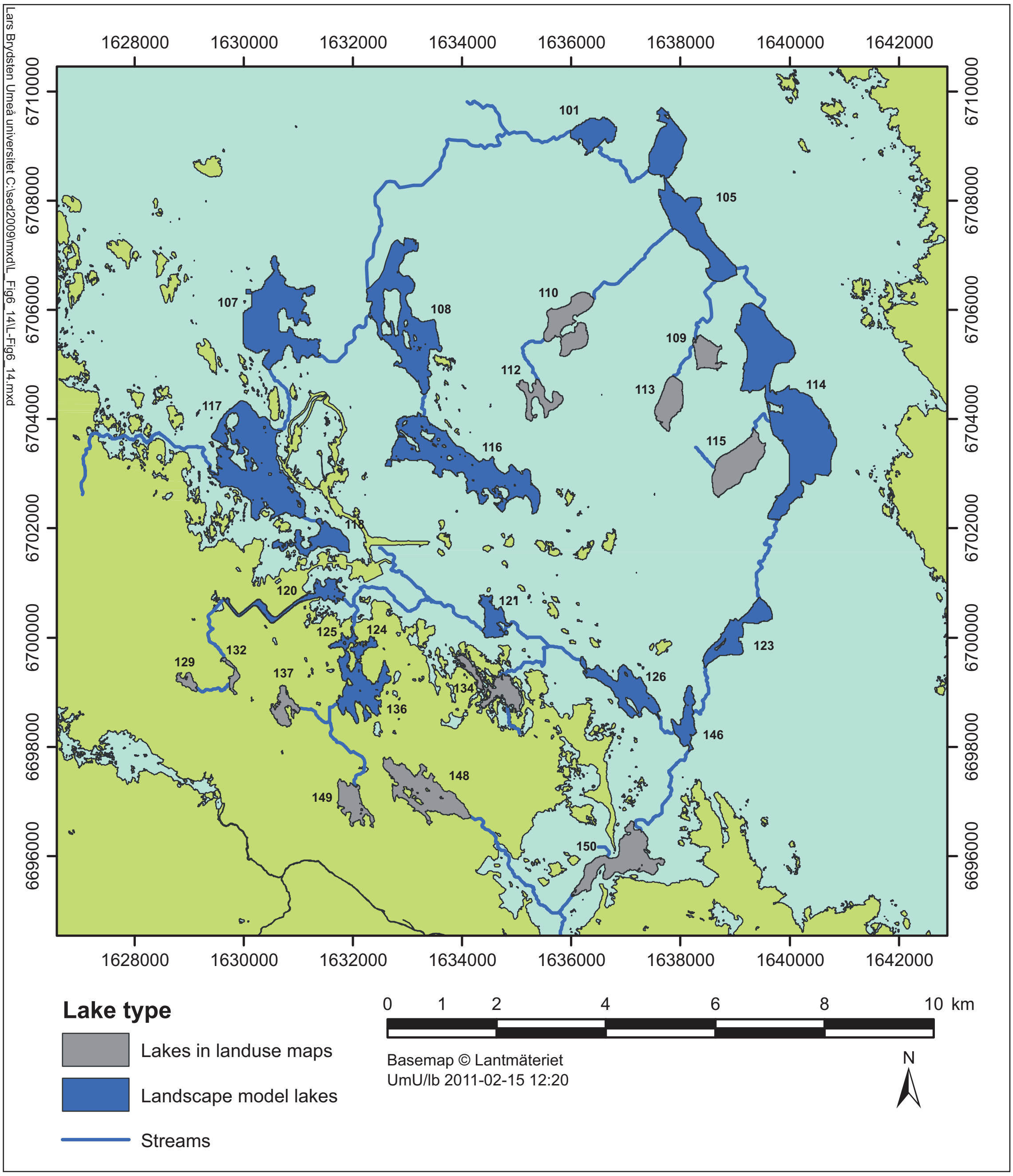

Figure 8-14. Lakes used in the landscape model (blue) and additional lakes (gray) that are only used in the land-use models.

biota. There is no clear distinction between deep and shallow lakes in literature but commonly deep lakes are considered to allow for summer stratification which divides the water column to an upper epilimnion and a deeper hypolimnion. Only three lakes are modelled to become deeper than 10 m meters whereas the others have maximum depths around 5 m or below (see Table 8-6). Therefore, in the description of ecosystem functioning, future lakes have been divided into shallow (objects 101, 107, 108, 116, 117, 118, 12_01, 123, 124, 125, 126, 136) and deep lakes (objects 105, 114 and 120). In predicting the functioning of future lakes and streams on a time scale of 100,000 years, one also has to take into account the different climate conditions that will occur in that time span. Therefore, also ecosystem functioning at periglacial and global warming conditions are discussed in the sections concerning ecosystem characteristics below.

Table 8-5. Summary of significant dates for lakes treated in the landscape model (for a detailed description of the landscape model, see /Lindborg 2010/). The Start parameter is the date for the first time the lake is isolated from the sea, the Isolation parameter is the date when the lake threshold is at the mean sea level and the Stop parameter is the last date when brackish water is flowing in to the lake. The Ter-parameters are dates for successive terrestrialisation (lake-infilling) values where Ter 100% is the date for fully developed wetland.

Basin	Lake	Start (AD)	Isolation (AD)	Stop (AD)	Ter 50%	Ter 75%	Ter 90%	Ter 100%
101	Nameless future lake	7480	8020	8380	–	–	–	8380
105	Nameless future lake	10450	11160	11630	12700	15400	18700	36000
107	Nameless future lake	3160	3500	3730	3500	5250	6300	9300
108	Nameless future lake	4610	5010	5280	5200	7300	9400	13400
109	Nameless future lake	6630	6940	7450	7000	9000	11600	17100
110	Nameless future lake	5660	5490	6400	5500	6900	7700	8300
112	Nameless future lake	4080	4330	4710	–	5200	5800	6200
113	Nameless future lake	5180	5450	5880	–	6450	7100	10500
114	Nameless future lake	7980	8550	8920	13300	17100	20100	34300
115	Nameless future lake	6300	6600	7090	7300	8950	11600	16900
116	Lake Charlie	4390	4780	5040	4900	6650	7700	8500
117	Nameless future lake	2680	3000	3210	3600	5500	6650	8900
118	Nameless future lake	2530	2850	3060	–	4000	4700	5200
120	Nameless future lake	2210	2410	2720	–	4000	6600	15100
121_1	Nameless future lake	3770	4000	4380	–	4600	5200	5600
124	Puttan	1600	1890	2080	–	2100	2350	2600
125	Norra Bassängen	1620	1900	2090	–	2100	2350	2600
126	Nameless future lake	4010	4380	4630	–	5500	6300	6900
129	Gunnarsboträsket	860	1020	1290	–	1100	1400	1600
134	Nameless future lake	2010	2200	2510	2300	3700	4900	8700
136	Bolundsfjärden	1610	1900	2090	–	3350	4200	4800
142	Gällsboträsket	1480	1660	1950	–	2300	2800	3200
144	Bredviken	1710	1890	2190	–	2200	2500	3300
148	Fiskarfjärden	1690	1870	2170	2000	3500	4500	9300
149	Eckarfjärden	930	1100	1370	–	3500	5200	7400
150	Nameless future lake	3230	3450	3800	–	5100	7200	11000

Tale 8-6. Physical characteristics of lakes used in the landscape model. Data from /Lindborg 2010/.

Basin	Lake	Mean depth (m)	Max depth (m)	Area (m^2)	Volume (m^3)	Altitude (m.a.s.l.)
101	Nameless future lake	0.65	1.39	336,800	218,920	–25.80
105	Nameless future lake	6.21	24.50	1,359,700	8,443,737	–34.27
107	Nameless future lake	1.83	5.03	1,431,600	2,619,828	–8.16
108	Nameless future lake	1.70	5.57	1,422,074	2,417,526	–15.00
114	Nameless future lake	6.10	17.78	2,655,500	16,198,550	–27.40
116	Charlies lake	1.37	4.79	1,601,900	2,194,603	–14.04
117	Nameless future lake	1.84	4.55	1,866,600	3,434,544	–5.64
118	Nameless future lake	1.12	3.12	359,800	402,976	–4.86
120	Inlet channel	2.01	10.19	301,100	605,211	–2.49
121_1	Nameless future lake	0.66	2.22	238,300	157,278	–10.59
123	Nameless future lake	0.69	2.38	465,500	321,195	–20.69
124	Puttan	0.37	1.29	82,741	30,614	0.48
125	Norra Bassängen	0.31	0.88	76,070	23,582	0.40
126	Nameless future lake	1.51	4.13	560,200	845,902	–12.28
136	Bolundsfjärden	0.61	1.81	611,311	372,900	0.42
146	Nameless future lake	0.83	2.30	241,400	200,362	–13.89

Characteristics of future shallow lakes

The future shallow lakes have mean depths of around 2 metres or shallower and many of these lakes are assumed to closely resemble present-day oligotrophic hardwater lakes in Forsmark. However, it is also possible that some of the future shallow lakes will be dystrophic brown water lakes. Besides lake depth, the environmental conditions within the drainage area determine the quality of the inflowing water, which constitute one of the most important factors determining the character of the lake ecosystem. In addition to quality, the volume of inflowing water is also important and determines the retention time. According to /Brunberg and Blomqvist 2000/, the development of brown-water systems is coupled to the retention time and character of upstream lakes. Lakes that have emerged in the catchments of Forsmark-Olandsån have evolved into dystrophic lakes, mainly due to the inflow of brown water from upstream dystrophic lakes. In contrast, emerging lakes without large input of brown water are likely to become oligotrophic hardwater lakes. One could hypothesize that lakes with short retention time should be dystrophic due to turbidity of water and high inflow of allocthonous material. Retention time is calculated from areal runoff, drainage area and lake volume in the radionuclide model (Chapter 10).

Only three of the present-day lakes in the Forsmark area are situated within the area included in the modelling of the future lakes (N=3, median retention time 8 days, mean 3 days, min 4 days, max 99 days), but for these lakes the modelled retention time in the year 2000 AD agrees well with the estimated retention time at present. For future lakes, retention times vary from less than 1 day to several years (Table 8-7). Besides differences between objects, retention time also differs with time. At the isolation from marine basins the lakes are rather large and maximum retention time for each object occur. As the lakes become smaller the retention time decreases and minimum retention time occurs just before the complete terrestrialisation of the lake basin. Thus, if retention time is important for the characteristics of the lakes it is possible that they would change towards more dystrophic conditions with lake age. However, the retention times of present-day oligotrophic hardwater lakes in the Forsmark area span a wide range from 5 to 328 days (n=25, median 44, mean 76 days, see Table 3-8) so also lakes with short retention time may become oligotrophic hardwater lakes. Thus, it is assumed that retention time does not determine ecological parameters in future limnic ecosystems. However, it may have an effect on the transport and accumulation of radionuclides and is therefore considered in the radionuclide model (see Chapters 10 and 11).

The succession of future shallow lakes is assumed to closely resemble succession in resent day lakes. The lake ontogeny of oligotrophic hardwater lakes suggests a transition towards more eutrophic conditions with time (see succession above). However, due to the shallow depths of present-day lakes in the Forsmark area, it is unlikely that they reached or will reach a stage of increasing eutrophication before they are completely filled with material /Brunberg and Blomqvist 2000/. Instead, a likely

Table 8-7. Retention times (days) in future lake objects from isolation from marine basin until the lake is transformed to a stream. Retention time is calculated for each time step in the transport model, i.e. each 100 year.

Object	Minimum	Maximum	Mean	Median
101	<1	23	8	<1
105	<1	8	2	2
107	<1	693	46	20
108	<1	19	34	21
114	<1	21	6	5
116	<1	2,041	225	126
117	1	1,041	156	117
118	6	2,562	338	197
120	1	617	42	19
121_01	<1	122	17	6
123	<1	3	1	<1
124	<1	140	21	7
125	<1	187	25	4
126	<1	512	43	17
136	1	735	82	55

ontogeny of the shallow hardwater lakes in Forsmark is growth of reed around the lakes and a succession towards a reed swamp, a fen and finally a bog ecosystem. This idea is supported by the fact that mires (fens) constitute a large part of the Forsmark area today (10–20% of the area in the three major catchments). It is also supported as riparian zone of most existing oligotrophic hardwater lakes in the area is dominated by mires. Interestingly, this was also supported by a vascular plant inventory of different mire types (i.e. previous lake sites) /Göthberg and Wahlman 2006/, where the number of indicator species for bog increased with the height above sea level (see /Löfgren 2010/). Also the future shallow lakes have relatively short life span and it is likely to be filled in before they are transformed into more eutrophic lakes.

The present-day oligotrophic hardwater lakes are dominated by benthic production and are net autotrophic, i.e. primary production exceeds respiration. The autotrophy of present-day lakes is, although common in Forsmark, unusual world wide /Brunberg et al. 2002/. The modelling of net productivity in future lakes used in the radionuclide model (see Chapters 10 and 11) takes into account lake depth. Respiration increases with lake depth and there is a gradient among the future lakes from deep heterotrophic to shallow autotrophic lakes, taking into account the proportion of photic area in the lakes. Therefore, future shallow lakes are modelled to be net autotrophic, but immediately upon isolation some of the shallow lakes may be dominated by respiration of allochtonous organic carbon entering the system from the surroundings. With time, also these lakes turn autotrophic as lake depth decreases due to sediment accumulation. On the contrary, if the emerging lakes are dystrophic it is likely that remain heterotrophic for their entire lake stage.

Present-day lakes in the area with maximum depths of less than 1 metre seems to lack fish (see Chapter 3). This is consistent with the theory that very shallow lakes have poor oxygen conditions during winter, preventing establishment of a permanent fish population. However, all future lakes except object 101 have maximum depths greater than 1 metre and the future shallow lakes are assumed to contain fish. Overall, future shallow lakes are assumed to closely resemble present-day lakes in Forsmark.

Future shallow lakes at periglacial conditions

All of the future shallow lakes are assumed to still be filled in at the time when periglacial domain begins. Still, if assuming shallow lakes persist during periglacial domain the lakes probably resemble lake functioning in present lakes (with high benthic production). The following differences from present lakes are expected though:

1) Some of the future shallow lakes will freeze to the bottom in winters. The period with ice coverage will be longer than at present affecting length of growth season as well as occurrence of anoxia under ice.
2) The lakes probably contain less fish due to poor oxygen conditions during winter periods and colder water temperature which affects metabolism and growth.
3) Crayfish are assumed to be prevented from inhabiting lakes due to the short growing season. Crayfish has not established in present oligotrophic hardwater lakes but may colonise the future shallow lakes if climate and bottom substrate is favourable.

Future shallow lakes at global warming conditions

The effects of global warming on shallow lakes are difficult to predict. As stated in Section 8.3.3 higher temperature and longer growing season may, or may not, lead to a shift from benthic to pelagic production. Biomass of phytoplankton may increase or decrease. Fish may be favoured by less winter fish kill but on the other hand may be inhibited if the benthic food decreases, visibility decreases and phytoplankton community becomes dominated by cyanobacteria. Different responses of lake ecosystems to global warming are discussed in Section 8.3.3. However, possible effects of global warming is an ongoing research and more studies are needed to be able to confidently predict the effects of global warming on specific lake ecosystems /Smith et al. 2008/.

Future deep lakes

The deep lakes that will emerge in the Forsmark area (objects 105, 114 and 120) will probably deviate in a number of aspects from present-day lakes. The future deep lakes in Forsmark will probably be more similar to other deep lakes in the county, Lakes Erken and Limmaren, regarding depth and volume. However, whereas Lakes Erken and Limmaren have long water retention times (6 and 7 years, respectively), the retention times for the future deep lakes are modelled to be short, often less than 1 month (see Table 8-7). Thus, the future deep lakes may deviate from both shallow and deep lakes in Uppland county today. Some of the expected similarities and differences between the future deep lakes and present-day lakes are discussed below.

The main difference from the present-day shallow lakes is that the future deeper lakes will probably be more nutrient rich. The greater depths of the future lakes result in aphotic areas where benthic photosynthesis does not occur. This together with short retention time and thereby large inflow of allocthonous material indicates that the lakes will become net heterotrophic. This is opposite from the shallow clearwater lakes in Forsmark today which are net autotrophic but similar to the majority of the worlds lakes that are found to be net heterotrophic (e.g. /del Giorgio et al. 1997b/).

The lakes are deep enough to allow for thermal stratification during both summer and winter. This may be important during different times of the year, but on the time scale of a year the water will be mixed at least twice (spring and autumn circulation). Nevertheless, stratification may be important for nutrient concentrations in the lakes as anoxic conditions in the hypolimnion may release phosphorus from lake sediments and thereby increase nutrient concentrations in the lakes. In both Lakes Erken and Limmaren, phosphorus is released from the sediments during certain periods of the year in response to low oxygen concentrations at stratification /Brunberg and Blomqvist 2000/. A possible but highly unlikely scenario in the future deep lakes is stratification due to different water salinities. Under present-day conditions there is no pronounced salinity gradient in the Bothnian Sea or the Gräsö trough, indicating that there will not be a gradient in the future lakes either. Moreover, the future lakes are deeper than the present-day lakes, but relatively shallow compared to other large lakes in the world.

An important factor for radionuclide accumulation is the sedimentation pattern of the deep lakes. True accumulation of sediments only occurs in the deepest parts of the lakes, while other soft bottoms are subject to substantial resuspension by waves and internal seiches, followed by further transport to the deeper areas ("sediment focusing"). In shallow lakes, accumulation is assumed to take place in the entire lake area.

There will most likely be greater habitat diversity in the larger lakes than in the small, shallow lakes. In the present deep Lakes Limmaren and Erken, all five key habitats (for definition of habitats see Section 3.7) can be identified, including a pelagic zone, a littoral zone dominated by emergent macrophytes (littoral I), a wind-exposed littoral zone (littoral II), a light-exposed soft-bottom zone (Litoral III), and a profundal zone. Wind-exposed littoral and profundal zones are lacking in the present-day lakes. The following assumptions of lake functioning in the different habitats in deep lakes in Forsmark can be made:

1. Carbon production in the **pelagic** habitat is probably much more important in the deep lakes. Much of the carbon produced in the pelagic habitat of the deep lakes Erken and Limmaren is utilized by other biota in the pelagic habitat, but a considerable portion is lost to the profundal habitat through sedimentation. Losses though the outlet are small due to a long retention time. In the future deep lakes in Forsmark, a large portion of the pelagic production may also be utilized directly in the pelagic habitat, but losses through the outlet are probably much larger than in Lakes Erken and Limmaren due to a short retention time in future lakes.
2. The **littoral zone dominated by emergent macrophytes** (littoral I) will be smaller in relation to the lake's area in larger lakes than in smaller lakes. In small lakes the inflow of nutrients and DOC from the reed belts may heavily influence the characteristics of the lake. In larger lakes, this inflow will have less effect on the characteristics of the lakes. This habitat is treated in the terrestrial report (TR-10-01) in order to treat all wetlands in a similar way, and it is therefore not further discussed here.
3. The **wind-exposed littoral** (littoral II) may be very productive, although it is probably not more productive than the thick microbial mats present in the shallow lakes. The fauna may differ greatly and mussels may form large colonies in this habitat. Up to 2,000 individuals per m^2 of the mussel *Dreissena polymorpha* are found in Lake Erken /Brunberg and Blomqvuist 2000, Naddafi et al. 2010/, and they could potentially affect many of the planktonic organisms /Horgan and

Mills 1997/. Accumulation of organic matter is low in the wind-exposed littoral, and most of the carbon produced is either respired or lost to deeper parts of the lake.

4. Although the **light-exposed soft-bottom littoral** (littoral III) comprises a smaller proportion in the deep lakes, it may contribute greatly to primary production in these lakes as well (cf. /Kahlert 2001/). However, it will probably make a smaller contribution to total lake production than in the present-day shallow lakes.
5. The presence of a **profundal zone** in deep lakes will have a large influence on the functioning of the lake ecosystems, as photosynthesis will not occur on aphotic bottoms. This will reduce the biomass of the benthic macroalgae and microphytobenthos. The incorporation of C-14 into this biota in the event of a release will therefore be less in deep lakes than in present-day shallow lakes, although this may be compensated for by higher incorporation of C-14 into pelagic phytoplankton. Large aphotic areas may also shift the focus in the food web from benthic to pelagic habitat and phytoplankton may be increasingly important.

The range in fish biomass in present-day shallow lakes in Forsmark covers the suggested mean biomass in large lakes in Uppland reported by /Nyberg 1999/. The fish biomass estimated in today's shallow lakes therefore presumably resembles the biomass in future deep lakes. However, there may be a shift in the species composition of the fish, which may include more pelagic species, and the deeper lakes may contain a greater number of species. In Lakes Erken and Limmaren, 16 and 9 species, respectively, have been encountered, which is more than is commonly found in the shallow lakes in Forsmark today (3–8 species in four investigated lakes).

Deep lakes at periglacial conditions

One of the deep lakes, object 114, is assumed to still be a lake when periglacial climate period begins whereas the other deep lakes are assumed to be filled in and transformed into wetlands. The lakes probably resemble lake functioning in deep lakes at temperate conditions, perhaps with a larger focus of production to the benthic habitat. The following differences from temperate lakes are expected though:

1) There will be a shorter growing season due to prolonged period with ice coverage. The exact length of period of ice cover and the depth of ice is difficult to predict since it depends on several factors such as temperature, lake depth, snow cover etc.
2) Probably lower phytoplankton biomasses than at temperate conditions.
3) Water colour is assumed to be lower and primary production is probably focus to the benthic habitat that are not too deep. However, primary production may reach considerable depths in clear water lakes.
4) The lakes probably contain less fish due to less food, colder temperature and possibly also poor oxygen conditions in winter.
5) Crayfish are assumed to be prevented from inhabiting lakes due to the short growing season.

Deep lakes at global warming conditions

Deep lakes are assumed to be affected by global warming. However, as for the shallow lakes different lakes responds differently and effects of global warming is an ongoing research and more studies are needed to be able to confidently predict the effects of global warming on specific lake ecosystems /Smith et al. 2008/. Possible responses of lake ecosystems to global warming are discussed in Section 8.3.3.

8.5.2 Future streams

Most of the future streams in the area will closely resemble the present-day streams, i.e. small with modest water flow. However, there will also be some larger streams with considerably larger discharge than in present streams. In Table 8-8, the depth of future streams are present together with the timing of when the objects are transfored from lake to streams.

Table 8-8. Time when lake objects are transformed to stream objects and mean and maximum depth of the modelled stream objects in Forsmark. Data from the landscape model /Lindborg 2010/.

Object	Time	Depth_aver	Depth_max
101	8,300	0.6	1.2
105	21,800	5.6	5.6
107	9,000	0.4	0.8
108	11,600	0.6	1.1
114	23,100	4.7	4.7
116	8,500	1.6	1.6
117	8,300	0.3	0.6
118	5,200	1.7	1.7
120	11,800	0.2	0.4
121_01	5,600	0.3	0.6
121_02	3,100	0.3	0.6
123	8,500	1.6	1.6
124	2,600	0.2	0.4
125	2,500	0.2	0.4
126	6,800	0.4	0.8
136	4,800	0.4	0.9

The specific discharge is the same for the entire area in the modelling but the larger drainage areas will bring larger volumes of water into the streams and thereby the water volumes passing the streams will be larger. The water flow may influence the species composition of biota but biomasses have been assumed to be similar to in present lakes with the exception of the deep streams as 105 and 114 that are assumed to not host benthic primary producers. On the other hand, these streams may contain larger amounts of pelagic producers.

At present, there are no permanent fish populations in lakes with maximum depths less than 1 meter. In the radionuclide model the same maximum depth was assumed to be valid for the determination of permanent fish population in streams. This assumption resulted in fish populations in all the larger streams (objects 101, 105, 108, 114 and 123), but not in the smaller streams. This is consistent with what could be expected from the site today, i.e. there are no permanent fish populations in smaller streams but in the larger Forsmark streams (see Section 3.12). Fish may use smaller streams for migration and migration (see Section 3.10.2). Larger streams may host large populations of crayfish. However, as the streams in Forsmark will be composed of former lake beds it is unlikely that the bottom substrate will be favourable for crayfish.

Although streams may host a large community of biota and be important for wildlife in terms of passages for fish and transport of nutrients they are principally regarded as transport routes in modelling of radionuclide transport. Deposition and accumulation of matter in streams are of minor importance and biological processes for long-term accumulation of matter are insignificant. On a short time scale elements may be trapped in streams, but at high discharge events, trapped elements are resuspended and transported further downstream and annual retention is small or nonexistent /Meyer and Likens 1979, Cushing et al. 1993, Reddy et al. 1999/. This is especially valid for very small streams like those in the Forsmark area. However, at high-flow periods flooding of wetlands surrounding the streams may occur, which may result in an accumulation of matter in the wetlands. An investigation conducted in parts of the Forsmark area indicates that the flat topography in the area promotes the occurrence of small floodplains in the area /Carlsson et al. 2005b/. The size of flooded areas adjacent to streams in Forsmark today is further described in Section 3.3.5. Flooding may occur also in future streams which may result in accumulation in surrounding wetlands although accumulation in the streams is assumed to be small.

Concluding the characteristics of future streams, there are no large differences assumed between small and relatively large streams in the area considering biota with exception for fish and benthic primary producers.

9 Important processes for transport and accumulation of radionuclides – a comparison with the radionuclide model

9.1 Introduction

This section provides an extensive description of processes influencing transport and accumulation of radionuclide in ecosystems considered in the safety assessment in SR-Site biosphere. It is essential that processes of importance for the transport and accumulation of radionuclides in the ecosystems are described in the construction of the radionuclide model for the biosphere. The aims of this chapter are the following:

1. Identify interactions between different components in the ecosystem that are important for the transport and accumulation of radionuclides.
2. Identify the processes behind the interactions.
3. Demonstrate that interactions of significance for the transport and accumulation of radionuclides are included in the radionuclide modelling. Interactions are considered to be included in the radionuclide modelling if they are represented in the radionuclide model or in the parameterisation of the model. Processes may be included in parameterisation either directly or indirectly if parameter values are based on *in situ* measurements where the effects of the process are included.

Ecosystems are extremely complex and contain a large number of processes and the aim of this chapter has not been to specify all the separate processes. The focus has rather been to identify interactions between different components in the ecosystems important for accumulation and transport of radionuclides and to characterise these interactions in terms processes. Full definitions of all processes discussed here can be found in /SKB 2010a/.

The estimated degree of importance of a process interaction is evaluated solely in terms of its potential effect on doses to humans and the environment from radionuclides released from a deep repository. Hence, process interactions of great importance from an ecological point of view may not necessarily be rated as important for the radionuclide modelling. In the radionuclide model, the worst case scenario is always considered and therefore, process interactions induced by humans are not included if they lead to lower doses. One example is aquaculture for fish that severely alters the natural ecosystem but that from a radiological impact point of view it is uninteresting since radiation exposure would be decreased due to consumption of uncontaminated food pellets by the fish.

Although only process interactions important for radionuclide transport are considered a large number of processes and complex interactions are still incorporated. When developing conceptual and mathematical models to illustrate transport in an ecosystem there is a risk that important components and interactions are omitted or underestimated due to the complexity of the ecosystem. The risk can be reduced if a systematic approach to characterisation is used, e.g. through the application of interaction matrixes /Avila and Moberg 1999/. Therefore, to ensure that all relevant and important processes for the transport and/or accumulation of radionuclides are identified and considered in the radionuclide model, an interaction matrix is used both for analysis and presentation.

All major processes in the ecosystems are listed in the interaction matrix. The period considered in the assessment is around 100,000 years representing a glacial cycle. It is assumed that human behaviour during that period is similar to human behaviour today. The interaction matrices for the biosphere are valid for the entire glacial cycle, i.e. including temperate, periglacial and glacial conditions, although the primary focus is on a temperate climate. This is justified by the fact that the highest exposure are expected in temperate conditions since production will decrease at colder climate and agricultural use of land will not be possible at perioglacial and glacial conditions. Only climate conditions that may occur in Sweden are included, which means that processes applicable only to other climate regions such as rainforests or deserts are not considered in this report. When terrestrial ecosystems are referred to in the remainder of this chapter, wetland ecosystems and agricultural land on such drained wetlands are implied. Wetlands have been identified as potential discharge areas for deep groundwater in the SR-Site safety assessment and are the natural end stage of the succession from aquatic to terrestrial ecosystems /Lindborg 2010/. Wetlands have also a long history of being used as agricultural land after drainage. However, for farmland water fluxes from geosphere and deeper regolith layers to the upper regolith layers are not considered since these fluxes are small or insignificant when the wetlands are drained

9.2 Concept of the interaction matrix

The general principles of an interaction matrix (IM) are illustrated in Figure 9-1. The ecosystem of interest is divided into various components that are listed along the lead diagonal of the matrix. These components, are in the following context, referred to as diagonal elements. These diagonal elements can be spatially or conceptually distinct. Thus, for example, two elements might be water in regolith and surface water (physically distinct) or herbivores and carnivores (conceptually distinct). An element may also be a property such as temperature. It is worth noting that different types of biota are distinguished by ecosystem function. Thus, omnivores do not appear in the interaction matrix because functionally they are a mix of herbivores and carnivores. The number of diagonal elements is a compromise between the need to keep the matrix to a manageable size and the requirement to be as specific as possible in defining the processes relating the various diagonal elements.

Processes that relate the diagonal elements (i.e. interactions) are entered into the off-diagonal elements, as shown in Figure 9-1. Note that the matrix is read in a clockwise sense, so that processes by which Component A affect Component C are found in the top right element, whereas processes by which Component C affect Component A are found in the bottom left element. It is important to ensure that the effects of processes are direct and are not mediated by interactions via a third element listed on the lead diagonal.

To specify all processes in an ecosystem model is not doable and from the perspective of radionuclide transport also unnecessary. Instead, processes similar to each other and/or with a similar mechanism or result have been grouped into larger comprehensive processes in the biosphere interaction matrix. As an example, the process ‘reaction’ includes chemical reactions in water and within biota (metabolic reactions) and thereby this particular process includes hundreds (or even thousands) of possible sub-processes if all separate reactions were treated individually.

The concept of interaction matrixes and methodology for determining diagonal elements and group processes are further described in /SKB 2010a/.

9.3 The limnic/marine/terrestrial interaction matrices

An aquatic IM for the limnic and marine ecosystems is presented in Figure 9-2, and an terrestrial IM for the terrestrial ecosystems is presented in Figure 9-3. The IMs are based on the general biosphere IM presented in /SKB 2010a/ and processes common to all three ecosystems are described together in Section 9.5. When the relevance of a process for a specific ecosystem differs, this is noted in the description in Section 9.5.

The aquatic and terrestial IMs includes 15 diagonal elements and 51 processes. The colour coding used in Figures 9-2 and 9-3 displays the priorities in the IMs, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant process interactions are coloured white. The importance of process interactions in this IM is based on temperate conditions, i.e. process interactions are valid also for other climate domains during an interglacial but may be more or less important. Diagonal elements, processes and interactions are further described in the following sections.

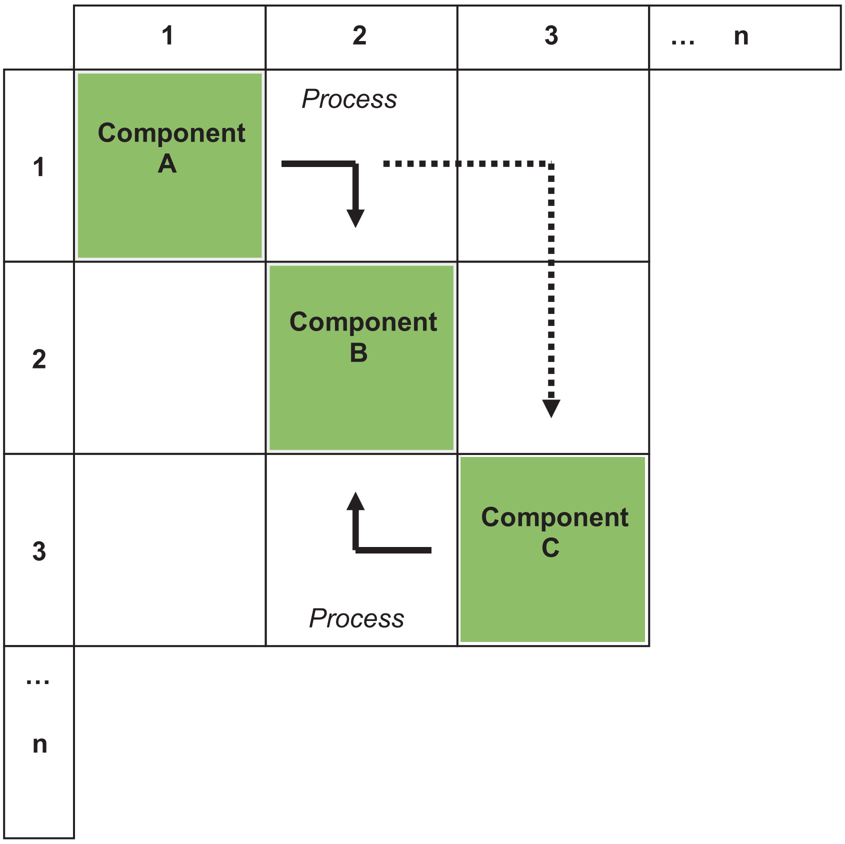

Figure 9-1. *Conceptual illustration of an interaction matrix (IM). The diagonal elements A, B and C are key components of the ecosystem and are placed on the diagonal. The off-diagonal elements (white boxes) represent processes. The arrows illustrate e.g. how Component A (1:1) affects Component B (2:2) through a process (1:2). The matrix is always read clockwise, e.g. processes by which component A affect component C are found in the top right element, whereas processes by which component C affect component A are found in the bottom left element. Coordinates are read (row:column).*

Necessary for dose assessment	Not necessary for dose assessment	No interaction

	1	2	3	4	5	6	7
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering	a) Habitat supply	a) Habitat supply	a) Habitat supply		
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Habitat supply b) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	a) Consumption b) Material use c) Species introduction/extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/extermination e) Stimulation/inhibition
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import

Figure 9-2. *The aquatic interaction matrix (IM) used for limnic and marine ecosystems in SR-Site. The colour coding display the priorities in the IM, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant processes interactions are coloured white. In cases where an interaction box contains more than one interaction, the interaction with the highest priority determines the colour of the interaction box.*

8	9	10	11	12	13	14	15
a) Material supply	a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Food Supply b) Habitat supply c) Material supply	a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transition b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Food supply b) Material supply c) Stimulation/inhibition	a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition	a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition		a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
Humans	a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
a) Water supply	**Water in regolith**	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Habitat supply b) Water supply	a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Stimulation/inhibition	a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Deposition b) Element supply c) Stimulation/inhibition	a) Convection b) Phase transition	a) Convection b) Deposition c) Phase transition d) Wind stress	a) Deposition b) Phase transition c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transition e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Stimulation/inhibition	a) Phase transition	a) Convection b) Phase transition	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transition	a) Export
a) Exposure			a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

	1	2	3	4	5	6	7
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering					
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Habitat supply b) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination e) Stimulation/inhibition
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import

Figure 9-3. *The terrestrial interaction matrix (IM) used for terrestrial ecosystems in SR-Site. The colour coding display the priorities in the IM, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant processes interactions are coloured white. In cases where an interaction box contains more than one interaction, the interaction with the highest priority determines the colour of the interaction box.*

8	9	10	11	12	13	14	15
a) Material supply	a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Food Supply b) Habitat supply c) Material supply	a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transition b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Food supply b) Material supply c) Stimulation/inhibition	a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition	a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition		a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
Humans	a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
a) Water supply	**Water in regolith**	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Habitat supply b) Water supply	a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Stimulation/inhibition	a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Deposition b) Element supply c) Stimulation/inhibition	a) Convection b) Phase transition	a) Convection b) Deposition c) Phase transition d) Wind stress	a) Deposition b) Phase transition c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transition e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Stimulation/inhibition	a) Phase transition	a) Convection b) Phase transition	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transition	a) Export
a) Exposure			a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

9.4 Diagonal elements in the interaction matrix

In the biosphere IM, 15 diagonal elements are identified (Figure 9-2 and 9-3). The diagonal elements with ecosystem-specific examples are described in Table 9-1. Note that the definitions of these diagonal elements are often more wide-reaching than inferred by their short names and a more comprehensive description of the diagonal elements is given in /SKB 2010a/.

Table 9-1. Elements (diagonal elements) of the limnic, marine and terrestrial ecosystems interaction matrix (IM). Placement is the numbering of boxes in the matrix according to row:column (see Figure 9-2 and 9-3).

Placement	Element	Definition
1:1	Geosphere	Geosphere is the rock surrounding the repository. It also includes deep groundwater and gases present in the saturated zone in the bedrock. In the ecosystems IM the geosphere corresponds to the solid rock below the sediments (aquatic ecosystems) and soils (terrestrial ecosystems).
2:2	Regolith	Regolith is the unconsolidated material that covers almost the Earth's entire surface and is composed of weathered rock debris covering the rock beneath it, as well as glacial and postglacial deposits, newly formed soils and sediments including dead organic material /Jones et al. 1992/. In the ecosystems(limnic, marine and terrestrial) IM the regolith corresponds to the sediment and soils including dead organic matter. It also includes rock outcrops.
3:3	Primary producers	Primary producers are autotrophic organisms able to use sunlight or the oxidation of inorganic compounds as an energy source to synthesise organic compounds from inorganic carbon sources. The organic compounds are used as fuel for cellular respiration and growth. Primary producers include green plants, algae and autotrophic bacteria (e.g. /Campbell 1993/). In the IM, primary producers include, phytoplankton, microphytobenthos, emergent and submerged macrophytes and macroalgae (aquatic), as well as grasses, herbs, bushes and trees (terrestrial).
4:4	Decomposers	Decomposers are organisms (bacteria, fungi or animals) that feed on dead plant and animal matter and break down complex organic compounds into carbon dioxide, water and inorganic compounds (e.g. /Begon et al. 1996, Porteous 2000/). In a sense, most carnivores live on dead material as they most often kill their prey, and plant matter is dead before its digestion in herbivores begins. However, decomposers do not actively affect the rate at which their food resource becomes available, but are instead dependent on other factors such as senescence, illness, fighting or shredding of leaves, whereas herbivores, filter feeders and carnivores directly affect the rate at which their resources become available /Begon et al. 1996/. In the IM decomposers include bacteria, some species of benthic fauna (aquatic) as well as bacteria, soilfauna and earthworms (terrestrial). Benthic and soil fauna may be omnivores, thus a mix of decomposers, herbivores and carnivores.
5:5	Filter feeders	Filter feeders are aquatic organisms that feed on particulate organic matter and small organisms (phytoplankton and zooplankton) filtered out by circulating the water through the animal's system. Filter feeders include a wide range of animals such as bivalves (e.g. mussels), sponges, crustaceans (e.g. shrimps) and even whales. Filter feeders are an important group of organisms in aquatic ecosystems as they can greatly affect the amount of particulate matter and nutrients in the water, and transport particulate matter from the water column into biota (e.g. /Holland 1993, Soto and Mena 1999, Wilkinson et al. 2008/). Hence they are treated as a separate diagonal element although they conceptually are a mix of decomposers, herbivores, and carnivores.
6:6	Herbivores	Herbivores are animals that feed on primary producers, i.e. plants, algae and autotrophic bacteria. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in carnivores (see below). In the IM herbivores include zooplankton, benthic fauna and some fish species (aquatic) as well as insects, rodents and larger mammals (terrestrial).

7:7	Carnivores	Carnivores are animals that feed on other animals. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in herbivores (see below). In the IM carnivores may include some species of zooplankton, benthic fauna, fish (aquatic), as well as, insects, mammals and birds (terrestrial).
8:8	Humans	Humans are defined as all human beings living in the affected area. This diagonal element includes the number of persons but also their activities in the modelled area. In the IM, activities such as fishing, water pumping and anthropogenic releases are included (aquatic) as well as agriculture, irrigation and construction (terrestrial).
9:9	Water in Regolith	Water in regolith is the water in the saturated zone of the regolith and the pore water in the unsaturated zone. All physical states of water are considered, i.e. this diagonal element includes also frost and ice. This diagonal element includes the quantity of water in regolith, whereas the chemical composition of the water is treated under water composition (see below). Water in regolith does not include the water in the bedrock as this is handled in the geosphere matrix.
10:10	Surface Waters	Surface water is defined here as water on the Earth's surface, collecting on the ground or in streams, rivers, lakes, open water wetlands or oceans, as opposed to water in rock, regolith or atmosphere /Heath 1987/. Atmospheric water is addressed under gas and local atmosphere in the matrix, in contrast to the classification made by some other authors, e.g. /Watson and Burnett 1993/ who include rain, fog and snow in surface water. Rainwater on rock surfaces, snow and ice on land and on water, as well as droplets on e.g. vegetation are included in surface water. This diagonal element includes the quantity of surface water, whereas the chemical composition of the water is addressed under water composition (see below).
11:11	Water Composition	Here, water composition comprises dissolved elements and compounds, colloids and suspended particles (including dead organic matter) in surface water and water in regolith. The content of ions and elements determines e.g. pH-values, salinity, and nutrient concentrations. Thus, water composition is important to the presence and viability of biotic components in aquatic ecosystems. Various transport, chemical and biological processes affect water composition (e.g. /Stumm 2004/).
12:12	Gas and local Atmosphere	Gas and local atmosphere includes the local atmosphere and gas in regolith and in water in regolith as well as gas bubbles in surface water. Gas flow and gas composition are included in this element which, therefore, includes wind and the content of particulates in the local atmosphere, i.e. water droplets, pollen, etc. The local atmosphere is defined as the layer of the atmosphere above the studied area that participates in gas exchange with the studied area. It is surrounded by the atmosphere, which is a boundary to the biosphere system. Gas bubbles in water are included in this diagonal element, whereas dissolved gases are treated in water composition.
13:13	Temperature	Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact /Pitt 1986/. Here, temperature is restricted to the temperature in the physical component of the system of interest (i.e. all physical diagonal elements such as geosphere, regolith, biota, and water). Temperature is dependent on climate, and local effects on climate belong to this diagonal element, whereas large-scale climate systems belong to external factors.
14:14	Radionuclides	Radionuclides include radionuclides in all physical and biological components of the biosphere system in question (i.e. in all physical diagonal elements such as geosphere, regolith, biota, and water).
15:15	External Conditions	External conditions are all external factors that affect the local conditions considered within the biosphere matrix or are affected by the biosphere identified in the matrix. External conditions include surrounding ecosystems and the atmosphere above and beyond the lateral boundaries of the local atmosphere. They also include global conditions such as global climate and solar insolation.

9.5 Processes in the interaction matrix

In total, 51 processes were identified in the biosphere IM. Biosphere processes are listed in Table 9-2 together with a short definition whereas a comprehensive description of the processes is given in /SKB 2010a/. In Table 9-2, a reference is also given to where in the IM the processes occur. Figure 9-4 is a conceptual representation of the Radionuclide model in which the incorporation of important processes is shown.

The International Atomic Energy Agency (IAEA) has produced a database of features, events and processes (FEPs) used for safety assessments of repositories for radioactive waste by several countries. All IAEA FEPs related to the biosphere are included in the processes here (unless irrelevant for Swedish conditions). Definitions of IAEA FEPs and how these correlate to the processes used by SKB can be found in SKB's FEP database, see further the **FEP report**. The numbering in the FEP database is presented in the right column in Table 9-2 and is also used in Figure 9-4.

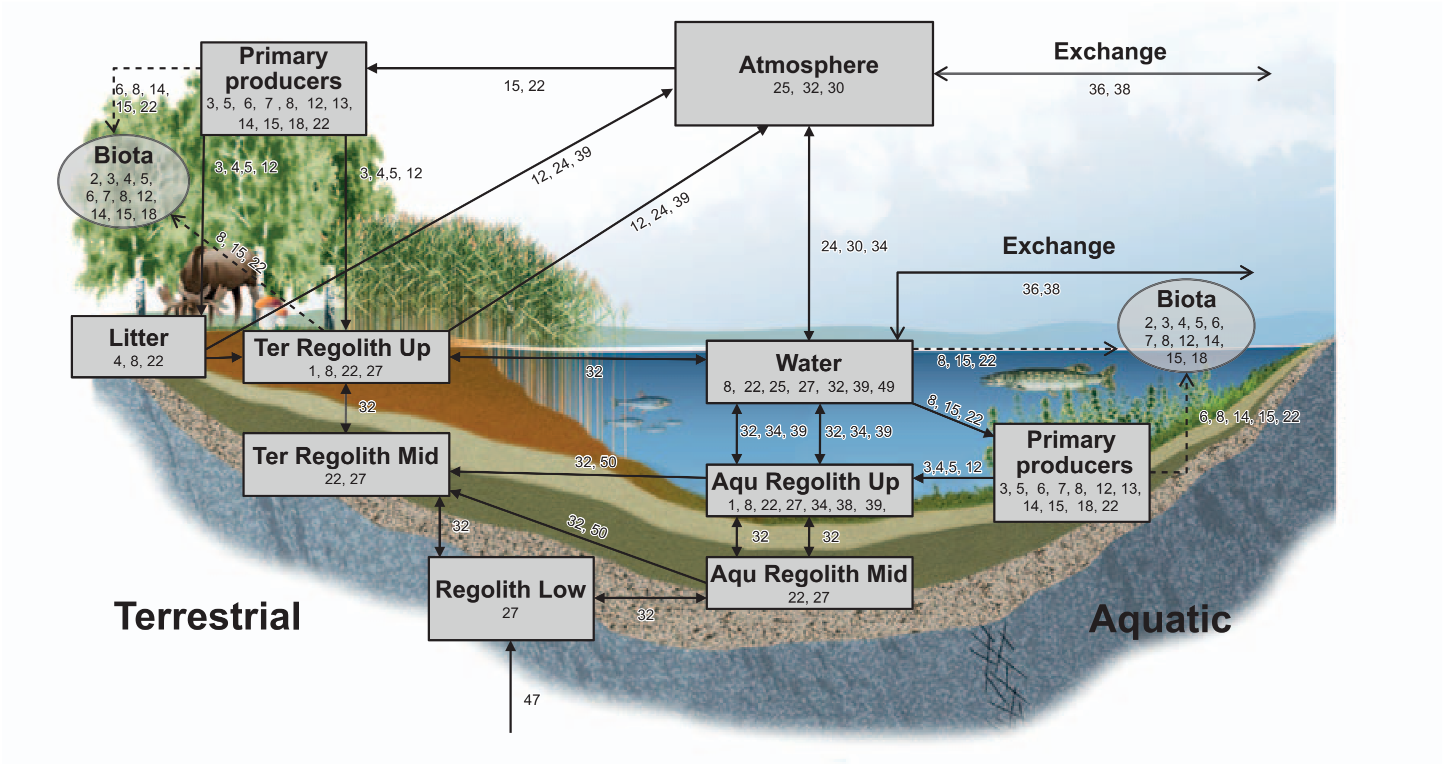

Figure 9-4. Conceptual illustration of the Radionuclide model for the biosphere and the location of processes identified as important (represented by numbers according to Table 9-2). Processes may occur in more locations than pointed out in the figure, because only the major occurrence is shown in the figure in order to improve readability. Boxes represent compartments, arrows represent fluxes, and dotted arrows represent concentration computations for biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. A detailed explanation of the Radionuclide model can be found in Chapter 10. Some of the processes identified as important to consider, e.g. decay, thresholding, external and internal exposure are not included in the illustration since they are hard to illustrate (but they are considered in the model).

Table 9-2. Processes in the interaction matrix (IM) for the limnic, marine and terrestrial ecosystems. In the third column, the specific coordinates for the interactions between elements are presented. The coordinates refer to the location in the IM (Figure 9-2 and 9-3) where the boxes are numbered according to row:column. In the fourth column, the location in the radionuclide model is listed. Processes marked with * denote that the processes are caused, or associated with, both human and non-human biota.

Process	Definition	Interactions in the matrix (read row:column)	Necessary to consider in the radionuclide modelling (dark yellow box in IM (Figure 9-2 and/or 9-3)	Numbering according to number in SKBs FEP data base, see the FEP report.
Biolgical processes				
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.	3:2, 4:2, 5:2, 6:2, 7:2	yes	1
Consumption*	When organisms feed on solid material and/or on other organisms.	4:2, 4:11, 5:3, 5:4, 5:5, 5:6, 5:7, 6:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7	yes	2
Death*	The generation of dead organic matter by organisms.	3:2, 3:11, 4:2, 4:11, 5:2, 5:11, 6:2, 6:11, 7:2, 7:11, 8:2, 8:11	yes	3
Decomposition	The breakdown of organic matter by organisms.	4:2, 4:9, 4:10, 4:11	yes	4
Excretion*	The excretion of water or elements to the surrounding media by humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14	yes	5
Food supply	The fraction of produced biomass and particulate matter that can be used as a food source for humans and other organisms.	2:4, 2:8, 3:5, 3:6, 3:8, 4:5, 4:7, 4:8, 5:5, 5:7, 5:8, 6:5, 6:7, 6:8, 7:5, 7:7, 7:8, 8:7, 11:3, 11:4, 11:5	yes	6
Growth*	The generation of biomass by organisms.	3:14, 4:14, 5:14, 6:14, 7:14, 8:14	yes	7
Habitat supply	The providing of habitat for organisms by abiotic elements or other organisms.	1:3, 1:4, 1:5, 1:6, 2:3, 2:4, 2:5, 2:6, 2:7, 2:8, 3:3, 3:4, 3:5, 3:6, 5:3, 5:4, 9:3, 9:4, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8, 11:4	yes	8
Intrusion	Non-human organisms or humans enter the repository, for example by locomotion, drilling or growth.	3:1, 4:1, 5:1, 6:1, 7:1, 8:1	no	9
Material supply	The amount of material that is available for human utilisation for purposes other than feeding.	1:8, 2:8, 3:8, 4:8, 5:8, 6:8, 7:8	no	10
Movement*	Animal locomotion in surface water.	4:10, 5:10, 6:10, 7:10, 8:10	no	11
Particle release/trapping*	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles (for example with gills, feathers and slime).	3:11, 3:12, 4:11, 5:11 6:11, 6:12, 7:11, 7:12	yes	12

Primary production	The fixation of carbon by primary producers in photosynthesis.	3:3	yes	13
Stimulation/inhibition*	When one diagonal element positively or negatively influences another diagonal element. The extreme of inhibition prevents settlement and leads to exclusion from the model areas.	3:3, 3:4, 3:5, 3:6, 3:7, 3:8, 4:3, 4:4, 4:5, 4:6, 4:7, 4:8, 5:3, 5:4, 5:5, 5:6, 5:7, 5:8, 6:3, 6:4, 6:5, 6.6, 6:7, 6:8, 7:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7, 8:8, 11:3, 11:4, 11:5, 11:6, 11:7, 11:8, 12:3, 12:8, 13:3, 13:4, 13.5, 13.6, 13:7, 13:8	yes	14
Uptake*	The incorporation of water or elements from the surrounding media into humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14	yes	15
Processes related to human behaviour				
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere.	8:10, 8:11, 8:12, 8:13, 8:14	yes	16
Material use	Human utilisation of the environment for purposes other than feeding.	8:1, 8:2, 8:3, 8:4, 8:5, 8:6, 8:7	no	17
Species introduction/extermination	Introduction or extermination of species from the model area by human activities. (e.g. introduction of crayfish in lakes).	8:3, 8:4, 8:5, 8:6, 8:7	yes	18
Water use	Water use by humans for other purposes than drinking, e.g. washing, irrigation and energy production. May affect the water table.	8:9, 8:10, 8:11	yes	19
Chemical, mechanical and physical processes				
Change of pressure	Pressure change in air or water above a surface.	9:1, 10:1, 10:13, 11:13, 12:13, 13.12	no	20
Consolidation	Any process whereby loosely aggregated, soft, or liquid earth materials become firm and coherent rock.	2:1, 2:2	no	21
Element supply	The availability of elements and substances for use by organisms.	2:3, 2:4, 11:3, 11:4, 11:5, 11:6, 11:7, 12:3, 12:4, 12:5, 12:6, 12:7, 12:8	yes	22
Loading	Force caused by the weight of material that affects the underlying rock.	2:1, 10:1	no	23
Phase transitions	Changes between different states of matter: solid, liquid and gas.	2:11, 2:14, 9:12, 10:12, 11:2, 11:12, 11:14, 12:9, 12:10, 12:11, 12:13, 13:9. 13:10, 13:12, 13:14, 14:12	yes	24
Physical properties change	Changes in volume, density and/or viscosity.	9:11, 10:11, 13:2, 13:11	yes	25

Reactions	Chemical reactions excluding weathering, decomposition and photosynthesis.	2:11,2:12, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 11:13, 12:2, 12:13, 13:11, 13:14, 14:11, 15:12	no	26
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.	2:11, 2:14, 3:14, 4.14, 5.14, 6.14, 7:14, 8:14, 11:14, 12:14	yes	27
Water supply	The amount of water available for drinking and other uses by humans and other organisms.	9:3, 9:4, 9:5, 9:6, 9:7, 9:8, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8	no	28
Weathering	Disintegration of solid matter into smaller pieces.	1:2, 9:1, 10:1, 11:1, 11:2, 13:1, 13:2	no	29
Wind stress	A mechanical force generated by wind affecting the biosphere.	12:10, 12:11	yes	30

Transport processes

Acceleration	The change in velocity of a fluid or body over time and/or the rate and direction of velocity change. May be either positive or negative (retardation).	2:10, 3:10, 3.12, 4.10, 5.10, 6:10, 8.10, 8:12	no	31
Convection	The transport of a substance or a conserved property with a fluid or gas.	1:9, 1:10, 1:11, 1.12, 1:13, 2:9, 2:10, 2:13, 3:13, 4.13, 5:13, 6.13, 7.13, 8:13, 9:1, 9:10, 9:11, 9:13, 9:14, 10:1, 10:9, 10:11, 10:13, 10:14, 11:1, 11:9, 11:10, 12:1, 12:9, 12:10, 12:13, 12:14, 13:1, 13:10, 13:11, 13:12, 15.10	yes	32
Covering	The covering of surface water by e.g. vegetation or ice that reduces light and prevents the exchange of gases and particles between the water and the atmosphere.	3:10, 8:10	no	33
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.	11:2, 12:8, 12:10, 12:11, 14:2	yes	34
Export	Transport out of the model area.	2:15, 3:15, 4:15, 5:15, 6:15, 7:15, 8:15, 9:15, 10:15, 11:15, 12:15, 13:15 14:15	no	35
Import	Transport into the model area.	10:15, 15:2, 15:3, 15:4, 15:5, 15:6, 15:7, 15:8, 15:9, 15:10, 15:11, 15:12, 15:13, 15:14	yes	36
Interception	The amount of precipitation that does not reach the ground but is retained on vegetation.	3:10	no	37
Relocation	The horizontal transport of solid matter and sessile organisms from one point to another.	2:3, 8:2, 9:2, 9:11, 10:2, 10:3, 10:4, 10:5, 10:6, 10:12, 11:12	yes	38
Resuspension	The stirring up of previously settled particles in water or air.	2:11, 10:2, 10:12, 11:12	yes	39

Saturation	Water content that affects physical and chemical properties of the regolith	9:2, 15:9	no	40
Radiological and thermal processes				
Decay	The physical transformation of radionuclides to other radionuclides or stable elements.	14:11, 14:13	yes	41
Exposure	The act or condition of being subject to irradiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.	14:3, 14:4, 14:5, 14:6, 14:7, 14:8	yes	42
Heat storage	The storage of heat in solids and water.	2:13, 9:13, 10:13, 12:13	yes	43
Irradiation	The process whereby an object is exposed to ionising radiation and absorbs energy.	14:2	no	44
Light related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.	2:3, 2:13, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 10:13, 11:3, 11:13, 12:13, 15:3, 15:13	yes	45
Radiolysis	The disintegration of molecules caused by radionuclide decay.	14:11	no	46
Radionuclide release	Release of radionuclides from the repository for spent nuclear fuel.	1:14, 14:1	yes	47
Landscape development processes				
Change in rock surface location	Changes in the location of the rock surface due to isostatic rebound or repository-induced changes.	1:2, 15:1, 15:2	yes	48
Sea level change	Alteration in the level of the sea relative to the land.	15:10	yes	49
Terrestrialisation	Infilling of a lake or shallow sea basin with mire vegetation.	15:2, 15:10	yes	50
Thresholding	The occurrence and location of thresholds delimits water bodies like lakes and sea basins.	2:9, 2.10, 2.15	yes	51

9.6 Interactions in the ecosystems

Diagonal elements may interact with each other by one or more processes. Some processes occur in many places in the IM. Although a process may be important for dose assessment in the interaction between two diagonal elements, it may be insignificant for the dose assessment in the interaction between two other diagonal elements. The significance for the radionuclide modelling, i.e. determining dose to man, is considered for each interaction at which a process is identified as mediating that interaction. In Figures 9-2 and 9-3, the significant process interactions are coloured dark yellow, whereas insignificant process interactions are coloured light yellow, and irrelevant processes interactions are coloured white. Thus, dark yellow process interactions have to be consider in the radionuclide modelling whereas light yellow process interactions do not have to be considered.

There are a large number of interactions among diagonal elements of the IM that are included in the radionuclide model even though they do not strictly need to be considered. This is because the radionuclide model is based on site-specific data and thereby implicitly includes many of the processes in the matrix, e.g. primary production is measured *in situ* and hence all processes affecting this parameter during present conditions (also those that are believed to have a small effect) are thereby included indirectly.

Below, each box in the IM is described separately to fully illustrate by which processes each diagonal component interacts with the other diagonal elements. Processes whereby diagonal components interact are presented in alphabetical order, i.e. they are not listed by importance in the radionuclide modelling. However, for each interaction, the processes are listed that need to be considered in the radionuclide modelling for each ecosystem (limnic, marine and terrestrial) and how the processes have been included in the radionuclide model or parameterisation of the model. The boxes in the interaction matrix are numbered according to row:column (see Figure 9-2 and 9-3).

1:1 Geosphere is a diagonal element (further described in Section 9.3). The geosphere is situated at the boundary of the biosphere matrix and processes by which the geosphere affects the geosphere are not described in this report. The reader is referred to /SKB 2001, SKB 2006d and the **FEP report**/ for more information on this topic.

1:2 Geosphere affects **regolith** by the processes a) Change in rock surface location and b) Weathering.

a) Change in rock surface location – Change in rock surface location may be caused by e.g. collapse of caverns resulting in cave-in of the surrounding rock. Other examples could be neotectonic movements /Lagerbäck et al. 2005/. This affects the stress conditions in the surrounding rock and may affect the height of the regolith. However, cavern collapse would be greatly attenuated at the surface, and fault throws of more than ~0.1 m are highly unlikely for deep repositories /SKB 2001/. Therefore other processes affecting regolith are more important for the topography and this interaction need not to be considered in the radionuclide modelling.

b) Weathering – Weathering of a solid rock (geosphere) may form regolith. However, weathering of the solid rock has a minor influence on the formation of regolith compared with other regolith formation processes (e.g. peat formation and sedimentation) and, therefore, it does not need to be considered this interaction in the radionuclide modelling.

1:3 There are no processes by which the **Geosphere** affects **primary producers** that are relevant to include in the radionuclide modelling.

1:4 There are no processes whereby the **Geosphere** affects **decomposers** that are relevant to include in the radionuclide modelling.

1:5 There are no processes by which the **Geosphere** affects **filter feeders** that are relevant to include in the radionuclide modelling.

1:6 There are no processes whereby the **Geosphere** affects **herbivores** that are relevant to include in the radionuclide modelling.

1:7 There are no processes by which the **Geosphere** affects **carnivores** that are relevant to include in the radionuclide modelling.

1:8 Geosphere affects **humans** by the process a) Material supply.

a) Material supply – Mineral resources can be used as material by humans and may influence the location of human settlements. However, the modelled area in Forsmark is underlain by granitic rocks and can be described as sterile from an ore viewpoint /Lindroos et al. 2004/. There are no deposits of industrial minerals or commercial stone in the area. An area south of the regional model area has a small ore potential for iron, however the type of ore is of no mining interest and compared with central parts of Bergslagen, the Forsmark area's ore potential is insignificant. Water from the geosphere may influence humans, but this interaction is via water in regolith. Therefore human utilisation of the geosphere is assumed to be small and this interaction does not need to be considered in the radionuclide modelling.

1:9 Geosphere affects **water in regolith** by the process a) Convection.

a) Convection – The hydrology in the geosphere influences the discharge and recharges of groundwater (i.e. convection) and thereby the hydrology in the regolith. Hydrological modelling /Bosson et al. 2010/ suggests that this influence is small and mainly is found along the shoreline or the mire surrounding the lake. Effects of water discharge from the geosphere to the regolith (discussed in Section 3.3.3 of this report and Section 4.3.7 in /Aquilonius 2010/ is acknowledged in the transport calculations in the radionuclide modelling (see interaction 1:14).

1:10 Geosphere affects **surface water** by the process a) Convection.

a) Convection – The hydrology in the geosphere influences the discharge and recharge of groundwater (convection) and thereby the surface water hydrology. However, precipitation and hydrology in the regolith are of more importance for convection of surface water and this interaction does not need to be considered in the radionuclide modelling. Discharge from the geosphere is included in the safety assessment in the transport calculations in the radionuclide modelling (see interaction 1:14).

1:11 Geosphere affects **water composition** by the process a) Convection.

a) Convection – Transport of elements in groundwater may affect the water chemistry in regolith and could be of importance for elements that only occur in the rock and the repository. Surface water chemistry on the other hand, is assumed to be more influenced by other factors. Nevertheless, the effect on water composition from this interaction both in regolith and surface waters is indirectly included in the radionuclide model as water composition measured *in situ* are used in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

1:12 Geosphere affects **gas and local atmosphere** by the process a) Convection.

a) Convection – The transport and release of gas from the geosphere may influence the amount and composition of gas in the biosphere. The transport of gas from the geosphere is normally of little significance in comparison to gas content in e.g. regolith (i.e. elements in gas form entering the gas phase of the regolith would be very diluted in the regolith gas phase). However, gas transports of e.g. H_2, CO_2, CH_4, Rn and SO_2 from a repository may be important and this interaction needs to be considered in the radionuclide modelling. The transport of C-14 is the largest radioactive gas flux within the biosphere and is covered in the interaction 1:14 and included in the radionuclide modelling (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

1:13 Geosphere affects **temperature** by the process a) Convection.

a) Convection – The heat exchange between geosphere and biosphere will affect the temperature in the biosphere. However, the temperature in surface waters and light related processes mainly determine the temperature in the regolith and surface waters. Therefore, the effect of the Geosphere on temperature does not need to be considered in the radionuclide modelling. The exception is during permafrost conditions when this interaction may be of importance (permafrost is considered in supporting calculations in the radionuclide modelling), see the **Biosphere synthesis report**. Although this interaction does not need to be considered in temperate conditions in radionuclide modelling, the effect of the interaction is indirectly included in temperature-dependent parameters, since parameter values are based on site data obtained under prevailing conditions (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

1:14 Geosphere affects **radionuclides** by the process a) Radionuclide release.

a) Radionuclide release – The release of radionuclides in water and gas phases from the geosphere affects the transport of radionuclides in aqueous and gaseous form in the biosphere. This is a significant interaction in the radionuclide modelling and it is included in the radionuclide model (see Chapter 10). (This process is called 'Contaminant transport' in the Geosphere interaction matrix /SKB 2006d/.

1:15 There are no processes by which **geosphere** affects **external conditions** that are relevant to include in the radionuclide modelling.

2:1 Regolith affects **the geosphere** by the processes a) Consolidation, and b) Loading.

a) Consolidation – The transformation of regolith to solid rock is a slow process that implies a gradual reduction in volume and increase in density in response to increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). For the transport of radionuclides in the radionuclide model, the thickness and the density of the regolith is included. However, the likely degree of consolidation would be very limited under present-day conditions and thus this interaction does not need to be considered in the radionuclide modelling.

b) Loading –The thickness of the regolith affects the stress on the geosphere. The depth of regolith is relatively small in the regional model area /Hedenström and Sohlenius 2008/ and should have a minor impact on the mechanical stress on the geosphere and, therefore, this interaction does not need to be consider in the radionuclide modelling.

2:2 Regolith is a diagonal element that is further described in Section 9.3. The regolith affects the regolith by the processes a) Consolidation, and b) Relocation.

a) Consolidation – The transformation of regolith to solid rock is a slow process that implies a gradual reduction in volume and increase in density in response to increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). For the transport of radionuclides in the radionuclide model, the thickness and density of regolith is included. However, the likely degree of consolidation would be very limited under present-day conditions and would have little impact on the amount and characteristics of regolith and thus this interaction does not need to be considered in the radionuclide modelling.

b) Relocation – The inclination and the topography of the land influence the possibility for and the extent of relocation of materials e.g. via resuspension and landslides. However, the low relief in the area suggests that this would be a rare phenomenon and that it does not need to be considered in the radionuclide modelling. However, due to shore-line displacement, the regolith is affected and the topography changes over time. The digital elevation model (DEM) adopted describes changes in topography over time in the regional model area and thus this interaction is considered in the radionuclide modelling (/Brydsten and Strömgren 2010/ and Chapter 10 in this report).

2:3 Regolith affects **primary producers** by the processes a) Element supply, b) Habitat supply, c) Light related processes, and d) Relocation.

a) Element supply – Micro-algae living in the sediments and rooted aquatic vegetation acquire some of their nutrient supply from the regolith. This is also true for terrestrial primary producers. Accordingly, this interaction might constitute a route of transport of radionuclides from regolith to biota and the interaction need to be considered in the radionuclide modelling. Hence, this interaction is included in the radionuclide model through the use of bioconcentration factors (BCF), which describe the relation between elements in the regolith and primary producers (described in /Nordén et al. 2010/).

b) Habitat supply – The regolith is one of several important factors for the settlement of primary producers, as primary producers are often dependent on the substrate (e.g. in aquatic ecosystems hard vs. soft bottoms, in terrestrial ecosystems coarse vs. fine-grained regolith). Habitat distribution differentiating between regolith conditions in aquatic ecosystems is described in Chapter 3 in this report, Chapter 4 in /Aquilonius 2010/ and in Chapter 3 in /Löfgren 2011/. This interaction needs to be included in the radionuclide modelling, since the occurrence of biota is important for transfer and accumulation of radionuclides. Accordingly, it is included in the radionuclide model as biomass of various organism types (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Light related processes – the topography of the sediments may shade primary producers and thereby influence primary production. This interaction is assumed to be less important than effects of e.g. water depth, transparency, and element supply. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included in the radionuclide model as the biomass of biota is based on site-specific measurements in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Relocation – Relocated regolith may deposit on primary producers and this might affect their production and biomass. Sedimentation is important for the transfer of radionuclides between water and sediment, but the effect of regolith on primary producers is not considered sufficiently important to include in the radionuclide modelling. Nevertheless, the net effect on biomass and primary production is included in the radionuclide modelling as the parameters biomass and net productivity are based on measurements *in situ* under prevailing depositional conditions (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:4 Regolith affects **decomposers by** the processes a) Element supply, b) Food supply, and c) Habitat supply.

a) Element supply – Bacteria present within the sediment take up elements directly from the sediment and thereby the regolith supplies elements to decomposers. This may be an important pathway for radionuclide transport from sediments into biota and thus this interaction needs to be considered in the radionuclide modelling. The amount of regolith is specified but not all elements may be available to decomposers. However, this interaction is included in the radionuclide model through the parameter net productivity where decomposers are assumed to utilize elements from, among other sources, the regolith (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Food supply – Regolith can be used as a food source by decomposers. This may be an important pathway for radionuclide transport from sediments into biota and thus this interaction needs to be considered in the radionuclide modelling. Although the amount of available food is not specified (amount of regolith is specified but some regolith may be unavailable for decomposers), this interaction is included in the radionuclide modelling through the parameter net productivity where decomposers are assumed to feed on, among other sources, regolith (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Habitat supply – Regolith is important for the settlement of decomposers as they are often dependent on a certain kind of substrate (hard vs. soft bottoms). Habitat distribution differentiates, in aquatic ecosystems, between hard bottoms and soft bottoms, and in terrestrial ecosystems between coarse and fine-grained regolith. Habitat distributions differentiating between regolith conditions in aquatic and terrestrial ecosystems are described in Chapter 3 in this report, in Chapter 4 in /Aquilonius 2010/ and in Chapter 3 in /Löfgren 2011/. This interaction needs to be included in the radionuclide modelling since occurrence of biota is important for transfer and accumulation of radionuclides and, accordingly, it is included as biomass of biota (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:5 Regolith affects **filter feeders** by the process a) Habitat supply.

a) Habitat supply –Filter feeders occur only in aquatic ecosystems. Regolith is important for the settlement of filter feeders as they are often dependent on the substrate. Thus, some species (e.g. in limnic ecosystems *Dreissena polymorpha* and in marine ecosystems *Mytilus edulis*) thrive on hard bottoms (i.e. geosphere) and others (e.g. in limnic ecosystems *Anodonta anatine* and in marine *Macoma baltica*) thrive on soft bottoms (i.e. regolith). The habitat distribution differs between hard bottoms and soft bottoms in aquatic ecosystems, and is, for marine ecosystems described in Section 4 in /Aquilonius 2010/, and for limnic ecosystems in Section 3.7.4 in this report. Hence, for aquatic ecosystems this interaction needs to be included in the radionuclide modelling, since the occurrence of biota is important for transfer and accumulation of radionuclides. Accordingly, this interaction is included as biomass of biota in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:6 Regolith affects **herbivores** by the process a) Habitat supply.

a) Habitat supply – The settlement of herbivores is mainly determined by the availability of primary producers and, therefore, the effect of regolith on the settlement of herbivores does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included in the radionuclide model as biomass of biota based on site-specific measurements, in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:7 Regolith affects **carnivores** by the process a) Habitat supply.

a) Habitat supply – Regolith is not directly important for carnivores, as they are not as dependent on substrate as on the availability of food. Nevertheless, it is indirectly included in the radionuclide model as biomass of biota based on site-specific measurements, in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:8 Regolith affects **humans** by the processes a) Food supply, b) Habitat supply, and c) Material supply.

a) Food supply – Regolith may be consumed accidentally with food or on purpose, e.g. by children. The accidental incorporation needs to be considered in the radionuclide modelling and, accordingly, the amount accidentally incorporated together with food is included in the radionuclide model /Nordén et al. 2010/. The intake on purpose does not need to be considered in the radionuclide modelling as LDF calculations are based on grown up individuals and these do not eat regolith.

b) Habitat supply – Human settlement is mainly determined by the area, soil type, and the type of ecosystem. The last determines the amount of available food and this interaction needs to be considered in the radionuclide modelling. Accordingly, the area of biosphere objects with which groups of humans are associated, is included in the radionuclide model (see /Brydsten and Strömgren 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Material supply – Humans may use regolith as material supply e.g. sand in concrete for buildings or peat used for generating heat. However, the terrestrial ecosystem considered in the radionuclide modelling is a mire or a drained mire (see /Löfgren 2010/ and Chapter 10 in this report) and peat and/or regolith from aquatic ecosystems is not usually used as material supply for buildings. Moreover, postglacial sand and other types of building material would be taken from other less contaminated areas than from peat covered low-laying areas that are in need of drainage before further utilisation. In earlier safety assessments the contribution to dose from the use of peat as fuel does not alter the resulting doses in radionuclide model /Avila et al. 2010/. Therefore, this interaction does not need to be considered in the radionuclide modelling.

2:9 Regolith affects **water in regolith** by the processes a) Convection, and b) Thresholding.

a) Convection – The magnitude and distribution of the water flow in the regolith is influenced by the hydraulic conductivity and storage capacity (porosity) of the regolith. This is an important process to consider in the radionuclide modelling. Accordingly, the depth and properties (Kd, density, porosity) of regolith (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/, Chapter 11 in this report, and /Nordén et al. 2010/) together with water transport in the regolith /Bosson et al. 2010/ are included in the radionuclide modelling.

b) Thresholding – The regolith determines the location of thresholds and thereby influences the water in regolith. Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models /Brydsten and Strömgren 2010/.

2:10 Regolith affects **surface water** by the processes a) Acceleration, b) Convection, and c) Thresholding.

a) Acceleration – In aquatic ecosystems the bottom topography determines the water depth and influences thereby the height of the waves. In addition, the fetch (the distance over which the blowing wind is not disturbed) influences wave formation e.g. sheltered areas occuring behind islands. Water depth is important for transport and accumulation of radionuclides and thus it needs to be considered in the radionuclide modelling. Therefore this interaction is considered in the radionuclide model where water depth is included in the calculation of parameter values (Chapter 10 in /Aquilonius 2010/, Chapters 10 and 11 in this report, and /Brydsten and Strömgren 2010/).

b) Convection – Regolith affects surface water by upward transport of water and by influencing wave formation. Water transport is important for transport of radionuclides and wave formation is important for the advective flow and residence time of sea water. Thus, this interaction needs to be considered in the radionuclide modelling. Water transport from the regolith to surface water is included in the hydrological models /Bosson et al. 2010/ that are used to derive input parameter values for the radionuclide model (Chapter 10). Wave formation is considered by using the Digital Elevation Model (DEM), which supplies all the geometric measures (the bottom topography) and the models for sedimentation /Brydsten and Strömgren 2010/.

c) Thresholding – Thresholding includes all processes that affect the occurrence and location of thresholds that delimit water bodies in height. Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models (see /Brydsten and Strömgren 2010/ and Chapter 10 in this report).

2:11 Regolith affects **water composition** by the processes a) Phase transitions, b) Reactions c) Resuspension, and d) Sorption/desorption.

a) Phase transitions – Regolith may affect water composition by leaching (in which minerals attached to solids are solubilised from the regolith and released to the water). The location of and chemical composition of the regolith and the mineralogy of rock surfaces thereby influence the chemical composition of the water. The rate of leaching of non-radioactive elements is not important for the radionuclide modelling but the net result, i.e. concentrations of elements in the water, may be of importance. However, other factors are assumed to be of greater importance for water chemistry and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction is indirectly included since water chemistry measured *in situ* is used in the calculations of parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Reactions – Elements in the regolith may be altered due to chemical reactions such as redox changes (oxidation) and elements may thereby be released to the water and influence the water composition. Other factors are assumed to have greater influence on the water chemistry and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since water chemistry measured *in situ* is used in the calculations of parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Resuspension – The size distribution of the particles in the regolith influences the amount of material resuspended in the water and thereby the content of particulate matter in the water (further described in Sections 3.6 and 3.9 for limnic ecosystems and in Chapter 3 in /Aquilonius 2010/ for marine ecosystems. Resuspension is an important route of transfer from sediments to water and needs to be considered in the radionuclide modelling. Accordingly, it is included as a parameter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of dissolved elements and particulates and thus the composition of the water in the regolith. The rate of sorption of non-radioactive elements is not important for the transport and accumulation of radionuclides but the net result, i.e. concentrations of elements in the water, may be of importance. However, sorption and desorption is assumed to be in equilibrium and reflected in present water chemistry. Nevertheless, the effect of this interaction is included in the radionuclide modelling by the use of water chemistry data measured *in situ* when calculating parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

2:12 Regolith affects **gas and local atmosphere** by the process a) Reactions.

Reactions – Elements in the regolith may react with elements in the gas phase in the regolith. The amounts of gases in regolith in aquatic and terrestrial systems are most often small and are not considered to be severely affected by elements in the regolith, and therefore the transport and accumulation of radionuclides are not significantly influenced. This interaction therefore does not need to considered in the radionuclide modelling.

2:13 Regolith affects **temperature** by the processes a) Convection, b) Heat storage c) Light related processes and d) Pressure change.

a) Convection – The composition and the grain size of regolith affects the heat transport (conduction) in the regolith and thereby influences the temperature in the different parts of the biosphere system. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Heat storage – The density and thermal properties of the regolith determine the amount of heat that can be stored in a given volume of regolith per unit of temperature change. The heat storage of water is of greater importance for the temperature in aquatic ecosystems and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Light related processes – The reflection properties of the regolith influence the amount of sunlight absorbed and thereby the temperature in the regolith in terrestrial areas. In aquatic ecosystems, regolith is always covered with water and the major part of the adsorption take place in the water column and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included both in terrestrial and aquatic ecosystems since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Pressure change – in terrestrial ecosystems the topography of the regolith affects the pressure which may lead to heating or cooling, so called adiabatic temperature changes. However, the model area that is affected by a release of radionuclides will always be a coastal site and will not be associated with any large changes in topography (as would be the case in e.g. mountain areas) and therefore this interaction does not need to be included in the radionuclide modelling of any ecosystem.

2:14 Regolith affects **radionuclides** by the processes a) Phase transitions and b) Sorption/desorption.

a) Phase transitions – The regolith may affect the concentration of dissolved radionuclides by dissolution to the gas phase of natural radionuclides included in minerals in the regolith. In comparison with sorption and desorption this process involves very small amounts of radionuclides, and the main focus of the safety assessment is the repository induced radionuclides and this interaction does not need to be considered in the radionuclide modelling.

b) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in the radionuclide modelling. Accordingly, it is included as radionuclide specific Kd values used in the radionuclide model (see /Nordén et al. 2010/ and Chapter 10 in this report).

2:15 Regolith affects **external conditions** by the processes a) Export, and b) Thresholding.

a) Export – The main exports of material from the aquatic systems are export of water and particles, whereas export of regolith is minor. Thus, the effect on the receiving ecosystem (i.e. external conditions) should, in contrast, in most cases be small and this interaction does not need to be considered in the radionuclide modelling.

b) Thresholding – Regolith determines the location of thresholds and thresholds influence the external conditions as they determine the functioning of the landscapes (lakes, land, and wetlands). Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models (/Brydsten and Strömgren 2010/ and Chapter 10 in this report).

3:1 Primary producers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Hypothetically roots may penetrate into fractures in the solid rock and into the plugged and backfilled access tunnels. This could in turn affect rock structures, hydraulic conductivity, potential for erosion, physical and mechanical properties of the tunnels, and amounts of biological material. In the aquatic systems in Forsmark there are few rooted species, but chemotropic primary producers may be present in backfills and boreholes. However, these are assumed to only be present within the geosphere and do not need to be considered in the radionuclide modelling. The root penetration depth of the terrestrial vegetation will generally be restricted to the upper 0.5 m, where the majority of roots are found. Deeper roots may be found, mainly in dry habitats such as pine forests on bedrock, but will not penetrate deep enough to affect the backfilled access tunnels. Therefore this interaction does not need to be considered in the radionuclide modelling.

3:2 Primary producers affect **regolith** by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Micro-primary producers are present within the regolith and may influence the composition of the regolith, e.g. by influencing oxygen concentrations. Bioturbation by root production in aquatic ecosystems is of minor importance since there are few rooted species in aquatic ecosystems in Forsmark. However, in the terrestrial ecosystems this interaction may be important. The composition of regolith is important for transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is considered since composition of the regolith and depth of the oxygenated layer measured *in situ* are used in the parameterisation of the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Death – Primary producers affect the amount of dead organic matter in the regolith of the ecosystems when dying and by litter fall. This flux of organic matter may be important for the redistribution of radionuclides in ecosystems and needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production for the aquatic ecosystems in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:3 Primary producers is a diagonal element further described in Section 9.3. Primary producers affect other primary producers by the processes a) Primary production, b) Habitat supply, and c) Stimulation/inhibition.

a) Primary production – Primary production is the fixation of carbon by primary producers mediated by photosynthesis. This is an important process that generates biomass which is fundamental for the existence of the diagonal element primary producers. Primary production is important for the incorporation of radionuclides (especially C-14) into biota and this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net primary production of biota (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Habitat supply – In aquatic ecosystems macrophytes are often colonised by epiphytic algae. The biomass of epiphytic flora on terrestrial vegetation is small in relation to biomass of the non-epiphytic vegetation. This interaction does not directly influence the transport of radionuclides in ecosystems and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production are included in the parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Primary producers may stimulate each other e.g. by sexual reproduction or inhibit each other by e.g. resource competition. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:4 Primary producers affect **decomposers** by the processes a) Habitat supply, and b) Stimulation/inhibition.

a) Habitat supply – Macrophytes are often colonised by epiphytic bacteria. Primary producers may affect the decomposers by the quality of the litter. These interactions are considered to be of relatively low importance to the transport of radionuclides in the ecosystems and therefore do not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance, production and decomposition, are included in the parameter calculations for the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

b) Stimulation/inhibition – Primary producers may stimulate decomposers by e.g. providing a substrate for epiphytic bacteria or they may inhibit decomposers by competition for resources e.g. phytoplankton and bacterioplankton competing for dissolved nitrogen and phosphorus. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in the parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:5 Primary producers affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition. This interaction is not applicable in terrestrial ecosystems since filter feeders are lacking there.

a) Food supply – Primary producers function as food for filter feeders (e.g. the consumption of phytoplankton). This may be an important transfer pathway for radionuclides and the interaction need to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic communities (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Habitat supply – Macrophytes can be colonised by filtering species of hydrozoans or small mussels. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Primary producers may inhibit filter feeders by e.g. space competition or toxin production. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:6 Primary producers affect **herbivores** by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition.

a) Food supply – Primary producers function as food for herbivores. This may be an important transfer pathway for radionuclides and the interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic communities (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Habitat supply – Primary producers may be colonised by e.g. herbivorous snails. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Primary producers may stimulate herbivores by e.g. providing substrate and a food source of specifix quality and palatability. Primary producers may inhibit herbivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:7 Primary producers affect **carnivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Primary producers may stimulate carnivores by e.g. providing sheltered areas for reproduction. Primary producers may inhibit carnivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the safety radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:8 Primary producers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Humans may consume primary producers as a food source and therefore the primary production that may be used as food by humans needs to be considered in the radionuclide modelling. However, in Sweden today, very few (if any) limnic primary producers are used as food and the food supply is set to zero for aquatic ecosystems in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Material supply – There are no primary producers in the aquatic ecosystems in Forsmark today that it is realistic to consider as being utilised as a material supply and therefore this interaction does not need to be considered in the radionuclide modelling. In the terrestrial ecosystem, reed belts in wetlands surrounding lakes may be used in thatching. However, even if thatching occurs, the effect on exposure to humans will be small and this interaction does not need to be considered in the radionuclide modelling for any ecosystem.

c) Stimulation/inhibition – Primary producers may affect humans e.g. toxic algal blooms in aquatic ecosystems. However, inhibition of humans would lead to less utilisation of the ecosystem and thereby less risk of exposure to potential radionuclides. In contrast, stimulation would lead to increasing utilisation by humans. However, as a cautious assumption, maximum utilisation of the ecosystem is assumed in the safety assessment and hence this interaction does not need to be considered in the radionuclide modelling.

3:9 Primary producers affect **water in regolith** by the processes a) Excretion, and b) Uptake.

a) Excretion – Microphytobenthos in aquatic ecosystems and rooted plants living in the regolith in ecosystems may excrete water into the regolith. However, the effect of the excretion of water by primary producers on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared to the water volume in the regolith. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Uptake – In aquatic ecosystems most primary producers take up water directly from surface water and the effect of the uptake of water by primary producers is minimal in comparison to the water volume in the regolith. Plant uptake of water can significantly affect water in regolith in terrestrial ecosystems in general and the effect is considered in hydrological modelling. In the other terrestrial ecosystem modelled in the radionuclide model (i.e. agricultural land) irrigation takes place, so also there, regolith are assumed to be unaffected by plant uptake. Hence, this interaction does not need to be considered in the radionuclide modelling.

3:10 Primary producers affect **surface waters** by the processes a) Acceleration, b) Covering, c) Excretion, d) Interception, and e) Uptake.

a) Acceleration – The type and amount of primary producers influence the movement of water, e.g. by overgrowing of a narrow sound or algae in surface water. Other factors influencing water movements are probably more important than the reduction of velocities due to primary producers and this interaction does not need to be considered in the radionuclide modelling.

b) Covering – The covering by biota in aquatic ecosystems is small since most primary producers are submerged and this interaction therefore does not need to be considered in the radionuclide modelling. Also in terrestrial ecosystems this interactions is assumed to be of minor importance.

c) Excretion – The effect of excretion by primary producers on surface waters in aquatic ecosystems is minimal, since the excretion of water is very small compared to the water volume of the aquatic system. Thus, this interaction does not need to be considered in the radionuclide modelling. Also in terrestrial ecosystems this interactions is assumed to be of minor importance.

d) Interception – Interception is the amount of precipitation that does not reach the ground but is retained on vegetation. In the aquatic ecosystems in the regional model area, most biota is submerged and therefore interception does not need to be consider in the radionuclide modelling. In terrestrial ecosystems interception may affect the runoff and this is considered in hydrological models.

e) Uptake –The effect of uptake by primary producers on surface waters in aquatic ecosystems is minimal, since the uptake of water is very small compared to the water volume of the aquatic system. Thus, this interaction does not need to be considered in the radionuclide modelling.

3:11 Primary producers affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Primary producers affect the amount of dead organic matter in surface water of ecosystems mainly due to death, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Death is included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Excretion – Excretion of elements by primary producers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect if this interaction is included in the calculation of parameter values for the radionuclide model, by the use of *in situ* measured water composition (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Primary producers in terrestrial areas release large amounts of particles by pollen release, but this interaction goes via gas and local atmosphere (see below). In aquatic ecosystems, macrophytes may also release particles although most probably in smaller quantities. Particles may be attached to macrophytes in aquatic ecosystems however this is most likely of minor significance compared to particle trapping by e.g. filter feeders (5:5) and this interaction does not need to be consideredfor aquatic ecosystems in the radionuclide model. Nevertheless, the effect on water composition of particle release and trapping by primary producers is included in the radionuclide model as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Uptake – Uptake by primary producers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included by the use of *in situ* measured water composition in the calculation of parameter values for the radionuclide model, (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:12 Primary producers affect **gas and local atmosphere** by the processes a) Acceleration, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Acceleration – The type, amount and location of primary producers determine the degree of sheltering and influence thereby wind directions and velocities. However, the turbulence and changing wind direction are more variable than the physical obstruction by vegetation, especially in aquatic systems with few emergent species. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – Primary producers affect the gas and local atmosphere by excreting oxygen during photosynthesis. Terrestrial primary producers have a direct impact on the gas content in the local atmosphere. In aquatic ecosystems the excretion of gas to the water volume may influence the amounts of gas in surface water and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in the radionuclide modelling. Therefore, the excretion of gases by primary producers is included in the calculation of the parameters concerning gas uptake and release and primary production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Particle release/trapping – Particle release and trapping to and from the atmosphere is small from aquatic ecosystems. Emergent macrophytes can spread particles with wind but most macrophytes in the aquatic ecosystems at Forsmark are submerged. In terrestrial ecosystems this interaction may be frequent, although the importance for transfer and accumulation of radionuclides is considered as minor. Therefore this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Primary producers may take up carbon dioxide and other elements (e.g. iodine) and release oxygen in terrestrial and aquatic ecosystems. In aquatic ecosystems the uptake of gas from the water volume may influence the amounts of gas in surface water and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in the radionuclide modelling. The uptake of gases by primary producers is included in the calculation of the parameters concerning gas uptake and release and primary production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

3:13 Primary producers affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Vegetation can act as an insulator between the atmosphere and underlying water or regolith and thereby affect the transport of heat in the biosphere. In the aquatic ecosystems at Forsmark, the abundance of emergent macrophytes is low, but in the terrestrial ecosystems the vegetation may have an insulating effect. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – The type, amount and location of primary producers determine the degree of adsorption and reflection of radiation and influence thereby the temperature in the biosphere. The radiation absorption by biota in aquatic ecosystems will be very small compared with the radiation absorption by the water body and this interaction does not need to be considered in the radionuclide modelling. Terrestrial vegetation does affect the temperature significantly and the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction), which are used for calculations of parameter values applied in the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of vegetation in aquatic ecosystems is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considered in the radionuclide modelling. This effect is also assumed to be of insignificant importance in terrestrial ecosystems. Nevertheless it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

3:14 Primary producers affect **radionuclides** by the processes a) Excretion, b) Growth, Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in other components of the biosphere and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapter 10 and 11 in this report).

b) Growth – Growth can potentially lower the concentration of radionuclides in primary producers due to dilution of radionuclides in biomass and need to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapter 10 in this report).

d) Uptake – The uptake of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in other components of the biosphere and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapter 10 in this report).

3:15 Primary producers affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave, since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem (i.e. external conditions) should, in contrast, in most cases be smaller (due to dilution in downstream aquatic objects). Supporting calculations has been performed to confirm this for the Forsmark area and this interaction does not need to be further considered in the radionuclide modelling. However, since it is important for the exporting system, the export of primary producers is included in the export of particulate matter in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:1 Decomposers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Macro-decomposers can only enter the repository in the geosphere if the passage is open to the repository (which is not assumed in the base case (**SR-Site main report**) and even then, it is unlikely that the macro-decomposers would thrive at a depth of 500 m. Micro-decomposers, on the other hand, are assumed to exist in the repository and are important to consider in the safety assessment for the geosphere. Accordingly, this interaction is treated as microbial interactions in the geosphere model, see the **FEP report**.

4:2 Decomposers affect **regolith by** the processes a) Bioturbation, b) Consumption, c) Death, and d) Decomposition.

a) Bioturbation – Decomposers affect the regolith in ecosystems by bioturbation (by e.g. worms). Bioturbation affects the physical properties and the chemical composition of the upper regolith which may be important for the transport of radionuclides and thus needs to be considered in the radionuclide modelling. Bioturbation is included in the radionuclide model as the depth of the upper oxygenated layer that has been investigated *in situ* (thereby including the effects of this interaction) (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Consumption – Decomposers may consume large quantities of organic compounds in the regolith and thereby affect the composition of the regolith. This interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Death – Decomposers affect the amount of dead organic matter in the regolith of ecosystems mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. Accordingly, in ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Decomposition – The type and efficiency of decomposers affects the content and quality of organic material in the regolith and this interaction needs to be considered in the radionuclide modelling. For the terrestrial ecosystem, decomposition in the mire is included in the radionuclide model as a parameter describing the long-term decomposition of organic material. In the aquatic ecosystems, decomposition is included in the radionuclide model through net productivity, i.e. the decomposition is subtracted from the gross production and only the net productivity of the system is used (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:3 Decomposers affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit primary producers by e.g. resource competition whereas they stimulate primary producers mainly indirectly by influencing water composition and regolith characteristics in aquatic ecosystems. In terrestrial ecoststems effects from fungus biodiversity that increases mineralisation and presence of myccorrhizal species can both directly affect primary production. However, this interaction is less studied in wetlands.

This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:4 Decomposers affect **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may stimulate each other by e.g. mating and they may inhibit each other by e.g. resource and space competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:5 Decomposers affect **filter feeders** in the aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition. This interaction is not applicable in terrestrial ecosystems since filter feeders are lacking there.

a) Food supply – Decomposers may function as a food source for filter feeders (e.g. filtering of pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Decomposers may stimulate filter feeders by e.g. providing food of different quality. Decomposers may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:6 Decomposers affect **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit herbivores by e.g. substrate competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:7 Decomposers affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Decomposers may function as a food source for carnivores (e.g. consumption of macro-decomposers, bacteria and fungi). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Decomposers may stimulate carnivores by e.g. providing food of different quality or they may inhibit carnivores by e.g. competition for space. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:8 Decomposers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Decomposers, e.g. fungi and crayfish (that are omnivorous and thus a mix of decomposers, herbivores and carnivores), may function as a food source for humans and therefore this interaction needs to be considered in the radionuclide modelling. Accordingly consumption of crayfish is included in the radionuclide model (see Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Material supply – Material use of decomposers by humans is small and the supply of decomposers for human utilisation does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – There are no decomposers that are likely to stimulate or inhibit human utilisation of the environment and therefore this interaction does not need to be considered in the radionuclide modelling.

4:9 Decomposers affect **water in regolith** by the processes a) Decomposition, b) Excretion and c) Uptake.

a) Decomposition – The type and efficiency of decomposers may influence the water content in the regolith as decomposers release water from pores and cells. The effect of decomposition on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the release of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – Decomposers (e.g. bacteria) living in the regolith excrete water into the regolith. The effect of the excretion of water by decomposers on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the excretion of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Uptake – Decomposers (e.g. bacteria) living in the regolith take up water from the regolith. The effect of the uptake of water by decomposers on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the uptake of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

4:10 Decomposers affect **surface water** by the processes a) Acceleration, b) Decomposition, c) Excretion, d) Movement, and e) Uptake.

a) Acceleration – The type and amount of decomposers attached to any surface may influence the properties of the surface and thereby water movement. Other forcing factors will have a much larger effect on surface water movement than decomposers and this interaction does not need to be considered in the radionuclide modelling.

b) Decomposition – Decomposers release water during decomposition, but the effect on surface waters is insignificant considering the large water volumes in aquatic ecosystems, and the effect of this interaction on temporarily occurring surface waters in terrestrial ecosystems is minimal for the same reason, therefore this interaction does not need to be considered in the radionuclide modelling.

c) Excretion – The excretion of water by decomposers is very small compared to the water volume of the aquatic system and to the water volume found below the surface of e.g. a mire, hence the effect on surface water is insignificant. Therefore, this interaction does not need to be considered in the radionuclide modelling.

d) Movement – The movement of organisms in surface waters may have an influence on the surface water movement. However, aquatic decomposers are relatively small and will most likely not affect a water body such as a sea/lake or a temporarily occurring surface water body during flooding or heavy rainfall. Moreover, the water is assumed to be homogenously mixed so this interaction does not need to be considered in the radionuclide modelling.

e) Uptake – The uptake of water by decomposers is very small compared to the water volume of the aquatic system and to temporarily occurring surface waters in terrestrial ecosystems. Hence, the effect on surface water due to uptake by decomposers is insignificant and does not need to be considered in the radionuclide modelling.

4:11 Decomposers affect **water composition** by the processes a) Consumption, b) Death, c) Decomposition, d) Excretion, f) Particle release/trapping, and g) Uptake.

a) Consumption – Decomposers may consume large quantities of organic compounds in water and thereby affect the water composition and also the transport and accumulation of radionuclides. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community where secondary production of decomposers is included. In addition, water composition, which is measured *in situ* (thereby including the effect of consumption), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Death – Decomposers affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Decomposition – Decomposers may influence the water composition by altering the structure of organic compounds. This may influence the transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model and thereby this interaction is indirectly included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Excretion – Excretion by decomposers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

e) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces and thus this interaction needs to be considered in the radionuclide modelling. The effect on water composition of particle release and trapping by decomposers is included in the radionuclide model as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

f) Uptake – Uptake by decomposers may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentration of oxygen. Therefor this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:12 Decomposers affect **gas and local atmosphere** by the processes a) Excretion, and b) Uptake.

a) Excretion – Decomposers excrete gases, mainly carbon dioxide and methane, and thereby influence the gas fraction in water and regolith. As an example, large amounts of methane gases have been found in sediments of lakes and shallow bays during site investigations in Forsmark /Borgiel 2004a/, and a large proportion of this gas is likely the result of decomposing organic regolith /Karlsson and Nilsson 2007/. Carbon dioxide is quantitatively the most important gas entering the atmosphere and this interaction is included in the calculation of transport and accumulation of C-14 in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

b) Uptake – Elements present in gas bubbles in water may be taken up by decomposers, i.e. methanotrophs. However, the uptake from gas bubbles should be minor compared to uptake from water and this process does not need to be considered in the radionuclide modelling.

4:13 Decomposers affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and thereby affect the transport of heat in the biosphere. However, the density of decomposers is small and other factors (e.g. heat storage of surface water will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the other components, e.g. water bodies and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

4:14 Decomposers affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore need to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

4:15 Decomposers affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave since the exported biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream objects) and this interaction does not need to be considered in the radionuclide modelling. However, since important for the exporting system, the export of decomposers is included in the export of particulate matter (including both abiotic and biotic particles) in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

Since filter feeders only are present in aquatic ecosystems the following interactions, 5:1–5:15, is only valid for aquatic ecosystems and does not treat interactions in terrestrial ecosystems.

5:1 Filter feeders affect **geosphere** in aquatic ecosystems by the process a) Intrusion.

a) Intrusion – Filter feeders normally penetrate at most a few decimetres through a sediment surface and it is highly unlikely that they would intrude to repository depth of 500 metres even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

5:2 Filter feeders affect **regolith** in aquatic ecosystems by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Filter feeders (e.g. bivalves) may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. In the aquatic ecosystem at Forsmark, the filter feeders are scattered in space and their effect on the regolith is relatively small. Therefore, this interaction does not need to be considered in the radionuclide modelling. However, bioturbation by other organisms may be important and the depth of the upper oxygenated sediment layer is included as a parameter in the radionuclide model. Since the depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of filter feeders) this interaction is indirectly included in the radionuclide model (Chapter 10 in /Aquilonius 2010/and Chapters 10 and 11 in this report).

b) Death – Filter feeders affect the amount of dead organic matter in the regolith in aquatic ecosystems mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

5:3 Filter feeders affect **primary producers** in aquatic ecosystems by the processes a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of primary producers (e.g. bivalves filtering phytoplankton). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

b) Habitat supply – Filter feeders may provide a substrate for epiphytic algae. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Filter feeders may inhibit primary producers by e.g. competition for space. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

5:4 Filter feeders affect **decomposers** in aquatic ecosystems by the processes a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of decomposers (e.g. bivalves filtering pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model through the representation of net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

b) Habitat supply – Filter feeders may provide a substrate for epiphytic bacteria. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Filter feeders may inhibit decomposers by e.g. competition for resources and substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

5:5 Filter feeders affect **filter feeders** in aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Larval filter feeders may be consumed by other filter feeders. However, the consumption of filter feeders is small compared to the consumption of other organisms and particles. Therefore this interaction does not need to be considereded in the radionuclide modelling. Nevertheless, the effect of this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

b) Food supply – Filter feeders are available as food source for other filter feeders as they may consume each other's larval stages. However, the consumption of filter feeders is small compared to the consumption of other organisms and particles. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Filter feeders may stimulate each other e.g. by mating. Filter feeders may inhibit each other by e.g. competition for resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

5:6 Filter feeders affect **herbivores** in aquatic ecosystems by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Most herbivores are too large to be consumed by filter feeders (with the exception of some zooplankton) and filter feeders consumption of herbivores is probably of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Filter feeders may potentially stimulate herbivores by e.g. food selection of some species that stimulate other species. Filter feeders may inhibit herbivores, e.g. by competition for substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

5:7 Filter feeders affect **carnivores** in aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction is probably of minor importance for radionuclide transport.

Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

b) Food supply – Filter feeders may function as a food source for carnivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, in this report). and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Filter feeders stimulate carnivores mainly indirectly by e.g. decreasing the amount of suspended particles in water, hence better visibility in the water column which in turn is beneficial for a hunting predator. Filter feeders may inhibit carnivores by e.g. competition for substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

5:8 Filter feeders affect **humans** in aquatic ecosystems by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply –Filter feeders may function as a food source for humans and this interaction needs to be considered in the radionuclide modelling. However, in the aquatic ecosystems in Forsmark there are few if any edible filter feeders present today and consumption of freshwater filter feeders has historically been low also globally /Parmalee and Klippel 1974/ and the consumption of filter feeders by humans is set to zero in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Material supply – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, today no activities of this kind in Forsmark are known to the authors, and even if they were, it would most likely contribute only minor to dose since it has been shown that the major long-term risk from human exposure to radionuclides from a repository is from internal exposure /Avila and Bergström 2006/. Therefore this interaction does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – Some species of filter feeders, e.g. *Dreissena polymorpha*, are known to cause problems for human utilisation of water resources by e.g. clogging of water filters /Griffiths et al. 1991/. However, the same species may improve water quality by grazing on toxic cyanobacteria and may be used as biofilters /Dionisio Pires et al. 2005/. There are no species present in the aquatic ecosystems in Forsmark today that inhibit human utilisation and therefore inclusion of this interaction does not need to be consider in the radionuclide modelling. This leads to a cautious assessment since inhibition of human utilisation of water resources would lead to a decrease in radiation dose.

5:9 There are no processes by which **filter feeders** affect **water in regolith** that are relevant to include in the radionuclide model.

5:10 Filter feeders affect **surface water** in aquatic ecosystems by the processes a) Acceleration, b) Excretion, c) Movement, and d) Uptake.

a) Acceleration – The type and amount of filter feeders attached to surfaces may hypothetically influence the properties of the surfaces and thereby water movement. In lakes and in sea, other forcing factors will have greater effects on the surface-water movement than filter feeders and this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – is the excretion of water or elements to the surrounding media by humans and other organisms. The excretion of water by filter feeders is very small compared to the water volume of the aquatic system and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Movement – Filter feeders influence the water flow by filtering water. However, compared to the turnover rates of water the effect of filter feeders is small at Forsmark since the abundance of filter feeders is relatively low. Moreover the water is assumed to be homogenously mixed and therefore this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – is the incorporation of water or elements from the surrounding media by humans and other organisms. The uptake of water by filter feeders is very small compared to the water volume of the aquatic system and this interaction therefore does not need to be considered in the radionuclide modelling.

5:11 Filter feeders affect **water composition** in aquatic ecosystems by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Filter feeders affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Excretion – Excretion by filter feeders may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces and thus this interaction needs to be considered in the radionuclide modelling. Filter feeders can trap large amounts of particles from the water by filtering thereby affecting water composition and attributes such as turbidity /Soto and Mena 1999, Wilkinson et al. 2008/. Filter feeders can release particles by e.g. releasing offspring. The particle release and trapping by filter feeders is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction) (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

d) Uptake – Uptake by filter feeders may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

5:12 Filter feeders affect **gas and local atmosphere** in aquatic ecosystems by the processes a) Excretion, and b) Uptake.

a) Excretion – Filter feeders may excrete gases and thereby influence the gas fraction in water and regolith. However, the gas excretion should be minor compared to e.g. that from decomposers (see 4:12) and this interaction should have only a minor effect on transport and accumulation of radionuclides and therefore does not need to be considered in the radionuclide modelling.

b) Uptake – Elements present in gas bubbles in water may be taken up by filter feeders. However, the uptake from gas bubbles should be minor compared to uptake from water and this process therefore does not need to be considered in the radionuclide modelling.

5:13 Filter feeders affect **temperature** in aquatic ecosystems by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and thereby affect the transport of heat in the biosphere. However, the density of filter feeders is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have greater impact on temperature in the aquatic ecosystems. Thus this interaction does not need to be considered in the radionuclide model. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by biota in aquatic ecosystems will be very small compared to the radiation absorption by the water body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of filter feeders is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considereded in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

5:14 Filter feeders affect **radionuclides** in aquatic ecosystems by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionuclide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

5:15 Filter feeders affect **external conditions** in aquatic ecosystems by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and this interaction does not need to be considered in the radionuclide modelling. However, since it is important for the exporting system, the export by filter feeders (e.g. offspring) is included in the export of particulate matter in the radionuclide model (includes both abiotic and biotic particles) in the (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

6:1 Herbivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Herbivores normally penetrate at most a few centimetres through a sediment surface and it is highly unlikely that they would intrude to repository depth of 500 metres even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

6:2 Herbivores affect **regolith** by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Herbivores may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. Herbivores do not penetrate the sediment to any large extent in aquatic ecosystems and their contribution to bioturbation should be small. Therefore, this interaction does not need to be considered in the radionuclide modelling.

However, bioturbation by other organisms may be important and the depth of the upper oxygenated sediment layer is included as a parameter in the radionuclide model. Since the depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of herbivores) this interaction is indirectly included in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Death – Herbivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:3 Herbivores affect **primary producers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Consumption of primary producers is an important transfer of energy in the ecosystem and this interaction is important to consider in the radionuclide modelling. Accordingly, the consumption by herbivores is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Herbivores may inhibit some species of primary producers by e.g. substrate competition. Besides that, herbivores mainly indirectly stimulate primary producers by inhibiting other organisms, e.g. changed competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary producers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:4 Herbivores affect **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Herbivores may stimulate decomposers by e.g. differences in the quality of food produced. Herbivores may inhibit decomposers by e.g. substrate competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:5 Herbivores affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may provide a food source for filter feeders (e.g. zooplankton and gametes). However, most herbivores are too large to be consumed by filter feeders and this interaction is probably of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Herbivores stimulate filter feeders by e.g. providing food of different quality. Herbivores may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

6:6 Herbivores affect **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Herbivores may inhibit each other by e.g. competition for substrate and resources. Herbivores may stimulate each other by e.g. mating. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:7 Herbivores affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for carnivores. This may be an important pathway for radionuclide transfer and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Herbivores may inhibit carnivores by e.g. substrate competition. Herbivores may stimulate carnivores by e.g. providing food of different quality. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:8 Herbivores affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for humans who may consume herbivorous fish or game. This interaction may be an important radionuclide transport route to humans and is important to include in the radionuclide modelling. Accordingly, the secondary production of herbivores and consumption by humans are included in the radionuclide model as consumption of fish and game (Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Material supply – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that herbivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – There is no identified stimulation or inhibition by herbivores of human utilisation of the ecosystem at Forsmark except for fishing or hunting which is treated in food supply (see a, above). Therefore this interaction does not need to be considered in the radionuclide modelling.

6:9 There are no processes by which **herbivores** affect **water in the regolith** that are relevant to include in the radionuclide modelling.

6:10 Herbivores affect **surface water** by the processes a) Acceleration, b) Excretion, c) Movement, and d) Uptake.

a) Acceleration – The type and amount of herbivores attached to surfaces (e.g. snails) may hypothetically influence the properties of the surfaces and thereby water movement in aquatic ecosystems, although other forcing factors will have greater effect on surface water movement than herbivores. In terrestrial ecosystems no known interaction of this kind is identified and this interaction therefore does not need to be considered in the radionuclide modelling.

b) Excretion – The excretion of water by herbivores is very small compared to the water volume of the aquatic system and to surface waters in terrestrial ecosystems, and this interaction does not need to be considered in the radionuclide modelling.

c) Movement – The movement of animals in surface waters may have an influence on surface water movement. However, the animals will most probably not affect large water bodies such as lakes. Moreover the water is assumed to be homogenously mixed so this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – The uptake of water by herbivores is very small compared to the water volume of the aquatic system and to surface waters in terrestrial ecosystems in Forsmark, and this interaction therefore does not need to be considered in the radionuclide modelling.

6:11 Herbivores affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Herbivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Excretion – Excretion by herbivores may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by herbivores may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from herbivores is assumed to be small. In terrestrial ecocsytems the release and trapping of particles to/from surface water by herbivores is assumed to be insignificant. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless it is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect herbivores) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Uptake – Uptake by herbivores may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

6:12 Herbivores affect **gas and local atmosphere** by the processes a) Excretion, b) Particle release trapping, and b) Uptake.

a) Excretion – Herbivores (e.g. herbivorous zooplankton in aquatic ecosystems and grazing animals in terrestrial ecosystems) may excrete gases and thereby influence the gas fraction in water, regolith and local atmosphere. However, the gas excretion should be small from herbivores and have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Particle release/trapping – Herbivorous birds may release or trap particles in the atmosphere. However, this interaction is assumed to be minimal in comparison to the particle release and trapping by e.g. primary producers and this interaction does not need to be considered in the radionuclide modelling.

c) Uptake – Elements present in gas bubbles in water may be taken up by herbivorous animals. In addition terrestrial birds and mammals take up elements directly from the atmosphere. However, the uptake from gas bubbles in water should be minor compared to uptake from water and in addition uptake from atmosphere should be minimal compared to the volume of the atmosphere. This process therefore does not need to be considered in the radionuclide modelling.

6:13 Herbivores affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Aquatic benthic herbivores can act as an insulator between the water and underlying regolith and may influence the temperature of the underlying regolith or rock. However, the density of herbivores is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have a greater impact on temperature in the aquatic ecosystems. Terrestrial herbivores represent a rather small part of the total biomass and the effect on the temperature will be insignificant. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 9 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the water or regolith body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of herbivores is limited compared with the heat absorption by the water and regolith body and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

6:14 Herbivores affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considereded in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for description of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific BCF-values (see /Nordén et al. 2010/ and Chapter 10 in this report).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

6:15 Herbivores affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem radionuclide inventory if contaminated biota migrate since it could cause a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and does not need to be considered in the radionuclide modelling. Export of herbivores in aquatic ecosystems (e.g. zooplankton) is included in the export of particulate matter (includes both abiotic and biotic particles) in the radionuclide model (Chapter 9 in /Aquilonius 2010/ and Chapters 10 and 11 in this report). Generally, terrestrial herbivores or herbivorous fish leaving the ecosystems are not included in the radionuclide modelling which is a cautious approach, since export of herbivores containing radionuclides would reduce the amounts of radionuclides in the exporting system.

7:1 Carnivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Carnivores normally penetrate at most a half a metre through a regolith surface and it is highly unlikely that they would intrude to repository depth of 500 meters even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

7:2 Carnivores affect **regolith** by the process a) Bioturbation, and b) Death.

a) Bioturbation – Carnivores may affect the regolith by bioturbation which may alter physical properties and chemical composition of the upper regolith. However, carnivores most probably have a local and limited effect on the regolith and this interaction does not need to be considered in the radionuclide modelling. However, bioturbation by other organisms may be important and the depth of the upper oxygenated regolith layer is included as a parameter in the radionuclide model. Since depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of carnivores) this interaction is indirectly included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Death – Carnivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

7:3 Carnivores affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Carnivores may stimulate or inhibit herbivores directly, but mainly they stimulate primary producers indirectly by reducing the amounts of herbivores. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary production, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

7:4 Carnivores affect **decomposers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume decomposers. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Carnivores may stimulate decomposers by e.g. by providing food of different quality. Carnivores may inhibit decomposers by e.g. resource competition. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

7:5 Carnivores affect **filter feeders** in the aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores consume filter feeders. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Food supply – Carnivores may function as a food source for filter feeders. Carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Carnivores may inhibit filter feeders by e.g. resource competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

7:6 Carnivores affect **herbivores** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume herbivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Stimulation/inhibition – Carnivores may stimulate or inhibit some species of herbivores by favouring certain species in their diet. This interaction does not influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

7:7 Carnivores affect **carnivores** by the processes a) Consumption, b) Food supply and c) Stimulation/inhibition.

a) Consumption – Carnivores consume carnivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Food supply – Carnivores may function as a food source for other carnivores. This may be important for transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – Carnivores may stimulate each other by e.g. mating. Carnivores may inhibit each other by e.g. competition for space and resources. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

7:8 Carnivores affect **humans** by the processes a) Consumption, b) Food supply, c) Material supply, and d) Stimulation/inhibition.

a) Consumption – In ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bear) were to occupy Forsmark this would not lead to higher radionuclide doses for humans and therefore this interaction does not need to be considered in the radionuclide modelling.

b) Food supply – Carnivores, e.g. carnivorous fish and mammals, may function as a food source for humans. Primarily fish may be an important route of transport of radionuclides to humans and needs to be considered in the radionuclide modelling. Accordingly, the production of edible carnivorous fish is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Material supply – Even if it does occur that shoes and various accessories are manufactured from for example pike skin /Rahme and Hartman 2006/ and skin from mammals, it is in insignificant volumes and such production has not been reported from Forsmark. Hence, this process does not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – There is no identified stimulation or inhibition by carnivores of human utilisation of the ecosystems at Forsmark and this interaction does not need to be considered in the radionuclide modelling.

7:9 There are no processes by which **Carnivores** affect **water in regolith** that are relevant to include in the radionuclide modelling.

7:10 Carnivores affect **surface water** by the processes a) Excretion, b) Movement, and c) Uptake.

a) Excretion – The excretion of water by carnivores is very small compared to the water volume of the aquatic system and the surface water in terrestrial ecosystems, and this interaction does not need to be considered in the radionuclide modelling.

b) Movement – The movement of animals in surface waters may have an influence on surface-water movement. However, the aquatic animals are relatively small and the terrestrial animals will only occasionally be located in water bodies, and this will most probably not affect water bodies, so this interaction therefore does not need to be considered in the radionuclide modelling.

c) Uptake – The uptake of water by carnivores is very small compared to the water volume of the aquatic system and the terrestrial surface waters and this interaction therefore does not need to be considered in the radionuclide modelling.

7:11 Carnivores affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Carnivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In aquatic ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Excretion – Excretion by carnivores may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Particle release/trapping – The concentration of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by carnivores may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from carnivores is assumed to be small. In terrestrial ecocsytems the release and trapping of particles to/from surface water by carnivores is assumed to be insignificant. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, particle release/trapping is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect carnivores) ((see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Nordén et al. 2010/ and Chapters 10 and 11 in this report).

d) Uptake – Uptake by carnivores may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

7:12 Carnivores affect **gas and local atmosphere** by the processes a) Excretion, b) Particle release/trapping, and c) Uptake.

a) Excretion – Carnivores (e.g. carnivorous fishes, birds and mammals) may excrete gases and thereby influence the gas fraction in water and directly to the local atmosphere. However, the gas excretion should be small from carnivores and have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Particle release/trapping – Carnivorous birds may release or trap particles to/from the atmosphere but this interaction is assumed to be minimal in comparison to particle release trapping by e.g. primary producers and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Uptake – Elements present in gas bubbles in water may be taken up by carnivorous animals. In addition terrestrial carnivorous birds and mammals take up elements directly from the atmosphere. However, the uptake from gas bubbles in water should be minor compared to uptake from water and in addition uptake from atmosphere should be minimal compared to the volume of the atmosphere. This process therefore does not need to be considered in the radionuclide modelling.

7:13 Carnivores affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Carnivores can act as an insulator between the water and underlying regolith and may influence the temperature of the underlying regolith or rock. However, the density of carnivores is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the water and regolith body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

7:14 Carnivores affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considereded in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific BCF-values (see /Nordén et al. 2010/ and Chapter 10 in this report).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in this report).

7:15 Carnivores affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and this interaction does not need to be considered in the radionuclide modelling. As it is important for the exporting system, the export by of carnivores (e.g. zooplankton) is included in the export of particulate matter (includes both abiotic and biotic particles) in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report). Carnivorous fish leaving the aquatic ecosystems are not included in the radionuclide model which is a cautious assumption, since export of fish containing radionuclides would reduce the amounts of radionuclides in the aquatic upstream ecosystem.

8:1 H**umans** affect **geospher**e by the processes a) Intrusion, and b) Material use.

a) Intrusion – Human intrusion may have a large impact on radionuclide transport and needs to be considered in the radionuclide modelling. However, human intrusion into the repository is unlikely due to the large depth of the repository and in the base case; humans are not assumed to enter the geosphere. All human activities that directly disturb the conditions in the geosphere (e.g. drilling) are treated as separate cases in the safety assessment, see the **SR-Site main report**.

b) Material use – Minerals and fossil fuels in the geosphere may be used by humans. Iron ores have been utilised in the Bergslagen region (Uppland), and are still utilised today in Dannemora (www.dannemoramineral.se). Compared with central parts of Bergslagen, the Forsmark area’s ore potential is insignificant and the entire candidate area is free of ore potential /Lindroos et al. 2004/. Therefore this interaction does not need to be considered in the radionuclide modelling.

8:2 Humans affect **regolith** by the processes a) Death, b) Material use, and c) Relocation.

a) Death – Humans may affect the amount of dead organic matter in regolith by e.g. municipal release (aquatic ecosystems) and by agricultural measures like fertilizing (terrestrial ecosystems), which contains organic matter such as faeces. This flux should however be of minor importance for the transport and accumulation of radionuclides in the ecosystems and does not need to be considered in the radionuclide modelling.

b) Material use – Regolith may be utilised by humans, e.g. peat used as fuel. For terrestrial ecosystems this has been considered in a supporting calculation /Avila et al. 2010/. However, regolith below lakes/marine basins are unlikely to be used by humans and this interaction does not need to be considered in the radionuclide modelling of aquatic ecosystems.

c) Relocation – Humans may affect and relocate regolith by e.g. dredging, digging and filling. Humans may lower thresholds in lakes (thereby affecting the regolith) to gain farmland. The transformation to farmland and thresholds may be important for the transport and accumulation of radionuclide and this interaction needs to be considered in the radionuclide modelling. This interaction is already included in the base case where all lakes transform into farmland, so a threshold change only alters time of transformation. Thereby, the effect of humans on regolith is accounted for in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

8:3 Humans affect **primary producers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may potentially utilize primary producers as a food source. Although this may be important for humans (3:8) the effect on primary producers should be minor and does not need to be considered in the radionuclide modelling. Terrestrial primary producers used for food are considered not to be restricted by human consumption and are assumed to always be present when the ecosystem is present. Since consumption by humans is important for the dose assessment the consumption of primary producers is evaluated in the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report). However, in Sweden today, very few (if any) aquatic primary producers are consumed and the consumption by humans is set to zero in the aquatic part of the radionuclide model.

b) Material use – Humans may utilise primary producers as building material etc. From terrestrial ecosystems, wood may be used in construction and reed belts may be used as in thatching. There are no aquatic primary producers in the ecosystems in Forsmark today that are being utilized. Although it may occur in the future the effect on primary producers will most probably be small. In most cases the effect on primary producers are assumed to be small and exposure of humans are not assumed to be higher than if spending time in the natural ecosystem (i.e. highest external exposure is assumed to be given from ground cf. /Nordén et al. 2010/) and this interaction does not need to be considered.

c) Species introduction/extermination – Humans may affect the settlement of primary producers by active dispersal, introduction or extermination of species. Examples of introduction of species to Swedish lakes and streams are Canadian pondweed (*Elodea Canadensis*, Sw. vattenpest), western water weed (*Elodea nuttallii*, Sw. small vattenpest), and fringed water-lily (*Nymphoides peltata*, Sw. sjögull) /Olsson 2000, Naturvårdsverket 2007/. There are also numerous examples from terrestrial ecosystems. However, although important from an ecological view point, introduction and extermination of species of primary producers are considered to be of minor importance for radionuclide transport and thus do not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit certain species of primary producers. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary production, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

8:4 Humans affect **decomposers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – The feeding by humans on decomposers is assumed to have a negligible impact on decomposers in Forsmark today and does not need to be considered in the radionuclide modelling. However, since consumption by humans is important for the dose assessment the consumption of limnic decomposers (e.g. crayfish which are omnivorous) and terrestrial (fungi) is included in the radionuclide model even if this does not occur in Forsmark today. Hence, consumption of limnic crayfish does occur in other lakes in the region and as a cautious assumption in the radionuclide model this interaction is included (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

b) Material use – In ecosystems, material use of decomposers by humans is considered an insignificant process and this interaction does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce decomposers (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species are important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. However, when introducing species utilised for food by humans, introduction may have a large impact on the exposure to radionuclides by humans and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source even though they are not present in the lakes today (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report). Cultivation or extermination of other edible decomposers in aquatic ecosystems at Forsmark is considered unlikely and do not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit decomposers. The human interference with decomposers are assumed to be small and this interaction therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

8:5 Humans affect **filter feeders** in aquatic ecosystems by the processes a) Consumption, b) Food supply, c) Material use, d) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – The potential consumption of filter feeders by humans is assumed to have a negligible impact on the filter feeder population and does not need to be considered in the radionuclide modelling. Since consumption by humans is important for the dose assessment, the consumption of filter feeders is evaluated in the radionuclide model. However, in Forsmark there are few if any edible filter feeders present today and consumption of freshwater filter feeders has historically been low also globally /Parmalee and Klippel 1974/ and the consumption of filter feeders by humans is set to zero in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Material use – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, today no activities of this kind in Forsmark are known to the authors, and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce filter feeders by cultivation but it is unlikely that they will exterminate filter feeders. Introduction of filter feeders does not need to be considered in the radionuclide modelling. Although cultivation may greatly influence the aquatic ecosystem from an ecological viewpoint, from the exposure of radionuclides viewpoint, it will not affect the transfer and accumulation of radionuclides in negative way. Cultivation of biota would decrease concentrations of radionuclides in the ecosystem due to the requirements of food import for the cultivated animals (e.g. pellets) which will dilute the organic matter in the ecosystem. Therefore, as a cautious assumption, introduction of filter feeders is not included in the radionuclide model.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit filter feeders. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

8:6 Humans affect **herbivores** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may feed on herbivores and this interaction needs to be considered in the radionuclide modelling. As consumption by humans is important for the dose assessment the potential production is estimated from herbivore populations that are exposed to fishing and hunting. The consumption of herbivores (i.e. some species of fish, crayfish and game) is included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

b) Material use – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that herbivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce herbivores to terrestrial (game) and aquatic environments (e.g. crayfish that are omnivorous). For most species, introduction or extermination of species is important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. Exceptions to this are if introduced species cause a cascade effect altering the entire food web (and thereby flux of radionuclides) as happened e.g. in Lake Victoria when Nile perch were introduced (e.g. /Goldschmidt et al. 1993/). The largest effect of an introduction for the exposure of humans is when the introduced species are utilised for food and this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source in the lakes even though they are not present in the lakes today (see Chapter 9 in /Aquilonius 2010/ and Chapter10 and 11 in this report). Cultivation or extermination of other edible herbivores in aquatic ecosystems at Forsmark is considered unlikely and does not need to be considered in the radionuclide modelling. As a cautious assumption we have chosen to neglect the possibility of extermination of fish species (a reduced fish biomass most certainly leads to a reduced flux of radionuclides to humans). In addition, we have assumed no aquaculture, which is also a cautious assumption as aquaculture demands extra nutrition for the fish (i.e. pellets) which would dilute the amounts of radionuclides in the fish.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit herbivores. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapter10 and 11 in this report).

8:7 Humans affect **carnivores** by the processes a) Consumption, b) Food supply, c) Material use, d) Species introduction/extermination, and e) Stimulation/inhibition.

a) Consumption – The feeding by humans on carnivores is assumed to have a negligible impact on the carnivore populations and this interaction does not need to be considered in the radionuclide modelling. Since consumption by humans is important for the dose assessment the consumption of carnivores (i.e. some species of fish) is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Food supply – In ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bear) were to occupy Forsmark they are not likely to have humans as a primary food source and this process does not need to be considered in the radionuclide modelling.

c) Material use – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that carnivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

d) Species introduction/extermination – Humans may introduce carnivores (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species are important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. However, when introducing species utilised for food, introduction may have a large impact on the exposure to radionuclides by humans and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source even though they are not present in the lakes today(see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report). Cultivation or extermination of other edible carnivores in ecosystems at Forsmark is considered unlikely and this interaction does not need to be considered in the radionuclide modelling. As a cautious assumption we have chosen to neglect the possibility of extermination of fish or seal species (a reduced biomass most certainly lead to a reduced flux of radionuclides to humans). In addition, we have assumed no aquaculture, which is also a cautious assumption as aquaculture demands extra nutrition for the fish (i.e. pellets) which would dilute the amounts of radionuclides in the fish.

e) Stimulation/inhibition – The activities of humans may stimulate or inhibit carnivores. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in the parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

8:8 Humans affect **humans** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Humans may interact in many ways. However, in the radionuclide modelling, maximum sustainable use of the ecosystem is assumed and no further considerations are needed.

8:9 Humans affect **water in regolith** by the processes a) Uptake, and b) Water use.

a) Uptake – Humans may affect water content and flow in the regolith by extraction from wells for drinking. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in the regolith is not a limiting factor for how many humans may utilise the area and uptake is not assumed to influence the amount of water in the regolith. However, the water uptake by humans is included in the radionuclide model to assess dose to humans (see /Avila et al. 2010/ and Chapter 10 in this report).

b) Water use – Humans may affect the water content and flow in the regolith by e.g. water extraction from wells or artificial infiltration of municipal water. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in regolith is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of water in the regolith. In the radionuclide model, water use by humans is included e.g. as irrigation /Avila et al. 2010/ and Chapter 10 in this report.

8:10 Humans affect **surface water** by the processes a) Acceleration, b) Anthropogenic release, c) Covering, d) Excretion, e) Movement, f) Uptake, and g) Water use.

a) Acceleration – Humans may influence water movement by constructions, e.g. dams, large-scale export, piping, and wave generation. Dam may have effect on the retention time in aquatic systems. A large span of retention times for aquatic ecosystems is already included in the radionuclide by the use of different biosphere objects of different sizes and different location in the landscape. Moreover, generally humans are considered to have a small impact on water movement compared to natural forces and this interaction does not need to be considered in the radionuclide modelling.

b) Anthropogenic release – Humans may influence the amount of surface water by releasing water by e.g. pumping from one location to another or by industrial discharge. This may influence the water retention times that are important for radionuclide transport. Therefore this interaction needs to be considered in the radionuclide modelling. In the radionuclide model this interaction is included in the water exchange estimate by assuming today's condition, i.e. no large releases occur into lakes. However, in marine ecosystems, discharge of cooling water from the nuclear power plant for the present conditions is included in calculation of water retention time which is a parameter in the radionuclide model /Karlsson et al. 2010/.

c) Covering – Use of icebreakers by humans influences the amount of surfaces covered with ice and may thereby potentially influence surface water movement. The influence of icebreakers on surface water is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

d) Excretion – Excretion of water by humans (urine) will not affect the amount of surface water in ecosystems since the volume is much smaller than the volume of surface waters and this interaction therefore does not need to be considered in the radionuclide modelling.

e) Movement – Human activities e.g. large-scale export, piping, wave generation etc. may have an influence on amount and movement of surface waters. Flow of surface water may have an effect on radionuclide transport and needs to be considered in the radionuclide modelling. No large-scale activities affecting surface water movements occur in Forsmark lakes today and are considered unlikely also in the future. Thus this interaction is not included in the radionuclide modelling.

f) Uptake – This may be important for the distribution of radionuclides and the interaction therefore needs to be considered in the radionuclide modelling. In the radionuclide modelling, as a cautious assumption, surface water is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. Nevertheless, the water uptake by humans is included in the radionuclide model to assess dose to humans (/Avila et al. 2010/ and Chapter 10 in this report).

g) Water use –Humans utilising lakes as freshwater reservoir may influence the water levels. This may be important for the distribution of radionuclides and the interaction therefore needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, surface water is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. Nevertheless, the water use by humans is included in the radionuclide modelling e.g. as irrigation in order to assess dose to humans (/Avila et al. 2010/ and Chapter 10 in this report).

8:11 Humans affect **water composition** by the processes a) Anthropogenic release, b) Death, c) Excretion, d) Uptake, and e) Water use.

a) Anthropogenic release – Humans may influence the composition of water by releasing substances. Today, there is no large release by humans to the lakes and most likely anthropogenic releases will be small also in the future. If assuming prevailing conditions this interaction does not need to be considered in the radionuclide modelling. Possible causes for anthropogenic releases in future could be if aquaculture were set up where large amounts of nutrients are added as food for the fish/mussels. However, as stated in 8:5 8:6 and 8:7, aquacultures would lead to reduced radionuclide concentrations (due to dilution with uncontaminated material) so this scenario has not been included in the radionuclide model.

b) Death – Humans may affect the amount of dead organic matter in water by municipal release, which contains organic matter such as faeces. This flux should be minor compared to the dead organic matter produced by aquatic organisms and the effect on transport and accumulation of radionuclides should be insignificant. Therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Excretion – Humans may influence the water composition by sewage which is known to increase e.g. nitrogen and phosphorus concentrations in water. Although the effect should be small for the entire aquatic area there may be local effects on the water chemistry by sewage. However, the water exchange is rather rapid in the future aquatic objects and therefore the excretion of humans is assumed to have a limited effect on the water composition and this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Humans may affect the water composition by filtering prior to using the water resource for drinking. Today, there is no large uptake by humans and most likely uptake will be small also in the future. If assuming prevailing conditions, this interaction does not need to be considered in the radionuclide modelling.

e) Water use – Humans may affect the water composition by filtering water for other purposes than drinking. Today, there is no large uptake by humans and most likely uptake will be small also in the future. If assuming prevailing conditions, this interaction does not need to be considered in the radionuclide modelling.

8:12 Humans affect **gas and local atmosphere** by the processes a) Acceleration, b) Anthropogenic release, c) Excretion, and d) Uptake.

a) Acceleration – Humans can potentially influence wind velocities and wind fields, by man-made structures such as buildings. This influence can be substantial in the immediate vicinity of those structures, whereas it is limited on a large scale. Therefore, the influence on mass transport is regarded as insignificant compared to natural causes for wind and this interaction does not need to be considered in the radionuclide modelling.

b) Anthropogenic release – Humans may influence the composition of the atmosphere by releasing substances. This is assumed to have minor influence on the dose to humans unless the release contains radionuclides, which is beyond the scope of this safety analysis. Therefore, this interaction does not need to be considered in the radionucide modelling.

c) Excretion – Humans can by respiration take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere and this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Humans can by respiration take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere and this interaction does not need to be considered in the radionuclide modelling.

8:13 Humans affect **temperature** by the processes a) Anthropogenic release, b) Convection, c) Light related processes, and d) Reactions.

a) Anthropogenic release – Human release may affect temperature, e.g. by increased temperature due to global warming or release heat from industries. Temperature changes leading to different climate conditions may have an effect on transport and accumulation of radionuclides and therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, this is considered in the safety assessment as a separate climate case (global warming case)

b) Convection – Humans may affect the flow of heat by constructing e.g. houses that in turn affect temperature by isolation. However, in comparison to other factors in the ecosystems, this is assumed to be insignificant and this interaction does not need to be considered in the radionuclide modelling.

c) Light related processes – Human constructions may affect the radiation balance. However, the effect of human constructions on temperature is assumed to be small and therefore this interaction does not need to be considered in the radionuclide modelling.

d) Reactions – The metabolic heat of humans has no effect on the temperature of aquatic ecosystems and therefore this interaction does not need to be considered in the radionuclide modelling.

8:14 Humans affect radionuclides by the processes a) Excretion b) Growth, c) Sorption/desorption, and d) Uptake.

a) Anthropogenic release – Human activities can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities. The release of radionuclides due to such activities is beyond the scope of this safety analysis and this interaction does not need to be considered in the radionucide modelling.

b) Excretion – Humans may excrete radionuclides. This is important since it affects the exposure of humans and this interaction needs to be considered in radionuclide modelling. The excretion of radionuclides by humans is accounted for in dose coefficients (which include excretion) that are used in the radionuclide model. In the modelling, radionuclide concentrations in the biosphere are not affected by uptake, i.e. the radionuclides are assumed to be available for ongoing transport as well as human utilizion of the food source. Therefore the excreted radionuclides are not added to the biosphere compartments in the radionuclide model (because if included the amount of radionuclides could be higher than the initial concentration).

c) Growth – The growth and life span of humans affects the concentration of radionuclides in humans and this interaction needs to be considered in the radionuclide modelling. Accordingly this is considered in the radionuclide model as committed effective dose is calculated for an integrated time of 50 years /Nordén et al. 2010, Avila et al. 2010/.

d) Sorption/desorption – Sorption of radionuclides to humans either in terrestrial or aquatic ecosystems is not assumed to alter the radionuclide inventories in the ecosystem where they are sorbed. Thus, this interaction does not need to be considereded in the radionuclide modelling.

e) Uptake – The uptake of radionuclides by humans is important for the exposure of humans (further discussed interaction 14:8), but the effect on radionuclide concentrations in the environment due to uptake by humans is of minor importance and is as a cautious assumption not considered in the radionuclide modelling.

8:15 Humans affect **external conditions** by the process a) Export.

a) Export – The effect on external conditions by humans moving out of the model area is assumed to be small (i.e. the migration of people from Forsmark will be small compared to the human population outside Forsmark) and this interaction does not need to be considered in the radionuclide modelling. In addition, humans may harvest and thereby export matter (and energy) from an ecosystem. Also this process is considered to be of minor importance for the ecosystems and does not need to be considered in the radionuclide modelling.

9:1 Water in regolith affects **geosphere** by the processes a) Change of pressure, b) Convection, and c) Weathering.

a) Change of pressure – Change of pressure affect the pore water pressure in the rock. However, there should be minor changes in pressure over time and this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The hydrology in the regolith influences the recharge and discharge of groundwater and thereby the hydrology in the geosphere and the composition of groundwater. This interaction may be important for the upward transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, discharge and recharge are included in the hydrological modelling that are used to calculate parameter values applied to the radionuclide model /Bosson et al. 2010/.

c) Weathering – The water flow in the regolith influences the weathering of rock. Weathering will not add radionuclides, unless the bedrock consists of radioactive minerals (which is not the case in Forsmark). Therefore, this interaction will have a minor effect on the transport and accumulation of radionuclides, and does not need to be considered in the radionuclide modelling.

9:2 Water in regolith affects **regolith** by the processes a) Relocation and b) Saturation.

a) Relocation – In ecosystems, the water in the regolith might affect the regolith by relocating it to another place, although other elements in the matrix (e.g. surface water) may affect the relocation of regolith to a larger degree. In the radionuclide model the upper regolith layer is treated as homogenously mixed and therefore it does not matter if regolith is relocated within an object, the prerequisites for accumulation of radionuclides will be identical. Therefore this interaction does not need to be considered in the radionuclide modelling.

b) Saturation – The magnitude and direction of the water flow influences the water content in the regolith. In the aquatic ecosystems and in the terrestrial mire ecosystem, the regolith is always saturated with water and this interaction does not need to be considered in the radionuclide modelling.

9:3 Water in regolith affects **primary producers** by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Primary producers may live in the water in the regolith. However, in general they are more dependent on nutrient concentrations, light conditions and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the egolith. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomass and production of microphytobenthos are included in the parameter calculations for the radionuclide model, since, these estimates are based on measurements *in situ*, the effect of water in regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Water supply – The amount of water in the regolith can affect biota on land. In aquatic and terrestrial (mire) ecosystems the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling. In other terrestrial ecosystems than mires, water in regolith may be more limiting to production but since irrigation takes place in the agricultural land in the radionuclide model this does not need to be further considered.

9:4 Water in regolith affects **decomposers** by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Decomposers in the form of bacteria may live in the water in the regolith. However, bacteria are more dependent on nutrient concentrations and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the regolith. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomass and respiration of bacteria are included in the radionuclide model. Since these estimates are based on measurements *in situ*, the effect of water in the regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:5 Water in regolith affects **filter feeders** in aquatic ecosystems by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:6 Water in regolith affects **herbivores** by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:7 Water in regolith affects **carnivores** by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the aquatic part of the radionuclide modelling.

9:8 Water in regolith affects **humans** by the process a) Water supply.

a) Water supply – The amount of water in regolith affects the amount of water that can be extracted by humans. This may affect the location of wells and number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in regolith does not place a constraint on human activities. In the radionuclide model, the supply of water is used for uptake by drinking as well as water use in e.g. irrigation (see /Avila et al. 2010/ and Chapter 10 in this report).

9:9 Water in regolith is a diagonal element defined as the water component in regolith. There are no processes by which water in regolith influences water in the regolith that are relevant to include in the radionuclide modelling.

9:10 Water in regolith affects **surface water** by the process a) Convection.

a) Convection – There is transport of water between the regolith and surface water. This interaction is of importance for the transport of radionuclides from the repository to the surface and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as input from the hydrological model (see /Bosson et al. 2010/ and Chapter 10 in this report).

9:11 Water in regolith affects **water composition** by the processes a) Convection, b) Physical properties change, and c) Relocation.

a) Convection – Water in the regolith affects the water composition by mixing of deep and near-surface groundwater. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of convection between different layers), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). In addition, convection between different regolith layers is modelled in the hydrological models that generate parameter values for the radionuclide model (see /Bosson et al. 2010/).

b) Physical properties change – Change in water pressure in the regolith induces density changes in the water in the regolith, in turn, affecting the water composition. This interaction is assumed to have a minor influence for the relatively thin deposits in the ecosystems at Forsmark. Therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Relocation – The magnitude and direction of the water flow influences the extent of erosion (relocation) of the regolith and thereby the amount and type of particulates in the water. In comparison with other processes affecting the water composition this interaction is probably of minor significance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, water composition, which is measured *in situ* (thereby including the effect of this interaction), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

9:12 Water in regolith affects **gas and local atmosphere** by the process a) Phase transitions.

a) Phase transitions – Water in the regolith may become gaseous and thus a part of gas and local atmosphere. This interaction is a transport pathway for water but it is assumed that radionuclides are not directly connected to this pathway and this interaction does not need to be considered in the radionuclide modelling.

9:13 Water in regolith affects **temperature** by the processes a) Convection, and b) Heat storage.

a) Convection – The water content as well as the magnitude, direction and distribution of water flow in the regolith affect heat transport and thereby the temperature in the different parts of the biosphere system. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature and this interaction does not need to be considered in the radionuclide modelling. Nevertheless it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Heat storage – The water content as well as the magnitude, direction and distribution of water flow in the regolith affect heat storage capacity and thus the temperature in the regolith. However, the temperature in ecosystems is mainly dependent on heat storage in surface waters and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

9:14 Water in regolith affects **radionuclides** by the process a) Convection.

a) Convection – Water in regolith affects radionuclide concentrations by mixing and if different regolith layers are assumed to be homogenously mixed, advective fluxes between layers thereby give rise to transport of radionuclides. This interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as fluxes of radionuclides between different compartments of the biosphere system /Avila et al. 2010/.

9:15 Water in regolith affects **external conditions** by the process a) Export.

a) Export – Water in the regolith is exported to external water volumes. Since amounts of exported water will most probably be small compared to the volumetric flows in external objects (downstream lakes or marine basins), the effect on the receiving ecosystem should be small and this interaction does not need to be considered in the radionuclide modelling. Since losses by export may be important for the exporting ecosystem it is included in the radionuclide model by the use of values from the hydrological models (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

10:1 Surface water affects **geosphere** by the processes a) Change in pressure, b) Convection, c) Loading, and d) Weathering.

a) Change of pressure – The pressure of the water column may affect the pore water pressure in the rock. However, surface-water-level fluctuations are modest in Forsmark and there should be small changes in pressure over time due to surface water pressure. Therefore this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The surface-water hydrology influences the recharge and discharge of groundwater and thereby the hydrology in the geosphere. This interaction may be important for the upward transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, discharge and recharge are included in the hydrological modelling that is used to calculate parameters values applied to the radionuclide model /Bosson et al. 2010/.

c) Loading – Changes in thickness of an ice sheet during periods of glaciation and deglaciation will affect the mechanical stress in the rock. It is dependent on gravitation, density and the height of the overlying matter. The effect on the geosphere is not a part of the biosphere modelling and thus does not need to be considered in the radionuclide modelling.

d) Weathering – Surface water flow influences the weathering of rock by e.g. ice scoring in near shore areas. Weathering will not add radionuclides, unless the bedrock consists of radioactive minerals (which is not the case in Forsmark). Therefore this interaction will have a minor effect on the transport and accumulation of radionuclides, and this interaction does not need to be considered in the radionuclide modelling.

10:2 Surface water affects **regolith** by the processes a) Relocation, and b) Resuspension.

a) Relocation – Surface water may affect the regolith by erosion i.e. relocating regolith from one point to another. This interaction is important for the distribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in calculation of regolith depths and distribution in aquatic ecosystems /Brydsten and Strömgren 2010/ and as the various bottom substrates used in the calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Resuspension – The magnitude and direction of water determines the amount of the regolith that takes part of resuspension. This interaction is important for the distribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Accordingly, resuspension is included as a parameter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

10:3 Surface water affects **primary producers** by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Relocation – Relocation of organisms from one part of a aquatic basin to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:4 Surface water affects **decomposers** by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Relocation – Relocation of organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water or dominated by periods with water, and therefore uptake of water never limits the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:5 Surface water affects **filter feeders** in the aquatic ecosystems by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Relocation – Relocation of organisms from one part of an object to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Therefore the water supply is not considered as an important interaction for aquatic organisms and does not need to be considered in the radionuclide modelling.

10:6 Surface water affects **herbivores** by the by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Relocation – Relocation of organisms from one part of a water body to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either. Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:7 Surface water affects **carnivores** by the by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Water supply – In aquatic ecosystems and mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:8 Surface water affects **humans** by the by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Human settlement is mainly determined by the area and type of the ecosystems, since this determines the amount of available food. The size and location of surface waters thereby affects the settlement of humans in the area and this interaction needs to be considered in the radionuclide modelling. The area of objects is included in the radionuclide model and thereby this interaction is considered /Lundborg 2010/.

b) Water supply – Water is extracted for drinking and other purposes by humans. Water supply may limit human utilisation of water bodies and this interaction needs to be considered in the radionuclide modelling. As a cautious assumption, surface water is assumed not to be a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. The drinking of water and water use for e.g. irrigation is included in the radionuclide model to assess dose to humans (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

10:9 Surface water affects **water in regolith** by the process a) Convection.

a) Convection – There is a transport of water between surface water and regolith. In lake ecosystems, this interaction might be of importance for transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model by input from the hydrological model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

10:10 Surface water is a diagonal element defined as water collecting on the ground or in streams, rivers, lakes wetlands, or oceans, as opposed to groundwater or atmospheric water. There are no processes by which surface water directly affects surface water that are relevant to include in the radionuclide modelling.

10:11 Surface water affects **water composition** by the processes a) Convection, and b) Physical properties change.

a) Convection – The magnitude, direction and distribution of surface water flow affect the mixing of the water (or the opposite, stratification) and thereby also affect the water composition. This may be important for the distribution of radionuclides and thus needs to be considered in the radionuclide modelling. Water composition measured *in situ* at the surface and bottom of the water column indicates that in Forsmark the water column may be treated as a homogenously mixed water body, both in limnic and marine ecosystems. Stratification occurs during winter and/or summer but over a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term characteristics. In addition, the water chemistry used in calculations of parameter values applied to the radionuclide model is sampled from the whole water column, thereby taking into account any differences in water chemistry due to stratification (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Physical properties change – At very large depths generally only occurring in the sea, water is compressed and this may cause density effects. During an interglacial the aquatic ecosystems in Forsmark will as a maximum reach relatively shallow depths (<200 m), hence, this interaction will have insignificant effects and does not need to be considered in the radionuclide modelling.

10:12 Surface water affects **gas and local atmosphere** by the processes a) Phase transitions, and b) Relocation.

a) Phase transitions – Surface water may affect the atmosphere by transformation of water in surface waters to the gas phase by evaporation and sublimation. Evaporation is an important process for water balance, but the effects on local atmosphere are assumed to be negligible compared with air exchange between the local and global atmosphere. Hence, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, since evaporation is important for the water balance it is included in the radionuclide model parameterisation in the calculation of runoff /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Relocation – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both relocation and resuspension occur (see below). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in the radionuclide modelling.

c) Resuspension – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both resuspension and relocation occur (see above). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in the radionuclide modelling.

10:13 Surface water affects **temperature** by the processes a) Change of pressure, b) Convection, c) Heat storage, and d) Light related processes.

a) Change of pressure – At large depths normally only occurring in the sea, adiabatic temperature increase may occur. Water with high density sink by gravitational forces and water becomes compressed when pressure increases. The compression leads to release of heat and thus a temperature increase, so called adiabatic temperature increase. However, very large water depths are needed to significantly increase the temperature, and the adiabatic temperature increase in sea water varies between 0.02 and 0.2°C per 1,000 m. Thus, this interaction does not need to be considered in the radionuclide modelling, since depths in aquatic ecosystems in Forsmark during an interglacial do not exceed 200 m. Nevertheless, since temperature statistics used for calculating parameter values in the radionuclide model are based on *in situ* measurements at prevailing conditions, any effect of adiabatic compression is indirectly included (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Convection – Surface water affects the temperature by heat transport in the water. However, this interaction is small compared to other factors influencing the temperature (e.g. heat storage of surface water) and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Heat storage – The amount and thermal properties of surface waters affect the heat storage capacity and thus the temperature in the surface waters. The heat storage in surface water is important for the circulation of water and heat storage influences the formation of taliks during permafrost conditions. Thus this interaction needs to be considered in the radionuclide modelling. Heat storage is considered in the radionuclide model since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report). Moreover, the occurrences of taliks are included in a separate climate case (periglacial climate).

d) Light related processes – Wave-formation on the surface waters, and surface water area together with its volume and depth affect light reflection and the amount of radiation that is adsorbed and thereby the temperature in the surface waters. This is an important interaction which needs to be considered in the radionuclide modelling. The interaction is considered to be indirectly included in the radionuclide model since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

10:14 Surface water affects **radionuclides** by the process a) Convection.

a) Convection – Distribution, magnitude and direction of surface water flow affect the concentration of radionuclides in aquatic ecosystems. Thus, this interaction needs to be considered in the radionuclide modelling. Water flow and retention time is included in the hydrological parameter values applied in the radionuclide model (see /Bosson 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Stratification, i.e. the opposite of mixing may lead to an uneven distribution of radionuclides in the water column. However, during one year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term distribution in the water column.

10:15 Surface water affects **external conditions** by the processes a) Export, and b) Import.

a) Export – Export of surface water includes the water flow from an upstream to a downstream water body and water flooding from streams and lakes into terrestrial areas during periods with heavy water flows. Although, from an ecological viewpoint, flooding may have large effect, the effect of transported radionuclides from an upstream to downstream object should be minor due to dilution in the receiving object. Thus, this interaction does not need to be considered in the radionuclide modelling. However, since important for the exporting ecosystem, the export is included as export of matter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Import – The effect on the area outside the model area should be minor due to the much larger volume of external basins compared with the model area in marine areas. In the limnic and terrestrial systems the import is even smaller as the only import occurs from occasional salt water intrusion from marine basins inside the model area, i.e. the effect on the external basin by this import to the model area should be insignificant (on a landscape level this is not external conditions, but on an object level it is). Therefore, this interaction does not need to be considered in the radionuclide modelling.

11:1 Water composition affects **the geosphere** by the processes a) Convection, and b) Weathering.

a) Convection – The composition of water in the regolith and surface waters infiltrating the geosphere may influence the composition of the groundwater. The water composition infiltrating the rock affects the composition in the rock. This is the reason why the salinity changes in the rock. This is important for the transport of radionuclides in the geosphere and is treated in geosphere modelling, see the **FEP report**.

b) Weathering – The water composition in the regolith influences the weathering of rock. The weathering of the rock is assumed to be low for the rock type in Forsmark. Thus, this interaction will have a minor effect on the transport and accumulation of radionuclides and does not need to be considered in the radionuclide modelling.

11:2 Water composition affects **the regolith** by the processes a) Deposition, b) Phase transitions, and c) Weathering.

a) Deposition – Sedimentation of particles and elements affect the composition of the regolith and can be important for the transport of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. The concentration of particles in the water affects the sedimentation rate, i.e. the deposition. This is included in the radionuclide model as parameter values for particle concentration and sedimentation rate (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Phase transitions – The composition of the water in the regolith will affect chemical precipitation and dissolution reactions (and thereby phase transitions). This will influence the material composition, geometry and porosity of the regolith. The physical structure of the regolith is assumed to be a result of this interaction. Since the structure of the regolith is important for the transport and accumulation of radionuclides this interaction needs to be considered in the radionuclide modelling. This is indirectly included in the radionuclide model as parameter values representing regolith and chemical composition of water are based on *in situ* measurements, thereby including the effects of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Weathering – The composition of water in the regolith and surface water influences the weathering of the regolith. For example the particle content in the water affects the amount of weathering. However, other factors are assumed to have larger effect on the regolith and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, this interaction is indirectly included in the radionuclide model as parameter values representing regolith and chemical composition of water are based on *in situ* measurements, thereby including the effects of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

11:3 Water composition affects **primary producers** by the processes a) Element supply, b) Food supply, c) Light related processes, and d) Stimulation/inhibition.

a) Element supply – Primary producers use carbon dioxide in surface water. The amounts of carbon dioxide in water is large and is assumed to never limit primary production and therefore this interaction does not need to be considereded in the radionuclide modelling.

b) Food supply – Primary producers in ecosystems take up nutrients in surface water. Nutrients may limit the production of primary producers and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model by assuming present-day conditions regarding water composition and using biomass and production estimates from measurements *in situ* (thereby including the effect of this interaction) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Light related processes – Water composition influences the light attenuation which in turn influences primary production in ecosystems. This determines the distribution of primary producers and needs to be considered in the radionuclide modelling. Light attenuation is considered in the parameterisation of the radionuclide model in the calculations of net primary production and depth of the photic zone (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the production of primary producers and thereby amount of primary producers. Biomass and production is important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

11:4 Water composition affects **decomposers** by the processes a) Element supply, b) Food supply, c) Habitat supply, and d) Stimulation/inhibition.

a) Element supply – Aquatic decomposers use oxygen in surface water. Oxygen concentrations may be low in winter in shallow lakes and thereby limit the occurrence of macro-decomposers. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model. Bacteria may use elements other than oxygen for respiration (e.g. sulphur) during anoxic conditions and therefore bacteria may be present in all environments, oxic or anoxic and no limitation on distribution has been set for them in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Food supply – Some bacteria feed on particulate matter in water and dissolved organic carbon. Carbon may be limiting for the production of bacteria and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model by assuming present-day conditions regarding water composition and using biomass and production estimates from measurements *in situ* (thereby including the effect of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Habitat supply – Some bacteria live attached to particulate matter in water or regolith and some live freely in the water column and bacteria are not dependent on water composition as habitat. Instead the water composition is more important as a food source (see above). Therefore, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomasses of bacteria and concentrations of particulate matter are included in the radionuclide model as it is important for other transport routes of radionuclides (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of decomposers. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

11:5 Water composition affects **filter feeders** in aquatic ecosystems by the processes a) Element supply, b) Food supply, and c) Stimulation/inhibition.

a) Element supply – Filter feeders use elements e.g. oxygen in surface water. Although oxygen concentrations can be low in winter especially in lakes, the supply is considered to be enough to support a permanent population of filter feeders and this interaction does not need to be considered in the radionuclide modelling.

b) Food supply – Filter feeders feed on among others, resuspended regolith and resuspended material from the catchments. This may be an important transport pathway for radionuclides and needs to be considered in the radionuclide modelling. Accordingly, the amount of resuspended material as well as net productivity of biota (including filter feeders) is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of filter feeders. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

11:6 Water composition affects **herbivores** by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – Aquatic and terrestrial herbivores may use essential elements in surface water, e.g. aquatic herbivores utilise dissolved oxygen in the water. In shallow lakes oxygen concentrations may be low in winter and thereby limit the occurrence of some herbivores. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model. Likewise, fish are not assumed to be present in lakes with shallower depths than 1 m (see Chapter 10 and 11). Other limnic herbivores are assumed to be in resting stages (some species of zooplankton) or being able to find patches with oxygen (fish). In the sea, limiting oxygen conditions for herbivores may occur during high nutritional load and thereby large consumption of oxygen during decomposition, although it is assumed that the herbivores will move to other marine areas, and hence it is not necessary to include them in the radionuclide modelling as it is for lakes. In terrestrial ecosystems the effects of element composition will be minor on the herbivores, assuming present conditions. However, the effect of the interaction is still included in the terrestrial part of the radionuclide model, by the use of *in situ* measurements of biomass (see Chapter 13 in /Löfgren 2010/).

b) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of herbivores. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

11:7 Water composition affects **carnivores** by the by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – – Aquatic carnivores use oxygen and terrestrial carnivores may use essential elements in surface water. In shallow lakes oxygen concentrations may be low in winter and thereby limit the occurrence of some carnivores. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Likewise, fish are not assumed to be present in lakes with shallower depths than 1 m. Other carnivores, such as species of zooplankton and benthic fauna are assumed to be in resting stages or being able to find patches with oxygen. In the sea, limiting oxygen conditions for carnivores may occur during high nutritional load and thereby large consumption of oxygen during decomposition, although it is assumed that the carnivores will move to other marine areas, and hence it is not necessary to include them in the radionuclide modelling as it is for lakes. In terrestrial ecosystems the effects of element composition will be minor on the carnivores, assuming present conditions.

b) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of carnivores. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

11:8 Water composition affects **humans** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – The water composition (e.g. salinity and toxicants) may affect humans and toxic elements and salinity determines human utilisation of water resources. Thus this interaction needs to be considered in the radionuclide modelling. Today, the surface water in Forsmark does not contain toxins that reduce human utilisation of the water resources. By assuming present conditions, no limitation of water resources due to toxins is assumed also for future freshwater systems in the radionuclide model. The surface water of lakes is assumed to be utilised also in periods with salt water intrusions. This is most probably an overestimate but is a conservative estimate in radionuclogical impact perspective.

11:9 Water composition affects **water in regolith** by the process a) Convection.

a) Convection – The composition of the water in the regolith will affect the density and viscosity of the water which in turn will affect the magnitude, distribution and direction of water flow in the regolith. The flow of water is important for the transport of radionuclides and thus this interaction needs to be considered in the radionuclide modelling. Accordingly it is taken into account in the hydrological model from which parameter values are taken for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

11:10 Water composition affects **surface water** by the process a) Convection.

a) Convection – Water composition affects viscosity and density which in turn affect the transport of water. Since water transport is important for the transport of radionuclides this interaction needs to be considered in the radionuclide modelling. In lakes the density differences are small and the water chemistry has little effect on water transport. Therefore, density has not been considered in lakes. In marine areas on the other hand, the density is important for water transport and is included in the oceanographic model as a forcing factor driving the water exchange /Karlsson et al. 2010/. For both lakes and marine areas, water transport is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/and Chapters 10 and 11 in this report).

11:11Water composition is a diagonal element defined as chemical composition of water which depends on dissolved elements and compounds, colloids, and suspended particles. There are no processes by which water composition directly affects water composition that are relevant to include in the radionuclide modelling.

11:12 Water composition affects **gas and local atmosphere** by the processes a) Phase transitions, and b) Relocation.

a) Phase transitions – There is an outflow of elements to the atmosphere by degassing and an inflow due to dissolution. This may be an important outflux of the radionuclide C-14 from aquatic systems and this may be important for the exporting system. However, the effect on the atmosphere is probably low, due to the large volume of the atmosphere in comparison to the volume of lakes and this interaction does not need to be considered in the radionuclide modelling. As it is important for the exporting aquatic ecosystem, this interaction is included as gas uptake and gas release to/from the atmosphere (see also interaction 12:11, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Relocation – There may be an outflow of elements to the atmosphere by spray and snowdrift. Both small and large particles may be released and both relocation and resuspension occur (see Resuspension below). The composition of water affects the composition of the sea spray and thus composition of the atmosphere. This does not affect the atmosphere to any significant degree due to the large volume of the atmosphere in comparison with the potential amounts of spray or snowdrift. Therefore this interaction does not need to be considered in the radionuclide modelling.

c) Resuspension – There may be an outflow of elements to the atmosphere by spray and snowdrift. Both small and large particles may be released and both relocation and resuspension occur (see Relocation above). The composition of water affects the composition of the sea spray and thus composition of the atmosphere. This does not affect the atmosphere to any significant degree due to the large volume of the atmosphere in comparison with the potential amounts of spray or snowdrift. Therefore this interaction does not need to be considered in the radionuclide modelling.

11:13 Water composition affects **temperature** by the processes a) Changes of pressure, b) Light related processes, and c) Reactions.

a) Change of pressure – Water with high density will by gravitational forces sink and the water will be compressed when the pressure increases. Changes in pressure may result in heating or cooling, so called adiabatic temperature changes. Adiabatic temperature changes vary with sea water composition between 0.02 and 0.2°C per 1,000 m. However, this interaction is not relevant in the relatively shallow systems of Forsmark (maximum 200 m in Forsmark marine basins during an interglacial) and the process is not included in the radionuclide modelling.

b) Light related processes – Water composition has a large effect on the absorption of light which in turn affects temperature. Temperature in surface water is important for stratification and water movement and thus this interaction needs to be considered in the radionuclide modelling. Light absorption is included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Reactions between substances in water can require heat or release heat and may thereby affect the temperature although the effect will be very small in comparison with temperature change induced by solar energy and therefore this process does not need to be considered in radionuclide modelling. Nevertheless, the effect of reactions on temperature is included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

11:14 Water composition affects **radionuclides** by the processes a) Phase transitions, and b) Sorption/desorption.

a) Phase transitions – The water composition in the different parts of the biosphere affects the dissolution/precipitation of radionuclides and thus the concentration of radionuclides in the water and as solid phases in the different parts of the biosphere. This interaction therefore needs to be considered in the radionuclide modelling. Dissolution and precipitation is not explicitly treated in the radionuclide model but is assumed to be included in the estimates of partitioning coefficients (Kd) (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Sorption/desorption – The water composition and amount of particles in the water in the different parts of the biosphere system affect the sorption and desorption of radionuclides and thus the concentration of radionuclides in the water and on the solid phases in the different parts of the biosphere system. This interaction needs to be considered in the radionuclide modelling. Accordingly it iincluded in the radionuclide model as concentration of particulate matter and different estimates of partitioning coefficients (Kd) (see /Nordén et al. 2010/ and Chapter 10 in this report).

11:15 Water composition affects **external conditions** by the process a) Export.

a) Export – Export of particulate and dissolved substances from one aquatic ecosystem to an aquatic object downstream most often have little effect on the downstream object due to dilution in that object. Therefore, this interaction does not need to be considered in the radionuclide modelling. However, the export may influence the exporting lake and therefore the export of particulate and dissolved matter is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

12:1 Gas and local atmosphere affect **geosphere** by the process a) Convection.

a) Convection – Air intrusion can take place via human activities and can also be a consequence of land-rise and climatic changes leading to unsaturated conditions. However, in aquatic systems and mires (were the regolith is saturated with water) air flow from the atmosphere reaching the repository (i.e. comparable to intrusion by organisms) is unlikely since the geosphere is always covered by regolith and/or surface water. Therefore this interaction does not need to be considered in the radionuclide modelling.

12:2 Gas and local atmosphere affect **the regolith** by the process a) Reactions.

a) Reactions – Elements in the gas phase in regolith may react with it. The amounts of gases in the regolith below aquatic ecosystems and mires (where the regolith is saturated with water) are most often small and other factors (e.g. elements dissolved in water) are assumed to have greater impacts on the regolith. Therefore, this interaction is of minor importance for transport and accumulation of radionuclides and does not need to be considered in the radionuclide modelling.

12:3 Gas and local atmosphere affect **primary producers** by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – In terrestrial ecosystems primary producers utilise carbon dioxide for photosynthesis and this uptake is depended on the estimated net primary production, which sets the limits for the potential uptake of e.g. C-14, which is important to consider in the radionuclide modelling. Accordingly, this is considered in the parameterisation of the radionuclide model, In aquatic ecosystems most primary producers do not directly take up elements from the atmosphere (with exception for some emergent macrophytes) but most primary producers take up elements dissolved in water. Elements present in gas bubbles in water may be utilised as a supply for primary producers. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling of aquatic or terrestrial ecosystems.

b) Stimulation/inhibition – The atmosphere includes shading by clouds that may inhibit primary production. However, the atmospheric conditions (including clouds) are assumed to be reflected in present conditions and do not need to be considered in the radionuclide modelling. The effect of clouds is indirectly included in the radionuclide model in parameter values representing primary production that include insolation measured at the sites (i.e. taking clouds into account) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

12:4 Gas and local atmosphere affect **decomposers** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for decomposers in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling.

12:5 Gas and local atmosphere affect **filter feeders** in aquatic ecosystems by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for filter feeders. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling.

12:6 Gas and local atmosphere affect **herbivores** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for herbivores in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition). Also in terrestrial ecosystems, this effect is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

12:7 Gas and local atmosphere affect **carnivores** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for carnivores in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition). Also in terrestrial ecosystems, this effect is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

12:8 Gas and local atmosphere affect **humans** by the processes a) Acceleration, b) Deposition c) Element supply, and d) Stimulation/inhibition.

a) Acceleration – The magnitude of the wind velocities and the distribution of the wind field affect humans. However, it is unlikely that human utilisation of the aquatic ecosystems in Forsmark will be influenced by wind and this interaction does not need to be considered in the radionuclide modelling.

b) Deposition – Amounts of precipitation (rain and snow) influence the behaviour of humans. However, it is unlikely that amounts of precipitation in Forsmark will affect utilisation of the ecosystems. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Element supply – Elements in the atmosphere are utilised by humans, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for human activities and thus this interaction does not need to be considered in the radionuclide modelling. Inhalation of radionuclides, on the other hand is an important interaction but this is treated in interaction 14:8 as exposure.

d) Stimulation/inhibition – The atmosphere may inhibit humans by toxins, smog, and humidity. Assuming prevailing conditions, the atmosphere will have only a limited effect on human utilisation of the ecosystem. Therefore, this interaction does not need to be considered in the radionuclide modelling.

12:9 Gas and local atmosphere affect **water in regolith** by the processes a) Convection, and b) Phase transitions.

a) Convection – The atmospheric pressure and the pressure of existing gas will affect the location of the groundwater table and thus also the water content and the water movement in the regolith. This interaction can lead to upward transport in the soil of e.g. radionuclide and needs to be considered in the radionuclide modelling. Accordingly, it is considered in the hydrological modelling that produces parameter values for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Phase transitions – Water in the gas phase of the regolith may condense and become liquid thereby a part of water in regolith. This interaction is of minor importance compared to other processes affecting the amount of water in the regolith and does not need to be considered in the radionuclide modelling. Nevertheless it is indirectly included in the hydrological modelling that is used to calculate parameters applied to the radionuclide model since the hydrological model is based on measurements of groundwater table *in situ*, thereby including the effect of this interaction (see /Bosson et al. 2010/ and Chapter 10 in this report).

12:10 Gas and local atmosphere affect **surface water** by the processes a) Convection, b) Deposition, c) Phase transitions, and d) Wind stress.

a) Convection – The atmospheric pressure will affect surface water levels and thus also the distribution of surface waters amounts and the water movement and water turnover. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Residence times and advective flows, sea level and lake levels are included in the modelling of succession from sea to lake to land in the Digital Elevation Model (DEM) and as water volumes applied to the radionuclide model (see /Brydsten and Strömgren 2010/ and Chapter 10 in this report).

b) Deposition – Deposition includes sedimentation, rainfall, and snowfall. The magnitude of the precipitation will influence the amounts of surface waters and the amounts of ice/snow on surfaces. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model by the use of annual averages of precipitation (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Phase transitions – The atmosphere may affect the surface water by the transformation of water in surface waters to the gas phase by evaporation and sublimation. Phase transitions are important for amounts of water, water movement and water turnover. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Accordingly, evaporation is included in the water balances in the hydrological calculations of runoff that are used for parameterisation of the radionuclide model (see /Bosson et al. 2010/ and Chapter 10 in this report).

d) Wind stress – The strength and direction of the wind will affect the movement of surface waters, e.g. wave formation and mixing of the water column. This is important for the distribution and transport of radionuclides and needs to be considered in the radionuclide modelling. Stratification occurs during winter and/or summer but during a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term statistics. In addition, parameter values based on biota and chemistry from surface waters applied to the radionuclide model are sampled from the whole water column, thereby taking into account any differences in water chemistry or distribution of biota due to stratification (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

12:11 Gas and local atmosphere affect **water composition** by the processes a) Deposition, b) Phase transitions, and c) Wind stress.

a) Deposition – Precipitation will influence the water composition. However, even though precipitation may vary between years, the effect on water composition is assumed to be minor and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the amount of precipitation is included in the hydrological model and water composition, which is measured *in situ* (thereby including the effect of deposition), is included in the calculation of parameter values for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Phase transitions – The atmosphere may affect the water composition by transformation of water in surface waters due to material transfers to and from the gas phase by dissolution, degassing, evaporation and sublimation. This interaction may be an important pathway for outflux of the radionuclide C-14 from eco systems and needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the radionuclide model in parameters describing carbon outflux and carbon uptake from the atmosphere (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Wind stress – Minor amounts of surface water may be blown away (i.e. sea spray) by the wind and cause concentration differences in the water composition. The magnitude of this process is assumed to be very small and this interaction does not need to be considered in the radionuclide modelling. However, it is indirectly included in the radionuclide model by the use of *in situ* measurements of water composition (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

12:12 Gas and local atmosphere is a diagonal element defined as the layer of gases above the ecosystem that participates in gas exchange with the water. The gas composition and the gas flow are included in this element. This element also includes atmospheric flow and wind. There are no processes by which gas and local atmosphere directly influence gas and local atmosphere that are relevant to include in the radionuclide modelling.

12:13 Gas and local atmosphere affect **temperature** by the processes a) Change of pressure, b) Convection, c) Heat storage, d) Phase transitions, e) Light related processes, and f) Reactions.

a) Change of pressure – Changes in air pressure may result in heating or cooling, so called adiabatic temperature changes. This is assumed to have a minor effect on temperature in comparison with solar radiation and hence the process does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Convection – The heat transport within the atmosphere is rapid but in ecosystems the temperature changes are dampened due to the heat storage of water and regolith and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Heat storage – The heat storage in atmosphere is limited compared to the storage in soil and water and thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

d) Phase transitions – Phase transitions can be exo- or endothermic and thereby affect the temperature. Other factors (e.g. heat storage of surface water and regolith) will have greater impact on temperature in the ecosystems. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

e) Light related processes – The composition of the atmosphere affects the absorption/scattering/reflection of radiation and thus the temperature. Even though there are minor changes in air composition over the year, this is not assumed to result in large changes in temperature and this interaction does not need to be considered in the radionuclide modelling. However, the release of greenhouse gases may over time result in warmer climate and this is accounted for in a separate climate case (global warming case) in the radionuclide modelling (further described in the **Climate report** and **Biosphere synthesis report**).

f) Reactions – Reactions may be exo- and endothermic thereby affecting the temperature. Other factors (e.g. heat storage of surface water and solar insolation) will have greater impact on temperature. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

12:14 Gas and local atmosphere affect **radionuclides** by the processes a) Convection, b) Sorption/desorption.

a) Convection – The distribution, magnitude and direction of gas (including air) flow in the different compartments of the biosphere affects the concentration of radionuclides in gas phase in the compartments. This may be important for certain radionuclides, e.g. I-129 and C-14 and for these this interaction needs to be considered in the radionuclide modelling. Accordingly, the transport of gaseous radionuclides is considered in the radionuclide model (e.g. the transport of C-14 between water and air atmosphere, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Sorption/desorption – The atmosphere could potentially influence the distribution of radionuclides by sorption of radionuclides in the gas phase on particles, pollen and water drops in the atmosphere. Since the radionuclides enters the ecosystems from below in SR-Site, this interaction is considered of small importance for the distribution of radionuclides and does not need to be considered in the radionuclide modelling.

12:15 Gas and local atmosphere affect **external conditions** by the process a) Export.

a) Export – The export of gas may be important for the transport of radionuclides from a local ecosystem but is assumed to be of little importance for the external conditions due to dilution in a large volume of the external atmosphere. Thus this interaction does not need to be considered in the radionuclide modelling. However, due to the importance for local ecosystems (objects), this interaction is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

13:1 Temperature affects **geosphere** by the processes a) Convection, and b) Weathering.

a) Convection – The heat transport from the biosphere to the geosphere will affect the temperature in the geosphere. The comparatively small area of the ecosystems in the model area will have an insignificant effect on the temperature in the geosphere compared to the effect of the external biosphere. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Weathering – Hypothetically temperature changes may influence the speed of weathering. At temperate conditions, temperature change is assumed to be of minor importance compared to other processes that influence the weathering. At periglacial and glacial conditions weathering may be altered but the other factors are more important in determining dose to humansand this interaction does not need to be considered in the radionuclide modelling.

13:2 Temperature affects **regolith** by the processes a) Physical properties change, and b) Weathering.

a) Physical properties change – The temperature can affect the volume of the components of the regolith by e.g. freezing. However, the temperature range in regolith in the aquatic systems is relatively narrow due to the isolating effect of the water body and freezing of regolith is not assumed to occur in an interglacial period. Under glacial conditions, regolith in a lake may freeze but at glacial conditions humans are only assumed to utilize marine ecosystems at glacial conditions and thus this interaction does not need to be considered in aquatic part of the radionuclide model. In terrestrial ecosystems, the effect may be larger which is further discussed in /Löfgren 2010/.

b) Weathering – Freezing of regolith may cause weathering of the regolith. However, the temperature range in regolith in the aquatic systems is relatively narrow due to the isolating effect of the water body and freezing of regolith is not assumed to occur in an interglacial period. Thus this interaction does not need to be considered in aquatic part of the radionuclide model. The long term weathering of regolith in terrestrial ecosystems is affected by a number of factors and the process as such has been addressed in the radionuclide modelling for Forsmark by including data from the site Laxemar-Simpevarp in the radionuclide model, that represents a stage where most of the calcite has been leached /Löfgren 2010/.

13:3 Temperature affects **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Although temperature affect the productivity of primary producers light is often considered more important in aquatic ecosystems and high productivity may occur at both high and low temperatures. Thus, this interaction does not need to be considered in the aquatic part of the radionuclide modelling. For terrestrial ecosystems, temperature has a larger impact on primary production and this is considered through evaluation of production in the terrestrial ecosystems under periglacial conditions in the radionuclide model (see Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in this report).

13:4 Temperature affects **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of decomposers (e.g. bacteria and crayfish) that may be important for distribution of radionuclides in the biotic community and exposure to man (production of herbivores may be utilised as food, see interactions 6:8 and 8:6). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the aquatic ecosystems which is calculated based on, among other factors, temperature. Similarly, in the terrestrial part of the radionuclide model, this effect is included in the parameter estimate of decomposition in wetlands (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

13:5 Temperature affects **filter feeders** in aquatic ecosystems by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of herbivores that may be important for distribution of radionuclides in the biotic community. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in this report).

13:6 Temperature affects **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of herbivores that may be important for distribution of radionuclides in the biotic community and exposure of man (production of herbivores may be utilised as food, see interactions 6:8 and 8:6). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

13:7 Temperature affects **carnivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of carnivores that may be important for distribution of radionuclides in the biotic community and exposure of man (production of carnivores may be utilised as food, see interactions 7:8 and 8:7). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

13:8 Temperature affects **humans** by the processes a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature influences where humans settle. In the radionuclide modelling humans are always assumed to utilise the environment in such a way that they get the highest reasonable exposure. Therefore this interaction does not need to be considered in the radionuclide modelling, e.g. temperature effects will not prevent humans from utilizing all parts of the ecosystem.

13:9 Temperature affects **water in regolith** by the process a) Phase transitions.

a) Phase transitions – The temperature affects the state of the water in the regolith (frozen or liquid). In aquatic systems, freezing of regolith is not assumed to occur in an interglacial period due to the isolating effect of the water body (with exception to regolith in water beneath very shallow ponds). Therefore this interaction does not need to be considered in the radionuclide model for aquatic ecosystems. In terrestrial , ground frost is a common feature during the winter period and this interaction needs to be considered in the terrestrial part of the radionuclide model. Effects of ground frost are included in calculations of hydrological flows and biotic parameters applied to the radionuclide model /Löfgren 2010/.

13:10 Temperature affects **surface waters** by the processes a) Convection, and b) Phase transitions.

a) Convection – Changes in surface water temperature influence water densities and thus surface water movements and water renewal times. Temperature variations are important for mixing of water columns and thus needs to be considered in the radionuclide modelling. Accordingly, the effect of temperature on surface water is considered by including site specific measurements of water transport, water renewal times and water temperature in calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

b) Phase transitions – Temperature affects the state of water (solid, liquid or gaseous). Freezing and evaporation of surface waters as a result of changes in temperature will affect water movement and amounts of water and ice. Ice coverage is important for transport of radionuclides, e.g. it prevents transport of radionuclides between surface water and atmosphere. Thus, phase transitions needs to be considered in the radionuclide modelling. Accordingly, they are included in the radionuclide model in calculations of parameter values dependent on ice coverage, e.g. productivity, degassing and gas uptake (in which period with ice coverage is included in the calculations) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

13:11 Temperature affects **water composition** by the processes a) Convection, b) Physical properties change, and c) Reactions.

a) Convection – The temperature influences diffusion. However, other factors affecting water chemistry (such as mixing and water turnover) are more important, and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, water composition, which is measured *in situ* (thereby including the effect of this interaction), is included in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Physical properties change – Temperature affects density and viscosity, which in turn may affect the water composition and stratification. The stratification/mixing are important for the distribution of radionuclides in aquatic ecosystems and thus, this interaction needs to be considered in the radionuclide modelling. Water composition measured *in situ* at the surface and bottom of the water column indicates that in Forsmark the water column may be treated as a homogenously mixed water body. Stratification occurs during winter and/or summer but over a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term characteristics. In addition, the water chemistry used in calculations of parameter values applied to the radionuclide model, are sampled from the whole water column, thereby taking into account any differences in water chemistry due to stratification. This variation in water composition caused by temperature is taken into account in the annual averages of water compositions used in the radionuclide modelling (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

c) Reactions – Temperature may have large effects the kinetics (rate of reactions) and chemical equilibrium. However if assuming prevailing conditions, water composition can be assumed to be reflected in site data and this interaction does not need to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of temperature variations over the year) are used in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in this report).

13:12 Temperature affects **gas and local atmosphere** by the processes a) Change of pressure, b) Convection, and c) Phase transitions.

a) Change of pressure – Changes in temperature contributes to pressure changes that affect air movements. Temperature is an important mechanism influencing the turnover of the atmosphere. However, external influences are assumed to have a greater effect on temperature than local occurrences and therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The temperature influences diffusion but also, more importantly the stratification of the atmosphere and thereby the composition of the atmosphere and fluxes of elements. However, external influences are assumed to be of greater importance than the local effect and therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Phase transitions – Temperature effects on gas are an important driving mechanism for phase transitions in the atmosphere. However, external influences are assumed to be larger than the local effect and therefore, this interaction does not need to be considered in the radionuclide modelling.

13:13 Temperature is a diagonal element that is a unique physical property. Temperature determines the direction of heat flow between two objects placed in thermal contact. If no heat flow occurs, the two objects have the same temperature; otherwise heat flows from the hotter object to the colder object. There are no processes where temperature directly affects temperature that are relevant to include in the radionuclide modelling.

13:14 Temperature affects **radionuclides** by the processes a) Phase transitions, and b) Reactions.

a) Phase transitions – Temperature can affect the transitions between different states of radionuclides, e.g. for iodine. For most radionuclides this does not occur and this interaction does not need to be considered in the radionuclide modelling.

b) Reactions – Radionuclides may react with other elements and change states. The kinetics and chemical equilibria are influenced by temperature. The seasonal temperature variation encompasses the natural extremes for kinetics and chemical equilibria of radionuclides. Thus, it is assumed that the annual average includes this variation and this interaction does not need to be considered in the radionuclide modelling.

13:15 Temperature affects **external conditions** by the process a) Export.

a) Export – The export of heat is regarded as quantitatively unimportant for the external conditions (i.e. surrounding ecosystem and atmosphere) and therefore this interaction does not need to be considered in the radionuclide modelling.

14:1 Radionuclides affect **geosphere** by the process a) Radionuclide release.

a) Radionuclide release – Transport of radionuclides and toxicants in water and gas phase from the repository into the geosphere will affect the amount of these in the geosphere and this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, the important flux is the upward, from geosphere to biosphere (interaction 1:14), whereas the flux of radionuclides to the geosphere is included as a source term.

14:2 Radionuclides affect **regolith** by the processes a) Deposition, and b) Irradiation.

a) Deposition – Deposition of radionuclides on the surfaces of regolith may change the physical and chemical properties (mineralogy) of the surfaces. The amounts of radionuclides considered in this safety assessment are too small to have any significant effect on the properties of the regolith and this interaction does not need to be considered in the radionuclide modelling. However, the deposition is important for the accumulation of radionuclides during the infilling of lakes that drives the transformation of lakes into arable land. Therefore deposition is an important element of landscape evolution and is included in the radionuclide model as sediment growth (see interaction 11:2, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Irradiation – Irradiation of material in the regolith by radionuclides in the materials and in the water may affect the mineralogical structure of the material. However the amount of radionuclides in this safety assessment is too small to have any significant effect on the regolith and therefore this interaction does not need to be considered in the radionuclide modelling.

14:3 Radionuclides affect **primary producers** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:4 Radionuclides affect **decomposers** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:5 Radionuclides affect **filter feeders** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:6 Radionuclides affect **herbivores** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:7 Radionuclides affect **carnivores** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:8 Radionuclides affect **humans** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Evaluation of effects (in terms of dose) of radiation on humans is the main purpose of the safety assessment and this needs to be considered in the radionuclide modelling and is calculated in the radionuclide model (see /Avila et al. 2010/, and Chapter 10 in this report).

14:9 There are no processes by which **radionuclides** affect **water in regolith** that are relevant to include in the radionuclide modelling.

14:10 There are no processes by which **radionuclides** affect **surface water** that are relevant to include in the radionuclide modelling.

14:11 Radionuclides affect **water composition** by the processes a) Decay, b) Radiolysis, and c) Reactions.

a) Decay – Decay of radionuclides to stable or other radioactive isotopes may affect the composition of the water in the different components of the biosphere system. However, the amounts of radionuclides considered in this safety assessment are probably too small to alter the water composition due to decay and this interaction does not need to be considered in the radionuclide modelling. However, since the distribution of radionuclides is important from a radionuclide perspective, the daughter nuclides that are formed during decay and that are of relevance to dose assessment are included in the radionuclide model (see /Nordén et al. 2010/ and Chapter 10 in this report).

b) Radiolysis – During radiolysis, water dissociates under alpha radiation into hydrogen and oxygen. Thus, radiolysis can locally modify redox conditions, and thereby the speciation and solubility of compounds. However, the amounts of radionuclides considered in this safety assessment are too small to have any major effect on the water composition due to radiolysis and therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Reactions – All reactions involving radionuclides in dissolved and in particulate form may affect the composition of the water in the different elements of the biosphere system. However, the amounts of radionuclides considered in this safety assessment are too small to have any significant effect and therefore this interaction does not need to be considered in the radionuclide modelling.

14:12 Radionuclides affect **gas and local atmosphere** by the process a) Phase transitions.

a) Phase transitions – Decay of some radionuclides form elements in the gas phase, e.g. Ra decaying to Rn. Radon is an example of a gas that can penetrate buildings and in some cases accumulate in areas with deficient ventilation. Doses from Radon inhalation could have a potential impact on LDFs for Ra-226 but it in SR-Site it is considered that in conditions where doses from "repository originated" Radon could be important, these will be outset by much higher doses from "natural" Radon and ingestion of other radionuclides (further discussed in /Avila et al. 2010/). However, radionuclides dissolved in water, e.g. C-14 may transform to gaseous form and be released to the local atmosphere. This interaction is important for the distribution of radionuclides between water and atmosphere but is treated interaction 12:11.

14:13 Radionuclides affect **temperature** by the process a) Decay.

a) Decay – Decaying radionuclides will generate heat that may influence the temperature in the different elements of the biosphere system. Other factors will influence temperature much more than decay of radionuclides and therefore this process does not need to be considered in the radionuclide modelling.

14:14 Radionuclides is a diagonal element with a radionuclide defined as an atom with an unstable nucleus. Radionuclides affect radionuclides by the process a) Decay.

a) Decay – The radionuclide undergoes radioactive decay, where one radionuclide transforms into another. Decay and half life of radionuclides are important for the calculation of radionuclides in the biosphere and decay is important to consider in the radionuclide modelling. Accordingly it is included in the radionuclide model through the half-lives of the different radionuclides (see /Nordén et al. 2010/ and Chapter 10 in this report).

14:15 Radionuclides affect **external conditions** by the process a) Export.

a) Export – The export of radionuclides out of the system is partly included in the radionuclide modelling and has been studied in supporting simulations. The effect on the surrounding ecosystem is most probably small due to dilution (downstream in a catchment) unless the receiving system is very small or receives inputs from several upstream objects. This interaction needs to be considered to provide assurance that concentrations in receiving ecosystems are lower than in the exporting system in the radionuclide modelling. In the radionuclide model, this is considered by calculating the maximum release to all objects and by supporting calculations evaluating dose from downstream objects (see /Avila et al. 2010/, and Chapter 10 in this report).

15:1 External conditions affect **geosphere** by the process a) Change in rock surface location.

a) Change in rock surface location – At large-scale glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in the radionuclide modelling. Accordingly, it is included and it is the driving force for the biosphere changes in the radionuclide model (see /Brydsten and Strömgren 2010, Lindborg 2010/, and Chapter 10 in this report).Other examples of changes in rock surface location are earthquakes. These are treated as separate scenarios in the safety assessment /Munier et al. 2010/.

15:2 External conditions affect **the regolith** by the processes a) Change in rock surface location, b) Import, c) Saturation, d) Terrestrialisation.

a) Change in rock surface location – At large-scale glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in the radionuclide modelling. Accordingly, it is included and it is the driving force for the biosphere changes in the radionuclide model (see /Brydsten and Strömgren 2010, Lindborg 2010/, and Chapter 10 in this report).Other examples of changes in rock surface location are earthquakes. These are treated as separate scenarios in the safety assessment /Munier et al. 2010/.

b) Import – The redistribution of regolith due to glacial processes is included in the radionuclide model as initial conditions in the model. Otherwise, the import of matter in this time perspective (interglacial) is assumed to be negligible except for human actions and thus, this interaction does not need to be considered in the radionuclide modelling. Human effects on the regolith are treated in 8:2.

c) Saturation – External factors may hypothetically influence the ground water level in the regolith. This may be important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values applied to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

d) Terrestrialisation – Reed growth leads to a mire expanding into the lake or marine bay altering the geometry of the basin. The final stage is when the lake ecosystem is transformed to mire. The transformation from aquatic to terrestrial ecosystem affects radionuclide distribution in the ecosystem, human utilisation of the ecosystem and human exposure and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, the transformation from lake to land is included in the radionuclide model (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

15:3 External conditions affect **primary producers** by the processes a) Import, and b) Light related processes.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in

/Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Import of particles and nutrients which may influence primary producers is an indirect interaction via water composition 11:3.

b) Light related processes – The amount of solar irradiation influences photosynthesis and thereby the type and amount of primary producers. This interaction may be important for the accumulation and transport of radionuclides into the food web and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as biomasses and net community productivity for the aquatic ecosystems and, biomass and primary production for the mire (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

15:4 External conditions affect **decomposers** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Import of particles and nutrients which may influence decomposers is an indirect interaction via water composition 11:4.

15:5 External conditions affect **filter feeders** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Import of particles and nutrients which may influence filter feeders is an indirect interaction via water composition 11:5.

15:6 External conditions affect **herbivores** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Import of particles and nutrients which may influence herbivores is an indirect interaction via water composition 11:6

15:7 External conditions affect **carnivores** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). Import of particles and nutrients which may influence carnivores is an indirect interaction via water composition 11:7.

15:8 External conditions affect **humans** by the process a) Import.

a) Import – The import of uncontaminated material to the regional model area from external conditions may affect the transfer and accumulation of radionuclides and needs to be considered in the radionuclide modelling. In the radionuclide model, it is assumed that human behaviour is predefined to give the highest reasonably possible doses and the import of uncontaminated material is disregarded as a cautious assumption since it will dilute the contamination.

15:9 External conditions affect **water in regolith** by the processes a) Import and b) Saturation degree.

a) Import – Inflow of water to regolith from water in regolith outside the studied ecosystem is important for the water flow and thereby transport and accumulation of radionuclides. Thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Saturation degree – External factor may hypothetically influence the ground water level in the regolith. This may be important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

15:10 External conditions affect **surface water** by the processes a) Convection, b) Import, c) Sea level changes, and d) Terrestrialisation.

a) Convection – The discharge from their catchments influences the water movements in lakes, wetlands and streams and, surrounding marine basins influence the advection in marine basins in the model area and this interaction needs to be considered in the radionuclide modelling. This is one of the major forces determining the water retention time and is therefore included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Import – Precipitation is a major force driving the discharge into streams, lakes and marine basins. This is one of the major forces determining the water retention time and therefore needs to be considered in the radionuclide modelling. Precipitation and discharge is included in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/ (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

c) Sea level change – The alteration in height of the sea relative to the land will affect the amount and movement of surface waters. The distribution of surface water is important for transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Sea-level changes can be caused by e.g. earth-quakes (tsunamis), global warming, land-slides, earth tides, weather and climatic changes. This has been addressed in the historical and future description in terms of development of the area and formation of lakes. The interaction is included in the radionuclide model by the representation of shore-line displacement, and the development of the landscape over time where sea-level changes on an inter annual basis are included (see /Lindborg 2010, Brydsten and Strömgren 2010/ and Chapter 10 in this report).

d) Terrestrialisation – The transformation of lakes and sea bays into mires affects the amount of surface water in the biosphere object and the radionuclide distribution in the ecosystem, and thereby human utilisation of the ecosystem and human exposure and thus this interaction needs to be considered in the radionuclide modelling. This interaction is included in the radionuclide model by describing the succession of sea bays to mires for each biosphere object /Avila et al. 2010/ and Chapter 10 in this report).

15:11 External conditions affect **water composition** by the process a) Import.

a) Import – The composition of surrounding waters outside the ecosystem may by import affect the composition of the surface waters and water in the regolith. The surrounding ecosystems have a large effect on the chemical composition of surface water and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included by the use of site specific water composition data (*measured in situ* and thereby including the effect of external factors) in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

15:12 External conditions affect **gas and local atmosphere** by the processes a) Import, and b) Reactions.

a) Import – The local atmosphere is influenced by global wind conditions, large-scale weather systems and solar insolation. The interactions between external conditions and local atmosphere may have a large effect on the transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Wind velocity and direction are important parameters for water turnover and shore erosion in the sea and lakes. These parameters are measured at Forsmark and are included in the radionuclide model through the oceanographic and sediment models and in calculations of gas flow between water and atmosphere (see /Karlsson et al. 2010, Brydsten and Strömgren 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report). In addition, solar insolation is used as direct input in the calculations of primary production in the aquatic ecosystems, whereas it is indirectly included in the measure of primary production for terrestrial ecosystems.

b) Reactions – Photo-chemical reactions close to the surface will affect the gas composition e.g. ozone formation, smog formation and reactions in exhaust gases. This is assumed to be a non-site-specific effect and does not need to be considered in the radionuclide modelling.

15:13 External conditions affect **temperature** by the processes a) Import, and b) Light related processes.

a) Import – Import of heat by different materials entering the system will influence the temperature in the different elements of the system. This interaction is assumed to be a forcing function for the temperature in the system. This interaction needs to be considered in the radionuclide modelling. Accordingly, it is considered by the use of *in situ* temperature statistics used for calculations of parameter values applied to the radionuclide model and in direct estimates of processes affected by temperature, such as primary production that are also applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

b) Light related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. This interaction needs to be considered in the radionuclide modelling, especially for the aquatic ecosystems. It is considered by using *in situ* temperature statistics in the calculations of parameter values applied to the radionuclide model and in direct estimate of processes affected by temperature, such as primary production that are also applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in this report).

15:14 External conditions affect **radionuclides** by the process a) Import.

a) Import – It is assumed that the only source of radionuclides is internal and this interaction does not need to be considered in the radionuclide modelling. This has also been investigated in a separate supporting simulation presented in /Avila et al. 2010/, where it was shown that the direct source of the release caused the highest potential exposure.

15:15 External conditions are a diagonal element defined as all global conditions that affects local conditions that are considered in the biosphere matrix. The external conditions are situated at the boundary of the biosphere matrix and processes by which the external factors influence each other are not described here.

9.7 Concluding discussion

Not all processes between the components in the IM are expected to be quantitatively important for transport and accumulation of radionuclides from a deep repository in Forsmark. Thus, of the 51 identified processes, 34 were considered to be necessary to consider in the radionuclide modelling (Table 9-3, Figure 9-4). These processes may be necessary to consider in one specific process interaction but not in others. For a detailed description of where processes need to be considered the reader is referred to Section 9.6 above. A general description of these important processes for each group of processes is presented below.

There are many biological processes that are judged necessary to consider in the radionuclide model. This is because the most important exposure pathway for humans is via intake of water and food. Thus it is important to consider the distribution of biota and food-web interactions. In addition, biota may influence the distribution of radionuclides in abiotic pools by e.g. disturbing sediment or affecting water composition thereby influence long term accumulation and transport of radionuclides. However, other groups of processes are equally important to consider (further explored below).

Table 9-3. The 34 processes identified as necessary for the radionuclide modelling. * denotes biological processes that may involve humans in some interactions. The second column gives the number of the process in SKBs FEP database. Where the processes occur in the matrix are given in Table 9-2.

Biological processes	Numbering according to SKBs FEP database, see the FEP report. SR-Site FEP Bio:
Bioturbation	1
Consumption*	2
Death*	3
Decomposition	4
Excretion*	5
Food supply	6
Growth*	7
Habitat supply	8
Particle release/trapping	12
Primary production	13
Stimulation /inhibition*	14
Uptake*	15
Processes related to human behaviour	
Anthropogenic release	16
Species introduction/extermination	18
Water use	19
Chemical, mechanical and physical processes	
Element supply	22
Phase transitions	24
Physical properties change	25
Sorption/desorption	27
Wind stress	30
Transport processes	
Convection	32
Deposition	34
Import	36
Relocation	38
Resuspension	39
Radiological and thermal processes	
Decay	41
Exposure	42
Heat storage	43
Light-related processes	45
Radionuclide release	47
Landscape development processes	
Change in rock surface location	48
Sea-level changes	49
Terrestrialisation	50
Tresholding	51

Consumption, death, decomposition, excretion, food supply, habitat supply, stimulation/inhibition, and uptake, are biotic processes that may influence transport and accumulation of radionuclides in the food web. These processes are considered in the radionuclide model as biomass and net productivity of the ecosystems and production of litter in the terrestrial ecosystem. The processes bioturbation and particle release/trapping influence the abiotic compartment of the environment. Bioturbation influences the properties of the regolith and thereby influence the accumulation of radionuclides in the regolith. Particle release/trapping influence the amounts of particles in water and air which is important for the transport of radionuclides adhered to particles.

Human behavior may have large effect on the biosphere e.g. by introducing species or elements or by disturbing or removing material in large quantities. Water use, anthropogenic release, and species introduction/extermination are processes related to human behaviour that needs to be considered in the radionuclide modelling. Humans are not assumed to introduce species in aquaculture as this would decrease the dose from repository derived radionuclides, as aquaculture requires import of food for the cultured species (that would imply non-radioactive pellets from sites outside the model area). On the other hand, introduction of free-living edible species (e.g. crayfish) is included in the radionuclide model as these can increase the dose to humans.

Chemical, mechanical and physical processes can influence the state of elements and compounds, which can be important for the transport of radionuclides. For example, in some states elements are tightly bound to particles and in other states they may be easily dissolved and transported with water. Chemical, mechanical and physical processes necessary to consider in the radionuclide modelling are; phase transitions and sorption/desorption. The process phase transition is important for transport of C-14 from water to air. The process sorption/desorption determines whether radionuclides are bound to surfaces or dissolved in water and is crucial to consider when determining the transport and biological uptake of radionuclides.

Transport processes necessary to consider in the radionuclide modelling are; convection, deposition, import, resuspension, relocation and saturation. Convection includes e.g. surface water flow, discharge and recharge. Discharge and recharge are important for the transport upwards from a repository to surface systems and the pattern of discharge vs. recharge is important for the understanding of why and how transport of deep groundwater occurs. Surface water flow is also important for relocation of radionuclides since relativly fast transport through the landscape can take place in surface waters compared to groundwater and may affect the retention time in water bodies. In addition, flooding may cause a redistribution of radionuclides in the landscape. Radionuclides that have reached the surface system can, via flooding, go back to the groundwater system again. Import is the transport of radionuclides from surrounding ecosystems. This process may be of importance for the amounts of radionuclides in an ecosystem. The processes resuspension, relocation and deposition (e.g. sedimentation) are important for the transport from sediment to the water column and vice versa. Deposition is in addition to sedimentation also used to describe precipitation which is important for water balances and surface water flows.

Thermal and radiological processes necessary to consider in the radionuclide modelling are; decay, exposure, heat storage, and light related processes. Radionuclide-specific characteristics influence the transport of radionuclides and are of course important to consider in the radionuclide modelling. The amount of radionuclides released (radionuclide release), decay and exposure are crucial for the safety analysis. The process heat storage has a great influence on both biotic and abiotic components of aquatic ecosystems influencing e.g. distribution of biota, mixing of the water column, and ice coverage preventing exchange over the air-water interface. Light related processes include insolation, light absorption, light reflection and light scattering which in turn influence primary production.

Finally, the type of ecosystem greatly influences transport and accumulation of radionuclides. Landscape development processes that needs to be considered in the radionuclide modelling are change in rock surface location, sea level change, terrestrialisation, and tresholding. These processes determine the ecosystem at the site, e.g. terrestrial, limnic or marine.

Summarising the essence of this Chapter, it illustrates major process interactions and identifies processes that is necessary to consider in the radionuclide model. Moreover, it demonstrates that processes identified as important for transport and accumulation of radionuclides are considered in the radionuclide model.

10 The radionuclide model for derivation of landscape dose conversion factors (LDF)

This chapter describes the methods used to calculate exposure of humans inhabiting potential discharge areas, and to calculate activity concentrations in the environments that are used in the assessment of the environment. The following sections consider the source term, conceptual and mathematical model used to simulate transport and accumulation of radionuclides, and the methods used to calculate the activity concentrations in environmental media, and human exposure through relevant pathways. The model is also described in /Avila et al. 2010/ The reason for duplicating the description of the model is that this chapter relates to previous ecosystem chapters in the report to visualise how the thorough ecosystem understanding is incorporated into the model development whereas the focus in /Avila et al. 2010/ is to relate the model description to the LDF concept and LDF results.

The LDF values are calculated for biosphere objects, i.e. areas in the landscape identified according to discharge areas of radionuclides. The identification of release points in the biosphere and the configuration of the landscape over time are described in detail in /Lindborg 2010/. In short, potential discharge areas affected by the release of radionuclides in the biosphere are identified from the modelling of deep groundwater discharge and from topography and ecosystem type. Each such area is called a biosphere object and is the smallest unit in the modelling of radionuclide transport and accumulation in the landscape. At the start of the modelling, all objects are marine. Over time they follow a successional path from a marine stage to a limnic stage and finally to a terrestrial stage, due to shoreline displacement. The criteria for this successional development are described in /Lindborg 2010/. The radionuclide model quantifies the potential annual effective dose to humans from a unit release rate to each biosphere object in each time step.

The simulation tool used is Pandora which is described in /Ekström 2010/ and results from the radionuclide modelling of the biosphere are presented in the **Biosphere synthesis report** and /Avila et al. 2010/.

10.1 Source terms

In the corrosion and the shear load scenarios (described in the **SR-Site Main report**), radionuclides from the repository are unlikely to reach the biosphere within the first 100,000 years. However, after this period, contaminated groundwater from the repository may reach the biosphere resulting in a continuous release of radionuclides over more than 1,000,000 years. When a release from the repository reaches the biosphere more than 100,000 years after closure, the peak release rates for most dose dominating nuclides will remain at a near-constant level for periods of 10,000 years or more, see the **SR-Site main report**.

In both of the significant release scenarios, radionuclides that reach the biosphere are most likely to originate from one single canister. In the corrosion scenario, the failing canister has been deposited in a position with a high groundwater flow rate, which is associated with low geosphere transport resistance. In the shear load scenario, the shearing fracture is assumed to be among the larger in the rock fracture network, and therefore radionuclide retention in the geosphere is not considered in the safety analysis, see the **SR-Site Main report**. For releases which are associated with low or negligible geosphere transport retardation, the shoreline position is expected to have only limited effect on the geographical location of the discharge area, restricting discharge of contaminated groundwater to only one biosphere object /Lindborg 2010/.

For the calculation of LDFs, it has consequently been assumed that the release to the biosphere from the fuel matrix and corroded metals will be approximately constant on the time scale of the biosphere assessment (~20,000 years). It is cautiously assumed that the whole release of radionuclides will reach the discharge area where it will cause maximum exposure (of the most exposed group), i.e. the release will not be subdivided into several biosphere objects. Similarly, for the calculations of the modified LDF for pulse releases, it is cautiously assumed that the total instantaneously accessible fraction of radionuclides from fuel dissolution will reach the assessed discharge area.

The effect of releases to a biosphere object from an indirect release originating from a contaminated object located upstream has not been considered in these simulations. This simplification is appropriate for derivation of LDF values that represent the maximum doses across all biosphere objects (areas that can receive discharges) in the Forsmark area during the whole simulation period.

In addition to the radionuclides released into deeper parts of the regolith of a biosphere object, it has been assumed that the released radionuclides also reach a well drilled in bedrock, as soon as a biosphere object has emerged from the sea

10.2 The conceptual model

The Radionuclide Model for the biosphere is a classical compartment model, in which system components that are considered internally homogeneous, are represented with distinct compartments. A graphical representation of the conceptual model is shown in Figure 10-1, where each box corresponds to a model compartment. The definition of the compartments is presented in Table 10-1. A main general assumption in the model is that radionuclides entering one compartment become homogeneously mixed in that compartment; within the relevant time scale of the model, i.e. a few years, because annual doses are estimated and the model uses yearly averages for parameter values. When defining the compartments and their size, it has been considered that the model will be applied for simulations of the long-term transport and accumulation of radionuclides in the biosphere.

The arrows in Figure 10-1 represent radionuclide fluxes between compartments and fluxes into and out of the biosphere object. Radionuclide fluxes are linked to the main fluxes of matter in the biosphere, i.e. water fluxes (2), gas fluxes (3) and particle fluxes (4). Radionuclide transfers mediated by biota, like uptake by primary producers, have also been considered (6). The arrow reaching the lower regolith compartment (1) represents radionuclide releases from the geosphere into the biosphere object. These releases are directed to the deeper parts of the regolith, which normally consists of glacial till deposited on the bedrock.

Radionuclides released to the lower regolith compartment are distributed to the upper layers of the ecosystems by advection and diffusion. The representation of the waterborne transport of radionuclides between compartments is based on detailed hydrological modelling with MIKE-SHE /Bosson et al. 2010/. These studies have shown that the vertical hydrological fluxes in the deep regolith layer of sea basins and bays are small. Discharge areas above sea level may, on the other hand, have substantial vertical fluxes with preferential flow paths through areas of higher permeability within a biosphere object, as in wetlands surrounding lakes and streams.

The effect of radionuclide sorption on the advective and diffusive transport of radionuclides is taken into account by assuming equilibrium between the pore water and the solid phase of the compartments. The model also considers the transport of radionuclides absorbed to suspended particles driven by surface water fluxes, sedimentation and resuspension processes.

The radionuclide transport mediated by biota is described in the model through fluxes driven by net primary production, in both terrestrial and aquatic ecosystems. It is assumed that equilibrium is established between the concentration of radionuclides in the newly produced biomass and the corresponding environmental media (regolith for terrestrial primary producers and water for aquatic primary producers). This is an improvement over traditional plant uptake models as plant uptake is made a function of growth, while at the same time mass balances are maintained /Avila 2006/.

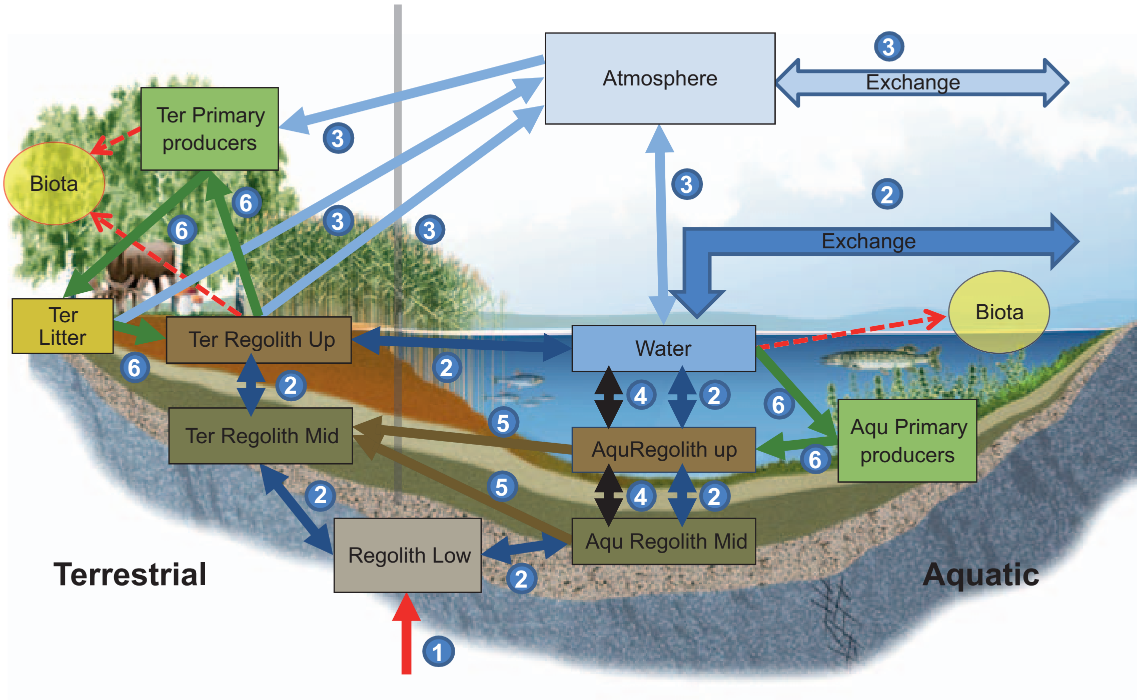

Figure 10-1. Conceptual illustration of the radionuclide model for a biosphere object. Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for biota (these are not included in the mass balance calculations). The model represents one biosphere object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. The source flux (1 Bq/y) is represented by a red arrow (1). The radionuclide transport is mediated by different major processes, indicated with dark blue arrows for water (2), light blue for gas (3), black for sedimentation/resuspension (4), dark brown for terrestrialisation (5), and green for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange". Descriptions of the compartments are given in Table 10-1.

Table 10-1. Compartments included in the radionuclide model for the biosphere.

Model name	Description
Regolith Low	The lower part of the regolith overlying the bedrock, primarily composed of till. It is common to the terrestrial and aquatic parts and its mainly origin is from the last glaciation.
Aqu Regolith Mid	The middle part of the regolith in the aquatic part of biosphere objects, usually consisting of glacial and postglacial clays, gyttja and finer sediments which originate mainly from the period after the retreat of the glacial ice sheet, or from later resuspended matter mixed with organic sediments.
Aqu Regolith Up	The part of the aquatic regolith with highest biological activity, comprising ca 5–10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidizing environment.
Ter Regolith Mid	The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. former sediments from the seabed / lake bottoms.
Ter Regolith Up	The upper part of the terrestrial regolith which has the highest biological activity, primarily composed of wetland peat.
Litter	Dead plant material overlying the regolith
Water	The surface water (stream, lake, or sea water).
Aqu Primary Producers	The biotic community in aquatic habitats, comprising both primary producers and consumers
Ter Primary Producers	Terrestrial primary producers.
Atmosphere	The lower part of the atmosphere where released radionuclides are fully mixed

10.2.1 Temporal development of biosphere objects

To be able to handle the continuous development of the landscape a novel approach was taken by a simultaneous simulation of both aquatic and terrestrial ecosystems in one model. Consequently, the radionuclide model has two parts when it is applied on a biosphere object, one aquatic (right side in Figure 10-1) and one terrestrial (left side). The temporal development of an object is handled by varying the sizes and properties of these two parts in accordance with the simulated development of the specific biosphere object, resulting from natural processes such as shoreline displacement, sedimentation, and lake infilling (see /Lindborg 2010/ and Chapters 3 and 8 in this report for details on site development and biosphere objects).

Throughout the succession from open sea to a wetland, the model representation of a biosphere object changes as follows. During the sea stage there are no terrestrial compartments, and all fluxes from the deep regolith layers are directed to aquatic sediments. During a transitional stage (~500 years), the sea bay is isolated and transforms into a lake, and a wetland starts to develop. The flux of radionuclides from the deep regolith will gradually shift from aquatic sediments to sediments under the wetland. During this phase, saltwater intrusions will occur with a continuously reducing intensity and frequency, and consequently the values of the aquatic model parameters are varied continuously from sea to lake values. After isolation is completed, the surrounding wetland will continue to expand into the lake. Thus, during the lake stage, aquatic sediments are gradually covered by a layer of peat. In the model this process is represented by a flux of radionuclides from the aquatic sediments to the terrestrial regolith (arrows 5 in Figure 10-1). The natural end state of the biosphere objects in the model is a wetland, though this may be transformed to agricultural land when the model is used to derive LDF values.

Aquatic environment

The aquatic part of the model is used to model radionuclides in the sea, lakes and streams. When a marine basin is isolated from the sea and the water becomes fresh, by definition a lake is formed. During the sea stage there are no terrestrial compartments. The formation of wetland (i.e. terrestrialisation, further discussed in Chapter 8 starts immediately upon lake isolation and thus terrestrial compartments are present throughout the lake stage. For the majority of biosphere objects, the end stage is a wetland that is drained by a small stream. Most fluxes are the same in the stream stage as in the lake stage although some fluxes (e.g. sediment accumulation) are set to zero to illustrate the specific conditions for streams (see Chapter 6 and 11).

Radionuclides released to the lower regolith compartment are distributed to the upper layers of the ecosystem by advection and diffusion. A flux of radionuclides enters the ecosystem going from the bedrock into the till (Regolith Low) and further through the sediments (Regolith_Mid) to the upper oxidizing sediment layer (Aqu_regoUp). Radionuclides are further transported to the surface water system. Representation of the waterborne transport of radionuclides between compartments is based on detailed hydrological modelling with MIKE-SHE /Bosson et al. 2010/. These studies have shown that the vertical hydrological fluxes in the deep regolith layer of sea basins and bays are small. Sorption of radionuclides will affect the advection and diffusion, i.e. by affecting the transport to the water above the regolith.

Radionuclides may also be attached to particles in the water. Radionuclides dissolved in water or attached to particles in the water may be exported from the biosphere objects by water outflux. This is considered for all stages of the aquatic objects. Sea objects interact with the entire Öregrundsgrepen via water exchange in both directions. Radionuclides from Öregrundsgrepen are then discharged to the rest of the Baltic Sea, which is treated as a sink in the model. Water fluxes from lakes are modelled as an addition to the next downstream object.

Water from lakes and streams during spring flood are sometimes transported to the surrounding wetland by flooding (further discussed in Chapter 3). Radionuclides may, therefore, in addition to downstream export, be transported from the lake and stream object to the surrounding wetland. A flux from the mire to the lake occurs through surface runoff. As discussed in carbon mass balances in Chapter 5, although difficult to measure, it is assumed that carbon entering lakes from the reed belts contribute to the total inflow of carbon to the lakes in Forsmark. This is strengthened by other studies were 30–40% of the reed production has been shown to contribute to lake metabolism

/Bertilson and Jones 2003/. Like carbon, other elements and radionuclides are assumed to be transported by water from wetlands to lakes in the radionuclide model.

Aquatic primary producers may incorporate radionuclides during primary production and this is a possible sink for radionuclides. It is assumed in the model that equilibrium is established between the concentration of radionuclides in the newly produced biomass and water. However, most aquatic primary producers in Forsmark have a short life cycle compared with terrestrial producers (e.g. trees). Phytoplankton and microphytobenthos have life cycles of days to weeks and most macroalgae have a life cycle of less than a year although there are a few perennial species (primary producers are further described in Chapter 3). Therefore, a large fraction of radionuclides incorporated during primary production would be released back to the water compartment upon degradation and respiration of the organic matter. Only a small fraction of the primarily incorporated radionuclides is assumed to be retained in organic matter. Therefore, the flux of radionuclides into aquatic primary producers in the model is estimated from net primary production (i.e. primary production minus respiration). Concentrations in water are also used to calculate concentrations in other biota (e.g. fish and crayfish) utilised by humans (biota utilised by humans are further discussed in Chapters 3, 4, and 11).

There is a flux of carbon dioxide across the air-water interface of lakes (further discussed in Chapter 5). In short, there is equilibrium of CO_2 between water and air which is influenced by primary production (taking up CO_2) and respiration (releasing CO_2) in the aquatic objects. C-14 is assumed to be exported from the lake via this gas flux whereas the gas flux for other radionuclides is assumed to be insignificant.

Aquatic sediments (Aqu_Regolith_Up and Aqu_Regolith_Mid) are gradually covered by a layer of organic material, i.e. peat, during the process of terrestrialisation. This process is represented in the model by a flux of radionuclides from the aquatic sediments to the terrestrial regolith (arrows 5 Figure 10-1). The time for terrestrialisation of the lake is dependent upon the lake depth and is driven by the accumulation of peat. This accumulation is based on the observed extension of vegetation in 25 lakes in the Forsmark area /Brydsten and Strömgren 2010/.

Terrestrial environment

The terrestrial part of the radionuclide model represents a forested wetland. A flux of radionuclides enters the ecosystem from bedrock into the glacial till (Regolith Low) and further through the suprapositioned sediments (glacial and post glacial clay), deposited during the aquatic stages, driven by advective and diffusive transport. Plant uptake of radionuclides is driven by net primary production and the subsequent litter production continuously transports radionuclides from the peat and water into plants and back to the peat via a litter compartment. The major part of the litter will decompose, and thereby release radionuclides into the peat compartment (Ter Regolith Up) of the wetland for further uptake by plants or transport to the lake. Radionuclides are to different extents discriminated during decomposition. The remaining non-decomposed material is regarded as recalcitrant material accumulated in the litter compartment and is not available for further transport /Löfgren 2010/. The wetland starts to develop from the lake margins and expands into the lake. The wetland and the lake interchange radionuclides depending on the advective fluxes between peat in the terrestrial system and water in the aquatic system. Transport from the wetland to the lake occurs through runoff, whereas transport from lake to wetland occurs during flooding events (see above).

The natural end state of the biosphere objects is a fen even though the fen would be replaced by a bog under the conditions prevailing in the region of Forsmark. However, the raised bog, with primary production on the bog plane that is sustained by meteoric water and with a restricted or non-existent connection to the groundwater table, is of less interest in the context of a safety assessment in which the radionuclides enter the ecosystem from below.

C-14 is the only radionuclide that is assumed to occur as gas in sufficient amounts in the terrestrial environment to be a potential risk to humans. It may degas from the wetland and be taken up by primary producers during photosynthesis. When it is incorporated into biota it is further cycled via the litter compartment and heterotrophic respiration to the atmosphere or by water flux to the lake environment.

When the wetland in a biosphere object has risen to a sufficiently high elevation to avoid periodic seawater intrusions, it is of potential use for agricultural purposes and can be drained. It has been assumed that human inhabitants will drain and subsequently use wetlands for production of crops and livestock fodder /Lindborg 2010, Löfgren 2010/. This is done for each simulation time point, starting from the moment when the use of the wetland for agricultural purposes is possible. The organic layers (peat and gyttja) on drained and cultivated wetlands will rapidly become oxidized and compacted, resulting in an agricultural soil /Lindborg 2010/, which, in the model, is a mixture of contaminated organic matter and deeper mineral layers (postglacial and glacial deposits), where radionuclides may have accumulated since the early sea stage.

Once the wetlands have been drained, further contamination through groundwater is assumed to be of no quantitative importance. Instead, radionuclides are leached from the soil through runoff. Accordingly, the highest concentrations of radionuclides in agricultural soil are expected in the period directly after drainage, and thus the 50 years immediately following drainage is used to assess the average exposure during a human life time from the use of contaminated agricultural soil.

10.2.2 Releases to drilled wells

In addition to the radionuclides released into deeper parts of the regolith of a biosphere object, a unit release rate has also been applied to a hypothetical well drilled through bedrock. The activity concentration in well water (Bq/m^3) has been calculated by dividing the release rate (Bq/y) by the well capacity (m^3/y). The value of the well capacity has been taken from statistics of the capacity of wells existing in the area near the proposed repository location at Forsmark, where a drilled well that might receive 100% of the release would be located. Drilled wells located farther away from the repository may have lower well capacity, but because of increased distance, they will also have a lower probability of receiving 100% of the releases. When a biosphere object has risen above the sea level, these activity concentrations, together with the concentrations in surface water, have been used to estimate doses from drinking water by humans and for calculation of radionuclide concentration in meat and milk from cattle consuming this water. Although sustainable irrigation of agricultural lands from a drilled well is considered unlikely at the site /Löfgren 2010/ it has been considered in uncertainty analyses of the derived LDF values /Avila et al. 2010/.

10.2.3 Modelling spatial distribution of radionuclides in the landscape

Deep groundwater from the repository is primarily attracted to low points in the landscape, e.g. shallow parts of the sea, along the shoreline, and in lakes, streams and wetlands. The outer boundary of each biosphere object was determined from the hypsography of the sea basin during the submerged phase, whereas the shoreline of the lake at time of isolation from the sea delineates the biosphere object during the lake and terrestrial phases. Key geometrical characteristics of the objects have been determined from the local (i.e. sea or lake basin) topography, whereas the regional geometry defined landscape characteristics, like hydrological links between biosphere objects and sizes of catchment areas. In total ten biosphere objects have been identified, containing a discharge area during any period of the present interglacial. Five additional biosphere objects located downstream of the discharge areas have also been identified. Finally, to represent discharge directly into a stream or a wetland without an initial lake stage, the basin of one of the original biosphere objects has been partitioned into three separate biosphere objects (objects 121-01, 121-02 and 121-03).

The Radionuclide Model for the biosphere is implemented for each biosphere object included in the landscape model. These models are then connected with each other to account for radionuclide fluxes between biosphere objects, driven by fluxes of surface waters and suspended particles. In the transitional, lake and terrestrial stages, the radionuclide fluxes from a biosphere object are directed to the connected downstream objects. Hence, all downstream objects will receive inputs from one or several upstream objects. In the Sea Stage, all objects interact only with the outer coastal area (Öregrundsgrepen) via water exchange in both directions. From Öregrundsgrepen, radionuclides are finally discharged to the Baltic Sea), which is treated as a sink in the model.

The simulations for derivation of LDFs (see /Avila et al. 2010/) were carried out for each separate biosphere object and the maximum LDF, across all biosphere objects, was selected for use in the SR-Site assessments. The landscape model (Figure 10-1) was used in supporting simulations, reported in /Avila et al. 2010/, to show that derivation of LDFs from simulations of separate biosphere objects does not lead to their underestimations.

10.3 The mathematical model

The mathematical model for each biosphere object consists of a System of Ordinary Differential Equations (ODEs). Each of the ODEs represents the rate of change for a radionuclide inventory (Bq) in a model compartment as a function the radionuclide fluxes (Bq y^{-1}) into and out of the compartment, and of radioactive decay and in-growth.

The model assumes that the radionuclide fluxes are proportional to the radionuclide inventory in the compartment, multiplied by a transfer rate coefficient (y^{-1}). Radionuclide-specific behaviour is taken into account by using element-specific values for some of the model parameters that describe e.g. retention (distribution coefficients or Kd values) and biological uptake (concentration ratios or CR values).

The radionuclide fluxes have been modelled in the same way for all radionuclides, except for C-14. In the case of C-14 the uptake by biota is modelled using a specific activity approach /Avila and Pröhl 2008/, and gas exchange between the peat and surface water on the one hand and the atmosphere on the other hand has been considered. The effect on the LDFs of neglecting these processes for other radionuclides is discussed in /Avila et al. 2010/.

The Radionuclide Model has the same mathematical formulation for all biosphere objects. The differences between biosphere objects have been captured by using object-specific values for parameters describing the geometry of the biosphere objects, the depths of regolith layers, and the rate and timing of transitions between sea, lake and terrestrial stages.

The ordinary differential equation for each model compartment (*k*) may includes inflows from outside the system, outflows from the system and transfer of radionuclides from and to other connected compartments (*i*), decay and in-growth of the radionuclide. The ODE of a compartment (*k*) has the following general form:

$$\frac{\mathrm{dA_k^j}}{\mathrm{dt}} = \mathrm{F^j_{out\ to\ k}} - \mathrm{F^j_{k\ to\ out}} + \sum\nolimits_\mathrm{i} \mathrm{F^j_{i\ to\ k}} - \sum\nolimits_\mathrm{i} \mathrm{F^j_{k\ to\ i}} - \lambda^\mathrm{j} \cdot \mathrm{A^j_k} + \mathrm{ingrowth^j}$$

$$\mathrm{F^j_{k\ to\ out}} = TC^j_{k\ to\ out} \cdot \mathrm{A^j_k}$$

$$\mathrm{F^j_{i\ to\ k}} = TC^j_{i\ to\ k} \cdot \mathrm{A^j_i}$$

$$\mathrm{F^j_{k\ to\ i}} = TC^j_{k\ to\ i} \cdot \mathrm{A^j_k}$$

where:

A^j_k is in inventory of the *j-th* radionuclide in compartment k (Bq).

λ^j is the decay constant for the *j-th* radionuclide ($year^{-1}$).

Ingrowth ^{j} is the in-growth of the *j-th* radionuclide from decay of the parents ($Bq \cdot year^{-1}$).

$F^j_{out\ to\ k}$ is the inflow of the *j-th* radionuclide from outside the system to *k-th* compartment ($Bq \cdot year^{-1}$).

$F_{k\ to\ out}$ is the outflow of the *j-th* radionuclide from *k-th* compartment out from the system ($Bq \cdot year^{-1}$).

$F^j_{i\ to\ k}$ is the flux of the *j-th* radionuclide from *i-th* to *k-th* compartment ($Bq \cdot year^{-1}$).

$F^j_{k\ to\ i}$ is the flux of the *j-th* radionuclide from *k-th* to *i-th* compartment ($Bq \cdot year^{-1}$).

$TC^j_{k\ to\ out}$ is the transfer rate coefficient of the *j-th* radionuclide from *k-th* compartment out from the system ($year^{-1}$).

$TC^j_{k\ to\ i}$ is the transfer rate coefficient of the *j-th* radionuclide from *k-th* to *i-th* compartment ($year^{-1}$).

$TC^j_{i\ to\ k}$ is the transfer rate coefficient rate of the *j-th* radionuclide from *i-th* to *k-th* compartment ($year^{-1}$).

In Appendix 13, the 10 differential equations describing the change in radionuclide inventory over time for the 10 compartments are presented starting with the lowest regolith compartment and going up to the atmosphere compartment. Also the transfer coefficients, TC, are described in Appendix 13. The parameters used in the model are all presented in Chapter 11.

10.3.1 Calculation of activity concentrations in the environment

The Radionuclide Model dynamically models the radionuclide inventory in ten compartments of the biosphere object. From these, the activity concentrations in peat, agricultural soil, atmosphere, surface water, aquatic sediments and primary producers are derived. Environmental concentrations are used to assess the safety of the environment /Torudd 2010/ and to calculate human exposure (see the following sections). Environmental activity concentrations are calculated as follows.

Activity concentrations in *peat* (Bq/kg dw) are calculated by dividing the radionuclide inventory (Bq) in the upper terrestrial regolith compartment by the mass of this compartment, (which is the product of the peat density and volume).

The activity concentrations in *aquatic sediments* (Bq/kg dw) are calculated by dividing the combined radionuclide inventories (Bq) in the upper and the middle aquatic regolith compartments by the summed mass of these compartments (where each mass is the product of the sediment density, area and depth).

The activity concentrations in *surface waters* (Bq/m^3) are calculated by dividing the inventory in the water compartment (Bq) by its volume (m^3).

The activity concentrations in *atmospheric air* (Bq/m^3) are calculated by multiplying the activity concentrations in peat and soil (Bq/kg dw) by the dust concentrations (kg dw/m^3) in air.

The initial inventory in *agricultural soil* (Bq) is calculated by summing the radionuclide inventories in the upper terrestrial regolith compartment and in 25 cm of the middle terrestrial compartment (the ploughing depth), assuming a uniform distribution through the depth of this compartment. The average inventory in the agricultural soil during a period of 50 years is then calculated assuming leaching due to runoff and, for vegetables, additional input via contaminated irrigation water. The activity concentration (Bq/kg dw) in soil is obtained by dividing the average radionuclide inventory by the soil mass (kg dw), which is the product of agricultural soil density (kg dw/m^3), area (m^2) and ploughing depth (m).

The activity concentrations in *terrestrial primary producers* (Bq/kg C) are calculated by dividing the inventory of the compartment Ter_Primary_Producers by the total biomass.

Concentrations in food

Biological uptake in organisms that are consumed by human inhabitants is not modelled dynamically (with the exception of the concentration in terrestrial primary producers). Instead the activity concentrations in human food (Bq/kg C) are calculated from concentrations in environmental media (peat or soil and surface water), assuming an equilibrium between the concentrations in food and in the corresponding environmental media.

For aquatic food types (fish and crayfish), the activity concentrations are calculated by multiplying the activity concentration in water by the Concentration Ratio (Bq/kg C per Bq/m^3) for each food type, respectively. The concentrations in fish and crayfish are calculated for both limnic and marine conditions.

For terrestrial food types, activity concentrations are calculated by multiplying the activity concentration in peat (for berries, mushrooms) and agricultural soil (for cereals, vegetables and root crops) by the corresponding Concentration Ratios (Bq/kg C per Bq/kg dw) /Nordén et al. 2010/. There is a lack of CR data for edible berries and therefore concentrations in edible berries are taken to be equal to the concentration in terrestrial primary producers as described above.

The activity concentrations in herbivores are calculated by assuming equilibrium between food consumed by the herbivore and the tissues of the herbivore. Since the herbivore diet consists of both green plants and mushrooms, the activity concentration in herbivore diet is calculated by summing the contributions from both sources.

To determine the activity concentrations in meat from game or cattle and in dairy products, the concentrations in the animal diet (wetland vegetation or green fodder) are first calculated by multiplying activity concentrations in peat or soil by the corresponding Concentration Ratios (Bq/kg C per Bq/kg dw). Activity concentrations in meat and milk are then calculated from the concentrations in animal diet and animal consumption rates, using simple equilibrium models /Nordén et al. 2010/. Radionuclide intakes from contaminated water and ingestion of soil are also included in the calculations.

10.4 Exposure assessments

The activity concentrations in environmental media are used to calculate human exposure. For these calculations, it is assumed that the representative individual of the most exposed group spends all time in the contaminated biosphere object, and gets his/her full supply of food and water from this biosphere object (see Future Human Inhabitants).

In the SR-Site biosphere analysis, the average exposure over the lifetime of individuals that will live in the Forsmark area in the far future is assessed. For this assessment, adults were considered to provide a sufficiently good approximation of the average exposure during a lifetime. This is in line with the ICRP recommendations /ICRP 2006/.

To estimate annual exposure during the lifetime of an individual, predicted doses have been averaged over a period of 50 years, which is the integration period used by ICRP in the derivation of Dose Conversion Coefficients for adults. Exposure has been calculated following the methods outlined in /Avila and Bergström 2006/, summing the contributions from all relevant pathways. Below is given a description of the assumptions and basis of calculations of human exposure from inhalation, external exposure, and consumption of contaminated food and water. The dose coefficients for exposure take radiation sensitivities of different tissues and organs into account, as well as accumulation of radionuclides in the human body and exposure from daughter radionuclides (i.e. exposure represents the committed effective dose from radionuclides and their progeny).

Humans can be exposed both externally and internally to radionuclides in the environment. Based on earlier assessments, e.g. /Bergström et al. 1999, Avila and Bergström 2006/, it is concluded that the major long-term risk from human exposure to radionuclides from a repository is from internal exposure. The internal exposure is always preceded by incorporation of radionuclides into the human body. This can occur mainly by ingestion of contaminated water and food or inhalation of contaminated air. The intake is for most radionuclides dominated by food ingestion, whereas drinking water will give an important contribution for a few radionuclides.

The internal exposure will, among other things, depend on the fraction of contaminated food and water consumed and the level of activity in the foodstuffs and water. In this methodology, it is assumed that the annual demand of water and food is contaminated, but other situations can easily be addressed by introducing corrections to account for the fraction of consumed water and food that is not contaminated. The dietary composition can also have an impact on internal exposure, as different foods can have different contamination levels. However, for long-term assessments it is difficult to postulate a particular dietary composition, as human habits and choices may change. Food intake and food production are important processes that will affect the potential exposure of humans to radionuclides derived from the repository. The assumptions of food intake used in calcuations is described in Section 10.4.2 and effects of alternative food intake is discussed in /Avila et al. 2010/.

Exposure via inhalation of contaminated air can occur both outdoors and indoors. However, exposure indoors may be lower than outdoors due to the filtering effects of buildings. In SR-Site, only outdoor exposure was considered, which in most cases gives a conservative estimate, as the radionuclide contamination of the air comes from resuspension of soil particles. The situation could, however, be different for isotopes of elements that can exist in gaseous form in the environment, such as radon and iodine. Other pathways for radionuclide penetration into the human body, for example through the skin, are irrelevant in the context of this safety assessment.

The external exposure comes from radiation emitted by the radionuclides in surrounding environmental media; air, water and soils. Previous safety assessments of planned geologic repositories in Sweden and Finland /Bergström et al. 1999/ and /Karlsson and Bergström 2000/ have shown that, for most radionuclides of relevance, external exposure gives only a minor contribution to the total dose. Thus, in most cases, external exposure contributes only marginally to total risk.

10.4.1 Exposure from external irradiation and inhalation

To calculate of exposure via inhalation and external irradiation it has been assumed that the human inhabitants are exposed 24 hours per day, and shielding by buildings has been neglected.

Dose rates via inhalation (Sv/y) are calculated by multiplying the activity concentration in air (Bq/m^3) by the inhalation rate (m^3/h), the exposure time (h/y) and the Dose Coefficient for inhalation (Sv/Bq).

Dose rates from external irradiation (Sv/y) are calculated by multiplying volumetric concentrations in peat and agricultural soil (Bq/m^3) by the exposure time (h/y) and the Dose Coefficient for external exposure (Sv/h per Bq/m^3).

10.4.2 Exposure from water consumption

To calculate exposure via ingestion of contaminated water it has been assumed that future human inhabitants satisfy their need for drinking water by equal contributions from a well drilled into the rock and from surface waters.

Dose rates due to water ingestion (Sv/y) are calculated by multiplying the activity concentration in drinking water (Bq/m^3) by the water ingestion rate (m^3/y) and the Dose Coefficient for ingestion (Sv/Bq).

The need of drinking water of future human inhabitants living in a biosphere object is assumed to be satisfied by equal contributions from a well drilled into the rock and from the surface water in the lake or stream passing through the object. This also covers the case of drinking water from a well dug into the till, since lake and stream water is likely to intrude into a well that is in contact with contaminated sediments beneath the wetland.

Exposure from contaminated drinking water is considered from the point in time when a biosphere object has emerged from the sea. Livestock are assumed to consume water from the same sources as human inhabitants, i.e. equal water contributions from surface water and a drilled well.

Exposure originating from irrigation with contaminated surface water has been considered in terms of the production of vegetables. Surface water for irrigation of agricultural soils will be readily available in all considered biosphere objects, and irrigation with well water has consequently been excluded from consideration because it is unlikely.

10.4.3 Exposure from food consumption

To calculate exposure via ingestion of contaminated food it has been assumed that human inhabitants are self-sustaining and utilize all available food sources in proportion to their production (see Future Human Inhabitants for details).

Doses due to food ingestion (Sv/y) are calculated by multiplying the activity concentration in food (Bq/kg C) with the food ingestion rate (kg C/y), and the Dose Coefficient for ingestion (Sv/Bq).

The production capacity of human food in a biosphere object is directly determined by the size of the contaminated object, (i.e. the size of the sea basin or the size of the wetland and the surface water), and the sustainable yield of natural food stuffs and agricultural products, which in turn may vary with climatic conditions. Assuming that food production is the limiting factor for humans living in the biosphere object, the number of individuals that can be sustained in a biosphere object is thus proportional to the area of the object. However, the size of the population that can be sustained also depends on land use, since the productivity per unit area of a crop is two to three orders of magnitude larger than the productivity of natural food stuffs in a wetland.

For the SR-Site assessment, it has been assumed that all available food sources from both aquatic and terrestrial parts of a biosphere object are utilized by human inhabitants. Additionally it is assumed that wetlands will at least partly be converted to agricultural land when this is possible (see next section). No assumptions have been made regarding food preferences of future individuals. Instead, the human diet reflects the production of different food stuffs in the object. Thus, when the object is submerged the human diet consists of sea food. When the object has been isolated from the sea, the diet consists of natural food stuffs from the lake/stream and from the wetland. When agriculture is possible, the diet will be a combination of natural food stuffs and agricultural produce. The contribution of each food type to the human diet is assumed to be proportional to the production of that food type in the object. When agriculture is possible, it is deemed equally likely that the wetland is used for production of natural food stuffs, cereals, root crops, vegetables or fodder for beef and dairy production.

The result is that biosphere objects with a large area that can be drained and cultivated can typically feed a population in the range of 170–1,300 persons (first and third quantile, respectively). In contrast, biosphere objects that cannot be cultivated can only supports a limited number of individuals, i.e. approximately 10 individuals during submerged or coastal conditions and typically one or a few individuals when inhabitants are limited to foraging the lake and wetlands for natural food stuffs.

It is important to note that the assumption of self-sustained future inhabitants of the area does not imply that this is a “stone-age”-like culture. It only sets the constraint that the population is obtaining all its food locally from available resources.

11 Radionuclide model parameterization

The radionuclide model for the biosphere presented in Chapter 10 relies on nearly 140 input parameters. For each parameter, a best estimate was derived from site and/or literature data, and the parameter uncertainty was described by a probability density function (PDF). The best estimate was used for deterministic calculations of human exposure and to assess potential radiological impacts on the environment. This chapter contains a reader's guide to the reports where parameter calculations are described. In addition, this chapter contains a description of how the parameters in the limnic part of the dose model are populated, with background data, calculations and the resulting input data.

11.1 Reader's guide to parameter calculation

In order to summarise the number and types of parameters that are used to model transport and accumulation of radionuclides in the biosphere and the potential exposure to organisms, the parameters have been divided into a number of categories (see Table 11-1). The model is hydrologically driven and the scenario is based on a below-ground release of radionuclides entering the biosphere. Potential discharge areas affected by the release of radionuclides in the biosphere are identified from the modelling of deep groundwater discharge and from topography and ecosystem type /Lindborg 2010/. Each such area is called a biosphere object and is the smallest unit in the modelling of radionuclide transport and accumulation in the landscape. The model is divided into two parts, one terrestrial and one aquatic (see Chapter 10). At the start of the modelling, all objects are marine. Over time they follow a successional path from a marine stage to a limnic stage to a terrestrial stage, due to shoreline displacement. The criteria for this successional development are described in /Lindborg 2010/.

The parameters presented in this chapter are those describing biota, hydrology and regolith associated with the limnic ecosystem in the dose model. Parameters associated with terrestrial and marine ecosystems are presented in /Löfgren 2010/ and /Aquilonius 2010/, respectively. Regolith and object geometries are described in /Lindborg 2010/ whereas parameters describing nuclide or element-specific properties (e.g. decay and concentration ratios), dose coefficients and parameters associated with human characteristics are presented in /Nordén et al. 2010/ (Table 11-1). All parameters are listed in Appendix 14.

Deterministic modelling has been based on the parameter values estimated for the temperate case (Chapter 8). In addition, alternative parameter value estimates have been produced for alternative future conditions, e.g. periglacial climate. Below follows a description of the parameter statistics and representation as well as a short discussion on parameter handling under alternative climate conditions.

11.1.1 Parameter statistics and representation

Deterministic modelling to derive landscape dose conversion factors (LDFs) has been based on the parameters estimated for the temperate case. Each parameter has been assigned a central value that was used in the deterministic modelling. Additionally, a potential range is presented for the central value estimate, which was used in a sensitivity analysis /Avila et al. 2010/.

Generally, the parameters in the model have been estimated using data from the site or from models populated with site data. In some cases when such data were lacking, data were obtained from other areas as similar to our sites (i.e. Forsmark and Laxemar-Simpevarp) as possible. The premises for the limnic parameter estimation are described in this chapter, along with statistical descriptions such as central value, maximum and minimum values, and standard deviation. For some data, such as for modelled or literature data, no statistical descriptions are available. The time resolution of the model is 1 year, and parameter values are described as yearly averages.

The central value for each parameter is representative of the property at the site. For example, the central value describing the biomass of a microbenthic community is a median based upon a few lakes at the site under present conditions, whereas the minimum and maximum values also take into consideration communities of other lakes than the representatives investigated at the site. Most lakes

Table 11-1. Parameters used in the radionuclide model. [a] each parameter estimated for 48 radionuclides, [b] each parameter estimated for 31 stable elements, [c] include time-dependent parameters for which a separate parameter value is given for each time step and object (8 landscape geometry parameters, 4 regolith parameters, 8 aquatic ecosystem parameters and 1 surface hydrology and water exchange parameter). The references are given in the footnote below the table. All parameters are listed in Appendix 14.

Type of parameter	N	Section	Example	Source	Reference
Nuclide specific[a]	1	9.2.1	Radionuclide half life	Literature	TR-10-07
Landscape geometries[c]	13	9.2.2	Size of biosphere objects and catchment areas, sedimentation and resuspension rates	Site investigation, site modelling	TR-10-05
Regolith properties[c]	27	9.2.3	Depth, density and porosity of sediments and soil	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03
Aquatic ecosystem properties[c]	17	9.2.4	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-02, TR-10-03
Terrestrial ecosystem properties	34	9.2.4	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-01, TR-10-07
Surface hydrology and water exchange[c]	9	9.2.5	Runoff, vertical and horizontal advective fluxes, marine water exchange	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03
Distribution coefficients and diffusivity[b]	10	9.2.6	Element-specific solid/liquid distribution coefficients (Kd) for regolith and particulate matter	Site investigation, literature	TR-10-07
Concentration ratios[b]	19	9.2.7	Element-specific ratios between environmental media and organisms (CR)	Site investigation, literature	TR-10-07
Human characteristics	5	9.2.8	Life span, energy and water consumption	Literature	TR-10-07
Dose coefficients[a]	4	9.2.8	Radionuclide-specific factors for radiation exposure through external exposure, inhalation and ingestion	Literature	TR-10-07

References:
TR-10-01: /Löfgren 2010/
TR-10-02: This report
TR-10-03: /Aquilonius 2010/
TR-10-05: /Lindborg 2010/
TR-10-07: /Nordén et al. 2010/

in Forsmark contain a thick benthic layer consisting of microbiota, i.e. a microbial mat. These microbial mats are very special for the oligotrophic hard-water stage that the lakes pass through during the first thousand years after isolation (see Section 8.2). However, some lakes along the coast lack these microbial mats, and during their succession the conditions in the lakes will change, and older lakes will also probably lack these microbial mats. The mean biomass value is an estimate from one lake with a microbial mat. The minimum and maximum values, on the other hand, are taken from the literature on other lakes in Sweden but adjusted for nutrient and temperature status. The minimum and maximum values therefore represent a span that takes the different types of benthic communities into account and thereby also the successional aspects of the lakes.

Standard deviation, and minimum and maximum values, were used in a sensitivity analysis that describes the relative importance of different parameters for the model result /Avila et al. 2010/. In addition, a parameter value distribution was suggested for each parameter, where mainly normal and lognormal distributions fit the actual data. In some cases no distribution is suggested, due to lack of data and/or no *a priori* anticipation as to the likely shape of the distribution. However, some of the field estimates have neither the spatial nor the temporal scope that is desirable for short-term modelling (e.g. 100 years). For example, modelling of climate parameters such as precipitation and runoff lacks a variation range since climate statistics are usually defined from station records that extend for more than 30 (often more than 50) years and changes in climate are typically defined relative to a baseline estimate obtained for a reference 30 year period. This means that the described variation for some site parameters does not cover the potential variation range, even though the estimated mean may be close to the true mean for a longer time. Most of the parameters describing the regolith have a rather limited range, reflecting a small number of samples in some cases but also a low degree of intrinsic variation.

11.1.2 Future conditions

The safety assessment is made over a period of 120,000 years and will therefore not only include successional changes, but also climate changes. Four different stages are distinguished in the modelling: temperate, periglacial, glacial and a stage where the sites are below sea level (see Chapter 8). The temperate conditions prevail during an interglacial (defined as the warmer period between two glacial events), but is preceded and followed by periglacial conditions (defined as occurrence of permafrost). An additional case is used to illustrate effects of global warming on the radionuclide modelling results.

The use of different stages and climate cases is especially important for terrestrial areas where e.g. a periglacial climate indicates tree less tundra compared with forest and agricultural land in temperate conditions. In limnic ecosystems, the response of biota to global warming is difficult to foresee, but it is likely that increased primary production would be associated with increased respiration and the net ecosystem production may be similar to present-day conditions (see Chapter 8). In periglacial conditions, productivity and sustainable yield of large organisms (i.e. fish and crayfish) are assumed to decrease at lower temperature. However, water buffers the extreme temperatures and for many parameters (e.g. biomass of primary producers) changes due to lower temperature in periglacial conditions are thought to be small. The same estimates are therefore most often used for the temperate, periglacial, and global warming stages but alternative parameter values are presented for fish and crayfish. No limnic parameters are presented for glacial conditions, since lakes are not modelled for the glacial stage (see Chapter 10). Nor are limnic parameters presented for the stage submerged below sea level, as no lakes exist at that stage.

Limnic systems go through a succession over time and are gradually transformed into wetlands. However, as the lakes are transformed into wetlands, a stream remains running through the wetland in most of the modelled objects. The transition from lake to stream occurs gradually. Generally, the distinction between lakes and streams is not clear and streams may be viewed as very narrow lakes with a short retention time (the definition of lakes and streams is further discussed in Section 2.3). In the dose model, lakes gradually become smaller until they reach the size of the residual stream, and the stream remains at this size for the remaining time steps that are modelled. For a few parameters, the parameter values change in this stream stage, but for most parameters the same values are used for the stream stage as for the lake stage. Unless otherwise stated, the same parameter values are applied for the entire limnic period (i.e. both lake and stream stage).

11.2 The limnic biosphere object in Forsmark

When marine basins are isolated from the sea, lakes are formed. A total of 17 objects are included in the dose model for Forsmark in SR-Site of which all but one pass through limnic stages before turning terrestrial. The future landscape is described in /Lindborg 2010/. The estimates for future lakes are based on knowledge of existing lakes in the area and region (further described in Chapter 3), and the ecological functioning of future lakes is discussed in the chapter dealing with future development (Chapter 8.3).

11.2.1 Lakes

The present lakes in the area are shallow oligotrophic hardwater lakes. Some of the lakes that will form in the future will be deeper and thereby differ from the present-day lakes. In parameterisation, all lakes are assumed to become oligotrophic hardwater lakes as this would lead to the highest net ecosystem production and thereby higher incorporation of radionuclides into biota. The situation with other lake types is also considered in the probabilistic simulations where minimum and maximum values may incorporate values also for other lake types. Lake-specific characteristics, such as lake depth, sediment depth, water retention time etc are considered for each lake in the modelling.

11.2.2 Streams

The present streams in the model area are very small and many dry out during summer. Some of the future streams will be larger due to larger drainage areas. The morphometry of future streams is considered and a theoretical photic depth is applied to represent also the situation in larger streams.

11.3 Dose model parameterization for Forsmark

This section contains descriptions of the site-specific limnic parameters for Forsmark. A schematic illustration of the numerical model describing the transport and accumulation of radionuclides is presented in Chapter 10. For some parameters, one value is valid for the entire modelling period, whereas others are time-dependent and there are different values for each object and time step (100 years in the limnic phase). All parameter names used in the dose model are listed in Appendix 14, which contains a reference to the report in which they are described (and to the source file at SKBdoc 1263189[20]).

The dose model focuses on the transport and accumulation of radionuclides. Some parameters, e.g. biomass and production, are therefore not always defined in the same way as in previous chapters in this report. In other words, only production and biomass where radionuclides are incorporated is of interest for the dose model, whereas in an ecosystem description all biomass and production in an ecosystem is of interest.

In the following section, parameters associated with the limnic part of the dose model are divided into 1) regolith parameters, 2) hydrological parameters, 3) chemical and biological parameters and 4) human food parameters.

11.3.1 Regolith parameters

The regolith parameters describe properties of different generalized geological units found in the biosphere objects. The regolith at each biosphere object is described according to the conceptual model of the spatial distribution of regolith at Forsmark (Figure 11-1). The mainput for describing properties of the regolith is the surface map of Quaternary deposits, the depth and stratigraphy model of the regolith, the Regolith Depth Model (RDM) /Hedenström et al. 2008/, the soil type map /Lundin et al. 2004/ and models of the future distribution of Quaternary deposits /Lindborg 2010/. The regolith is divided into four layers: regoUp, regoMid_PG, regoMid_GL and regoLow, representing peat (in the mire), postglacial deposits, glacial deposits and till, respectively (Figure 11-1). In the dose model, RegoMid_PG and regoMid_GL are combined into one layer, regoMid. PG represents the postglacial organic sediments, i.e. gyttja and clay gyttja, whereas GL constitutes the glacial clay. Below follows a description of the derivation of parameter value estimates describing the regolith

Lake_z_regoUp (m)

Lake_z_regoUp represents the depth of the upper oxygenated regolith layer in lakes and streams. Most of the lake sediments in the Forsmark area are covered by a loose layer of algae and cyanobacteria (microbial mat) that can be very thick (further described in Section 3.10). This layer is easily mixed and the thickness of the oxygenated zone is estimated to equal that of the microbial mat. In lakes lacking a microbial mat, the thickness of the oxygenated zone is estimated to be 1 cm (see Section 3.6). There is no correlation between lake bathymetry and the occurrence or absence of microbial mats (Andersson and Brunberg, unpublished). Lake_z_regoUp was calculated as the mean thickness of the oxygenated zone investigated lakes of today: mean 0.053 m, (min 0.01 m, max 0.30 m, n=9 lakes, 149 subsamples). In streams, the redox zone may be thinner than in the lakes (0.053 m) as no thick microbial mat is found in the streams. On the other hand, stream currents stir up the sediments, and benthic fauna in streams may create a deeper oxygenated zone than in lakes lacking a microbial mat (0.001 cm). As no measurements of Lake_z_regoUp are available for the streams today, the value for the lakes is also used for the streams.

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[20] Data stored at SKBdoc 1263189 might be given on request.

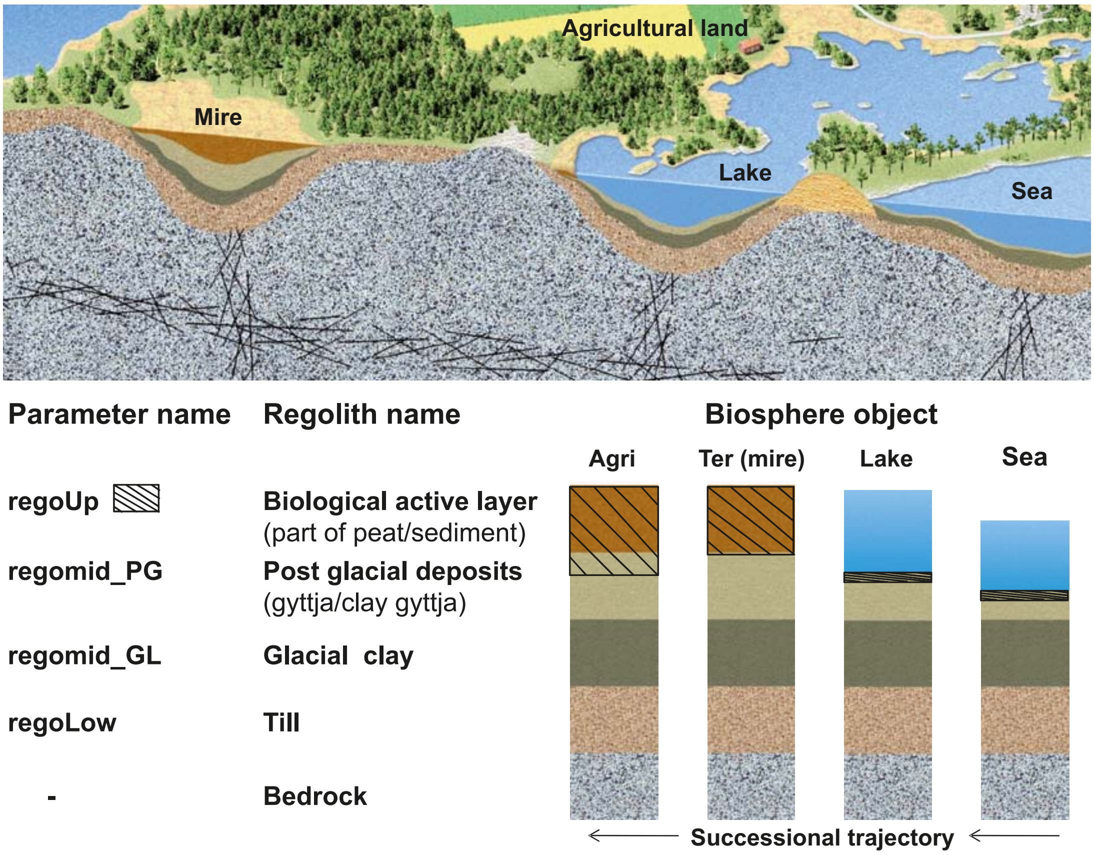

__Figure 11-1.__ The conceptual model of the generalized distribution of the regolith for different types of biosphere objects, agricultural land, mire, lake and sea. The parameter names in the radionuclide model on the left ares used together with the biosphere object prefix, e.g. Ter_z_regoUp to describe the depth of peat layer. The different depths of the various regolith layers in soil profiles are also seen in the landscape pictures, which represent a generalized succession trajectory from sea to mire that is later converted to agricultural land by draining.

Table 11-2. Depth of the upper oxygenated layer, Lake_z_regoUp, in 9 investigate lakes. The mean value for all 9 lakes is used as a parameter value.

Lake	Mean (m)	Minimum (m)	Maximum (m)	Number of observations
Bolundsfjärden	0.020	0.010	0.070	26
Eckarfjärden	0.040	0.010	0.120	32
Fiskarfjärden	0.048	0.010	0.110	27
Labboträsket	0.010	0.010	0.010	23
Gunnarsbo-Lillfjärden	0.046	0.010	0.080	16
Lillfärden	0.010	0.010	0.010	3
Stocksjön	0.196	0.080	0.300	6
Fräkengropen	0.043	0.040	0.050	7
Vambördsfjärden	0.062	0.025	0.140	9
Mean	0.053			
Maximum	0.30			
Minimum	0.01			

Aqu_dens_regoUp _acc (kg m^{-3})

Aqu_dens_regoUp _acc represents the dry bulk density of the upper sediment on accumulation bottoms in the limnic and marine areas, represented by soft organic sediment with very high water content (Table 11-3). The proportions of accumulation and erosion bottoms at each site/basin the marine area are based on the sedimentation model /Lindborg 2010/. In the isolated lake basins, the entire bottom area is regarded as accumulation bottom. The parameter values are based on measurements of the water content and organic carbon content of sediments from both limnic and coastal surface samples (Brunberg, unpublished data Table 11-5, /Hedenström 2004/). For the shallow marine area, measurements of the dry bulk density of the upper 10 cm of sediments were used (Table 11-4).

Aqu_poro_regoUp_acc (m^3 m^{-3})

Aqu_poro_regoUp_acc represents the porosity of the upper sediment on accumulation bottoms in the limnic and marine areas, represented by soft organic sediment with very high water content. In the isolated lake basins (objects), the entire bottom area is regarded as accumulation bottom. The porosity values are based on measurements of the water content in surface sediment from 7 lakes at Forsmark (Table 11-5) and measurements of the water content and organic carbon content of lake sediments from the site investigations (Table 11-6). The formula for calculating porosity (n) is given below /Talme and Almén 1975/. Mean, minimum, and maximum values of porosity in the upper regolith are presented in Table 11-7.

$n=Vp/V$

Vp represents the volume of water, V represents the total volume
1 g/cm^3 is used for the density of water and organic matter
2.65 g/cm^3 is used for the density of the minerogenic fraction.

Table 11-3. Parameter values for Aqua_dens_regoUp_acc, representing the dry bulk density of the surface sediments in accumulation bottoms in the aquatic system in Forsmark.

Dry bulk dens	(kg m^{-3})
Mean	126
Max	220
Min	72
n	8

Table 11-4. Measured dry bulk density in Forsmark /Sternbeck et al. 2006/.

Site	Idcode	Depth (m)	Dry bulk dens. (kg m^{-3})
Tixelfjärden	PMF 005785	0.00–0.02	37.8
Tixelfjärden	PMF 005785	0.02–0.04	133.6
Tixelfjärden	PMF 005785	0.04–0.05	208.6
Tixelfjärden	PMF 005785	0.06–0.07	175.7
Tixelfjärden	PMF 005785	0.07–0.08	170.0
Kallrigafjärden	PMF 005784	0.00–0.02	90.3
Kallrigafjärden	PMF 005784	0.02–0.04	151.9
Kallrigafjärden	PMF 005784	0.04–0.05	205.9
Kallrigafjärden	PMF 005784	0.06–0.07	194.4
Kallrigafjärden	PMF 005784	0.08–0.09	174.7

Table 11-5. Water content in the organic surface sediments from lakes at Forsmark, used for calculation of the porosity of regoUp Brunberg (unpublished data). * Not within the site investigation area.

Site	Depth (m)	Water content %	Porosity ($m^3\,m^{-3}$)
Fiskarfjärden	0.00–0.05	97.8	0.98
Fiskarfjärden	0.09–0.14	96.9	0.97
Bolundsfjärden	0.0–0.05	96.9	0.97
Bolundsfjärden	0.05–0.10	96.2	0.96
Stocksjön	0.0–0.05	97.7	0.98
Stocksjön	0.09–0.14	95.6	0.96
Labboträsk	0.0–0.05	98.0	0.98
Hällefjärd*	0.0–0.05	98.1	0.98
Hällefjärd*	0.08–0.13	96.0	0.96
Eckarfjärden	0.0–0.05	98.3	0.98
Eckarfjärden	0.12–0.17	97.5	0.97
Landholmssjön*	0.0–0.05	98.1	0.98

Table 11-6. Organic carbon and water content in gyttja from lakes at Forsmark, used for calculation of the porosity and dry bulk density of regoUp (from /Hedenström 2004/).

	Organic C (%)	Water content (%)	Porosity ($m^3\,m^{-3}$)	Dry bulk density ($kg\ m^{-3}$)
Eckarfjärden	0.27	93	0.95	71.7
Fiskarfjärden	0.17	93	0.96	72.6
Stocksjön	0.27	86	0.92	149.5
Gällsboträsk	0.27	86	0.92	149.5
Bolundsfjärden	0.27	90	0.94	104.8
Puttan	0.20	89	0.94	116.4

Table 11-7. Parameter values for porosity of the top sediment in accumulation bottoms in the aquatic systems in Forsmark.

Porosity	($m^3\,m^{-3}$)
Mean	0.96
Max	0.98
Min	0.92
Std	0.02
n	18

Aqu_z_regoMid_GL_lake and Aqu_z_rego_pg (m)

Aqu_z_regoMid_GL_lake represents the depth of glacial clay below the identified biosphere objects when they are in the lake/terrestrial stage. The depth and distribution of this layer is regarded as constant over time, covering the till and bedrock surface from deglaciation onwards. The depth of this layer is specific for each object, based on the RDM (Table 11-8) /Hedenström et al. 2008/. After isolation from the sea, the glacial sediments are covered by postglacial deposits Aqu_z_rego_pg. The parameter values of this layer changes over time (due to sedimentation) and are calculated for each object and time step (further described in /Lindborg 2010/). The parameter values for Aqu_z_rego-Mid_PG are stored at SKBdoc[21] .

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[21] Data stored at SKBdoc 1263189 might be given on request.

Table 11-8. Mean, minimum and maximum depth (m) of glacial clay (Aqu_z_regoMid_gl_lake) below the identified biosphere objects when they are in the lake/terrestrial stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified lake basins. The biosphere objects 121_02 and 121_03 do not have a lake stage and the glacial clay layers are assumed to be similar to the glacial clay layers of the sea basins.

Object	mean	minimum	maximum
10	Does not reach a lake stage		
101	1.87	0.00	5.30
105	3.28	0.00	5.30
107	1.87	0.00	5.30
108	2.22	0.00	5.30
114	3.75	0.00	5.30
116	1.62	0.00	5.30
117	0.39	0.00	5.30
118	0.85	0.00	5.30
120	0.00	0.00	5.30
121_01	3.22	0.00	5.30
121_02	0.44	0.00	2.29
121_03	1.17	0.00	2.29
123	5.30	0.00	5.30
124	0.00	0.00	5.30
125	0.03	0.00	5.30
126	3.66	0.00	5.30
136	0.00	0.00	5.30

Aqu_dens_regoMid_PG (kg m^{-3})

Aqu_dens_regoMid_PG represents the dry bulk density of regoMid_PG, found in the aquatic systems, i.e. both the limnic and marine areas as well as under the peat at mires. The values are based on measurements of water content and organic content in the sediments from 6 lakes at the Forsmark site (Table 11-5) (Brunberg, unpublished, /Hedenström 2004/). Measurements of sediments from coastal bays were used as well (Table 11-9) /Sternbeck et al. 2006/. The mean, maximum and minimum values are presented in Table 11-10.

Table 11-9. Measured dry bulk density of coastal sediments in Forsmark /Sternbeck et al. 2006/.

Site	Idcode	Depth (m)	Dry bulk dens (kg m^{-3})
Tixelfjärden	PMF 005785	0.10–0.11	157.4
Tixelfjärden	PMF 005785	0.12–0.13	163.7
Tixelfjärden	PMF 005785	0.16–0.17	168.0
Tixelfjärden	PMF 005785	0.20–0.22	190.5
Tixelfjärden	PMF 005785	0.24–0.26	186.1
Tixelfjärden	PMF 005785	0.28–0.30	192.4
Tixelfjärden	PMF 005785	0.32–0.34	256.3
Tixelfjärden	PMF 005785	0.36–0.38	218.7
Tixelfjärden	PMF 005785	0.40–0.41	215.7
Kallrigafjärden	PMF 005784	0.10–0.11	179.6
Kallrigafjärden	PMF 005784	0.12–0.13	161.1
Kallrigafjärden	PMF 005784	0.14–0.15	180.1
Kallrigafjärden	PMF 005784	0.16–0.17	156.8
Kallrigafjärden	PMF 005784	0.18–0.20	180.7
Kallrigafjärden	PMF 005784	0.20–0.22	204.7
Kallrigafjärden	PMF 005784	0.24–0.26	170.5
Kallrigafjärden	PMF 005784	0.28–0.28	183.8
Kallrigafjärden	PMF 005784	0.32–0.34	219.8
Kallrigafjärden	PMF 005784	0.34–0.36	164.8
Kallrigafjärden	PMF 005784	0.38–0.39	187.9
Kallrigafjärden	PMF 005784	0.65–0.68	215.7

Table 11-10. The parameter values of Aqu_dens_regoMid_PG and Ter_dens_regoMid_PG, representing the dry bulk density of postglacial gyttja and clay gyttja in Forsmark.

Dry bulk dens	(kg m^{-3})
Mean	138
max	256
min	72
Std	38
n	12

Aqu_poro_regoMid_PG (m^3 m^{-3})

Aqu_poro_regoMid_PG represents the porosity of the organic postglacial sediments, i.e. gyttja and clay gyttja, found in the limnic and marine areas as well as under the peat at mires. The values are based on measurements of the water content and organic content of gyttja and clay gyttja from the Forsmark site (Table 11-11) /Hedenström 2004, Hedenström and Risberg 2003, Nordén 2007/. The mean, maximum and minimum values are presented in Table 11-12.

Table 11-11. Input data used for calculations of the porosity of the postglacial sediments. */Hedenström 2004/, site-specific for each lake, ** /Hedenström and Risberg 2003/ Eckarfjärden, * /Nordén 2007/ site-specific but the water content of clay gyttja is based on values from Frisksjön, Laxemar-Simpevarp.**

Stratum/lake	Stratum thickness * (m)	C** (% of dw)	Water content*** (% of wet sample)	Dry bulk dens. kg m^{-3}	Porosity (m^3 m^{-3})
Eckarfjärden	(Σ 1.75 m)				
Gyttja	0.96	27	93	71.7	95.2
Clay gyttja	0.11	8	**86******	152.2	93.5
Clay	0.68	1	53	662.0	74.6
Fiskarfjärden	(Σ 3.52 m)				
Gyttja	1	17	93	72.6	96.5
Clay gyttja	0.61	05	**86******	152.7	93.8
Clay	1.91	1	53	661.7	74.6
Stocksjön	(Σ 0.49 m)				
Gyttja	0.4	27	86	149.5	91.8
Clay gyttja	0.03	8	86	152.2	93.5
Clay	0,06	1	53	662.0	74.6
Gällsboträsket	(Σ 1.41 m)				
Gyttja	0.34	27	86	149.5	91.8
Clay gyttja	0.37	8	**86******	152.2	93.5
Clay	0.7	1	53	662.0	74.6
Bolundsfjärden	(Σ 0.6 m)				
Gyttja	0.48	27	90	104.8	94.3
Clay gyttja	0.07	8	**86******	152.2	93.5
Clay	0.05	1	53	662.0	74.6
Puttan	(Σ 0.82 m)				
Gyttja	0.8	20	89	116.4	94.2
Clay gyttja	0.02	9	**86******	152.1	93.4
Clay	0	1	53	661.7	74.6
N:a Bassängen	(Σ 0.16 m)				
Gyttja	0.15	27	86	149.5	91.8
Clay gyttja	0.01	8	**86******	152.2	93.5
Clay	0	1	53	664.2	74.9

Table 11-12. Parameter values for Aqua_poro_regoMid_PG and Ter_poro_regoMid_PG, representing the porosity of postglacial gyttja and clay gyttja in Forsmark.

Porosity	$m^3\ m^{-3}$
Mean	0.93
Max	0.96
Min	0.90
Std	0.02
n	7

Aqu_dens_regoMid_GL (kg m^{-3})

Aqu_dens_regoMid_GL represents the dry bulk density of the glacial clay found in both the limnic and marine areas. The values are based on calculations based on analyses of water content and organic carbon content in glacial clay from lakes /Hedenström 2004/. The mean, maximum and minimum values are presented in Table 11-13.

Aqu_poro_regoMid_GL ($m^3\ m^{-3}$)

Aqu_poro_regoMid_GL represents the porosity of the glacial clay found in the limnic and marine areas. The porosity values for glacial clay are based on secondary calculations from grain-size distribution curves of clay collected offshore at Forsmark /Risberg 2005/ and calculations based on analyses of water content and organic carbon content in glacial clay from lakes /Hedenström 2004/. The mean, maximum and minimum values are presented in Table 11-14.

Lake_z_regoLow (m)

Lake_z_regoLow represents the total depth of the glacial till. The depth and distribution of this layer are constant over time, covering the bedrock surface from the deglaciation onwards. The depth of this layer is based on the RDM /Hedenström et al. 2008/. Mean values for the lake basin after isolation are used in the model. Mean, minimum and maximum values of the depth of the regoLow are presented in Table 11-15.

dens_regoLow (kg m^{-3})

The parameter dens_regoLow represents the dry bulk density of the deeper parts of the glacial till. The dry bulk density values for till are based on measurements from >0.3 m depth in the terrestrial area of the Forsmark site /Lundin et al. 2005, Sheppard et al. 2009/. Mean, minimum and maximum values of the density of the regoLow are presented in Table 11-16.

Table 11-13. Parameter values for Aqua_dens_regoMid_GL and Ter_dens_regoMid_GL, representing the dry bulk density of glacial clay in Forsmark.

Dry bulk dens	(kg m^{-3})
Mean	663
Max	664
Min	662
n	3

Table 11-14. Parameter values for Aqua_poro_regoMid_GL and Ter_poro_regoMid_GL, representing the porosity of glacial clay in Forsmark.

Porosity	($m^3\ m^{-3}$)
Mean	0.64
Max	0.75
Min	0.55
n	10

Table 11-15. Mean, minimum and maximum depth (m) of the lower regolith (z_regoLow) in the Forsmark objects. * In the case of objects 121_02 and 121_03, values are not initially defined but assumed from the depth of regoLow of the sea basin.

Object	mean	minimum	maximum
10	0.78	0.00	12.89
101	4.78	0.00	12.89
105	5.09	0.00	8.69
107	4.78	0.00	12.89
108	5.09	0.00	18.26
114	5.12	0.00	10.22
116	4.00	0.00	23.04
117	3.53	0.00	11.33
118	3.29	0.85	10.41
120	2.57	0.00	5.69
121_01	7.73	1.98	19.33
121_02	4.53*		
121_03	3.21*		
123	7.06	0.00	19.27
124	2.99	0.42	6.12
125	3.16	0.42	9.07
126	9.45	0.00	21.42
136	3.01	0.00	4.70

Table 11-16. Parameter values for dens_regoLow, representing the dry bulk density of till in Forsmark.

Dry bulk density	(kg m^{-3})
Mean	2,132
Max	2,200
Min	1,980
Std	87
N	5

poro_regoLow (m^3 m^{-3})

The parameter poro_regoLow represents the porosity of the glacial till. The porosity values for till are based on measurements from >0.3 m depth in the terrestrial area of the Forsmark site /Lundin et al. 2005, Sheppard et al. 2009/. Mean, minimum and maximum values of the porosity of the regoLow are presented in Table 11-17.

Table 11-17. Parameter values for poro_regoLow, representing the porosity of till in Forsmark.

Porosity	(m^3 m^{-3})
Mean	0.21
Max	0.27
Min	0.18
Std	0.04
n	4

11.3.2 Hydrological and meteorological parameters

This section includes hydrological parameters that describe water fluxes (adv_low_mid, fract_mire, Aqu_adv_mid_up_norm, Flux_Flooding, runoff) and a meteorological parameter describing wind speed (vel_vind).

In order to calculate the hydrological parameters for the dose model, water balances for today's conditions have been analysed for different lakes. By simulating different time periods (characterised by different shoreline positions and regolith distributions) and climate cases, the hydrological fluxes for future conditions have been described /Bosson et al. 2010/. A preliminary SR-Site MIKE SHE model was set up and calibrated based on previous modelling /Bosson et al. 2008, Bosson et al. 2010/. This model was set up to represent three different times: 2000 AD, 3000 AD and 5000 AD. Results from the preliminary SR-Site model for 5000 AD were used in order to calculate water fluxes to, from and between lake and mire areas in Forsmark /Bosson et al. 2010/. Six different lake objects were selected for the calculation of water balances in 5000 AD. The main reason for choosing existing lakes (and not including future lakes) is that the body of data is more extensive and the lakes are better described in the model. The lakes are of different sizes, with different vegetation and different thicknesses of underlying sediments. In this way the average value for the six lakes should represent an average lake within the model area. The six lakes are all oligotrophic hardwater lakes and even if othe lake types may form in the future (see Chapter 8) we expect highest doses to man from limnc system to arise from oligotrophic hardwater lakes (see Section 11.3.3) further supporting the choice of lakes in the water balances. Each water balance is calculated for one year, i.e. the results are annual mean values. Three different water balances were calculated for each object: one for the lake area, one for the mire area, and one for the total area (lake+mire), resulting in a total of 18 water balances. The calculations are fully described in /Bosson et al. 2010/.

A schematic description of the fluxes considered in the lake/mire water balances is shown in Figure 11-2. In the MIKE SHE model, 4 layers are identified: 1) Overland (OL) corresponds to lake water, 2) L1 is lake sediments (corresponds to Aqu_regoUp, Aqu_regoMid_GL and Aqu_regoMid_PG in Section 11.3.1), 3) L2 is till (corresponds to regoLow in Section 11.5) and 4) L3 is the bedrock. Fluxes between the different vertical layers (surface water, sediment, till and bedrock) are modelled as well as horizontal fluxes between the lake and the mire. In addition, the total horizontal fluxes into and out of the total lake+mire area are calculated. After calculations of water balances, all values are normalized with respect to the area, i.e. expressed in mm y^{-1}.

The water balance for the six investigated lakes is presented in Figure 11-3a. This water balance was used to calculate the hydrological parameters used in the dose model. MIKE SHE and the radionuclide model divide the ecosystem components somewhat differently and the outputs from water balances in MIKE SHE had to be transformed for use in the radionuclide model. A box model for the hydrological fluxes was set up (Figure 11-3b). The OL in Mike SHE corresponds to Aqu_water in a limnic ecosystem. L1 Mike SHE consists of lake sediments and corresponds to Aqu_regoMid. L2 consists of till and corresponds to Aqu_regoLow and L3 is the bedrock i.e. belonging to the geosphere and not included in the radionuclide model for the biosphere. In the hydrological box model a fictive box (Ter_water) was introduced which is not present in the radionuclide model. This box was necessary to include in the hydrological modelling in order to get a correct water balance for each box and for the entire model. Finally, the hydrological parameter values are used in the Pandora model to calculate flows between different compartments in the ecosystems (Figure 11-3c).

In the model simulations, the radionuclide releases from the geosphere are directed to the lower regolith. Thereafter a vertical flux from the lower regolith to the Aqu_regoMid (lake_ adv_low_mid) and distribution of this flux between terrestrial area (i.e. mire) and lake is calculated (fract_mire). In the mire, a flux from Ter_regoMid (i.e. post-glacial and glacial deposits) to the Ter_regoUp (peat) is calculated. The vertical fluxes between the lake water and sediment are assumed to be equal in both directions. The same fluxes are used to represent the water exchange between Aqu_regoUp and Aqu_regoMid. Thus, in the radionuclide model, there is a flux from the middle regolith layer to surface water (Lake_Aqu_adv_mid_up_norm). The lateral fluxes between mire and lake are calculated as functions of area_subcatch (the sub-catchment area of the object) and runoff (runoff) and by introducing a flooding coefficient (Flooding_coef). The runoff and flooding coefficient were estimated based on water balances in the MIKE SHE SDM-Site model /Bosson et al. 2008, Bosson et al. 2010/. A description of these parameter calculations follows below, and parameter values are presented in Table 11-18.

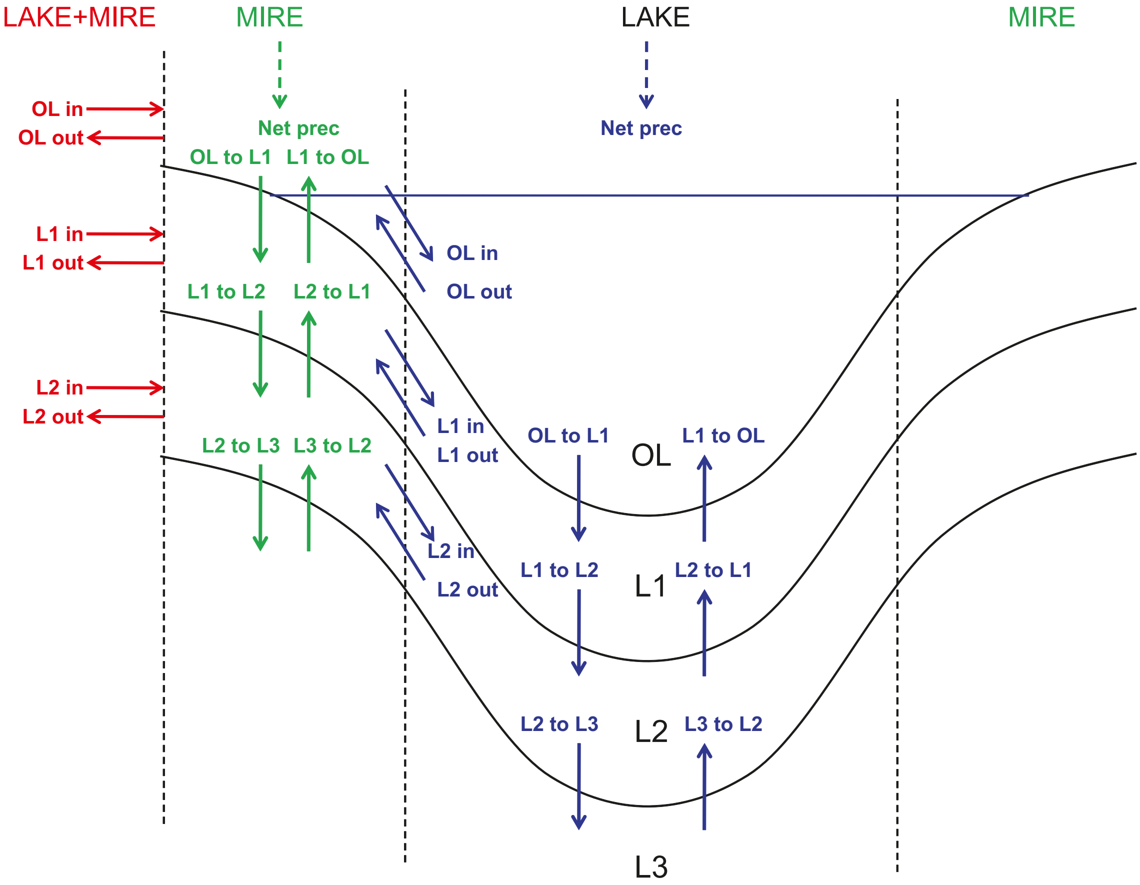

Figure 11-2. *Figure showing parameters calculated by water balances for lake and mire areas in Forsmark. OL is short for overland and corresponds to lake water in limnic ecosystem. L1 consists of lake sediments (corresponds to Aqu_regoUp, Aqu_regoMid_GL and Aqu_regoMid PG in Section 11.5). L2 consists of till (corresponds to regoLow in Section 11.5) and L3 is the bedrock. The blue arrows represent fluxes from the lake water balance, the green arrows represent fluxes from the mire water balance, and the red arrows represent fluxes from the lake+mire water balance.*

Lake_adv_mid (my^{-1})

The parameter Lake_adv_low_mid represents the total advective flux from the till (L2) to the postglacial and glacial deposits (L1). This was estimated by summing the net fluxes from L2 to L1 in the mire and lake parts of the model in Figure 11-3, i.e. (60–17) + (9–8) = 44 mm y^{-1} = 0.044 m y^{-1}.

Lake_fract_mire (unitless)

The parameter Lake_fract_mire represents the fraction of the advective flux from the till (L2) that goes to the mire. This fraction is needed in the dose model due to the differences in set-up between the dose model and the hydrological model. In the hydrological model, the lower regolith is divided into two compartments (mire and lake), whereas in the dose model there is only one compartment (rego_Low). The fraction of the total flux from the lower regolith that goes to the mire was estimated from the water balance as: net outflux from L2 to L1 in the mire part divided by total influx to L2, i.e. (60–17) / 44 = 0.98 (see Figure 11-3).

Lake_aqu_adv_mid_up_norm (unitless)

Lake_aqu_adv_mid_up_norm represents the advective flux in the aquatic object between the sediment (L1) and the water (OL) normalized by the lateral advective fluxes from the mire. The vertical fluxes between the lake water and the upper sediment (Rego_Up, described in 11.5) are assumed to be equal in both directions. The same fluxes are used to represent the water exchange between the

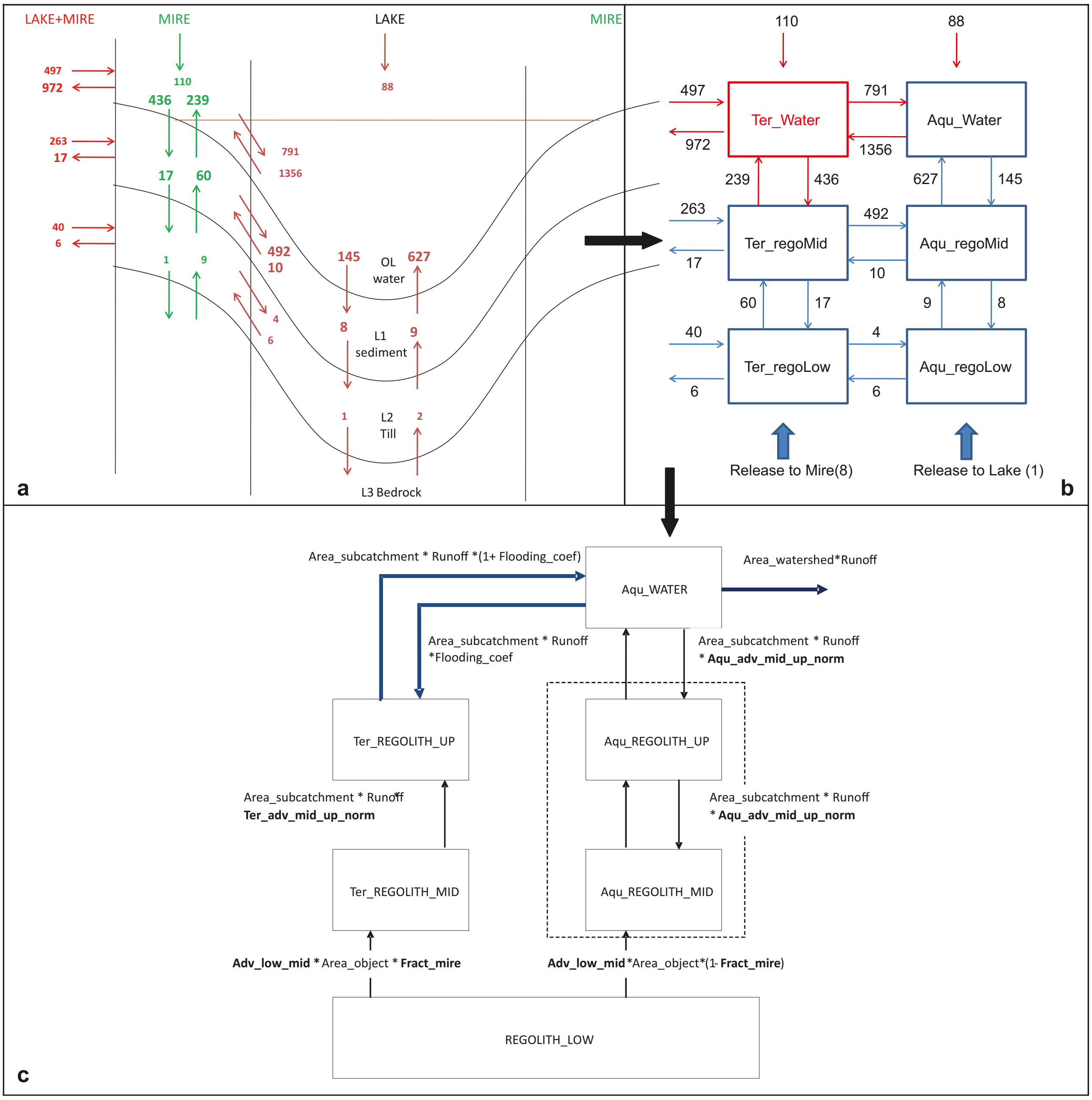

Figure 11-3. *Detailed hydrological models are used to parameterise water fluxes between compartments in the radionuclide model. a) Advective fluxes represent fluxes for the average lake-mire object obtained from the MIKE SHE simulations (n=6). The numbers are mean values for the six lakes (see Table 11-18) included in the modelling. Units are in mm y^{-1}. Net precipitation is included in the figure to obtain the water balance in each compartment. b) Advective fluxes (units of mm y^{-1}) for an average lake-mire object obtained from Mike SHE simulations and transformed to a box model. c) Conceptual representation of the water fluxes in the Pandora model with parameter names in bold representing hydrological fluxes described in this section and in /Löfgren2010/ .*

top sediment (Rego Up) and the rest of the sediment (Regolith mid). Thus, in the model, the flux is seen as a flux from regoMid (L1) to surface water (OL). The flux between L1 an OL was obtained by adding all fluxes to and from the lake sediment and normalizing by the fluxes out from the mire (sub-catchment area *runoff, including both layers L1 and OL): Total flux to the lake sediment is set to (145 + 492)/(972+17) = 637/(989) = 0.64 and total flux from the lake sediment is set to (627+10)/(972+17) = 637/(989) = 0.64.

Flooding_coef (unitless)

Flooding_coef describes the gross annual lateral flux of water from the lake to the mire relative the net lateral flux from the mire to the lake. In the model the gross flux from the mire to the lake is represented by runoff*area_catchment*(1+Flooding coefficient) (see Figure 11-3c). The flux out from OL and L1 in the MIKE-SHE water balance (972+17) (Figure 13-2a and b) was taken to approximate the net lateral flux (see above) from the mire to the lake. The total flux from the mire to the lake was derived by adding the flux from the top two terrestrial compartments (791+492) to the net lateral flux (927+17). Thus after rearrangement the flooding_coef becomes (791+492+972+17)/(972+17)–1=1.3.

Runoff (m y^{-1})

The runoff parameter represents the total mean annual runoff for the SDM-site model area in MIKE SHE. Of the total mean annual runoff of 0.186 m, 0.144 m is runoff in surface streams and 0.042 m is direct runoff from the surface to the sea. The runoff was estimated by calculating a water balance based on three years of simulation. The calculation was based on the final MIKE SHE SDM-site model /Bosson et al. 2008/. Minimum, maximum and the standard deviation for runoff were taken from long time series regional measurements at Vattholma (SMHI station 50110). The statistics were based on a time series of monthly mean discharge from 1917 to 2000. The long time serie was also compared to results from the MIKE SHE model of the Forsmark area describing the hydrological conditions at different time periods (2000 AD, 5000 AD and 10,000 AD). The model results are similar to the long term data set from Vattholma. Hydrological data from the Vattholma station are described in /Larsson-McCann et al. 2002/. (Mean=0.186, SD= 0.08, min= 0.07, max= 0.45 my^{-1}).

Supporting calculations – Periglacial domain estimate

For the supporting calculation describing radionuclide behaviour during permafrost, values were derived from a separate MIKE SHE modelling for a potential talik in biosphere object 114 (Table 11-19) and are further described in /Bosson et al. 2010/.

Table 11-18. Hydrological parameter values used in the dose models for Forsmark.

Parameter	Unit	Lake-Mire period
Lake_adv_low_mid	m y^{-1}	0.044
Lake_fract_mire	unitless	0.98
Lake_Aqu_adv_mid_up_norm	unitless	0.64
Flooding_coef	unitless	1.3
Runoff	m y^{-1}	0.186

Table 11-19. Parameter values describing hydrological fluxes during a periglacial domain estimated from MIKE SHE simulations for Forsmark /Bosson et al. 2010/. These values were used in a supporting calculation studying the effect of periglacial conditions in radionuclide modelling.

Parameter	Unit	Lake-Mire period
Lake_adv_low_mid	m y^{-1}	0.003
Lake_fract_mire	unitless	0.33
Lake_Aqu_adv_mid_up_norm	unitless	0.03
Flooding_coef	unitless	1.1
Runoff	m y^{-1}	0.217

11.3.3 Chemical and biological parameters

This section describes both chemical and biological parameters, as they are often closely connected in lakes. Chemical parameters that are important for the distribution of radionuclides are the concentration of particulate matter (Lake_conc_PM) and the concentration of inorganic carbon (Lake_conc_DIC). Other chemical parameters are fluxes of carbon dioxide gas across the air-water interface (Aqu_degass_C and gasUptake_C). These fluxes are mainly driven by biotic production and respiration and can therefore also be considered to be biological parameters. The concentrations of radionuclides in biota are calculated using bio-concentration factors, which are further described in /Nordén et al. 2010/.

Production of biota is important not only for the flux across the air water interface, but also for the flux of radionuclides to sediment in lakes. The biota incorporates radionuclides and the production excess (i.e. the net ecosystem production) settles on the lake floor as sediment or is transported to downstream objects. It is therefore important to estimate the biomass and the net productivity of the biota. The biota in lakes is divided according to habitat into: 1) the pelagic community (Aqu_biom_pp_plank, Aqu_prod_pp_plank), 2) the benthic macro community (Aqu_biom_pp_macro macro, Aqu_prod_pp_macro) and 3) the benthic micro community (Aqu_biom_pp_micro, Aqu_prod_pp_micro).

1) The pelagic community comprises: phytoplankton, bacterioplankton, zooplankton, and benthivorous, zooplanktivorous and piscivorous fish.
2) The benthic macro community comprises: macrophytes and benthic macrofauna.
3) The benthic micro community comprises: microphytobenthos and benthic bacteria.

The calculations of the chemical and biological parameters used in the radionuclide model are described below. In addition, the calculation of photic depth is described. This parameter is not used in the radionuclide model but is used in the calculations of biological parameters, i.e. primary production is only allowed in the photic zone.

Lake_conc_PM (kg DW m^{-3})

Lake_conc_PM represents the concentration of particulate matter in lake water. This is estimated based on site investigations of suspended particles in three Forsmark lakes in 2007 and 2008 (n=63) (Data from SICADA[22], March 2009). In addition, on one occasion in April 2008, suspended particles were analysed with a somewhat higher resolution /Engdahl et al. 2008/. Monthly averages were calculated from the standard site investigations for each lake and the annual mean concentration was calculated from these monthly means and used as the parameter value (Table 11-20). Many measurements were below the detection limit (<2 mg L^{-1}), in which case half the detection limit was used in the calculations. The minimum value was taken from the one sampling occasion in April 2008 and was assumed to represent an annual minimum. This is because many of the measurements in the site investigations were below detection limit and may very well have been as small, or smaller, than the measurement in April 2008. The maximum value was set to the maximum observed value during the site investigations (i.e. a single observation) and is assumed to be a representative annual mean value for lakes in a temperate region although it is a somewhat higher annual estimate than what is expected to occur in the present oligotrophic hardwater lakes of Forsmark. However, it might be appropriate for other lake types forming in Forsmark in the future.

Table 11-20. Parameter values of particulate matter and dissolved inorganic carbon used for Forsmark in the dose model. In the right column measured concentrations of DIC in streams are presented as a comparison to the lake values that were used in the model.

	Lake_conc_PM (kg DW m^{-3})	Lake_conc_DIC (kgC m^{-3})	Measured concentration of DIC in Forsmark streams
Median	0.0011	0.021	0.026
Mean	0.0011	0.022	0.026
Minimum	0.0003	0.0023	0.0009
Maximum	0.0025	0.029	0.059

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[22] SKBs database SICADA, access might be given on request.

The concentration of particulate matter in streams was also measured in the site investigations in Forsmark. However, almost all the values were below the detection limit, and the differences in concentrations were too small to indicate any difference between the concentrations in streams and lakes. The lake value of Lake_conc_PM was therefore used for the stream stage as well.

Lake_conc_DIC (kgC m^{-3})

Lake_conc_DIC represents the concentration of dissolved inorganic carbon, which was sampled and analyzed during the site investigations in Forsmark. The median values from 6 lakes (n=255 subsamples) /Tröjbom and Söderbäck 2006b/ have been used in the dose model calculations. The high concentration of DIC in the Forsmark lakes is due to the calcareous soils in the area. With time, the calcite will be depleted and the contribution of DIC to lakes will be small /Tröjbom and Grolander 2010/. Therefore the median value for lakes in the Laxemar area (0.0023 kgC m^{-3}) has been used as a minimum value of this parameter. This is one order of magnitude lower than the mean value but can be considered realistic as some individual observations during the year are even lower in the Forsmark area (see Section 3.9). The maximum value was set to the highest mean value of the 6 observed lakes in the Forsmark area /Tröjbom 2006b/. The median, mean, minimum and maximum values of dissolved inorganic carbon are presented in Table 11-21. The measured concentration of dissolved inorganic carbon in streams (0.026 kg C m^{-3}) is similar to that in lakes (0.021 kg C m^{-3}) and the values for lakes have also been used also for the stream stage.

Photic depth (m)

The photic depth, i.e. where there is enough light for photosynthesis to occur, corresponds to the depth at which 1% of the incoming light remains. The present-day lakes in Forsmark are all very shallow and the entire lake bottoms are photic. Some of the future lakes will be much deeper (maximum depth in the lake stage c. 23 m in object 105) and several of the objects will most probably contain aphotic bottoms, i.e. where the light climate is too poor to allow photosynthesis. Although the entire depth of the present-day Forsmark lakes is photic, a theoretical photic depth in the lakes has been calculated with the aid of light extinction curves from present lakes.

Light measurements in Bolundsfjärden and Eckarfjärden were performed biweekly from year 2003 to 2008 in the SKB site investigations (SICADA[23], March 2009). For each date, a regression of light extinction was used to extrapolate the curve until only 1% of the incoming light remained (Figure 11-4). For weeks lacking measurements, a mean of the photic zone was calculated from the week before and after. Production in the lakes occurs mainly during the summer /Andersson and Brunberg 2006a/, so the mean annual photic depth was calculated from week 14 to 39. A calculation from Eckarfjärden and Bolundsfjärden resulted in a mean photic depth of 4.3 m. This photic depth has been assumed to be valid for future lakes and streams. Of course other factors may influence photic depth, such as water chemistry and the biomass of planktonic biota. In two large Uppland lakes, Limmaren and Erken, the Secchi depth (approximately half the photic depth) is c. 2 and 5 m, respectively /Weyhenmeyer 1999, Weyhenmeyer et al. 1999/ thus indicating photic depths of 4 and 10 metres, respectively. Thus, although photic depth may vary it is clear that our estimate is within the range of values derived from present-day Secchi depths in deep lakes in the region.

Aqu_biom_pp_macro, Aqu_biom_ pp_ubent , Aqu_biom_pp_plank (kgC m^{-2})

These parameters represent the biomasses of benthic macroscopic and microscopic biota and pelagic biota in aquatic systems. Calculations of these parameters in the limnic stages (lake and stream) are described below whereas the parameter calculations for marine stages are presented in /Aquilonius 2010/. For the benthic communities, only the photic zone is considered, as it is assumed that the aphotic biota mainly respire allochthonous material (produced in the terrestrial ecosystem) and thereby do not influence the biotic transport of radionuclides to sediment. On a longer time scale, production in the photic zone may be transported to the aphotic zone, but in order to avoid overestimating the respiration of autochthonous material (produced within the lake and thereby potentially containing radionuclides), only the respiration in the photic zone is considered. Some of the future lakes may become dystrophic brow-water lakes in contrast to present oligotrophic hardwater lakes (further

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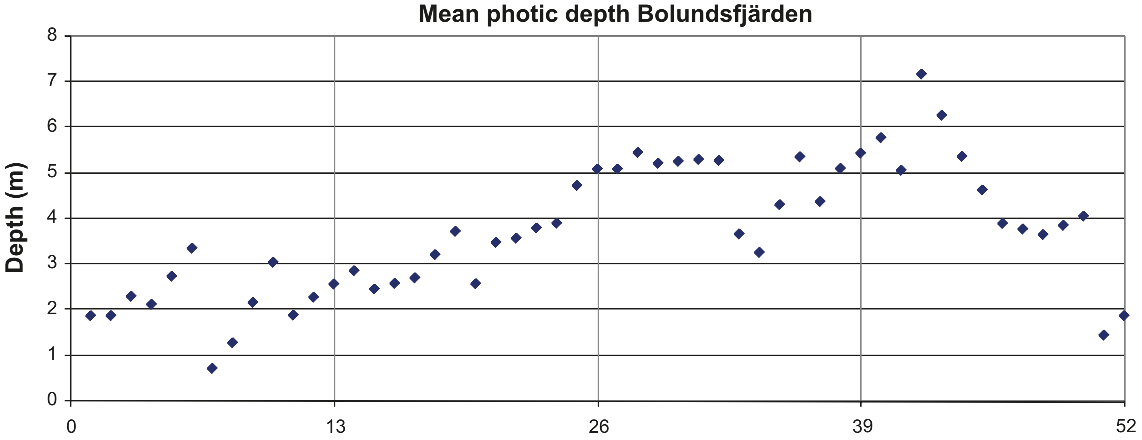
[23] SKBs database SICADA, access might be given on request.



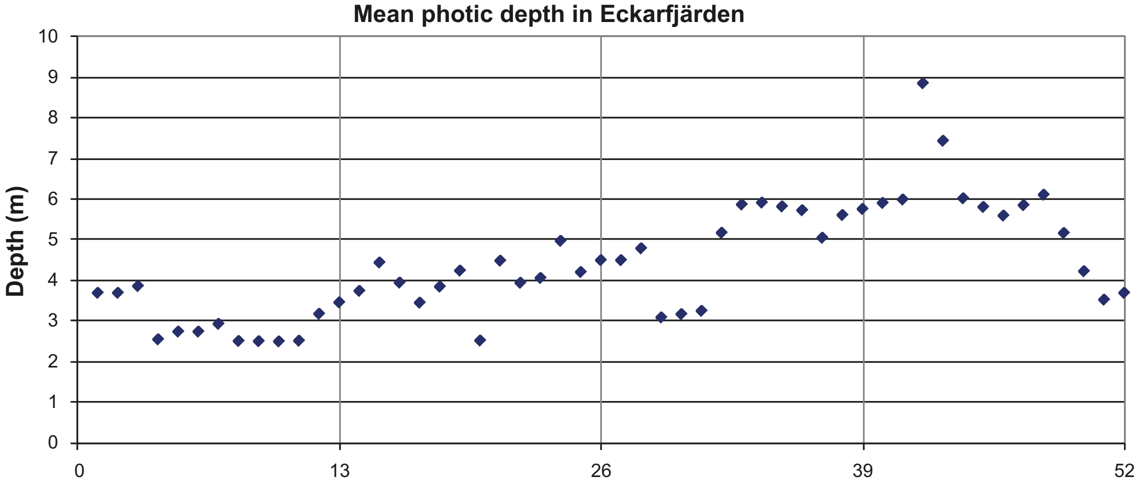


Figure 11-4. *Theoretical photic depth in lakes Bolundsfjärden and Eckarfjärden, calculated by extrapolating light exctinction curves in the lakes.*

discussed in Chapter 8). However, as net ecosystem production (NEP) is higher in oligotrophic hardwater lakes, all lakes are assumed to be transformed into oligotrophic hardwater lakes. This is a conservative assumption as a higher NEP allows for higher incorporation of radionuclides into biota.

The parameter is described as a mean biomass per m^2 lake area, so for Aqu_biom_pp_macro and Aqu_biom_ pp_ubent, the biomass in the photic zone is multiplied by the photic area and divided by the lake area. Pelagic biota is sometimes situated in the photic and sometimes in the aphotic zone due to continuously mixing of the water column. Therefore the entire pelagic community is included in this parameter. The parameters values are dependent on lake depth and photic area and thus changes over time.

Although the production and biomass of biota may be altered during warmer or colder climates no separate biomass values have been applied to the permafrost domain or global-warming conditions. The effect on biota due to a changing climate is difficult to predict due to multiple interactions between abiotic and biotic conditions as well as between different food web interactions in lakes (further discussed in Chapter 8). However, parameters such as sedimentation rate are altered in periglacial simulations and this affects lake depth and geometry of the lakes which in turn affect biota. Therefore limnic parameter values for periglacial conditions are calculated but with the same assumptions regarding biomasses of functional groups as described below[24].

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[24] The parameter values for interglacial and periglacial conditions are stored at SKBdoc 1253189, access might be given upon request.

Aqu_biom_pp_macro in lakes

Aqu_biom_pp_macro represents the biomass of macroalgae and benthic fauna. In the Forsmark lakes, the biomass of macroalgae in the photic zone is estimated as the median biomass of macroalgae *Chara sp.* from site investigations in Lake Bolundsfjärden (22 g C m^{-2}, further described in Section 3.10). The biomass was used for the entire photic zone although measurements in present-day lakes only reach depths of c. 2 m. However, other macrophytes have been shown to colonise greater depths in the photic zone and vascular plants have been found down to depths of 10 m in lakes /Wetzel 2001/.

The biomass of benthic fauna differs between areas with and without macrophytes /van den Berg et al. 1997/. In Eckarfjärden, about 75% of the photic zone is covered by vegetation. This proportion was used in the calculation of the mean biomass of benthic fauna in the photic zone (further described in Section 3.10); i.e. the mean biomass was calculated as the sum of the mean benthic fauna biomass on macrophytes (0.5 g C m^{-2}) multiplied by 0.75 and the mean benthic fauna biomass on vegetation-free bottoms (5 g C m^{-2}) multiplied by 0.25, resulting in a biomass of 1.6 g C m^{-2} in the photic zone.

Minimum and maximum estimates of pelagic community biomass were calculated as the sum of the possible minimum and maximum biomasses of the separate functional groups: 1) macroalgae and 2) benthic fauna.

1. The median value of the macroalgae biomass in Forsmark (22 g C m^{-2}) is in the lower part of the range found in a literature review by /Kufel and Kufel 2002/ (42–500 g dw m^{-2}, equivalent to 11–134 g C m^{-2} using the same conversion factors as in this study). The minimum and maximum values for macroalgae were set to the minimum and maximum values found in the literature, although the higher values most probably represent more nutrient-rich lakes than the Forsmark lakes.
2. The dataset used for statistical analysis of minimum and maximum values for benthic fauna is small (which of course also makes the mean parameter value somewhat uncertain.The benthic fauna biomass in areas without macrophytes in the Forsmark lakes is 5 g C m^{-2}, which is one order of magnitude larger than the biomass on *Chara*. This is the same biomass as in the benthic fauna-rich Chara-Lake Krankesjön in the south of Sweden (c 15 g dw m^{-2}, corresponds to 4.9 g C m^{-2}) /Kufel and Kufel 2002/. 5 g C m^{-2} is assumed to be a realistic maximum biomass that can be achieved in this kind of lake. The minimum biomass is set to the lowest biomass found in Lake Fiskarfjärden on macrophyte bottoms, 0.24 g C m^{-2}.

By combining the above assumptions regarding minimum and maximum biomasses for the separate functional groups with the proportional photic area of the different objects, different minimum and maximum values are obtained for each time step and object. Results are stored at SKBdoc 1263189[25].

Aqu_biom_ pp_ubent in lakes

Aqu_biom_ pp_ubent represents the biomass of microbiota (microphytobenthos and benthic bacteria). Most Forsmark lakes contain a "microbial mat", i.e. a thick microbial matrix consisting of microphytobenthos and benthic bacteria (further described in Section 3.10). Values of biomass per m^2 of microphytobenthos (3.8 g C m^{-2}) and benthic bacteria (3.7 g C m^{-2}) in the photic zone were set to annual averages from site-specific measurements at 1.5 m depth in one of the Forsmark lakes (further described in Section 3.10). The biomass of microphytobenthos at 1.5 m depth was assumed to be valid for the entire photic zone. Some Forsmark lakes in the area lack a thick microbial mat, and in these lakes the biomass is undoubtedly lower. However, no correlations have been found between occurrence of microbial mats and depth or height above sea level. Therefore, it is not possible to predict which of the future lakes will contain the microbial mats. Since most lakes contain these thick microbial mats, the same biomass is assumed for all future lakes.

Minimum and maximum estimates of pelagic community biomass were calculated as the sum of the possible minimum and maximum biomasses of the separate functional groups: 1) microphytobenthos and 2) benthic bacteria.

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[25] SKBdoc 1263189, access might be given upon request.

1) The annual mean biomass of the microphytobenthos in Lake Eckarfjärden ranged from 2.8 to 5.8 g C m^{-2} during the period 2000 to 2002 (n=3) /Andersson et al. 2003, Blomqvist et al. 2002/. The geometric and arithmetic mean microphytobenthos biomass values are similar, 3.6 and 3.8 g C m^{-2}. The dataset is small (n=3 years) and it is difficult to draw any conclusion regarding distribution. However, the range assuming a lognormal distribution (1.6–8.1 g C m^{-2}) is somewhat larger, and in order to avoid underestimating maximum values, the larger value of a 95% confidence interval (8.1 g C m^{-2}) has been used in calculating the maximum benthic community biomass. The microbial mats in Forsmark are several centimetres thick, which is remarkable in comparison with most other lakes in Sweden and Europe /Andersson 2005/. In general, light is assumed to penetrate benthic matrixes down to depths of millimetres /Hill 1996 and references therein/, and the algal matrix in lakes in Sweden and Europe is usually only millimetres thick (e.g. /Hargrave 1969, Wiltshire 2000/). Some lakes in Forsmark lack the thick microbial mats representative of the majority of lakes. A minimum biomass of microphytobenthos was assumed to be a few millimetres thick, and the biomass in the photic area was set to one order of magnitude lower (0.38 g C m^{-2}) than in lakes with microbial mats.
2) Benthic bacteria in the literature span a wide range from 10^8 to 10^{10} cells per ml sediment /Schallenberg et al. 1989/. The bacterial biomass is dependent on concentrations of organic carbon and nutrients, and temperature. The range in the literature may therefore be much larger than what can be expected for Forsmark lakes. The annual mean over a period of three years in Lake Eckarfjärden ranged from 3.0 to 4.2 g C m^{-2}, indicating a rather constant biomass. The arithmetic and geometric means are similar, 3.7 and 3.6 g C m^{-2}, respectively. Since the dataset is small, it is difficult to determine the distribution (normal or lognormal). However, the difference in range between a normal distribution (2.5–4.8) and a lognormal distribution (2.6–5.1) is small. The lognormal distribution gives a slightly larger range, so these values have been used to calculate minimum and maximum values.

By combining the above assumptions regarding minimum and maximum biomasses for the separate functional groups with the proportion of the photic area of future lake objects, different minimum and maximum vales are obtained for each time step and object (results are stored at SKBdoc 1263189[26])

Aqu_biom_pp_plank in lakes

Aqu_biom_pp_plank represents the biomass of the biota in the pelagic habitat, i.e. phytoplankton, bacterioplankton, zooplankton, and benthivorous, zooplanktivorous and piscivorous fish.

Average biomasses per m^3 of phytoplankton (0.04 g C m^{-3}), bacterioplankton (0.05 g C m^{-3}) and zooplankton (0.07 g C m^{-3}) were multiplied by the average depth to obtain the biomass per m^2 (biomasses are further described in Section 3.10). Fish biomass was estimated from fish surveys in Forsmark lakes (see Section 3.10) and is presented per m^2. The mean value for four lakes (Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden) was used as parameter value and was assumed to be valid for larger lakes in the future as well. A survey in Uppland County has shown larger catches of fish in lakes above 50 ha than in smaller lakes. However, the catch in the Forsmark lake Fiskarfjärden is greater (4.64 kg ww per unit effort) than suggested for large lakes above 50 ha (4.34 kg ww per unit effort) in the study by /Nyberg 1999/. Therefore, the large span in the investigation of Forsmark lakes is assumed to cover catches in future large lakes as well. Fish are not assumed to be present in lakes with maximum depths less than 1 metre due to poor oxygen conditions in shallow lakes during winter (further discussed in Section 11.8.3).

Minimum and maximum estimates of pelagic community biomass were calculated as the sum of the possible minimum and maximum biomasses of the separate functional groups: 1) phytoplankton, 2) bacterioplankton, 3) zooplankton and 4) fish.

1) The minimum and maximum measured annual phytoplankton biomass in Forsmark is 0.022 and 0.057 g C m^{-3} (n=3 years), respectively. Both the geometric and the arithmetic mean phytoplankton biomass is 0.04 g C m^{-3}. The dataset is small (n=3 years) and it is difficult to draw any conclusion regarding distribution. However, the range assuming a lognormal distribution is some-

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[26] SKBdoc 1263189, access might be given on request.

what larger, and in order to avoid underestimating minimum and maximum values this range has been used: minimum 0.015 g C m^{-3}, maximum 0.097 g C m^{-3}. This range is very similar to the phytoplankton range in oligotrophic lakes obtained from the literature (0.02 to 0.10 g C m^{-3} /Wetzel 2001 and references therein/). Although the minimum value is somewhat lower than the literature range, the site data are assumed to be valid and represent the special characteristics of the oligotrophic hardwater lakes regarding e.g. pH and alkalinity.

2) The annual mean bacterioplankton biomass measured in Forsmark ranged between 0.023 and 0.069 g C m^{-3} (n= 3 years). Both the arithmetic and the geometric mean is 0.05 g C m^{-3}, but due to the small dataset it is difficult to determine whether the dataset is normally or log normally distributed. The lognormal distribution is assumed as it provides a realistic range (0.01 to 0.170 g C m^{-3}), whereas the normal distribution provides unrealistically low minimum values (0.001 g C m^{-3}, which is one order of magnitude lower than the lowest biomass encountered in three whole year measurements (0.01). It is therefore unrealistic that an annual mean would be that low. The geometric range on the other hand is similar to the lowest and highest biomasses encountered during the measurements (0.011–0.164 g C m^{-3}), and these values have been chosen to represent the annual minimum and maximum biomasses.

3) /Gyllström et al. 2005/ reported zooplankton biomasses in European lakes ranging between 0.02 and 2.3 g C m^{-3}. The maximum values are much larger than reported biomass values for Forsmark lakes (0.07 g C m^{-3}), probably due to different nutrient conditions in the lakes. A more realistic maximum is one order of magnitude larger than the present-day annual mean (0.7 g C m^{-3}). The minimum biomass value of 0.02 g C m^{-3} is taken from /Gyllström et al. 2005/.

4) Fish biomass values measured in Forsmark range from medium to high compared to lakes in the county /Nyberg 1999/. Although the sample size is small (n=4), the samples indicates that the fish biomass is normally distributed. The arithmetic mean from 4 lakes (Eckarfjärden, Bolundsfjärden, Gunnarsbo-Lillfjärden and Fiskarfjärden) was 1.0 g C m^{-2}, and the 95% confidence interval of fish biomass was calculated from the standard deviation to be between 0.5 and 1.6 g C m^{-2}. This interval was assumed to represent minimum and maximum biomasses.

By combining the above assumptions regarding minimum and maximum biomasses per m^3 or per m^2 for the separate functional groups with the depths of the different objects, estimates of minimum and maximum values for each time step and object were obtained. Results are stored at SKBdoc 1263189[27].

Aqu_biom_pp_macro, Aqu_biom_ pp_ubent , Aqu_biom_pp_plank in streams

The biomasses of benthic macrobiota, microbiota, and pelagic biota in the stream stage of the objects are assumed to be identical to those of the lake stage. Below follows a short description of the measurements in streams that justify this assumption.

For streams in the area, only data on percent coverage are available for macrophytes and estimates of biomass are rather rough. Nevertheless, the estimated biomass of macrophytes in streams (mean 35 g C m^{-2}, median 12 g C m^{-2}) (further described in Section 3.10.2) is close to the median biomass in lakes. There are no field data available on benthic fauna in the Forsmark streams and thus the applied value fro the lakes are uncertain. However, the characteristics of lakes and streams (e.g. chemistry, pH, water colour etc) are similar and biomass of vegetation is similar, and thus the biomasses of benthic fauna are most probably in the same order of magnitude in lakes and streams.

The biomass of the microphytobenthos in streams is probably smaller than that in lakes, since there are no thick microbial mats. The benthic bacterial biomass may still be high. The biomass of the microbiota depends on many factors: flow rates, nutrients, temperatures and catchment characteristics. In arid regions where streams have little riparian vegetation, autotrophic production may be the major energy input, but in temperate regions with conifer catchments (as in Forsmark), energy input is dominated by allochthonous inputs /Lamberti 1996/. In the latter areas, year-round shading by conifers probably limits autotrophic production. However, production may be equally high and the same biomass and production has been assumed. Biomass has therefore also been set to the same value as in lakes.

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[27] SKBdoc 1263189, access might be given upon request.

Plankton biomass differs a great deal along the stream section. Immediately downstream of the lake outlet, the biomasses of phytoplankton and zooplankton are very similar to the biomasses in the lake (further discussed in Section 3.10.2 and /Wetzel 2001/). Further downstream from a lake outlet, the phytoplankton biomass becomes smaller. In larger streams there may be an active phytoplankton and zooplankton community. Assuming the same phytoplankton biomass as in lakes most probably leads to an overestimation (see Section 3.10.2 and Chapter 6), but this should not have any large influence on the model considering the shallow depth of most streams in the model. Bacterioplankton are assumed to be abundant in the entire stream section due to large inputs of degradable allochthonous material, and the same biomass is assumed for streams as for lakes.

Even if production in one community decreases it is possible that this is compensated for by increased production in another. Thus, as data are scarce from the streams it is a reasonable assumption to use the same data as for lakes as nutrient conditions are similar.

Aqu_prod_pp_macro, Aqu_prod_pp_ubent, and Aqu_prod_pp_plank (kgC kgC^{-1} y^{-1})

These parameters represent the net productivity (NEP) of the benthic macro- and micro communities and pelagic community in aquatic systems. NEP is the difference between primary production and respiration. Calculations of NEP in the different communities in lakes and streams are described below, whereas the parameter values calculations for marine stages are presented in /Aquilonius 2010/. Only the photic zone is considered since most of the respiration of autochtonous carbon (produced within the lake) are assumed to occur in the photic area. Radionuclides are incorporated into biota through primary production and released from biota through respiration. In the aphotic areas both autochthonous and allochthonous carbon (produced outside the lake) may be respired and in order not to overestimate the release of radionuclides from biota only the photic area is considered. Some of the future lakes may become dystrophic brown-water lakes in contrast to present oligotrophic hardwater lakes (further discussed in Chapter 8). However, as NEP is higher in oligotrophic hardwater lakes all lakes are assumed to be transformed into oligotrophic hardwater lakes. This is a conservative assumption as a higher NEP allows for higher incorporation of radionuclides into biota.

The net production, i.e. primary production minus respiration, in the photic zone is divided by the lake area to achieve a mean net productivity per lake area. In the dose model, the parameter is presented per biomass (kg C kgC^{-1} y^{-1}), i.e. the mean net productivity per area (kg C m^{-2}) has been divided by the biomass of the community (Aqu_biom_pp_macro, Aqu_biom_pp_ubent, and Aqu_biom_pp_plank, respectively). These parameters are dependent on lake depth and photic zone and stored at SKBdoc 1263189[28] for each object and time step.

The minimum and maximum values of NEP for the different communities are based on expert judgements. Although the literature contains wide ranges of primary production and respiration values, it is not possible to combine maximum production with minimum respiration and vice versa. Instead, high primary production often leads to high respiration. /Cole et al. 2000/ state that "In aquatic ecosystems we recognize several levels of control for both primary production and respiration but have little expectation for controls of NEP". NEP in lakes is often highly influenced by the catchment's characteristics, and it is not possible to use literature data on net productivity without considering parameters such as water chemistry, climate, hydrology etc. The specific considerations for each community are described below.

Aqu_prod_pp_macro in lakes

Aqu_prod_pp_macro represents the net productivity of macroalgae, macrophytes and benthic fauna. The annual production of macroalgae (8.7×10^{-2} kg C m^{-2}y^{-1}) was measured in site investigations in Forsmark (further described in Section 3.10) and this production has been applied to the entire photic area. Respiration by benthic fauna in the photic zone (8×10^{-3} kg C m^{-2}y^{-1}) is estimated from site investigations of biomass and literature conversion factors (further described in Section 3.10).

Primary production by macroalgae is within the range of values reported in the literature. Benthic fauna biomass, which is the basis for calculating respiration, is also within the literature range, but rather low. Although primary production may be somewhat higher than estimated, it is unlikely that primary production will increase without an associated increase in respiration, as this estimate

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[28] SKBdoc 1263189, access might be given upon request.

is already considered to be somewhat low. Consequently, it is assumed that the maximum net productivity of the benthic community can be at most twice the estimated value at photic bottoms (maximum 1.6×10^{-1} kg C $m^{-2}y^{-1}$). A hypothetical minimum value of net productivity is set to one order of magnitude lower than the estimated value at photic bottoms (minimum 7.9×10^{-3} kg C $m^{-2}y^{-1}$). For simplicity, the same biomass as at present is used to express the productivity per biomass in the input data to the radionuclide model. By combining the above assumptions regarding minimum and maximum biomasses for the separate functional groups with the proportion of the photic area of future lake objects, different minimum and maximum vales are obtained for each time step and object (results are stored at SKBdoc 1263189[29]).

Aqu_prod_pp_ubent in lakes

Aqu_prod_pp_ubent represents the net productivity of the microbenthic community.

The annual production of the microphytobenthos (5.6×10^{-2} kg) measured at 1.5 m depth (further described in Section 3.10) in one of the Forsmark lakes has been applied to the entire photic area in future lakes. Primary production by microphytobenthos may increase at shallower depths and decrease at larger depths than 1.5 metres, but in a whole ecosystem perspective this is compensated for by decreased and increased production of phytoplankton (Aqu_prod_pp_plank). No corrections for depth have been made for either microphytobenthos or phytoplankton, since the responses are assumed to offset each other.

Respiration by benthic heterotrophic bacteria (6.5×10^{-2} kg) is estimated from site investigations of secondary production and growth efficiency for bacteria (further described in Section 3.10). Since a large portion of the respiration in lakes may be caused by degradation of allochthonous material only the respiration in the photic zone is considered in order to not overestimate respiration of autochthonous material.

The productivity parameter is used to illustrate the transport of radionuclides to the sediment by incorporation in biota, i.e. biota take up radionuclides and fall to the lake floor on death and decomposition. The productivity parameter for the benthic micro-community becomes negative for all objects and times, due to higher respiration than production. The parameter is therefore set to zero, as the negative value indicates that all allochtonous material is respired and that there is also a respiration of allochthonous material.

The minimum value of net productivity in the micro-benthic community is set to the same value as at present, i.e. zero, indicating a high input of allochthonous material and a net heterotrophic system.

The maximum value of microbenthic community production is estimated by assuming another growth efficiency of benthic bacteria but assuming present primary production. Growth efficiency of bacteria is typically assumed to be c. 25% in lakes /del Giorgio et al. 1997b/. However, in some reports, growth efficiency as high as 50% has been encountered /del Giorgio and Cole 1998/. A theoretical maximum net productivity of the benthic micro-community was estimated by assuming present primary production and bacterial respiration calculated from bacterial production with a growth efficiency of 50%. This result in a net productivity of the micro-benthic community of 1.6×10^{-2} kg C m^{-2} y^{-1} in the photic zone (or by assuming the same biomasses as at present: 2.2 kg C kgC^{-1} y^{-1}).

Aqu_prod_pp_plank in lakes

Aqu_prod_pp_plank represents the net productivity of the pelagic community.

The integrated primary production of phytoplankton to 1.5 m depth (2.4×10^{-2} kg) was used as a measure of primary production for all future lakes (further described in Section 3.10). Although some future lakes will be shallower and others deeper, no correction has been made for depth, but the estimate is assumed to be reasonable for the entire photic zone. Most primary production occurs in the upper part of the pelagic habitat and primary production of phytoplankton has been shown to be directly proportional to light /Wetzel and Likens 1991/. The median light extinction equation from site measurements during the period 2003 to 2008 resulting in the photic depth of 4.3 m showed that 80% of total primary production occurs in the upper 1.5 metres (Figure 11-5)

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[29] SKBdoc 1263189, access might be given upon request.

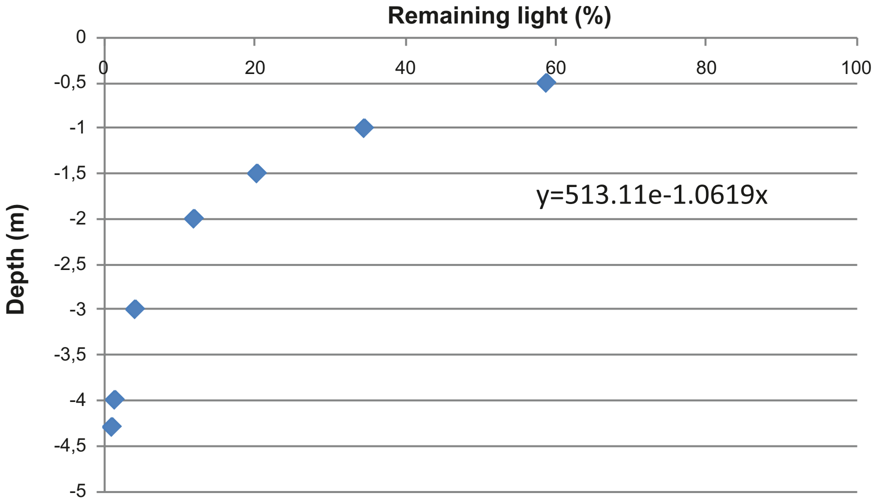

Figure 11-5. Light extinction curve from May 2005 in Eckarfjärden. This equation results in a photic depth of 4.3 m (photic depth is the depth at which 1% of the incoming light remains).

(March 2009, SICADA[30]). Thus, in lakes that are deeper than 1.5 metres, primary production may be underestimated by at most 20%. Likewise, the shallowest lake is 1 metre deep in a few time steps, and for these time steps the primary production is overestimated by up to at most 40%. However, as primary production decreases in the pelagic community it may increase in the benthic community (Aqu_prod_pp_micro and Aqu_prod_pp_macro) due to increased light conditions when water depths decreases. No cchanges are made for production in the benthic community when water depth decreases and thus it is realistic to assume the same production value as at present.

Respiration of bacterioplankton, zooplankton, fish and mixotrophic phytoplankton is calculated from site-specific measurements of biomass and secondary production together with conversion factors (Chapter 5). The depth of 1 m (mean depth of Eckarfjärden and Bolundsfjärden) is assumed to cover the respiration of autochthonous material. Although some lakes may be deeper and thereby host larger plankton biomasses, respiration is not assumed to differ greatly from present-day respiration as most respiration occurs in the upper water column (e.g. /Coloso et al. 2008/). Moreover, much of the respiration in lakes is dependent on allochthonous material (i.e. material produced in the catchment, not in the lake), and it is assumed that the contribution of allochthonous material from the catchments will be similar in future lakes to what it is today.

The productivity parameter is used to estimate the transport of radionuclides to the sediment by incorporation in biota, i.e. biota take up radionuclides and fall to the lake floor on death, there to be subject to decomposition. The productivity parameter for the pelagic community becomes negative for all time steps, due to higher respiration than production. Therefore, this parameter is set to zero as the negative value indicates that there is a respiration of allochthonous material and not that radionuclides are transported up from the sediment.

Under present-day conditions, the pelagic systems in Forsmark are net heterotrophic, and their net productivity is set to zero (discussed above). The future pelagic habitats, on the other hand, could hypothetically be net autotrophic. Values for phytoplankton production in the literature range from 1 to 1,400 g C m^{-2} y^{-1} /Wetzel 2001/. As primary production increases, so often does respiration, so with increasing primary production there is a larger amount of exudates that may be utilized by bacteria in respiration. Therefore, it is clear that even though production may increase by 2 orders of magnitude, a coupled increased respiration dampens the effect on net productivity. It is therefore the relationship between primary production and respiration that is important for the estimate of net community production. The relationship between bacterial production and phytoplankton production in Eckarfjärden is c. 80%, which is within the range (9–305%) for oligotrophic to mesotrophic lakes reported in the literature /Wetzel 2001 and references therein/.

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[30] SKBs database SICADA, access might be given on request.

Both minimum and maximum values were set to zero, i.e. indicating a high input of allochthonous material and a net heterotrophic system. This was justified as even if NEP was calculated with maximum primary production (estimated from site data with 95% confidence interval) and minimum respiration (also based on site data), it becomes negative. This result is consistent with research in recent years concerning net heterotrophy in the pelagic habitats in the majority of lakes in Scandinavia and world wide (e.g. /del Giorgio et al. 1997b, Sobek et al. 2003, Kortelainen et al. 2006/).

Aqu_prod_pp_macro, Aqu_prod_pp_ubent, and Aqu_prod_pp_plank in streams

The productivity in streams is assumed to be identical to the productivity in lakes.

The biomass of macrophytes is similar between lakes and streams in Forsmark (see Sections 3.10.1 and 3.10.2), indicating similar net productivity in the macrobenthic community in streams and lakes. Respiration in benthic sediments in streams has been shown to be large (e.g. /Fisher and Push 2001/). Consequently, many streams are net heterotrophic although there are examples of unshaded tundra streams with low input of allochtonous matter that are net autotrophic due to high productivity of algae (e.g. /Bowden et al. 1992/). Although production by epilithic algae (living on stones) in streams may be high, it is unlikely that microphytobenthos production will be greater in combination with decreased respiration in Forsmark streams compared to the lakes. There is therefore no reason to believe that the net productivity of the micro-benthic community in the Forsmark streams should be positive and the parameter value is set to zero.

The productivity of the plankton community is, as for biomass, the same immediately downstream of the lake outlets, after which it decreases thus indicating lower primary production of phytoplankton in streams than lakes. Bacterial respiration on the other hand, may remain similar throughout the stream section. Thus there is a negative net community production and the parameter is set to zero as in the lakes.

gasUptake_C, Aqu_degass_C (kg C m^{-2} y^{-1})

These parameters represent the flux of carbon dioxide over the air-water interface. We have data to estimate these fluxes for carbon, whereas for other radionuclides and their analogues this flux is considered to be small or insignificant. The carbon flux across the air-water interface is driven by the equilibrium of CO_2 as a response to the partial pressure of the gas within the lake water and the atmosphere. This flux is mainly driven by the primary production and respiration processes that consume or release carbon dioxide. Although the uptake of CO_2 is driven by a fast uptake of CO_2 by primary producers, not all CO_2 needed for primary production is taken up from the air. Nor is all CO_2 released by respiration released to the air; CO_2 is also circulated within the lake. Even if a lake is net heterotrophic on an annual basis , i.e. dominated by gas flux from water to air, there are often periods with gas flux from the atmosphere to the water. Likewise, in autotrophic lakes dominated by a flux from air to water, there are periods with gas flux from the lake water to the air.

gasUptake_C

This flux represents the flux of carbon from the atmosphere to the lake water. Uptake and release over the water/air surface in present-day lakes has been calculated from chemical equilibria and the partial pressure of CO_2 (pCO_2) in Bolundsfjärden and Eckarfjärden over a period of 4 years (Chapter 5). The lowest and highest annual flux values in Eckarfjärden and Bolundsfjärden have been assumed to represent the range (minimum and maximum values). The influx was relatively constant (11.1 g C m^{-2} y^{-1}, std dev 1.9 g C m^{-2} y^{-1}, minimum and maximum 8.4 and 14.0 g C m^{-2} y^{-1}, respectively). The mean influx corresponds to 7% of the primary production in lakes which is similar to what was has been found in the marine area at Forsmark /Kumblad and Kautsky 2004, Aquilonius 2010/. The gasUptake in future lakes has been set to be 7% of primary production. Primary production is calculated as shown in Aqu_prod_pp_macro, Aqu_prod_pp_ubent, and Aqu_prod_pp_plank above. The parameter is expressed per unit lake area and is thus dependent on the proportion of the photic area, and thereby changes with time. Values of gasUptake for each time step and object are stored at SKBdoc 1263189[31].

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[31] SKBdoc 1263189, access might be given uponm request.

Gas influx calculated from chemical equilibria for four years in the two lakes in Forsmark seems to be normally distributed. The standard deviation is used to calculate a hypothetical minimum and maximum (95% confidence interval). These minimum and maximum gas influxes for the Lakes Eckarfjärden and Bolundsfjärden are divided by the present primary production to obtain a "gas influx per primary production" ratio that can be used for future lakes. The minimum ratio is a gas flux equivalent to 4% of primary production and the maximum ratio is a gas flux equivalent to 15% of primary production. The proportion is applied to the calculated primary production to achieve minimum and maximum gas uptake estimates for each time step and object (results are stored at SKBdoc 1263189[32]).

Aqu_degass_C

Aqu_degass_C represents the flux of carbon dioxide from the lake water to the atmosphere. Whereas the calculated influx of carbon in two present-day lakes was relatively constant (see gas_Uptake_C), the outflux varied more: between 5 and 140% of the influx (mean 6 g C m^{-2} y^{-1}, std dev 6 gC m^{-2} y^{-1}, min 1 max 20 g C m^{-2} y^{-1}) (further described in Chapter 5). The average outflux was c. 55% of the influx, indicating that the lakes are net autotrophic. However, this figure is probably only valid for the very shallow lakes of today and future lakes will most probably have a larger ouflux than influx via the air-water interface due to larger aphotic areas and thereby larger respiration. Since uptake over the air water interface was relatively constant and in good agreement with literature data, the influx was set at 7% of primary production in future lakes. Aqu_degass_C may be calculated by assuming a mass balance for the lakes, i.e. the amount of carbon entering the lake must be the same as the amount of carbon leaving the lake (equation 11-1 and 11-2):

$$\text{Inflow}_{H20} + \text{Dep}_{\text{rain}} + \text{Aqu\_gasuptake} = \text{Outflow}_{H20} + \text{Sed} + \text{Aqu\_gasrelease} \qquad (11\text{-}1)$$

By assuming that the influx and outflux of gas is mainly driven by primary production and respiration, the equation can also be written:

$$\text{Inflow}_{H20} + \text{Dep}_{\text{rain}} + \text{PP} = \text{Outflow}_{H20} + \text{Sed} + \text{Resp} \qquad (11\text{-}2)$$

where Inflow_{H20} and Outflow_{H20} are inflow and outflow of carbon via the inlets and outlets to and from the lake, Dep_{rain} is carbon deposition with precipitation, Sed is permanent carbon accumulation in sediment, PP is primary production and Resp is respiration.

We do not know the future inflow and outflow of carbon to lakes. However, equations 11-1 and 11-2 can be combined to give equation 11-3:

$$\text{Aqu\_gasrelease} = \text{Respiration} - \text{PP} + \text{Aqu\_gasuptake} \qquad (11\text{-}3)$$

In Equation 3, primary production and respiration are estimated from site data combined with photic area of future lakes. Primary production is calculated as shown in Aqu_prod_pp_macro, Aqu_prod_pp_ubent, and Aqu_prod_pp_plank. In contrast to the estimates of net productivity, respiration in the aphotic zone is included in the calculation of degass. All CO_2 production in the lakes influences the equilibrium of CO_2 and thereby the outflux of carbon from water to air, whereas not all respiration includes radionuclides. The following assumptions have been made in the calculation of the respiration of 1) the pelagic community, 2) the microbenthic community and 3) the macrobenthic community:

1) The respiration of the pelagic community (75 g C m^{-2} y^{-1}) (bacterioplankton, mixotrophic phytoplankton, zooplankton and fish) is assumed to be the same as at present per m^2 and is calculated in the same way as in Aqu_prod_pp_macro, Aqu_prod_pp_ubent, and Aqu_prod_pp_plank above, i.e. no correction has been made for depth.
2) The respiration of the micro-benthic community is calculated by assuming the same respiration of benthic bacteria in the aphotic area as in the photic area (65 g C m^{-2} y^{-1}) (see Section 3.10).

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[32] SKBdoc 1263189, access might be given uponm request.

3) The respiration of the macro-benthic fauna is calculated as the sum of benthic fauna respiraiton of aphotic and photic bottoms. For photic areas, the same assumptions were used as for Aqu_prod_pp_macro (see above). For the aphotic areas biomass from site investigations and biomass estimates on vegetation-free bottoms were used togheteher with the same conversion factors from biomass to respiration as used for the photic areas.

Equation 3 results in lower degassing than gasUptake in present lakes, which is also indicated by carbon models /Andersson and Kumblad 2006, Andersson and Brunberg 2006a/. As expected, equation 3 results in higher gas_outflux than influx in future deep lakes. However, in very shallow lakes where primary production is much larger than respiration, equation 3 gives rise to a negative gas outflux. This may be caused by the fact that more than 7% of primary production is taken up over the water/air interface, but may also be caused by underestimated respiration or by underestimated uptake from the catchment. A minimum gas outflux is therefore set to 10% of gas influx. Values of gasUptake for each time step and object are stored at SKBdoc 1263189[33].

Minimum and maximum gas release rates are calculated as above but assuming the minimum and maximum gas influxes. As the parameter depends on primary production and respiration, it changes with time, and the minimum and maximum values for each object and time step are presented in SKBdoc 1263189[34].

Aqu_df_degass

Aqu_df_degass represents the discrimination of the radionuclide C-14 in relation to its analogue C-12 in connection with diffusion across the water/air interface. There is no significant discrimination in the dissolution of C-14 gas in relation to C-12, so this parameter is set to 1.

Aqu_df_gasUptake

Aqu_df_gasUptake represents the discrimination of the radionuclide C-14 in relation to its analogue C-12 in connection with diffusion across the water/air interface. There is no significant discrimination in the dissolution of C-14 gas in relation to C-12, so this parameter is set to 1.

11.3.4 Human food parameters

Fish, crayfish and mussels are biota that is commonly consumed by humans. Other biota in the lakes – such as microbiota, macroalgae, benthic fauna and mussels – are considered unlikely as food sources. The macroalgae is mainly made up of *Chara sp.* which is not used as food, the microbiota is too small to be easily managed, and there is no record of insect larvae from freshwater aquatic systems being eaten on a regular basis.

Freshwater mussels are not eaten in Sweden today as they are considered to taste bad. The mussel *Anodonta anatina* is abundant in the lakes today, although it is not likely that it will be eaten. Firstly, it does not taste good, and secondly, the effort required to collect the mussels is considered greater than that required to collect mussels from the nearby coastal areas. Even in other parts of the world where other species of freshwater mussels have been consumed, in the past, the contribution of freshwater mussels to total diet has been small due to low energy input from the mussels /Parmalee and Klippel 1974/. Combining the facts that present species does not taste good, the effort to collect them is rather high, and that mussels have contribute only in a minor way to total diet even in other parts of the world hosting more tasteful species, leads to the assumption that mussels in the Forsmark lakes will not be utilized as a food source.

Thus, a realistic appraisal of edible food in future lakes is therefore: fish and crayfish, described in the two parameters prod_edib_fish_Lake and prod_edib_cray_Lake. As crayfish and fish populations are assumed to be affected by colder temperatures, different parameter values are given for a periglacial climate domain. A minimum depth is required to allow fish and crayfish populations in lakes and streams as these animals do not inhabit systems with poor oxygen conditions which may occur in shallow lakes and streams during winter. This depth requirement is described in the parameters z_min_prod_edib_fish_Lake and z_min_prod_edib_crayfish_Lake.

[33,34] SKBdoc 1263189, access might be given upon request.

prod_edib_fish_Lake (kgC m^{-2} y^{-1})

prod_edib_fish_Lake represents the productivity of fish normally consumed. Today, fishing in the lakes is considered minimal. Some fishing may occur, but to the authors' knowledge the local inhabitants do not use the lakes much for fishing. However, fish is widely used as a food source today, and in the future fish from the lakes may be utilized to a higher degree than at present.

Fish production was calculated from production/biomass (P/B) ratios. P/B ratios are dependent on fish size (weight and length), and an allometric relationship has been established from studies of 79 freshwater species in Canada /Randall and Minns 2000/. Several of the fish species are similar to the Scandinavian species, and the P/B ratio is well correlated to size for most animals /Banse and Mosher 1980, Downing and Plante 1993, Randall and Minns 2000/. The maximum lengths of the fish species caught in the surveying gillnets were taken from the site study at Forsmark /Borgiel 2004b/. These ranges were compared with the data from /Randall and Minns 2000/, and for each species a mean P/B was estimated for this range (see Table 3-24 in Section 3.10). This P/B ratio was multiplied by the estimated biomass per m^2 to obtain the area-specific fish production for each tabulated species in each of the studied lakes: Eckarfjärden, Fiskarfjärden, Bolundsfjärden and Gunnarsbo-Lillfjärden. The total sum of fish production for each lake was used to obtain an average fish production estimate for the area, which is 0.53 g C m^{-2} year^{-1}. The mean fish production of 0.53 g C m^{-2}–y^{-1} corresponds to 60 kg ww ha^{-1} y^{-1} and is within the reported production range for European lakes (range between 10 and 700 kg ww ha^{-1} y^{-1}). although it is 2.4 times higher than the highest production values reported for Swedish lakes for which the suggested range is 3–25 kg ww ha^{-1} /Alanärä and Näslund 1995/. However, the Swedish estimates of fish production only include fish species that are normally consumed and do not, as in our estimate, include e.g. *Crucian carp*. Different fish species are preferred in the diet in different areas of the world due to cultural differences as well as the amount of other available food sources. All edible fish species are therefore considered in our estimate, as future populations in Forsmark may utilize other species than at present. However, it is an unreasonable assumption that the entire fish production can be harvested from lake ecosystems. Different sources suggest that between 10 and 75% of the fish production can be sustainably harvested /Alanärä and Näslund 1995, Degerman et al. 1998, Näslund et al. 2000, Waters 1992/. However, it seems that the higher figure 75% is an overestimate since severe effect on fish populations has been notet at much lower catches. /Näslund et al. 2000/ and /Waters 1992/ states that 50% is the highest possible sustainable yield for a long time sustainable fish population. Since over-fishing leads to reduced catches for long time afterwards we have chosen a 50% cath of fish population to illustrate maximum annual yield. This corresponds to a sustainable yield of 0.27 g C m^{-2} y^{-1}.

The minimum and maximum production of edible fish was calculated as a 95% confidence interval from the catches in the four investigated Forsmark lakes. This resulted in a range from 0.12 to 0.41 g C m^{-2} y^{-1}.

Supporting calculations – Periglacial domain estimate

Fish production is assumed to be lower during the permafrost domain than at present. Our estimate of present-day fish productivity was 2.4 times higher than the highest value reported by /Alanärä and Näslund 1995/. The fish production values in the lower range reported by /Alanärä and Näslund 1995/ (3–25 kg ww ha^{-1}) correspond to fish production in the northern part of Sweden, i.e. with a colder climate, and could be a good estimate for the permafrost domain. However, the estimate by Näslund only includes species that are normally consumed at present. We therefore multiply the production value of 3 kg ww ha^{-1} by 2.4 (corresponding to the ratio between estimated production in Forsmark and the highest production values given by /Alanärä and Näslund 1995/. It is assumed that 50% can be sustainably harvested, resulting in an edible fish productivity of 0.01 g C m^{-2} y^{-1}.

z_min_prod_edib_fish_Lake (kgC m^{-2} y^{-1})

z_min_prod_edib_fish_Lake represents the threshold at which there can no longer be a permanent fish population in lakes. There seem to be a correlation between maximum depth and occurrence of fish and catches decrease with decreasing maximum depth of lakes and approach zero at a maximum depth of 1 m (Section 3.10.1). We have therefore posed the constraint that there are no fish in future aquatic objects if the maximum depth is less than 1 m. This results in the presence of fish in all future lakes and the larger streams (objects 101, 105, 108, 114 and 123) but not in the smaller streams. This is consistent with what could be expected from the sites today, i.e. no permanent fish populations in smaller streams but permanent fish populations in the larger nearby Forsmarksån. Fish may use smaller streams for migration, but this is not considered in the radionuclide model as they must forage there in order to have an impact on radionuclide transport.

Since the lakes in the Forsmark area have ice coverage in winter, the theoretical minimum depth that will allow for permanent fish population must be at least as deep as the ice cover. In addition, oxygen is consumed in the water below the ice so there must be sufficient additional unfrozen water depth that ensures that there is not total anoxia. The ice cover of the Forsmark lakes is c.40 cm (Borgiel and Andersson, personal observation) and it is reasonable to assume that the water depth below the ice must be at least 3 dm in the deepest parts to allow for a permanent fish population. Therefore we set the minimum of this parameter to 0.7 m. The maximum is set to 1.3 m in order to vary the parameter symmetrically.

prod_edib_cray_Lake (kgC m^{-2} y^{-1})

prod_edib_cray_Lake represents the productivity of crayfish that may be consumed by humans. There are no crayfish in the present-day shallow lakes in Forsmark but some of the future lakes in the area will be considerably deeper than the present-day lakes. In these deeper lakes, significant areas will consist of aphotic bottoms lacking microbial mats, and they can be assumed to more closely resemble other deep lakes in the region, such as Lake Erken, where crayfish are abundant. Therefore, in order to avoid underestimating potential food production in the Forsmark lakes, it has been assumed that crayfish occur and contribute to human food in lakes with a mean depth in excess of 2 metres (further discussed in z_min_prod_edib_crayfish_Lake below). Although the Swedish Board of Fisheries reports crayfish yields of 5–50 kg ha^{-1} in productive crayfish lakes /Fiskeriverket 2003/, the higher value in this range are seldom reported. In Lake Erken, which is considered to be a very good crayfish location in Uppland, 5–10 tonnes of signal crayfish (equivalent to 2–4 kg ha^{-1} or 0.015–0.03 g C m^{-2}) was caught in 2008. This is the highest catch in the lake since the crayfish plague wiped out the native noble crayfish in the 1930s (www.erkenkräftan.se). Thus, a high crayfish yield in deep future Forsmark lakes is assumed to be similar to that in Lake Erken. Although 0.03 g C m^{-2} y^{-1} is the maximum yield in Lake Erken over the last 40 years, it is chosen as a conservative value in order to avoid underestimating the importance of this food source.

The minimum crayfish yield is set to 0 as it is assumed that many of the future lakes will not contain crayfish. The maximum crayfish yield could be higher than the highest recent catch in Lake Erken. Estimated maximum catches in Lake Erken before the crayfish plague wiped out the noble crayfish population in the 1930s vary between 20 tonnes per year (www.fiskekortet.com) and 75 tonnes per year (www.erkenkräftan.se). However, such large catches were most probably not sustainable in the long-term. Moreover, there are rumours that the lake was almost empty of crayfish in the late 19th century, probably due to other diseases than the plague that came in the 1930s. Thus, although the yield in future Forsmark lakes could be very high for some years, a sustainable yield is assumed to be at most twice the present yield in Lake Erken, i.e. maximum crayfish yield is set to 0.06 g C m^{-2} y^{-1}.

Supporting calculations – Periglacial domain estimate

It is assumed that no crayfish are present in the lakes during permafrost periods as crayfish needs longer ice-free periods than those experienced in a cold periglacial climate.

z_min_prod_edib_crayfish_Lake (m)

z_min_prod_edib_crayfish_Lake represents the minimum depth of lakes to enable crayfish population. Crayfish do not occur in the present-day lakes in the Forsmark regional model area. There are two main factors which prevent crayfish from establishing in the oligotrophic hardwater lakes which are typical of the Forsmark area. Firstly, crayfish prefer stony or hard bottom substrates with a rich abundance of shelters. The thick and fluffy microbial mat and the rich *Chara* vegetation that dominate the shallow Forsmark lakes provide unsuitable substrates for crayfish, and areas with more suitable crayfish habitats in the present-day lakes are very restricted (Eva Andersson, personal observation). Secondly, crayfish are sensitive to low oxygen conditions. The Forsmark lakes show strongly reduced oxygen concentrations during periods with ice cover (see Section 3.9.1), and this is reflected in the fish community which is dominated by species tolerant to low oxygen conditions (see Section 3.10). Even if it is not possible to totally rule out a future establishment of crayfish in shallow lakes in the area, these two factors mean that there will never be more than a sparse crayfish population that will only marginally contribute to human food supply. It is likely that any future shallow lake (mean depth <2 m) in the area will develop into an oligotrophic hardwater lake, which means that crayfish production in these lakes will be insignificant. Consequently, crayfish are assumed not to occur in future shallow lakes (mean depth <2 m) and this parameter is set to 2 m.

The minimum depth of 2 m for crayfish population to be able to inhabit the Forsmark lakes is derived from discussion and is not measured at the site since no crayfish occurs today. Therefore, it is difficult to give an absolute variation of the parameter. To see the effect on Dose to humans, minimum and maximum values for this parameter was set to 1.5 and 2.5 metres in the probabilistic test of the modelling although this span is probably somewhat large.

11.4 Dose model parameterisation for Laxemar-Simpevarp

This section contains descriptions of the site-specific limnic parameters for the Laxemar-Simpevarp area. The text below describes only parameters for which the values differ from the Forsmark site (described above). Moreover, no additional parameter values describing conditions during a periglacial domain are presented for Laxemar-Simpevarp. For Laxemar-Simpevarp only deterministic radionuclide modelling was done using the central value for each parameter. No alternative parameterisation was performed for periglacial conditions for Laxemar. The resulting landscape dose conversion factors from the radionuclide modelling for the Laxemar-Simpevarp site are presented in /SKB 2010b/. For a review of the characteristics of the Laxemar-Simpevarp area the reader is referred to Chapter 4.

11.4.1 Regolith parameters

Definitions of regolith parameters are given in Section 11.3.1. The regolith at each biosphere object is described according to the conceptual model of the spatial distribution of regolith in Forsmark and Laxemar-Simpevarp. The main input for describing properties of the regolith in Laxemar-Simpevarp is the surface map of Quaternary deposits (Figure 11-1), the depth and stratigraphy model of regolith, Regolith Depth Model (RDM) /Sohlenius and Hedenström 2008/, the soiltype map /Nyman et al. 2008/ together with models of future distribution of Quaternary deposits /Brydsten and Strömgren 2010/.

The regolith can be divided into different compartments, specified according to their characteristics and location in; Aqu_regoUp, regoMid_PG, regMid_GL and regoLow. These layers exhibit specific properties, e.g. density and porosity. In this section the site-specific input data and parameter values for Laxemar-Simpevarp are presented.

Lake_z_regoup (m)

The same depth of the upper oxygenated regolith layer was assumed for the Laxemar-Simpevarp lakes as for the Forsmark lakes, i.e. 0.05 m.

Aqu_dens_regoUp (kg m^{-3})

The parameter value represents the dry bulk density of the uppermost sediments on accumulation bottoms in the limnic and marine areas, represented by soft organic sediment with very high water content. The dry bulk density of regolith at accumulation bottoms was calculated based on results from analyses of clay gyttja sampled by /Fredriksson 2004/ at the floor of Borholmsfjärden. The parameter value are based on measurements of water content and content of organic material. For the calculation of dry bulk density it was assumed that the pore volume is water saturated, and the organic and minerogenic materials have densities of 1 and 2.65 g cm^3 respectively. Mean, minimum and maximum values of the parameter for dry bulk density in the upper regolith (Aqu_dens_regoUp) are presented in Table 11-21.

Table 11-21. The parameter values for Aqua_dens_regoUp for Laxemar-Simpevarp, representing the dry bulk density of the surface sediments in the aquatic system.

Dry bulk dens	kg m^{-3}
Mean	96.1
Max	153.5
Min	66.0
Std	17.8
n	58

Aqu_poro_regoup (m^3 m^{-3})

Aqu_poro_regoup represents the porosity of the uppermost sediments at accumulation bottoms in the limnic and marine areas. The porosity of regolith at accumulation bottoms was calculated based on results from analyses of clay gyttja sampled by /Fredriksson 2004/ at the floor of Borholmsfjärden. The parameter value are based on measurements of water content and content of organic material. For the calculation of porosity it was assumed that the pore volume is water saturated, and the organic and minerogenic materials have densities of 1 and 2.65 g cm^3 respectively. Mean, minimum and maximum values of the parameter for porosity in the upper regolith (Aqu_poro_regoup) are presented in Table 11-22.

Aqu_z_regoMid_GL (m)

The depth and distribution of Aqu_z_regoMid_GL is regarded as constant over time, covering the till and bedrock surface from the deglaciation onwards. The depth of this layer is specific for each object, based on the RLDM /SKB 2010b, Brydsten and Strömgren 2010/. Mean values of Aqu_z_regoMid_GL prior to isolation for the basins range between 0.08 abd 0.43 m The mean depths of regomidGL for each basin prior to isolation are shown in Table 11-23.

Table 11-22. The parameter values for pososity of the top sediment in accumulation bottoms in the aquatic systems for Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.95
Max	0.96
Min	0.92
Std	0.01
n	58

Table 11-23. Mean depth, in m, of the lower regolith (Aqu_z_regoMid_GL) in the Laxemar-Simpevarp objects.

Object	mean
Basin 201	0.31
Basin 202	0.16
Basin 203	0.19
Basin 204	0.23
Basin 205	0.16
Basin 206	0.18
Basin 207	0.17
Basin 208	0.43
Basin 209	0.14
Basin 210	0.16
Basin 211	0.08
Basin 212	0.08
Basin 213	0.09
Basin 214	0.16
Basin 215	0.20
Basin 216	0.11

Aqu_dens_regoMid_PG (kg m^{-3})

The postglacial clay in the Laxemar-Simpevarp area contains a significant amount of organic material and is therefore referred to as clay gyttja (see /Sohlenius and Hedenström 2008/). The calculation of dry bulk density is based on results from analyses of water content and organic carbon content of clay gyttja. For these calculations it was assumed that the organic carbon and minerogenic materials have densities of 1 and 2.65 g cm^3 respectively. Altogether 42 samples from lakes and shallow bays /Nilsson 2004/ were used to determine the density of postglacial clay. The mean, maximum and minimum values of the parameter (Aqu_dens_regoMid_PG) are presented in Table 11-24.

Aqu_dens_regoMid_GL (kg m^{-3})

The dry bulk density of glacial clay is based on calculations from analyses of water content and content of organic material. For these calculations it was assumed that the organic and minerogenic materials have densities of 1 and 2.65 g cm^3 respectively. Altogether 11 samples from /Sohlenius et al. 2006/ and /Nilsson 2004/ were used for estimating the dry bulk density. The samples were taken from lakes and shallow bays, but also from machine dug trenches in the terrestrial part of the Laxemar-Simpevarp area. The mean, maximum and minimum values of the parameter (Aqu_dens_regMid_GL) are presented in Table 11-25.

Aqu_poro_regoMid_PG (m^3 m^{-3})

The postglacial clay in the Laxemar-Simpevarp area contains a significant amount of organic material and is therefore referred to as clay gyttja (see /Sohlenius and Hedenström 2008/). The calculation of porosity is based on results from analyses of water content and organic carbon content of clay gyttja. For these calculations it was assumed that the pore volume is water saturated, and the organic carbon and minerogenic materials have densities of 1 and 2.65 g cm^3 respectively. Altogether 42 samples from lakes and shallow bays /Nilsson 2004/ were used to determine the porosity of postglacial clay. The mean, maximum and minimum values of the parameter (Aqu_poro_regoMid_PG) are presented in Table 11-26.

Table 11-24. The parameter values of Aqu_dens_regoMid_PG, representing the dry bulk density of postglacial clay gyttja in Laxemar-Simpevarp.

Dry bulk dens	kg m^{-3}
Mean	181
max	394
min	76
Std	0.06
n	42

Table 11-25. The parameter values for Aqua_dens_regoMid_GL, representing the dry bulk density of glacial clay in Laxemar-Simpevarp.

Dry bulk dens	kg m^{-3}
Mean	696
Max	1,053
Min	446
stdev	171
n	11

Table 11-26. Parameter values for Aqua_poro_regoMid_PG, representing the porosity of postglacial clay gyttja in Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.9
Max	0.94
Min	0.75
Std	0.03
n	42

Aqu_poro_regoMid_GL (m^3 m^{-3})

The porosity of glacial clay is based on calculations from analyses of water content and content of organic material. For these calculations it was assumed that the pore volume is water saturated, and the organic and minerogenic material have densities of 1 and 2.65 g cm^3 respectively. Altogether 11 samples from /Sohlenius et al. 2006/ and /Nilsson 2004/ were used for estimating the porosity. The samples were taken from lakes and shallow bays, but also from machine dug trenches in the terrestrial part of the Laxemar-Simpevarp area. The porosity values for glacial clay are based secondary calculations from grain size distribution curves of clay collected offshore at Forsmark /Risberg 2005/ and calculations based on analyses of water content and organic carbon content in glacial clay from lakes /Hedenström 2004/. The parameter values for the parameter (Aqu_poro_regoMid_GL) are presented in Table 11-27.

Lake_z_regoLow (m)

Lake_z_regoLow represents the total depth of the glacial till. The depth and distribution of this layer are constant over time, covering the bedrock surface from the deglaciation onwards. Mean values for each lake basin after isolation are used in the model. Mean, minimum, and maximum values of the depth of the Lake_z_regoLow are presented in Table 11-28.

Table 11-27. Parameter values for Aqua_poro_regoMid_GL and Ter_poro_regoMid_GL, representing the porosity of glacial clay in Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.74
Max	0.83
Min	0.60
stddev	0.07
n	11

Table 11-28. Mean, minimum and maximum depth (m) of the lower regolith (z_regolow) in the Laxemar-Simpevarp objects.

Object	mean	minimum	maximum
Basin 201	1.16	0.94	1.66
Basin 202	0.94	0.94	1.66
Basin 203	0.97	0.94	1.66
Basin 204	1.11	0.94	1.66
Basin 205	1.13	0.94	1.66
Basin 206	1.60	0.94	1.66
Basin 207	1.01	0.94	1.66
Basin 208	1.55	0.94	1.66
Basin 209	1.35	0.94	1.66
Basin 210	1.19	0.94	1.66
Basin 211	1.66	0.94	1.66
Basin 212	1.48	0.94	1.66
Basin 213	1.31	0.94	1.66
Basin 214	1.26	0.94	1.66
Basin 215	1.43	0.94	1.66
Basin 216	1.21	0.94	1.66

dens_regoLow (kg m^{-3})

The till in the Laxemar-Simpevarp area has a relatively high content of gravel and stones. It has therefore not been possible to take samples with a known volume and the density of till was consequently not measured. Instead, typical bulk density values of till were taken from the literature. According to /Pusch 1973/ the dry bulk density of typical Swedish till varies between 1,850 and 2,300 kg m^3. Based on these values the average dry density of till is assumed to be 2,075 kg m^3. The parameter (dens_regoLow) values presented in Table 11-29, are means for each marine basin, prior to isolation.

poro_regoLow (m^3 m^{-3})

The parameter poro_regoLow represents the porosity of glacial till. The till in the Laxemar-Simpevarp area has a relatively high content of gravel and stones. It has therefore not been possible to take samples with a known volume and the porosity of till was consequently not measured. Instead, typical bulk density values of till were taken from the literature. According to /Pusch 1973/ the porosity of typical Swedish till varies between 0.10 and 0.25 m^3 m^{-3}. Based on these values the average porosity of till is assumed to be 0.18 m^3 m^{-3} (Table 11-30).

Table 11-29. The parameter values for dens_regoLow, representing the dry bulk density of till for Laxemar-Simepvarp.

Dry bulk dens	kg m^{-3}
Mean	2,075
Max	2,300
Min	1,850

Table 11-30. The parameter values for dens_regoLow, representing the porosity of till for Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.18
Max	0.25
Min	0.10

11.4.2 Hydrological parameters

The hydrological parameter values for Laxemar-Simpevarp were modelled using MIKE-SHE and have been derived using the same approach as described above for Forsmark. Some additional parameters were estimated directly using measurements at the site. Parameter values used in the model are presented in Table 11-31.

Table 11-31. Parameter values estimated from the MIKE SHE simulations for Laxemar-Simpevarp. The modelling and derivation of the values is further described in the section describing the values for Forsmark.

Parameter	Unit	Lake-Mire period
Lake_adv_low_mid	m y^{-1}	0.057
Lake_fract_mire	unitless	0.25
Lake_Aqu_adv_mid_up_norm	unitless	0.62
Flooding_coef	unitless	0.99
Runoff	m y^{-1}	0.87

Runoff (m y^{-1})

The runoff parameter represents the total mean annual runoff for the SDM-site model area in MIKE SHE. Of the total mean annual runoff (0.170 my^{-1}), 0.145 my^{-1} is runoff from surface streams and the rest is direct runoff to the sea via the surface or the saturated zone. The runoff was estimated by calculating a water balance based on three years of simulation, October 1, 2004 to September 30, 2007. The calculation was based on the final MIKE SHE SDM-site model /Bosson et al. 2009/. Data describing minimum, maximum and standard deviation were taken from long time series regional measurements at the station in Forshultesjön nedre (SMHI station 1619) /Larsson-McCann 2002/. The annual mean values, based on daily mean discharge during the period 1955 to 2000, were used when calculating the statistics of the runoff in the area. The calculated runoff from the MIKE SHE SDM-site model is in the same range as the long time mean annual runoff in Forshultesjön nedre.

11.4.3 Chemical and biological parameters in Laxemar

This section describes both chemical and biological parameters in limnic systems in Laxemar-Simpevarp, as they are often closely connected. These parameters are site specific and therefore differ from the Forsmark parameters although they are calculated in the same way. Parameters for Laxemar-Simpevarp are used in the LDF-calculations for Laxemar used in the comparative analysis of the Forsmark and Laxemar sites /SKB 2010b/. Below follow site-specific details and a brief descriptions of the parameters.

Lake_conc_PM (kg DW m^{-3})

Lake_conc_PM represents the concentration of particulate matter in lake and stream water. This is estimated based on site investigations of suspended particles in one lake and 6 streams in Laxemar-Simpevarp in 2007 and 2008 (n=63) (Data from SICADA[35], March 2009). In addition, on one occasion in April 2008 suspended particles were analysed with different filters and examining chemical composition of the suspended material in 3 lakes /Engdahl et al. 2008/. In the long-term investigation, the detection limit was in most cases set to 2 mg L^{-1} whereas on some occasions lower values were recorded (down to 1.3 mg L^{-1}). For dates where measurements indicated concentrations below detection limit, half the detection limit was used as an estimate of particulate matter concentration.

Monthly averages were calculated from the log-term site investigations for the lake and each stream and the annual mean concentration for each sampling site was calculated from these monthly means. Lake_conc_PM was calculated as the mean from the seven sampling sites (both lake and stream) The lake (Frisksjön) have very similar concentration of particulate matter (0.003 kg DW m^{-3}) to the 6 streams (mean 0.004 ±0.002 kg DW m^{-3}) /Engdahl et al. 2008/.

The minimum and maximum particulate matter concentrations were estimated from the 95% confidence interval assuming a normal distribution of particulate matter concentrations in Laxemar-Simpevarp. The mean, maximum and minimum values used in the dose model are presented in Table 11-32.

Table 11-32. Parameter values of particulate matter and dissolved inorganic carbon in Laxemar-Simpevarp used in the radionuclide model. In the right column measured concentrations of DIC in streams are presented as a comparison to the lake values.

	Lake_conc_PM (kg DW m^{-3})	Lake_conc_DIC (kgC m^{-3})	Measured concentration of DIC in Laxemar streams
Mean	**0.0040**	**0.0030**	0.0039
Median	0.0036	0.0023	0.0030
Minimum	0.0008	0.0015	0.0002
Maximum	0.0073	0.008	0.020

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[35] SKBs database SICADA, access might be given on request.

Lake_conc_DIC (kgC m^{-3})

Lake_conc_DIC represents the concentration of dissolved inorganic carbon (DIC) in surface waters of lakes and streams. The parameter value is set to the mean DIC concentrations in 4 lakes measured during the site investigations in Laxemar-Simpevarp (n=112 subsamples /Tröjbom and Söderbäck 2006a/). The measured concentration of DIC in streams (median 0.0030 kg C m^{-3}, mean 0.0039) is similar to that in lakes (median 0.0023, mean 0.0030) and the values for lakes have been used in the modelling of future stream objects. The DIC is much lower than in Forsmark where calcareous soils give rise to high DIC. The DIC concentrations in Laxemar-Simpevarp are as expected considering the location and soil type. Minimum and maximum values of this parameter were set to the minimum and maximum values measured in the lakes at the site. This probably results in over- and under-estimations as the measured values are only valid for a short time whereas the parameter values represent annual means. The median, mean, minimum and maximum values of dissolved inorganic carbon are presented in Table 11-34.

Photic depth (m)

The photic depth, i.e. where there is enough light for photosynthesis to occur, corresponds to the depth at which 1% of the incoming light remains. The present-day lakes in Laxemar-Simpevarp are brown water lakes and large areas of the bottoms are considered to be aphotic (i.e. with too low light intensities to allow for photosynthesis).

Photic depth may be estimated by three different methods, 1) observations of the depth distribution of primary producers, 2) Secchi depth and 3) light measurements and light extinction curves in the water column.

Reed belts surround Frisksjön but this is considered as wetlands surrounding the lake. Otherwise, investigations of macrophytes in Frisksjön show sparse examples of yellow water lily (*Nuphar lutea*) at a maximum depth of 2.1 metres and floating leaved Pondweed at 1.25 metres depth. Other macrophytes are found at shallower depths. There may be microorganisms at lower depths than 2 m but no distinct microbial mats such as those in Forsmark are found on sediment cores from the lake (personal observations in field). Therefore we consider the macrophytes investigation to indicate a maximum photic depth of c. 2 m.

Secchi depthwas determined at one occasion in mid August 2004 during the macrophyte investigation mentioned above /Aquilonius 2005/. The Secchi depth on that occasion was 1 m indicating a photic depth of 2 m, consistent with the results from the macrophyte distribution.

Light measurements in the water column in Lake Frisksjön from year 2003 to 2008 (n=47) were used to calculate photic depth (SICADA[36], March 2009). For each measuring date, a regression of light extinction was used to extrapolate the curve until only 1% of the incoming light remained. For weeks lacking measurements, a mean of the photic zone was calculated from the nearest week before and after. However, there were problems with the equipment and the resulting light extinction curves are not considered reliable. For the entire year, a photic depth of 5 metres is calculated which is more than 1 metre deeper than the much clearer Forsmark lakes. In Lake Frisksjön, the water colour is brown and 5 metre is not considered a realistic photic depth. Thus, a more realistic photic depth is set to 2 m which is estimated by macrophytes distribution and secchi depth in Lake Frisksjön.

Aqu_biom_pp_macro, Aqu_biom_pp_plank, Aqu_biom_ pp_ubent (kgC m^{-2})

These parameters represent the biomasses of benthic macroscopic and microscopic biota and pelagic biota in aquatic systems. Calculation of these parameters in the limnic stages (lake and stream) are described below whereas the parameter calculation for marine stages is presented in /Aquilonius 2010/. For the benthic communities, only the photic zone is considered, as it is assumed that the aphotic biota mainly respire allochthonous material (produced in the terrestrial ecosystem) and thereby does not influence the biotic transport of radionuclides to sediment. On a longer time scale, production in the photic zone may be transported to the aphotic zone, but in order to avoid overestimating the respiration of autochthonous material (produced within the lake and thereby

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[36] SKBs database SICADA, access might be given on request.

potentially containing radionuclides), only the respiration in the photic zone is considered. This is a conservative assumption as a higher net production allows for higher incorporation of radionuclides into biota.

The parameter is described as a mean biomass per m^2 lake area, so for Aqu_biom_pp_macro and Aqu_biom_ pp_ubent, the biomass in the photic zone is multiplied by the photic area and divided by the lake area. Pelagic biota is sometimes situated in the photic and sometimes in the aphotic zone due to continuously mixing of the water column. Therefore the entire pelagic community is included in this parameter. The parameters are dependent on lake depth and photic area and thus change over time.

Aqu_biom_pp_macro

Aqu_biom_pp_macro represents the biomass of macrobiota in the benthic habitat and is calculated as the sum of macrophytes and benthic fauna in each time step. The biomass of macrophytes in lakes is derived from a macrophyte investigation in 2004 in littoral III and is set to 1.6 gC m^{-2} in the photic area. Biomass of benthic fauna in wind-exposed littoral zone (littoral II) and light-exposed soft-bottom zone (Litoral III) was used for the photic area (for description of the littoral types, see Section 3.7).

The biomass of macrophytes and macrofauna is similar between streams and lakes i Laxemar-Simpevarp (see Section 4.10.1 and 4.10.2). Therefore, the same parameter values are used for stream as for lake. Therefore, the same parameter values are used for stream as for lake.

Aqu_biom_pp_plank

Aqu_biom_pp_plank represents the biomass of the biota in the pelagic habitat, i.e. phytoplankton, bacterioplankton, zooplankton, and benthivorous, zooplanktivorous and piscivorous fish.

Average biomasses per m^3 of phytoplankton (0.28 g C m^{-3}), bacterioplankton (0.03 g C m^{-3}) and zooplankton (0.11 g C m^{-3}) were multiplied by the average depth to obtain the biomass per m^2 (biomasses are further described in Chapters 4 and 5). Fish biomass was estimated from fish survey in four Laxemar-Simpevarp lakes and is presented per m^2. The biomasses span from 0.2 to 0.6 g C m^{-2} in the lakes and the mean of 0.4 is much lower than in Forsmark (1.1 g C m^{-2}). However, the Forsmark biomasses are considered to be high in comparison to lake size and the catches in the brown water lakes in Laxemar-Simpevarp are considered realistic for this lake type. The same depth dependence as in Forsmark has been applied to Laxemar-Simpevarp, i.e. fish can only form year round populations in lakes and streams with maximum depths above 1 m. In shallower lakes, anoxic conditions during winter are assumed to prevent stationary populations of fish.

Biomass in streams was calculated using the same data as for lakes. Bacterioplankton are assumed to be abundant in the entire stream section due to large inputs of degradable allochthonous material. Phytoplankton and zooplankton biomass, on the other hand, differs a great deal along the stream section. Immediately downstream of the lake outlet, the biomasses of phytoplankton and zooplankton are very similar to the biomasses in the lake. Further downstream from a lake outlet, the phytoplankton biomass becomes smaller. In larger streams there may be an active phytoplankton and zooplankton community. Assuming the same phytoplankton biomass as in lakes may lead to a slight overestimation of radionuclide incorporation, but this should not have any large influence on the model considering the shallow depth of most streams in the model.

Aqu_biom_ pp_ubent

Aqu_biom_ pp_ubent represents the biomass of microbiota (microphytobenthos and benthic bacteria) in and on photic lake bottoms.

The biomass of microphytobenthos is considered to be insignificant in comparison to the biomass of heterotrophic bacteria in these brown-water lakes. As discussed in the section on photic depth, no visible green layers (i.e. algal mats) are found on the sediments of Frisksjön. Although microphytobenthos are found in low light intensities the biomass should be very small in comparison to the biomass of heterotrophic bacteria and thus is excluded from the estimate here. The biomass of heterotrophic bacteria on photic bottoms is taken from investigations in Frisksjön and is set to 5 g C m^{-2} which is close to the estimated benthic bacterial biomass in Forsmark (4 g C m^{-2}).

The biomass of the microphytobenthos in streams is probably larger than in the lakes considering the much shallower depths. The biomass of the microbiota depends on many factors: flow rates, nutrients, temperatures and catchment characteristics. In arid regions where streams have little riparian vegetation, autotrophic production may be the major energy input, but in temperate regions with conifer catchments (as in Laxemar-Simpevarp), energy input is dominated by allochthonous inputs /Lamberti 1996/. In the latter areas, year-round shading by conifers probably limits autotrophic production. However, as the biomass of phytoplankton is probably over estimated (see above) no adjustments for streams are made considering biomasses of microbiota.

Aqu_prod_pp_macro, Aqu_prod_pp_plank, Aqu_prod_pp_ubent (kgC kgC^{-1} y^{-1})

These parameters represent the net productivity of the macro-benthic, planktonic and microbenthic communities. Only the photic zone is considered, as it is assumed that the aphotic biota mainly respire allochthonous material and thereby does not influence the incorporation of radionuclides and subsequent biotic transport of radionuclides to sediment. On a longer time scale, production in the photic zone may be transported to the aphotic zone, but in order to avoid overestimating the respiration of autochthonous material (containing radionuclides), only the respiration in the photic zone is considered. The net production in the photic zone is divided by the lake area to achieve a mean net productivity per unit lake area. In the radionuclide model, the parameter is presented per biomass of respectively community (macrobenthic, plantkonic and microbenthic), i.e. the net productivity per unit area is divided by the biomass per unit area.

Aqu_prod_pp_macro

Since the majority of the macrophyte community is composed of annual species, the annual production of macrophytes is assumed to equal maximum biomass (1.6×10^{-3} kg C $m^{-2}y^{-1}$). Respiration by benthic fauna in the photic zone (2.5×10^{-3} kg C $m^{-2}y^{-1}$) is estimated from site investigations of biomass and literature conversion factors (further described in Chapter 5). The net productivity becomes negative, i.e. the production by macrophytes is not sufficient to supply the growth of benthic fauna but they are dependent on other carbon sources. The incorporation of radionuclides cannot be negative and therefore net productivity of the macrobenthic community is set to 0.

The productivity in streams is assumed to be the same as the maximum biomass. The biomass of macrophytes is similar between lakes and streams in Forsmark (see Sections 3.10.1 and 3.10.2), so this is a reasonable assumption. Biomass of benthic fauna is similar between lakes and streams in Laxemar-Simpevarp. Therefore, respiration of benthic macrofuana was assumed to be the same in lakes and streams.

Aqu_prod_pp_plank

Primary production has not been measured in the lakes in Laxemar-Simpevarp. Instead production was estimated from literature. Correlation graphs between chl *a* and production and between phosphorus concentration and production presented by /Nürneberg and Shaw 1999/ were used together with chl *a* concentrations and phosphorus concentrations in Frisksjön to estimate primary production in Frisksjön. This leads to a primary production of phytoplankton of 0.04 kg C m^{-2} y^{-1}.

Respiration of bacterioplankton, zooplankton, fish and mixotrophic phytoplankton was calculated from site-specific measurements of biomass together with conversion factors (Chapter 5). Only respiration in the photic zone was considered and respiration of plankton was calculated per m^3 and multiplied by depth as long as depth is below 2 m (photic depth). For lakes with mean depth above 2 m plankton respiration was multiplied by the photic depth. The net productivity for the pelagic community becomes negative for all time steps, i.e. the production by phytoplankton is not sufficient to supply the growth of pelagic fauna but they are dependent on other carbon sources. The incorporation of radionuclides cannot be negative and therefore net productivity of the planktonic community is set to 0.

In streams, the productivity of the plankton community is, as for biomass, assumed to be similar to the lake immediately downstream of the lake outlets, after which it decreases. We have assumed the same value as in the lakes, although this may be a slight overestimation of the primary production. However, this does not alter the estimate of a negative net community production.

Aqu_prod_pp_ubent

The biomass of microphytobenthos implies that the production of microphytobenthos is insignificant in comparison to bacterial respiration and accordingly the primary production by microphytobenthos is considered to be very small in comparison to bacterial respiration and this parameter is set to 0, i.e. it is negative but only positive values are considered (see above).

gasUptake_C and Aqu_degass_C (kgC m^{-2} y^{-1})

gasUptake_C and Aqu_degass_C represent the flux of carbon dioxide over the air-water interface. We have data to estimate these fluxes for carbon, whereas for other radionuclides and their analogues this flux is considered to be small or insignificant. The carbon flux across the air-water interface is driven by the equilibrium of CO_2 as a response to the partial pressure of the gas within the lake water and the atmosphere. This flux is mainly driven by primary production and respiration processes that consume or release carbon dioxide. Although the uptake of CO_2 is driven by a fast uptake of CO_2 by primary producers, not all CO_2 needed for primary production is taken up from the air. Nor is all CO_2 released by respiration released to the air; CO_2 is also circulated within the lake. Even if a lake is net heterotrophic on an annual basis , i.e. dominated by gas flux from water to air, there are often periods with gas flux from the atmosphere to the water. Likewise, in autotrophic lakes dominated by a flux from air to water, there are periods with gas flux from the lake water to the air.

These parameters are calculated somewhat differently than for the Forsmark lakes. In the Forsmark lakes, gasUptake was related to primary production. In Laxemar-Simpevarp, the gas uptake across the air/water interface is assumed to be insignificant. At 46 dates in 4 years for which gas flux across the air-water interface was calculated, only 3 dates indicated a gas uptake and the remaining 43 dates indicated gas outflux (for calculations se Chapter 5). This is consistent with the theory that Frisksjön is net heterotrophic and strongly dominated by mineralisation of terrestrial organic matter and subsequent release of carbon dioxide to the atmosphere in the lakes. Therefore the parameter gasUptake is set to 0 for the Laxemar-Simpevarp lakes.

Also Aqu-degass_C is estimated as a constant. Although respiration may occur in aphotic areas, the majority of respiration occur in the epilimnion, i.e. the upper warmer (in summer) column and only about 20% is assumed to occur in the hypolimnion /Coloso et al. 2008/. Moreover, the respiration is dependent on allochthonous carbon sources from the catchment, Regardless of depth of the lake, the amounts of DOC from the catchment is assumed to be similar and the same release over unit area as in present lake Frisksjön (0.044 kg C m^{-2} y^{-1}) is assumed to be a realistic estimate of carbon degassing also in future lakes.

Aqu_df_degass

Aqu_df_degass represents the discrimination of the radionuclide C-14 in relation to its analogue C-12 in connection with diffusion over the water/air interface. There is no significant discrimination in the dissolution of C-14 gas in relation to C-12, so this parameter is set to 1.

Aqu_df_gasUptake

Aqu_df_gasUptake represents the discrimination of the radionuclide C-14 in relation to its analogue C-12 in connection with diffusion over the water/air interface. There is no significant discrimination in the dissolution of C-14 gas in relation to C-12, so this parameter is set to 1.

11.4.4 Human food parameters

Fish and crayfish are limnic biota that is commonly consumed by humans. Other biota in the lakes – such as microbiota, macrophytes, benthic fauna and mussels – is considered unlikely as food sources. There are no macroptytes in the limnic ecosystems of Laxemar-Simepvarpthat are utilised as a food source, the microbiota is too small to be easily managed, and there is no record of insect larvae from freshwater aquatic systems being eaten on a regular basis.

Freshwater mussels are not eaten in Sweden today as they are considered to taste bad. The mussel *Anodonta anatina* is found in the lakes today, although it is not likely that it will be eaten. Firstly, it does not taste good, and secondly, the effort required to collect the mussels is considered greater than that required to collect mussels from the nearby coastal areas. Even in other parts of the world where other species of freshwater mussels have been consumed in the past, the contribution of freshwater mussels to total diet has been small due to low energy input from the mussels /Parmalee and Klippel 1974/. Combining the facts that present species does not taste good, the effort to collect them is rather high, and that mussels have contribute only a minor part of total diet even in other parts of the world hosting more tasteful species, leads to the assumption that mussels in the Laxemar-Simpevarp lakes will not be utilised as a food source.

Thus, a realistic appraisal of edible food in future lakes is therefore: fish and crayfish, described in the two parameters prod_edib_fish_Lake and prod_edib_cray_Lake. A minimum depth is required to allow fish and crayfish populations in lakes and streams as these animals do not inhabit systems with poor oxygen conditions which may occur in shallow lakes and streams during winter. This depth requirement is described in the parameters z_min_prod_edib_fish_Lake and z_min_prod_edib_crayfish_Lake.

prod_edib_fish_Lake (kgC m^{-2} y^{-1})

The parameter prod_edib_fish_Lake represents the productivity of fish normally consumed. Today, fishing in the lakes is considered minimal. Some fishing may occur, but to the authors' knowledge the local inhabitants do not use the lakes much for fishing. However, fish is widely used as a food source today, and in the future fish from the lakes may be utilized to a higher degree than at present.

Fish production was calculated from production/biomass (P/B) ratios. P/B ratios are dependent on fish size (weight and length), and an allometric relationship has been established from studies of 79 freshwater species in Canada /Randall and Minns 2000/. Several of the fish species are similar to the Scandinavian species, and the P/B ratio is well correlated to size for most animals /Banse and Mosher 1980, Downing and Plante 1993, Randall and Minns 2000/. The maximum lengths of the fish species caught in the surveying gillnets were taken from the site study at Laxemar-Simpevarp (see Section 4.10). These ranges were compared with the data from /Randall and Minns 2000/, and for each species a mean P/B was estimated for this range. This P/B ratio was multiplied by the estimated biomass per m^2 to obtain the area-specific fish production for each tabulated species in each of the studied lakes: Frisksjön, Jämsen, Söråmagasinet and Plittorpsgöl. The total sum of fish production for each lake was used to obtain an average fish production estimate for the area, which is 0.26 g C m^{-2} year^{-1}. The mean fish production of 0.26 g C m^{-2}–y^{-1} corresponds to 30 kg ww ha^{-1} y^{-1} and is within the reported production range for European lakes (range between 10 and 700 kg ww ha^{-1} y^{-1}), although it is high compared with the suggested range for Swedish lakes (3–25 kg ww ha^{-1}) /Alanärä and Näslund 1995/. However, the Swedish estimates of fish production only include fish species that are normally consumed and do not, as our estimate, include other species such as e.g. ruff (*Gymnocephalus cernua*). Different fish species are preferred in the diet in different areas of the world due to cultural differences as well as the amount of other available food sources. All edible fish species are therefore considered in our estimate, as future populations in Laxemar-Simpevarp may utilize other species than at present. However, it is an unreasonable assumption that the entire fish production can be harvested from lake ecosystems. Different sources suggest that between 10 and 75% of the fish production can be sustainably harvested /Alanärä and Näslund 1995, Degerman et al. 1998, Näslund et al. 2000, Waters 1992/. However, it seems that the higher figure 75% is an overestimate since severe effect on fish populations has been notet at much lower catches. /Näslund et al. 2000/ and /Waters 1992/ states that 50% is the highest possible sustainable yield for a long time sustainable fish population. Since over-fishing leads to reduced catches for long time afterwards we have chosen chosen a 50% cath of fish population to illustrate maximum annual yield. This corresponds to a a sustainable yield of 0.13 g C m^{-2} y^{-1}.

z_min_prod_edib_fish_Lake (m)

The parameter z_min_prod_edib_fish_Lake represents the threshold below whihch there can no longer be a permanent fish population in lakes. In Forsmark lakes, fish biomass approach zero at a maximum depth of 1 m, which is most likely valid also for lakes in Laxemar-Simpevarp. In shallow lakes, anoxia may occur in winter preventing stationary fish populations. We have therefore posed the constraint that there are no fish in future aquatic objects if the maximum depth is less than 1 m.

prod_edib_cray_Lake (kgC m^{-2} y^{-1})

The parameter prod_edib_cray_Lake represents the productivity of crayfish that may be consumed by humans. At present, crayfish have been observed in Lake Frisksjön, but there is no large crayfish population. In order to avoid underestimating potential food production in the Laxemar-Simpevarp lakes, it has been assumed that crayfish occur and contribute to human food in lakes with a mean depth in excess of 2 metres. The same value as in Forsmark has been used for this parameter. Although the Swedish Board of Fisheries reports crayfish yields of 5–50 kg ha^{-1} in productive crayfish lakes /Fiskeriverket 2003/, the higher values of this range are seldom reported. In Lake Erken, which is considered to be a very good crayfish location in Uppland, 5–10 tonnes of signal crayfish (equivalent to 2–4 kg ha^{-1} or 0.015–0.03 g C m^{-2}) was caught in 2008. Thus, a high crayfish yield in Laxemar-Simpevarp lakes is assumed to approach the catches in Lake Erken. Although 0.03 g C m^{-2} y^{-1} is the maximum yield in Lake Erken over the last 40 years, it is chosen as a conservative value in order to avoid underestimating the importance of this food source.

z_min_prod_edib_crayfish_Lake (m)

The parameter z_min_prod_edib_crayfish_Lake represents the minimum depth of lakes to enable crayfish populations to be sustained. Crayfish only occur as a sparse crayfish population in the Laxemar-Simpevarp model area. In Forsmark, lakes shallower than 2 metre were assumed to become oligotrophic hardwater lakes, i.e. lakes unsuitable for crayfish. In Laxemar-Simpevarp, lakes will not turn into oligotrophic hardwater lakes due to the different chemistry of regolith. However, in very shallow lakes and streams, there will be anoxia during winter preventing crayfish populations. In Laxemar-Simpevarp there are a large number of streams that will be very shallow, less than 1 dm deep in summer or even dry. These streams are assumed to be unsuitable for crayfish and a minimum depth for crayfish population is set to 0.3 m. In shallower lakes and streams single observations of crayfish may be made but the crayfish production will be insignificant.

11.5 Uncertainties in the parameterization

The site-generic parameterization is in most cases derived from investigations performed at the site. This ensures that local conditions are used to constrain the possible output from the biosphere radionuclide modelling. However, some uncertainties associated with spatial and temporal variation, and with the extrapolation of present-day site properties to the future, are discussed below.

11.5.1 Spatial and temporal variation

In the parameterization, most of the parameters include, in addition to an estimate of the central value, estimates of the standard deviation and minimum and maximum values as well in order to describe the potential variation under present-day conditions. These estimates served as a basis for a sensitivity analysis that identified the relative importance of different parameters under present-day conditions (see /Avila et al. 2010/). However, some of the field estimates have neither the spatial nor, perhaps more importantly, the temporal scope that would be desirable in a short-term perspective (e.g. 100 years). This means that the described variation for some parameters at the site does not cover the potential variation range, even though the estimated mean may be close to the true mean for a longer time period. For example, the modelling of climate parameters, such as precipitation and runoff, lacks a variation range. In the case of runoff, the variation range has been shown to be rather small, around 10% /Larsson-McCann et al. 2002/. Similarly, most of the parameters describing the regolith have a rather small range, which further emphasis the validity of using site-generic parameters rather than parameters describing a specific biosphere object, e.g. areas or volumes. For those parameters where variation is presented, a sensitivity analysis is used to explore how this variation could influence the result of the dose modelling /Avila et al. 2010/. Generally, the variation or range in the site-generic parameter statistics can be regarded as small in comparison with the uncertainties associated with the radionuclide-specific parameterization that is presented in /Nordén et al. 2010/.

11.5.2 Future conditions

The parameterization presented above is used for future conditions up to 120,000 AD covering the three climate domains: temperate, periglacial and glacial. In the glacial domain, the terrestrial area is assumed to be covered by ice /**Climate report**/. In the radionuclide modelling, the temperate estimates are also used for periglacial and global warming conditions. The changes in some parameter values in connection with shifts between temperate and periglacial domains are potentially large. In some cases, the estimated parameters together with their measures of variation will undoubtedly be valid even under permafrost conditions, e.g. the density of regolith. In other cases, the estimates will be overestimates for permafrost conditions. Still, as pointed out above, the variation generated by a changing climate will probably be subordinate to the large range found in radionuclide-specific parameterization, see the **Biosphere synthesis report** and /Avila et al. 2010/.

12 Concluding descriptions of the limnic ecosystems in Forsmark and Laxemar-Simpevarp and comparison between the two areas

The overall objective of this report was to describe the limnic ecosystem at the two sites Forsmark and Laxemar-Simpevarp. In addition, the radionuclide model for the biosphere is presented and an interaction matrix is used to illustrate how important processes in limnic ecosystems are considered in the radionuclide model.

Large quantities of data from site investigations and models have been presented in the previous chapters in order to thoroughly describe the limnic ecosystems, human impact, pools, fluxes and sinks of elements in the ecosystems. In this chapter, we summarize this knowledge in an attempt to address the special characteristics of the limnic ecosystems at each site and to identify differences between the sites. We do that by describing a typical lake in each of the two areas, including identification of the major pathways of carbon and other elements, thereby identify the functioning and the biogeochemical cycling of matter of the lakes at the two sites. In addition a short summary is given on how this knowledge on lake functioning has been used in the production of the radionuclide model and parameterisation of the model.

12.1 Characterization of the limnic ecosystems in Forsmark and Laxemar-Simpevarp

The lakes in the Forsmark and Laxemar-Simpevarp areas resemble each other in the sense that they are relatively small and shallow, but they also differ in a number of aspects. The lakes in the Forsmark area have relatively clear water and are strongly influenced by calcium-rich water and low phosphorus concentrations. They are dominated by primary producers, especially benthic macroalgae and microphytobenthos. The lakes in Laxemar-Simpevarp, on the other hand, are strongly influenced by humic substances transported to the lake from the surrounding catchment. This leads to a brown water colour and a dominance of consumers, especially benthic bacteria.

12.1.1 Lake size and influence of the catchment

The lakes in both Forsmark and Laxemar-Simpevarp can be considered to be small (Table 12-1). The mean lake area is similar in the two areas, while the mean depth of the Forsmark lakes is considerably shallower than the mean depth of the Laxemar-Simpevarp lakes, leading to smaller lake volumes in Forsmark.

The catchments in both Forsmark and Laxemar-Simpevarp are dominated by forest, but the influence of wetlands is higher in the Forsmark area. Lakes in the Laxemar-Simpevarp area are strongly influenced by humic substances produced in the terrestrial parts of the catchment, leading to brown-water systems. The Forsmark lakes are, on the other hand, strongly influenced by the calcareous soils transported into the area during the last glaciation.

Catchment size influences the water retention time in lakes, and retention time is generally longer in the Laxemar-Simpevarp lakes than in the Forsmark lakes. A long retention time increases the chance that elements entering the lake will be incorporated into the food web. However, there is a wide range in retention times for the Forsmark lakes, which makes it difficult to draw any general conclusions for the area concerning the influence of lake retention time.

Table 12-1. Median and mean values for morphometry parameters in lakes in the Forsmark and Laxemar-Simpevarp areas. Data for Forsmark is based on 25 lakes (Table 3-8) and data for Laxemar-Simpevarp is based on 5 lakes (Table 4-6).

Parameter	Median lake		Mean lake		Range	
	Forsmark	Laxemar-Simpevarp	Forsmark	Laxemar-Simpevarp	Forsmark	Laxemar-Simpevarp
Area (km^2)	0.05	0.10	0.12	0.11	0.01–0.75	0.03–0.24
Max depth (m)	1.0	4.9	1.2	5.6	0.4–2.2	2.0–10.9
Mean depth (m)	0.3	2.0	0.4	2.4	0.1–0.9	1.1–3.7
Volume (Mm^3)	0.01	0.199	0.053	0.290	0.002–0.374	0.029–0.877
Retention time (days)	44	275	76	397	5–328	218–829

12.1.2 Water chemistry

Lakes in Forsmark and Laxemar-Simpevarp differ considerably in their chemical characteristics (Table 12-2). The water chemistry of the lakes in Forsmark is very uncommon compared with lakes in the rest of Sweden, while the water chemistry in the Laxemar-Simpevarp lakes is typical of boreal forest lakes. The water chemistry in the streams at both sites resembles the water chemistry in the lakes and, accordingly, the stream water chemistry differs between the two sites.

The water chemistry of the Forsmark lakes is strongly influenced by the calcareous soils, leading to high pH and high conductivity. The ions are strongly dominated by calcium and carbonate (HCO_3). The high calcium concentration leads to precipitation of $CaCO_3$ and co-precipitation of phosphorus. This, in turn, leads to low phosphorus concentration in the lakes. The concentration of nitrogen and dissolved organic carbon (DOC) is high, even higher than in the brown-water lakes in Laxemar-Simpevarp. The high DOC concentration in combination with the moderate water colour in the Forsmark lakes is especially unusual, and it indicates that much of the DOC is produced within the lakes.

Table 12-2. Water chemistry for the average Forsmark and Laxemar-Simpevarp lakes. Data from Table 3-16 and 4-16 (originally from /Tröjbom and Söderbäck 2006a, b/).

	Mean	Mean	Range	
	Forsmark	Laxemar-Simpevarp	Forsmark	Laxemar-Simpevarp
Element				
pH (unit)	7.94	7.01	6.31–9.52	6.22–8.01
Conductivity (mS m^{-1})	45	13	17–450	9.4–18
Tot-P (mg/l)	0.012	0.019	0.0044–0.039	0.0054–0.043
Tot-N (mg/l)	1.1	0.92	0.33–3.7	0.52–1.3
TOC (mg/l)	17	15	5.5–35	8.6–25
Fe (mg/l)	0.094	0.86	0.0069–0.67	0.031–2.0
Mn (mg/l)	0.034	0.051	<0.003–0.64	<0.003–0.22
Cations				
Ca (mg/l)	49	8.8	13–130	6.3–13
Mg (mg/l)	5.4	2.6	0.70–26	1.9–4.3
Na (mg/l)	23	10	1.4–210	2.7–17
K (mg/l)	2.8	1.7	0.73–9.6	0.86–2.9
Anions				
Cl (mg/l)	38	14	0.90–430	7.6–24
HCO_3 (mg/l)	160	18	46–370	11–48
F (mg/l)	0.27	0.69	<0.2–3.1	<0.2–1.5
Br (mg/l	<0.2	<0.2	<0.2–12	<0.2–0.50
I (mg/l)	0.0073	0.019	<0.001–0.026	0.0040–0.033

The Laxemar-Simpevarp lakes also have relatively high pH values, and, although lower than in the Forsmark lakes, the pH values in the Laxemar-Simpevarp lakes are somewhat higher than the mean regional pH value for Kalmar County /Wilander et al. 2003/. Cations in the Laxemar-Simpevarp lakes are dominated by sodium followed by calcium, while anions are dominated by carbonate and chlorine. Concentrations of nitrogen and DOC are high. The lakes are brown-water systems influenced by humic substances, which explains the high DOC concentrations. The rich occurrence of humic substances also leads to high concentrations of iron and manganese, and, accordingly, these elements are more abundant in the Laxemar-Simpevarp lakes than in the Forsmark lakes.

Lakes in both the Forsmark and Laxemar-Simpevarp areas develop low oxygen concentrations in the bottom water during stagnant conditions, i.e. winter in the Forsmark lakes and winter and summer in Frisksjön in Laxemar-Simpevarp.

12.1.3 Biota

The composition of the biota in lakes differs considerably between the two areas, as the lakes in Forsmark are strongly dominated by primary producers, whereas Frisksjön in Laxemar-Simpevarp is strongly dominated by consumers (Table 12-3). The microbiota in the Forsmark lakes is, although common in the coastal areas in Upland, unique for the rest of Sweden and worldwide, whereas the lake biota in the Laxemar-Simpevarp area is typical of boreal forest lakes in Sweden.

The biota in the Forsmark lakes is strongly dominated by the macroalgae *Chara sp.* and in many lakes the benthic habitat is also covered by a thick microbial mat consisting of microphytobenthos and benthic bacteria. A large biomass of *Chara sp.* is found also in other hardwater lakes, both in Sweden and worldwide, and the *Chara* biomasses in the Forsmark lakes are within the values reported in the literature (e.g. /Pereyra-Ramos 1981, Blindow 1992, Kufel and Kufel 2002/). The thickness of the microbial mat in the Forsmark lakes, reaching several centimetres up to decimetres, is on the other hand unique, as most investigations of microbial mats in other lakes show values of a few mm (e.g. /Hargrave 1969, Wiltshire 2000/). The biomass of the biota in the Forsmark lakes is strongly concentrated to the benthic habitat, and the biomasses of plankton (phytoplankton, zooplankton, bacterioplankton) are low.

The biomass of biota in Laxemar-Simpevarp is also strongly concentrated in the benthic habitat and consists mainly of benthic bacteria. The total biomass of benthic bacteria and benthic fauna is similar in the Laxemar-Simpevarp and Forsmark lakes, whereas the biomass of the pelagic biota is much larger in Laxemar-Simpevarp. In both areas, the phytoplankton communities are to a large extent composed of mixotrophic species that are able to consume bacteria as an alternative energy source. This is often the case in brown-water lakes where light is a limiting factor, as well as in very nutrient-poor lakes where there is strong competition for nutrients between phytoplankton and bacteria. Thus, although the magnitude of the phytoplankton biomass differs between the Forsmark and Laxemar-Simpevarp lakes, different mechanisms lead to a similar composition of the phytoplankton community.

The fish biomass is larger in the Forsmark lakes than in the Laxemar-Simpevarp lakes, and there is also a difference in species composition. The Forsmark lakes are strongly influenced by the low oxygen concentrations during winter. As an effect of this, Crucian carp, a species resistant to low oxygen concentrations, is common in the Forsmark lakes but not in Laxemar-Simpevarp. The limnic fish community in Forsmark is also composed of species feeding on benthic fauna to a greater extent than in Laxemar-Simpevarp. This functional group is common in Laxemar-Simpevarp as well, but the fish community is also composed of piscivorous species to a higher degree.

In both areas, reed belts surrounding the lakes are extensive and the biomasses of the reed belts are high. However, to ensure a similar treatment of all areas covered by reed in the site description, the entire reed belt has been regarded as wetland in this report and is further described in /Löfgren 2010/.

Primary production in Forsmark is concentrated in the benthic habitat, whereas phytoplankton dominates primary production in the Laxemar-Simpevarp. Due to the higher phytoplankton biomasses in Laxemar-Simpevarp, pelagic primary production is larger there than in Forsmark lakes. However, due to the high benthic primary production in the Forsmark lakes, primary production is considerably larger in these lakes.

Table12-3. Biomasses of biota in habitats where they are present, i.e. in the case of phytoplankton bacterioplankton, zooplankton and fish in the pelagic habitat, and in the case of macroalgae and microphytobenthos in Littoral II and III and in the case of benthic bacteria in Littoral II, III, and profundal habitats. All data for Laxemar-Simpevarp are from Frisksjön. As regards Forsmark, all data except for benthic fauna and fish are from one lake (Eckarfjärden or Bolundsfjärden). Values for benthic fauna are means of data from two lakes (Fiskarfjärden and Bolundsfjärden), while values for fish are means of data from four lakes (Eckarfjärden, Bolundsfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden). Reed belts are treated as part of the terrestrial area in the site description and are thus not included in this compilaiton.

	Biomass		Primary production		Respiration	
	Forsmark	Laxemar-Simpevarp	Forsmark	Laxemar-Simpevarp	Forsmark	Laxemar-Simpevarp
Primary producers						
Phytoplankton (gC m^{-3})	0.04	0.28	15	20	8.4	14.5
Macroalgae (gC m^{-2})	22	–	87	–		–
Microphytobenthos (gC m^{-2})	3.8	–	56	–	–	–
Consumers						
Bacterioplankton (gC m^{-3})	0.054	0.026	–	–	39	16
Zooplankton (gC m^{-3})						
Ciliates	0.007	–	–	–	0.20	–
Heterotrophic flagellates	0.002	–	–	–	0.05	–
Metazooplankton	0.06	0.11	–	–	0.81	2.93
Fish (zooplanktivore) (gC m^{-2})	0.013	0.014		–	0.062	0.083
Fish (benthivore) (gC m^{-2})	0.84	0.29		–	5.1	1.7
Fish (carnivore) (gC m^{-2})	0.20	0.27		–	1.2	1.56
Benthic bacteria (gC m^{-2})	3.6	5.3	–	–	45	64
Benthic fauna (gC m^{-2})	0.43	0.39			2.4	2.2

In the Forsmark lakes containing a microbial mat, primary production is larger than respiration and the lakes have a positive net ecosystem production (NEP). Primary production and respiration are of equal size in the Forsmark lakes lacking a distinct microbial mat, and it is more uncertain whether the lakes have a positive or negative NEP. Mass balances for lakes in the Forsmark area indicate that the NEP depends on lake size rather than the occurrence of a microbial mat, and in the mass balances the smaller lakes have a negative NEP. In Frisksjön in Laxemar-Simpevarp, respiration is much larger than the primary production and the lake has a negative NEP. The question of positive or negative NEP is of importance for the functioning of the lake ecosystem. A positive NEP indicates that the lake is dependent on in-lake primary production and that there is a net inflow of inorganic carbon to the lakes. A negative NEP indicates that the lake is dependent on allochtonous organic carbon entering the lake ecosystem from the surrounding catchment and that there is a net outflux of inorganic carbon to the atmosphere.

12.2 Major pools, fluxes and sinks of elements in the lake ecosystems

12.2.1 Pools of elements

In both Frisksjön in Laxemar-Simpevarp and in the average Forsmark lake, the sediment contains by far the largest amount of matter in the lake ecosystem, comprising c. 99% of total weight of all elements. The elemental composition of the limnic system is similar in the two areas: aside from the components of water (hydrogen and oxygen), silicon is the most common element in the sediment (and thus also totally), followed by carbon. Due to a thicker sediment layer in Frisksjön, almost all elements are more abundant per unit area in the Frisksjön sediments than in the average Forsmark lake.

Lake water in Frisksjön contains more suspended matter, and the lake has a greater mean depth than the average Forsmark lake. The particulate components in the two areas reflect the special characteristics of the lakes. In Forsmark, carbon and nitrogen are the most abundant particulate elements, but calcium is also very abundant, illustrating the high concentration of calcium in the area. In Frisksjön, silicon is the dominant element. This is probably due to a diatom bloom during sampling and is most probably not representative of the entire year. Relatively high amounts of iron in the particulate component in Frisksjön, on the other hand, are probably representative of the entire year (iron concentrations are high in humic substances and large quantities of humic substances reach brown-water lakes such as Frisksjön).

The larger mean depth in Frisksjön than in the average Forsmark lake also leads to a larger dissolved compartments in Laxemar-Simpevarp than in Forsmark. Accordingly, the pool of elements dissolved in lake water is, for most elements, larger in Laxemar-Simpevarp than in Forsmark. Exceptions are the major ions Ca, Cl, K, Mg and Na, illustrating the high conductivity and high concentration of ions in the Forsmark lakes. This difference between Forsmark and Laxemar-Simpevarp is due mainly to two factors: 1) the calcareous soils in Forsmark, leading to high calcium levels, and 2) the younger age of the Forsmark lakes and thereby the stronger influence of marine ions.

The pool of elements in biota in both areas is dominated by carbon, but the second most common element differs between the two areas: calcium in Forsmark and nitrogen in Laxemar-Simpevarp. Calcium precipitates on the surface of the benthic macroalgae *Chara sp.* which explains the very high content of this element in Forsmark. Due to the high biomasses (macroalage and microphytobenthos) of primary producers in Forsmark, all elements are strongly concentrated in the primary producers there. In Laxemar-Simpevarp, where the lakes are heterotrophic depending on allochtonous material from the catchment, most elements are found in consumers. Elemental pools contained in benthic fauna differ between the two areas. Pools of lanthanides and non-metals in benthic fauna are of similar sizes in the two areas, while most metals and metalloids are more abundant in benthic fauna in Frisksjön than in the average Forsmark lake. One explanation for this could be the high calcium concentrations in Forsmark. Mercury, an element known for biomagnification, shows high concentration in fish in both areas. Other similarities between the areas are that rubidium and zinc are common in fish, and bromine is strongly concentrated in zooplankton.

12.2.2 Fluxes within the lake ecosystems

In both Forsmark and Laxemar-Simpevarp, the main pathway for food consumed by the top predator fish goes from benthic fauna via benthivorous fish to piscivorous fish. Thus, in both areas, the pelagic part of the food web plays a minor role in the processing and transfer of matter compared with the benthic part. However, there is a difference in the base of the food web between the two areas. In Forsmark, the benthic fauna derives most of its food from benthic primary producers, whereas in Frisksjön the benthic fauna feeds mainly on benthic bacteria.

In the Forsmark lakes, only a minor portion (7–10%) of the carbon incorporated into primary producers is directly consumed by organisms and transported upwards in the food chain. This indicates that any pollutant incorporated into primary producers would to a great extent circulate within the microbial food web. In Frisksjön, on the other hand, as much as 34% of the carbon incorporated into primary producers is consumed by higher organisms, mainly zooplankton. Thus, any pollutant incorporated into primary producers in Frisksjön has a high probability of being transported upwards in the food chain.

As the food web in both areas has its largest base in the benthic habitat (benthic primary producers and/or benthic bacteria), elements settling on the sediments have a relatively large chance of being re-incorporated into the food web.

12.2.3 Fluxes to and from the lake ecosystems

In both areas, inflow via water is the most important influx to the ecosystem for almost all elements. The relative importance of atmospheric deposition for a specific lake is a function of lake size and area of the catchment. Accordingly, in Forsmark, atmospheric deposition plays a more important role in the larger lakes than in the smaller ones. Nevertheless, the atmospheric deposition makes a small contribution to total influx in all Forsmark lakes as well as in Frisksjön in Laxemar-Simpevarp. This is because the relatively small lake areas compared to the catchment areas. On a landscape level, deposition is an important influx of elements compared to weathering whereas for lakes most deposited elements enter the lakes via water influx due to the large catchment areas, i.e. most elements deposit on land and are transported to the lakes via water (water influx).

In Laxemar-Simpevarp, the most important outflux from the lake ecosystem for most elements, and particularly for the lanthanides, is via sediment accumulation. In the average Forsmark lake as well, the most important outflux for lanthanides is via sediment accumulation, but for metalloids, metals and non-metals, outflow via water is the largest outflux. In Forsmark there is a difference between smaller and larger lakes in that outflow via water dominates in the smaller lakes, whereas sediment accumulation dominates for many elements in the larger lakes. Moreover, the results from the relatively small Lake Puttan indicate that, in addition to lake size, position within the catchment also influences which outflux that is the most important. Puttan has a very small inflow and outflow of water and elements, which means that although sediment accumulation is low, the relative contribution of sediment accumulation to the total outfluxes, is larger in Puttan than in other small lakes with larger inflows from the catchment.

Different sorption properties of elements may also influence the flow pattern. In both Forsmark and Laxemar-Simpevarp, this is clearly illustrated by the flows patterns of iodine, thorium and uranium. The inflow and outflow of the highly soluble iodine is totally dominated by in- and outflow via water. The largest outflux of thorium, which is almost immobile, is via sediment accumulation. The outflow of uranium, which has sorption properties between those of iodine and thorium, has a lower share of sediment accumulation than thorium but a higher share of sediment accumulation than iodine.

12.2.4 Sinks of elements

The ecosystem models indicate that in both Frisksjön and in larger lakes in Forsmark, the fluxes of carbon involved in the in-lake processes (primary production and respiration) are larger than the fluxes of carbon entering the lake from the catchment. This implies that there is a high probability that carbon entering the lake will be incorporated into the food web. Primary production dominates the in-lake processes in Forsmark, while bacterial processing of organic carbon dominates in Laxemar-Simpevarp. In Laxemar-Simpevarp, carbon consumption by bacteria is larger than inflowing organic carbon, which means that the models are not balanced. However, although the absolute numbers may be incorrect, the models strongly indicate that the in-lake processes are of great importance in the Laxemar-Simpevarp area. Moreover, sediment accumulation is the dominant outflux for many elements in both the larger lakes in Forsmark and in Frisksjön. The lakes in both areas are thus important sites of biogeochemical processing and may act as sinks of elements in the landscape. Some of the smaller lakes in Forsmark differ from both Frisksjön and the larger lakes in Forsmark in the sense that in-lake processes are small compared to the influx of carbon from the surroundings. For many of the smaller lakes, outflux of carbon is totally dominated by outflow via water, and these lakes probably do not functions as sinks of elements, but rather as flow-through systems. However, some of the smaller lakes, e.g. Puttan, also exhibit relatively high sediment accumulation compared with outflow. Thus, elements may be permanently bound in the sediments in the smaller lakes as well, but the amounts are most probably greater in the larger lakes.

12.3 Human impact on the limnic ecosystem

The limnic ecosystems in both Forsmark and Laxemar-Simpevarp are affected to a great degree by human activities. This is especially true for the streams at both sites, since only small portions flow in natural and unaffected channels. Most parts of the streams are highly affected by excavation and straightening, and these stretches can often be categorized as man-made ditches. Moreover, many of the lakes in the Laxemar-Simpevarp area are affected by lowering of the lake level for the purpose of creating new farmland. As an example, Frisksjön has been artificially lowered over the past few centuries by 1 m, or even more. The names of some wetlands and fields in the area indicate that a number of former lakes have disappeared. Lowering of lakes has been considerably less extensive in Forsmark; the only lake known to have been affected by lowering activities is Eckarfjärden.

A major human influence on lakes in Laxemar-Simpevarp is the construction of the Söråmagasinet reservoir. This reservoir was previously a sea bay, which was dammed during the 1970s to ensure a freshwater supply to the nuclear power plant. Occasional pumping of water from the stream Laxemarån to Söråmagasinet takes place a few days each year or every second year in order to maintain the water volume in Söråmagasinet. There are also other pumping activities that influence the limnic systems in the Laxemar-Simepvarp area: 1) since 1983, drinking and process water for the nuclear power plant (OKG) is pumped from Lake Götemar (situated north of the Laxemar subarea) in a pipeline to a water supply plant operated by OKG, 2) historically (up to 1987), water was pumped from Lake Trästen (situated west of the Laxemar subarea, upstream of Lake Fårbosjön) into Lake Jämsen, which discharges into the stream Laxemarån, in order to compensate for the pumping from Laxemarån. Historical and present-day pumping activities in the Laxemar-Simpevarp area are further described in /Werner et al. 2008/.

The largest human impact on lakes in Forsmark is the construction of a road in Lake Gunnarsbo-Lillfjärden, which divides the lake into a northern and a southern basin. The basins are connected to each other and to the outlet by pipes, which probably restrict migration possibilities for aquatic animals between the Baltic Sea and the basins. Another technical encroachment in streams, beside the examples of excavation and straightening mentioned above, is conducting stream water via pipes under roads, which may introduce barriers for migration of fish and other organisms between lakes. Man-made technical encroachments in streams at the two sites, such as installation of pipes (of the necessary diameter, length and height for water to descend to the substrate), construction of dams and filling of channels are described in detail in /Carlsson et al. 2005a, b/.

Today, the areas have few inhabitants and the lakes and streams are most probably not used for fishing or bathing to any great extent. Moreover, farmland, which may affect lakes via high nutrient inputs, comprises a relatively small portion of the catchments. Accordingly, the influence of agricultural activities on the limnic ecosystems at the sites is limited.

12.4 Long-term development of lakes

The long-term development of the limnic systems in Forsmark is considered to be driven mainly by three factors: 1) shoreline displacement, 2) successional processes (transforming lakes to terrestrial areas) and 3) climate change.

In coastal areas such as Forsmark and Laxemar-Simpevarp, isostatic land uplift, eustatic sea level variation and the resulting shoreline displacement has strongly influenced ecosystem development and is still causing continuous changes in the abiotic boundary conditions for the limnic ecosystems. Shoreline displacement in the area result in that sea bottom is uplifted and transformed into new terrestrial areas or to freshwater lakes. Thereby, new lakes are continuously formed in the landscape.

The new lakes that will form in the Forsmark area with time are assumed to closely resemble the present-day lakes although some will be larger and deeper. The newly formed lakes are by successional processes transformed to terrestrial areas by terrestrialisation. All lake ecosystems gradually matures in an ontogenetic process, which includes subsequent sedimentation and deposition of substances and vegetation growth from the edges of the lakes. Hence, the ultimate, inevitable fate of all lakes is infilling and transformation to either a wetland or a drier land area. All Forsmark lakes are assumed to become wetlands with time.

In SR-Site a reconstruction of the last glacial cycle are used to describe possible future changes in climate and climate-related processes, thus including both warmer and colder (permafrost) conditions. The effects of a climate change, from the present temperate conditions, in the limnic ecosystem are for many processes hard to predict since ecosystems are complex with multiple interactions. However, although net ecosystem production may remain similar between different climate conditions, higher organisms (i.e. fish and crayfish) are assumed to be strongly influenced by colder climate.

12.5 Processes of importance to the safety assessment SR-Site

The identification and handling of features, events and processes that are important for transport and accumulation of radionuclides in the environment is also of importance in the assessment of human health and the safety of the environment. The knowledge of ecosystem functioning in limnic, marine and terrestrial ecosystems has been used in the identification of processes that may be of importance for radionuclide transport accumulation and exposure. Ecosystems are complex systems with a large number of structures and functions, and the number of interactions within an ecosystem is immense. A large number of ecosystem properties has been described (Chapters 3 and 4) and quantified for a number of ecosystems at both Forsmark and Laxemar-Simpevarp (Chapter 5, 6 and 7). Additionally, an historic aspect has also been included in order to deepen the understanding of the present configuration of the landscape and its land use (Chapter 8). Form present and historical description of the site, predictions of future development of limnic ecosystems in Forsmark are discussed taking into account shore-line development, natural succession and climate change (Chapter 8). This has resulted in a cross-validated site description of Forsmark and Laxemar-Simpevarp. Corresponding descriptions of the marine and terrestrial ecosystems are found in /Aquilonius 2010/ and /Löfgren 2010/.

The interaction matrix (IM), described in Chapter 9, is a practical tool to display components and pathways that may potentially affect radionuclide accumulation and exposure. The systematic approach of using an IM to identify relevant processes and interactions may save valuable time in an assessment context and also ensure that relevant processes are included, both in site investigations as well as in the radionuclide modelling. The comparison in Chapter 9 includes subjects that are only partly or not treated at all in this report. For example hydrological fluxes have only been briefly handled in this report and are described elsewhere e.g. /Johansson 2008, Werner et al. 2010, Bosson et al. 2010/, and sorption and desorption processes is handled by /Nordén et al. 2010/. This exercise suggested that all important identified interactions were considered in the radionuclide model. Figure 12-1 is a compilation of the most important process that was identified from the descriptions of ecosystems.

Ecosystem characteristics, such as biomass, net primary production, consumption and accumulation of soil organic matter, have been in focus since they are considered to be of interest in a safety assessment perspective because of their direct implication to food web transfer and long-term accumulation in the landscape. In this report these properties have been quantified, discussed and compared to national or international literature using both data from the site investigations and quantitative modelling approaches (also based on site data as far as possible). A number of other processes that are important are related to water fluxes and have direct consequences for a biological process such as decomposition and for transporting elements to and from ecosystems.

The ecosystems have also been presented in a context of developmental/successional trajectories (Chapter 8), in order to support the assumptions concerning spatial delimitation and distribution of ecosystems and ecosystem succession during an interglacial in the safety assessment. Processes involved in ecosystem succession and landscape development are also of importance for the transport and accumulation of radionuclides and are included in the radionuclide modelling although not illustrated in Figure 12-1. Parameters used in the radionuclide modelling are presented in Chapter 11 and in /Aquilonius 2010, Löfgren 2010, Nordén et al. 2010/. In some cases the correspondence between the process in Figure 12-1 and the parameters are not direct and the reader is referred to the parameter descriptions for a comprehensive description of how different parameters are used to illustrate different processes.

In conclusion, a systematic approach has been used to guarantee that the ecosystem knowledge achieved in this and other reports has been used throughout the radionuclide model development and model parameterisation.

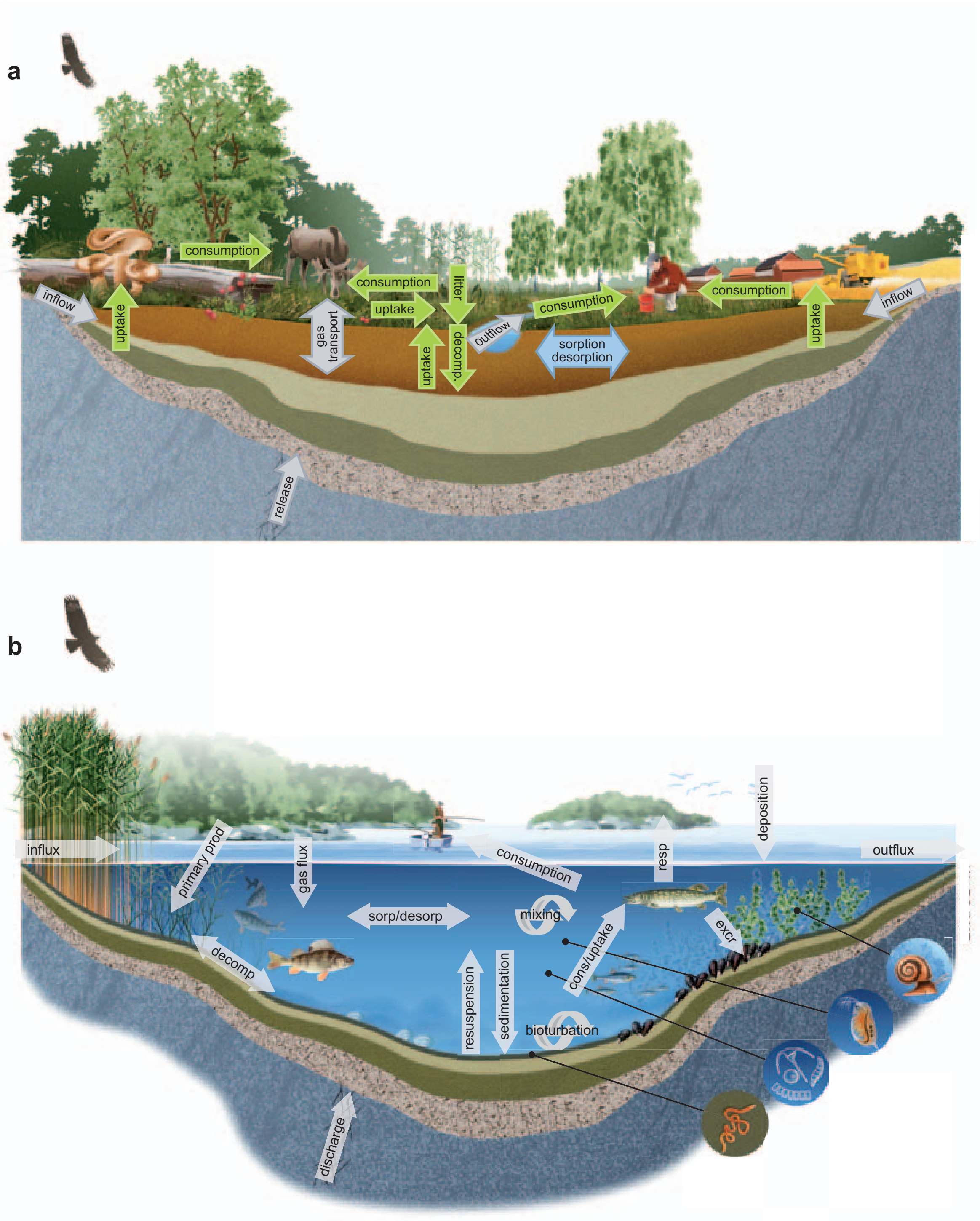

Figure 12-1. *Conceptual descriptions of important fluxes affecting the transport and accumulation of elements in a) wetland ecosystem, and b) an aquatic ecosystem and in an arable land on a drained part of a mire, where the human exposure in a safety assessment*

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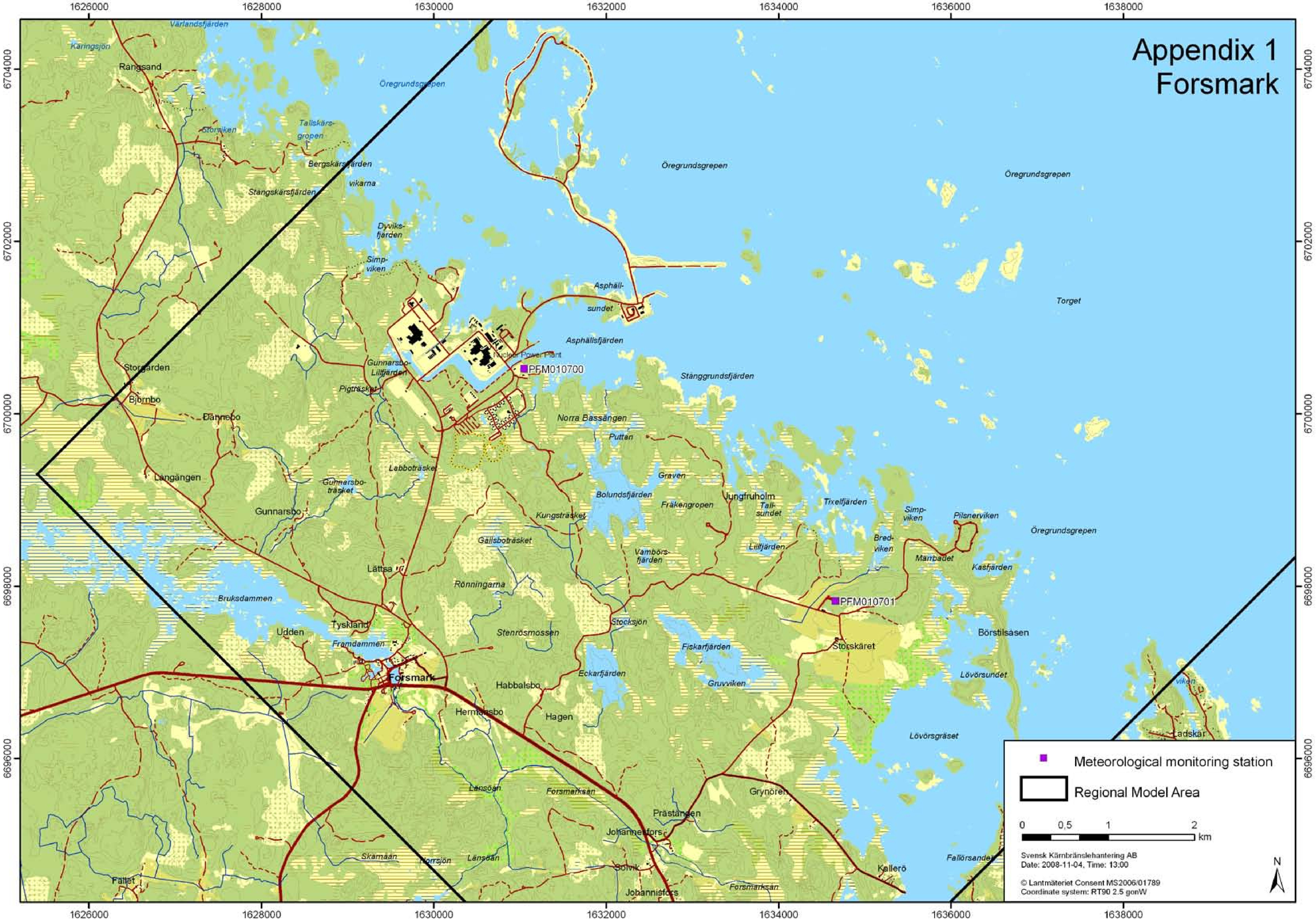
Appendix 1

Map Forsmark



Svensk Kärnbränslehantering AB
Date: 2008-11-04, Time: 13:00

© Lantmäteriet Consent MS2006/01789
Coordinate system: RT90 2.5 gonW

Map Laxemar-Simpevarp

Appendix 3

Input data table

In this table, SKB-reports used in the description and modelling of the lakes and streams are listed. In addition, site data from the database SICADA and limnic data in literature have been used in some of the models in Chapter 5 and 7. For these references, see method descriptions in the chapters.

Available data	Reference	Usage in the report	Section
Hydrology			
Discharge	P-07-135	Description	3.3
	P-07-172	Description	4.3
	R-06-49	Description	3.3
	R-08-08	Description	3.3
	R-07-55	Description and modelling	Chapter 7
	R-08-71	Description	4.3
Stream characteristics			
Flooded areas, bottom substrate, morphmetry	P-05-150	Description	3.3, 3.8
	P-04-141	Description	3.3, 3.8
	P-05-40	Description	4.8
	P-06-05	Description	4.3
Meteorologic data			
Global radiation	R-08-10	Description, modelling	3.4
	P-07-172	Description, modelling	4.4
Temperature	R-08-10	Description	3.4
	R-08-71	Description	4.4
	R-02-03	Description	4.4
Precipitation	R-08-10	Description and mass balance models	Chapter 3, 5, and 7
		Description and mass balance models	Chapter 4, 5 and 7
	R-08-73		
Snow and ice cover	P-03-117	Description, modelling	3.4, 4.4
	P-04-137	Description, modelling	3.4, 4.4
	P-05-134	Description, modelling	3.4, 4.4
	P-06-97	Description, modelling	3.4, 4.4
	P-07-81	Description, modelling	3.4, 4.4
Lake bathymetry and habitat distribution			
Habitat borders	P-04-25 and P-04-141	Description, Ecosystem models, mass balance models	3.5
	P-04-242	Description, Ecosystem models, mass balance models	4.5
Chemistry in water			
Water chemistry	R-05-41	Understanding, description and models	Chapter 3, 45, and 7
	R-06-19		
	R-06-18		
Chemistry in sediment			
Sediment stratigraphy	TR-03-17	Understanding, Description and modelling	3.6, Chapter 5 and 7
	P-04-86		
	R-01-12		
	P-03-24		
	R-08-04		
	R-08-05		

Available data	Reference	Usage in the report	Section
Sediment chemistry	P-04-17 P-04-05 P-04-273 P-06-220 R-06-96 P-06-301 P-06-320 p-07-196	Description and mass balance models	3.6, 4.6, Chapter 5 and 7
Marine sediments	P-06-301	Understanding	3.6 and 4.6
Primary producers in the Forsmark lakes			
Phytoplankton, Microphytobenthos	R-02-41	Description, modelling	3.10
	R-03-27	Description, modelling	3.10
	P-04-253	Description, modelling	4.10
Microphytobenthos	R-02-41	Description, modelling	3.10
	R-03-27	Description, modelling	3.10
	P-04-05	Description	3.10
Emergent macrophytes	R-03-27	Description, modelling	3.10
	P-06-232	Description, modelling	4.10
Submerged vegetation	P-05-136	Description	3.10
	P-06-221	Description, modelling	3.10
	P-05-173	Description, modelling	4.10
Consumers in the Forsmark lakes			
Bacteria	R-02-41	Description, modelling	3.10
	R-03-27	Description, modelling	3.10
	P-06-232	Description, modelling	4.10
	R-02-41	Description, modelling	3.10
	R-03-27	Description, modelling	3.10
Zooplankton	R-03-27	Description, modelling	3.10
	P-04-253	Description, modelling	4.10
Benthic fauna	P-05-136	Description, modelling	3.10
	R-03-27	Description	3.10
	P-04-252	Description, modelling	4.10
Fish	P-04-06	Description, modelling	3.10
	P-04-251	Description, modelling	4.10
Biota in streams			
Vegetation	P-05-40	Description	4.10
	P-05-150	Description	3.10
Fish migration	P-06-251	Description, understanding in modelling	4.10
Benthic fauna	P-04-252	Description	4.10
Chemical composition of biota	P-06-220	Description, modelling	Chapter 3, 4, 7
	P-06-320	Description, modelling	

Appendix 4

Species list

In the following table, species found in the site investigations in Forsmark (Fm) and Laxemar-Simpevarp (L-S) are listed. Data are gathered from SKB-reports (Appendix 3) and in some cases from the database SICADA (microphytobenthos and phytoplankton in Forsmark). For fish, species in the Forsmark region (Section 3.12) are also listed.

Latin name	English namne	Swedish namne	Fm/L-S
Phytoplankton			
Bacillariophyceae	Diatoms	Kiselalger	
Aulacoseira alpigena-typ			L-S
Aulacoseira sp.			L-S
Centriska kiselalger			L-S
Cyclotella			Fm
Pennate diatoms			Fm
Rhizosolenia longiseta			L-S
Chlorophyceae	Green algae	Grönalger	
Botryococcus sp.			Fm
Crucigenia sp.			L-S
Elakotrix sp.			Fm
Elakatothrix genevensis			L-S
Monoraphidium sp.			Fm
Monoraphidium dybowskii			L-S
Monosigales			Fm
Nephrocytium			Fm
Oocystis			Fm, L-S
Pediastrum privum			L-S
Pediastrum tetras			L-S
Quadrigula sp.			L-S
Scenedesmus sp.			Fm, L-S
Scourfieldia			Fm
Tetraedon sp.			Fm
Tetraedron caudatum			L-S
Chrysophyceae	Golden algae	Guldalger	
Bikosoeca			Fm
Bitrichachodati			Fm
Bitrichia			Fm
Chrysochromulina			Fm
Chrysoikos skujai			Fm
Chrysomonadales			Fm
Dinobryon spp.			Fm
Dinobryon bavaricum			L-S
Dinobryon crenulatum			L-S
Dinobryon divergens			L-S
Kephyrion			Fm
Mallomonas akrokomos			L-S
Mallomonas tonsurata			L-S
Mallomonas caudate			L-S
Synura sp.			L-S
Uroglena sp.			L-S
Conjugatophyceae	”Jewelry algae”	Smyckesalger	
Closterium acutum var. variabile			L-S
Cryptophyceae	Cryptophytes	Rekylalger	
Chroomonas sp.			L-S
Cryptomonas spp.			Fm, L-S
Rhodomonas			Fm
Cyanophyceae	Cyanobacteria	Cyanobakterier, blågröna alger	
Anabaena			Fm
Anabaena lemmermannii			L-S
Aphanothece sp.			L-S
Chroococcus			Fm
Komvophoron			Fm
Merismopedia sp.			Fm
Merismopedia warmingiana			L-S
Microcystis aeruginosa			Fm
Oscillatoria			Fm

Latin name	English namne	Swedish namne	Fm/L-S
Dinophyceae	“Dinoflagellates”	Dinoflagellater/	
Ceratium hirundinella		Pansaralger	Fm, L-S
Gymnodinium			Fm
Peridinium sp.			Fm
Peridinium umbonatum			L-S
Peridinium willei			L-S
Woloszynskia			Fm
Euglenophyceae		Ögondjur	
Euglena			Fm
Trachelomonas sp.			L-S
Microphytobenthos			
Bacillariophyceae	Diatoms	Kiselalger	
Pennate diatoms			
Chlorophyceae	Green algae	Grönalger	
Botryococcus			Fm
Scenedesmus			Fm
Tetraedron			Fm
Cyanophyceae	Cyanobacteria	Cyanobakterier,	
Chrococcus		blågröna alger	Fm
Komvophoron			Fm
Lyngbya			Fm
Merismopedia			Fm
Oscillatoria			Fm
Konjugatophyceae			
Staurastrum			Fm
Macrophytes-Macroalgae			
Alchemilla sp.	Lady’s mantle	Daggkåpa	Fm
Alisma plantago-aquatica	Water-plantain	Svalting	Fm, L-S
Aldus glutinosa	Alder	Klibbal	Fm, L-S
Batrachospermaceae	Red algae	Rödalger	Fm
Callitriche sp.	Water-starwort	Lånke	Fm, L-S
Cardamine pratensis	Cuckooflower	Kärrbräsma	Fm
Carex sp.	Sedge	Starr	Fm, L-S
Carex acuta	Slender tufted sedge	Vasstarr	Fm
C. elata	Tufted sedge	Bunkestarr	Fm
C. nigra	Common sedge	Hundstarr	L-S
C. rostrata	Bottle Sedge	Flaskstarr	Fm, L-S
C. vesicaria	Bladder-sedge	Blåsstarr	Fm, L-S
Chara spp.	Stoneworths	Kransalger	Fm
C. baltica	Baltic Stonewort	Grönsträfse	Fm
C. tomentosa	Coral stonewoth	Rödsträfse	Fm
C. intermedia.	Intermediate stonewort	Mellansträfse	Fm
C. virgata	Delicate stonewoth	Kransalg	Fm
Equisetum fluviatile	Water horsetail	Sjöfräken	Fm, L-S
Equisetum palustre	Marsh Horsetail	Kärrfräken	L-S
Eriophorum angustifolium	Common cottongrass	Ängsull	Fm
Filipendula ulmaria	Meadowsweet	Älggräs	Fm, L-S
Fontinalis sp.	Water moss	Näckmossa	Fm
F. antipyretica	Common water moss	Stor näckmossa	Fm, L-S
F. dalecarlica	Water moss	Smal näckmossa	Fm
Galium palustre	Marsh-bedstraw	Vattenmåra	Fm, L-S
Glyceria fluitans	Floating Sweetgrass	Mannagräs	Fm, L-S
G. maxima	Reed Sweetgrass	Jättegröe	Fm, L-S
Hippuris vulgaris	Mare´s-tail	Hästsvans	Fm
Hottonia palustris	Water-violet	Vattenblink	Fm, L-S
Hydrocharis morsus-ranae	Frogbit	Dyblad	Fm
Iris Pseudocouros	Yellow Iris	Svärdslilja	Fm, L-S
Juncus sp.	Rush	Tåg	Fm, L-S
Juncus bulbosus	Bulbous Rush	Löktåg	L-S
Juncus effusus	Soft-Rush	Veketåg	L-S
Lemna minor	Common Duckweed	Vanlig andmat	Fm, L-S
Lycopus europaeus	Gypsywort	Topplösa	Fm, L-S
Lysimachia thyrsiflora	Tufted Loosestrife	Strandklo	Fm, L-S

Latin name	English namne	Swedish namne	Fm/L-S
L. vulgaris	Yellow Loosestrife	Videört (strandlysing)	Fm, L-S
Lythrum salicaria	Purple-loosestrife	Fackelblomster	L-S
Mentha arvensis	Corn mint	Åkermynta	Fm, L-S
Menyanthes trifoliata	Bogbean	Vattenklöver	Fm, L-S
Myosotis laxa	Tufted Forget-me-not	Sumpförgätmigej	Fm, L-S
Myriophyllum alterniflorum	Alternate water-milfoil	Hårlsinga	L-S
M. spicatum	Spiked Water-milfoil	Axslinga	Fm, L-S
Najas marina	Spiny Naiad	Havsnajas	Fm
Nuphar lutea	Yellow Water-lily	Gul näckros	Fm
Nymphaeaceae	Water lily	Näckros	Fm, L-S
Nymphea alba	White Water-lily	Vit näckros	L-S
Oenanthe aquatica	Fine-leaved Water dropwort	Vattenstäkra	L-S
Peusedanum palustre	Milk-parsley	Kärrsilja	Fm
Phalaris arundinacea	Reed Canary-grass	Rörflen	Fm, L-S
Phragmites australis	Common reed	Vass	Fm, L-S
Potamogeton berchtoldii	Small Pondweed	Gropnate	L-S
P. filiformis	Slender-leaved Pondweed	Trådnate	Fm
P.natan	Floating-leaved Pondweed	Gäddnate	Fm, L-S
P.pectinatus	Sago Pondweed	Borstnate	Fm
P.polygonifilus	Bog Pondweed	Bäcknate	Fm, L-S
Potentilla palustris	Marsh Cinquefoil	Kråkklöver	L-S
Ranunculus flammula	Lesser Spearwort	Ältranunkel	L-S
Rumex hydrolapathum	Water Dock	Vattenskräppa	L-S
Salix sp.	Willow	Vide	L-S
Salix caprea	Goat Willow	Sälg	L-S
Schoenoplectus lacustris	Common club-rush	Säv	Fm, L-S
Sparganium sp.	Unbranched Bur-reed	Igelknopp	L-S
S. angustifolium Michx.	Floating Bur-reed	Plattbladig igelknopp	L-S
S.emersum	Unbranched Bur-reed	Vanlig igelknopp	Fm
Typha sp.	Bulrush	Kaveldun	L-S
T. latifolia	Bulrush	Bredkaveldun	L-S
Utricularia sp.	Bladderwort	Bläddra	L-S
Purple Sulphur bacteria			
Zooplankton			
Heterotrophic flagellates			
Chrysophycae	Golden algae	Guldalger	
Monosigales			Fm
Cryptophycae			
Kateblepharis			Fm
Ciliphora	Ciliates	Ciliater	Fm
Metazooplankton			
Cladocera	Water fleas	Hinnkräftor	
Acroperus			Fm
Alonella nana			L-S
Bosmina sp			Fm
Bosmina longispina			L-S
Ceriodapnia sp.			Fm , L-S
Chydorus			Fm
Daphnia			Fm
Daphnia cucullata			L-S
Diaphanosoma sp.			Fm
Diaphanosoma brachyurum			L-S
Leptodora kindti			L-S
Copepoda	Copepods	Hoppkräftor	
Cyclopoida			Fm
Calanoida			Fm, L-S
Eudiaptomus			L-S
Mesocyclops			L-S
Thermocyclops sp			L-S
Rotifera	Rotifers	Hjuldjur	
Ascomorpha			Fm
Asplanchna sp.			Fm L-S
Collotheca			Fm
Conochilus sp.			Fm, L-S
Euchlanis			Fm

Latin name	English namne	Swedish namne	Fm/L-S
Kellicottia longispina			Fm, L-S
Keratella cochlearis			Fm, L-S
Keratella quadrata			L-S
Lecane			Fm
Ploesoma			Fm
Polyarthra			Fm
Pompholyx sp			Fm, L-S
Synchaeta sp.			Fm , L-S
Trichocerca sp.			Fm, L-S
Trichotria			Fm

Benthic fauna

Hydrozoa		Hydror	
Hydridae			Fm
Nematoda			
Nematoda			Fm, L-S
Hirudinea	Leeches	Iglar	
Erpobdella octoculata			Fm, L-S
Erpobdella sp.			Fm, L-S
Glossosiphonia heteroclita			Fm
Glossosiphonia sp.			L-S
Helobdella stagnalis			Fm
Piscicola geometra			Fm
Turbellaria	Flatworms	Virvelmaskar	
Dendrocoelum lacteum			L-S
Planaridae			L-S
Polycelis sp.			L-S
Oligochaeta	Earthworms	Fåborstmaskar	
Limnodrilus sp.			L-S
Naididae			Fm
Oligochaeta sp.			L-S
Potamotrix hammoniensis			L-S
Ripistes parasita			L-S
Stylaria lacustris			Fm
Tubifex tubifex			L-S
Tubificidae			L-S
Isopoda	Water slater	Gråsuggor	
Asellus aquaticus			Fm, L-S
Hydrocarina	Water mites	Sötvattenskvalster	
Hydracarina sp.			Fm, L-S
Aranea	Water spiders	Spindlar	
Argyroneta aquatica			L-S
Odonata	Damselflies and dragonflies	Trollsländor	
Aeshnidae			Fm
Aeshna grandis			L-S
Anisoptera			L-S
Coenagrionidae			Fm, L-S
Coenagrion sp.			L-S
Cordulidae			L-S
Cordulia aenae			Fm, L-S
Erythromma najas			L-S
Libellulidae			Fm
Platycnemidae			Fm
Platycnemis pennipes			Fm, L-S
Somatochlora metallica			L-S
Zygoptera			L-S
Ephemeroptera	Mayflies	Dagsländor	
Caenis horaria			Fm, L-S
Caenis lactea			Fm
Caenis robusta			Fm
Caenis sp.			Fm
Centroptilum luteolum			L-S
Cloeon sp.			Fm, L-S
Heptagenia fuscogrisea			L-S
Leptophlebia marginata			L-S
Leptophlebia vespertina			L-S
Leptophlebia sp.			L-S
Leptophlebia sp.			L-S
Plecoptera	Stoneflies	Bäcksländor	
Amphinemura sulcicollis			L-S
Amphinemura sp.			L-S
Nemoura cinerea			L-S
Nemoura sp.			L-S

Latin name	English namne	Swedish namne	Fm/L-S
Megaloptera	Alderflies, Dobsonflies and Fishflies	Sävsländor	
Sialis lutaria			Fm, L-S
Sialis sp.			L-S
Trichoptera	Caddisflies	Nattsländor	
Anabolia sp.			L-S
Athripsoides sp.			Fm
Cyrnus flavidus			L-S
Cyrnus sp.			Fm, L-S
Ecnomus tenellus			L-S
Glyphotaelius pellucidus			L-S
Halesus			L-S
Trichoptera			
Holocentropus			Fm
Hydropsyche angustipennis			L-S
Leptoceridae			Fm
Limnephilidae			L-S
Limnephilus sp.			L-S
Lype phaeopa			L-S
Mystacides azurea			L-S
Mystacides longicornia			Fm
Mystacides sp.			Fm, L-S
Oecetis ochracea			L-S
Oecetis sp.			Fm
Oxyethira sp.			L-S
Phryganeidae			Fm
Phryganea bipunctata			L-S
Phryganea sp.			Fm
Polycentropodidae			L-S
Polycentropus flavomaculatus			L-S
Polycentropus irroratus			L-S
Potamophylax cingulatus			L-S
Trianodes sp.			L-S
Ylodes sp.			L-S
Lepidoptera	Butterflies	Fjärilar	Fm
Coleoptera	Beetles	Skalbaggar	
Donacia sp.			Fm
Dyticidae			Fm
Gyrinus sp.			L-S
Haliplus sp.			Fm
Oulimnius tuberculatus			L-S
Oulimnius sp.			L-S
Hemiptera	True bugs	Skinnbaggar	
Gerris lacustris			L-S
Nepa cinerea			L-S
Notonecta glauca			L-S
Sigara fossarum			L-S
Diptera	True flies	Tvåvingar	
Ceratopogonidae			Fm, L-S
Chaoborus flavicans			L-S
Chaoborus sp.			L-S
Chironomidae			Fm, L-S
Chironomus anthtracinus			Fm
Cladopelma sp.			L-S
Cladotanytarsus sp.			L-S
Culicidae			L-S
Ephydridae			Fm
Heterotanytarsus apicalis			L-S
Limoniidae			L-S
Orthocladinae			Fm

Latin name	English namne	Swedish namne	Fm/L-S
Muscidae			Fm
Parachironomus sp.			L-S
Parakiefferiella sp.			L-S
Pediciidae			L-S
Pentaneurini			L-S
Phaenopsectra sp.			L-S
Polypedilum sp.			L-S
Procladius sp.			L-S
Sergentia sp.			L-S
Simuliidae			L-S
Tanypodinae			Fm
Tanytarsinae			Fm
Tanytarsus sp.			L-S
Diptera			
Tipulidae			L-S
Gastropoda	Snails	Snäckor	
Acroloxus lacustris			L-S
Bithynia tentaculata			L-S
Gyraulus albus			Fm
Gyraulus sp.			L-S
Hippeutis complanatus			L-S
Lymnea stagnalis			Fm
Lymnea peregra			Fm
Lymnea spp			Fm
Marstoniopsis scholtzi			L-S
Planorbidae			Fm
Planorbis cavinatus			Fm
Physa fontinalis			Fm
Valvata cristata			Fm
Valvata sp.			Fm
Bivalvia	Bivalves	Musslor	
Anodonta anatina			L-S
Anodonta sp.			Fm
Pisidium sp.			Fm, L-S
Sphaerium spp			Fm
Copepoda	Copepods	Hoppkräftor	
Cyclopoida			
Cladocera	Water fleas	Hinnkräftor	
Chydoridae			Fm
Diaphansosoma brachyurum			Fm
Eurycercus lamellatus			Fm
Sida crystallina			Fm
Ophryoxus gracilis			Fm
Ostracoda	Seed shrimp	Musselkräftor	Fm
Crustacea			
Astacus astacus	Noble crayfish	Flodkräfta	L-S
Pacifastacus leniusculus	Signal crayfish	Signalkräfta	L-S
Fish			
Abramis brama	Bream	Braxen	Fm region, L-S
Alburnus alburnus	Bleak	Löja	L-S
Blicca bjoerkna	White bream	Björkna	Fm
Carassius carassius	Crucian carp	Ruda	Fm
Cottus gobio	Bullhead	Stensimpa	Fm region
Esox lucius	Pike	Gädda	Fm, L-S
Gymnocephalus cernua	Ruffe	Gärs	Fm, L-S
Lampetra planeri	European brook lamprey	Bäcknejonöga	Fm region
Leuciscus idus	Ide	Id	Fm region, L-S
Lota lota	Burbot	Lake	Fm region
Perca fluviatilis	Perch	Aborre	Fm, L-S
Rutilus rutilus	Roach	Mört	Fm, L-S
Salmo trutta	Brown trout	Öring	Fm region
Scardinius erythrophthalmus	Rudd	Sarv	Fm, L-S
Tinca tinca	Tench	Sutare	Fm
Vimba vimba	Wimba	Vimma	Fm region

Appendix 5

Fish histograms

This appendix contains histograms showing length or weight distribution data for each species in the 8 lakes which has been fished during the site investigations /Borgiel 2004b, Engdahl and Ericson 2004/. Data is presented for Bolundsfjärden, Eckarfjärden, Fiskarfjärden and Gunnarsbo-Lillfjärden in the Forsmark area, and for Frisksjön, Söråmagasinet, Plittorpsgöl and Jämsen in the Laxemar-Simpevarp area.

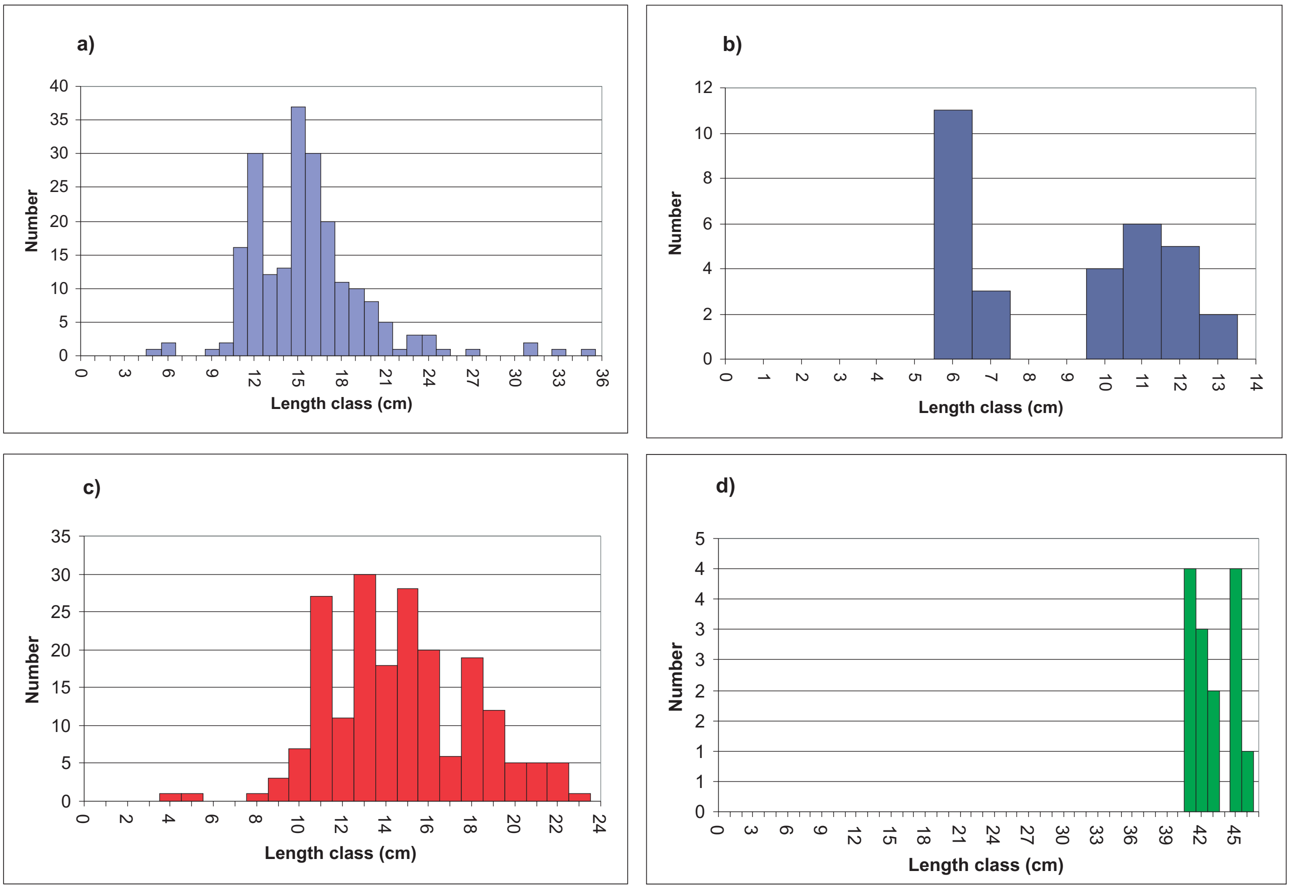


Figure A5-1. *Length frequency distribution for the most common species in Bolundsfjärden a) perch, b) ruffe, c) roach and d) tench. Species with too few replicates (not shown) were white bream (n=1), pike (n=3), crucian carp (n=4) and rudd (n=4).*

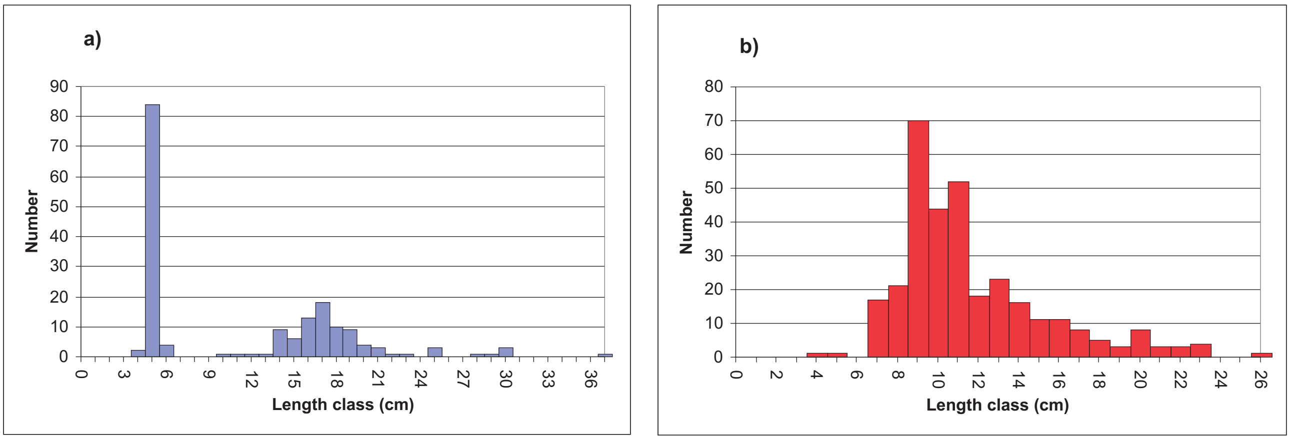


Figure A5-2. *Length frequency distribution for the most common species in Eckarfjärden, a) perch and b) roach. Species with too few replicates (not shown) were pike (n=2), ruffe (n=1) and tench (n=5) /data from Borgiel 2004b/.*

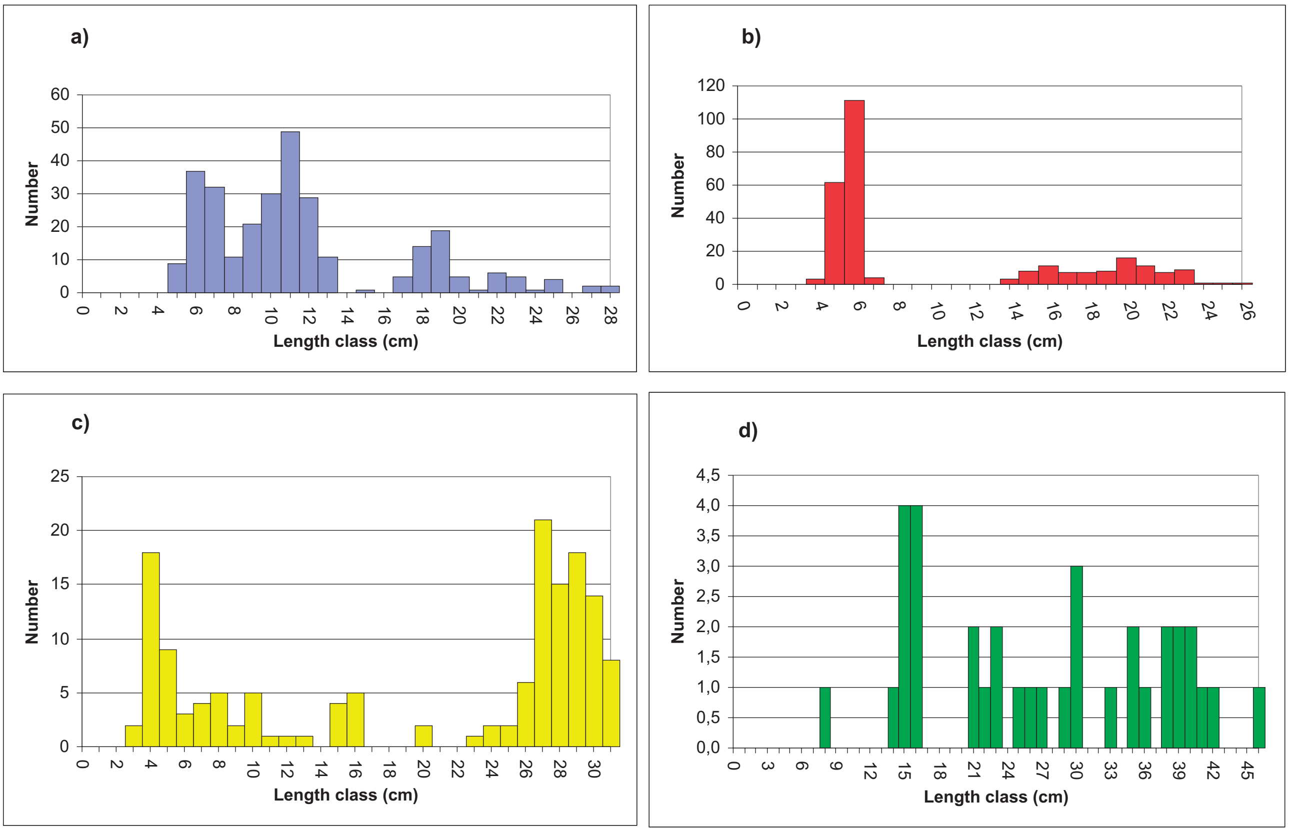


Figure A5-3. *Length frequency distribution for the most common species in Fiskarfjärden a) perch, b) roach, c) tench and d) crucian carp. Species with too few replicates (not shown) were pike (n=5) and ruffe (n=1) /data from Borgiel 2004b/.*

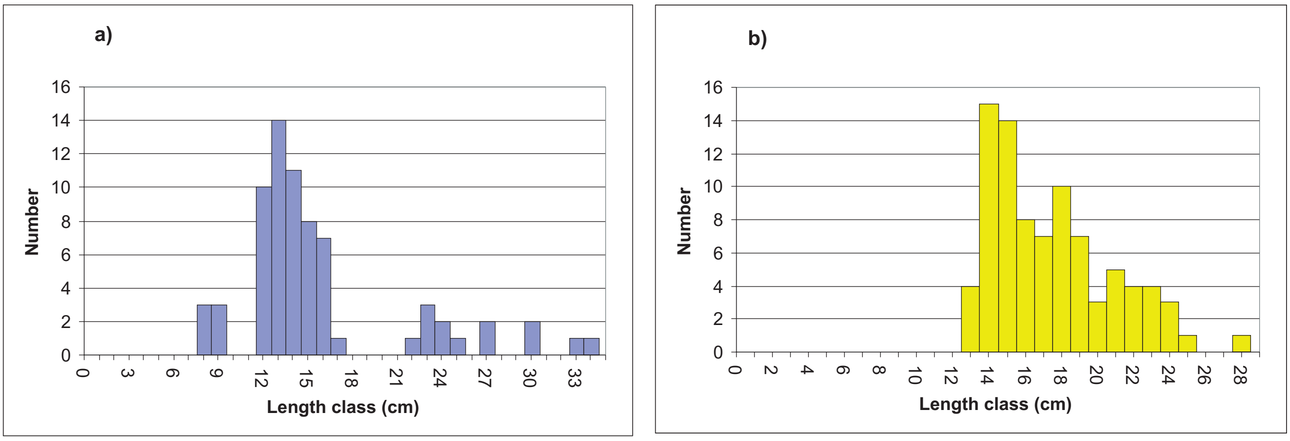


***Figure A5-4.** Length frequency distribution for the most common species in Gunnarsbo-Lillfjärden a) perch and b) crucian carp. Species with too few replicates (not shown) was roach (n=2) /data from Borgiel 2004b/.*

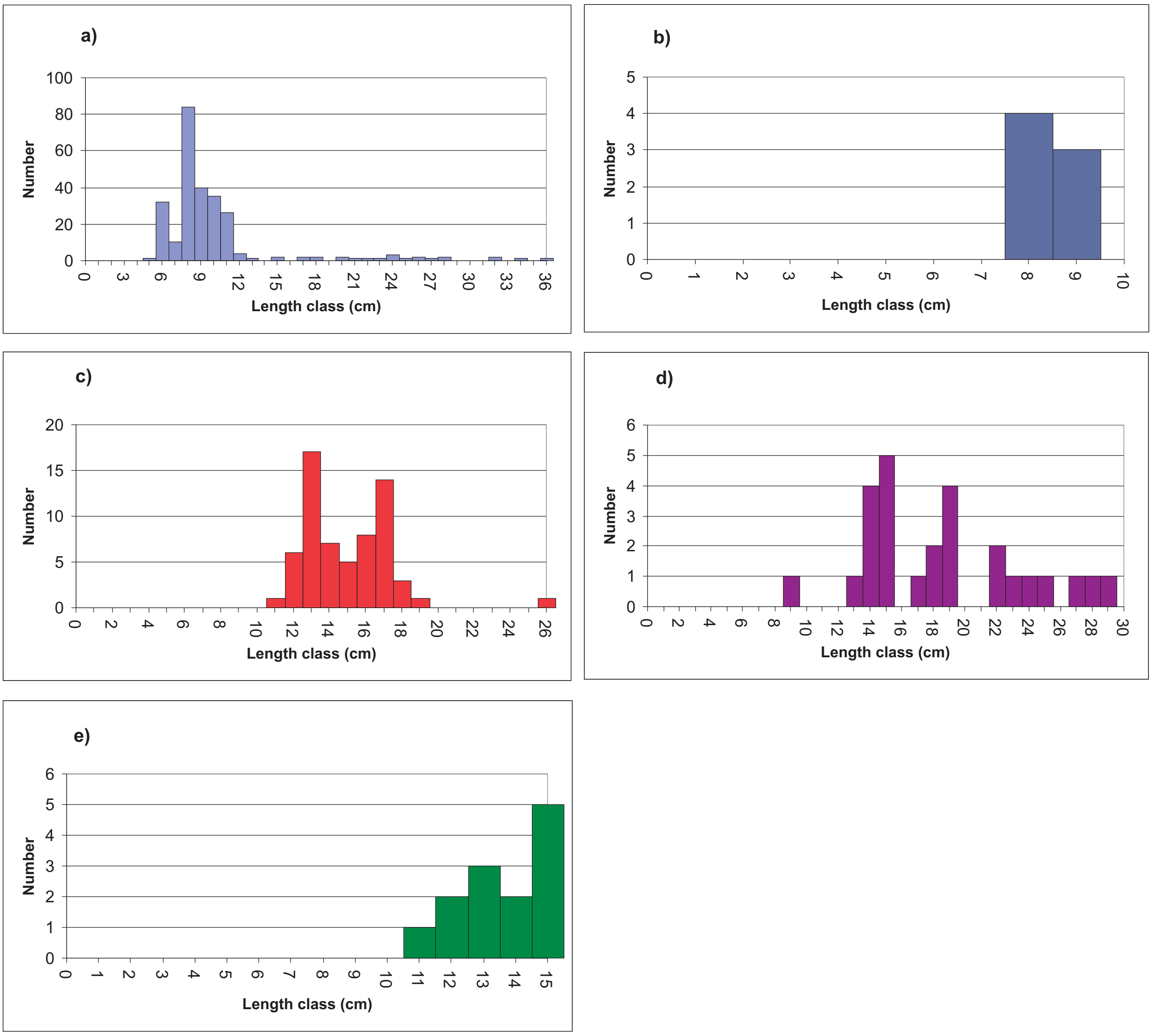


***Figure A5-5.** Length frequency distribution for the most common species in Frisksjön a) perch, b) ruffe, c) roach, d) bream and e) rudd. Species with too few replicates (not shown) was pike (n=2) /data from Engdahl and Ericsson 2004/.*

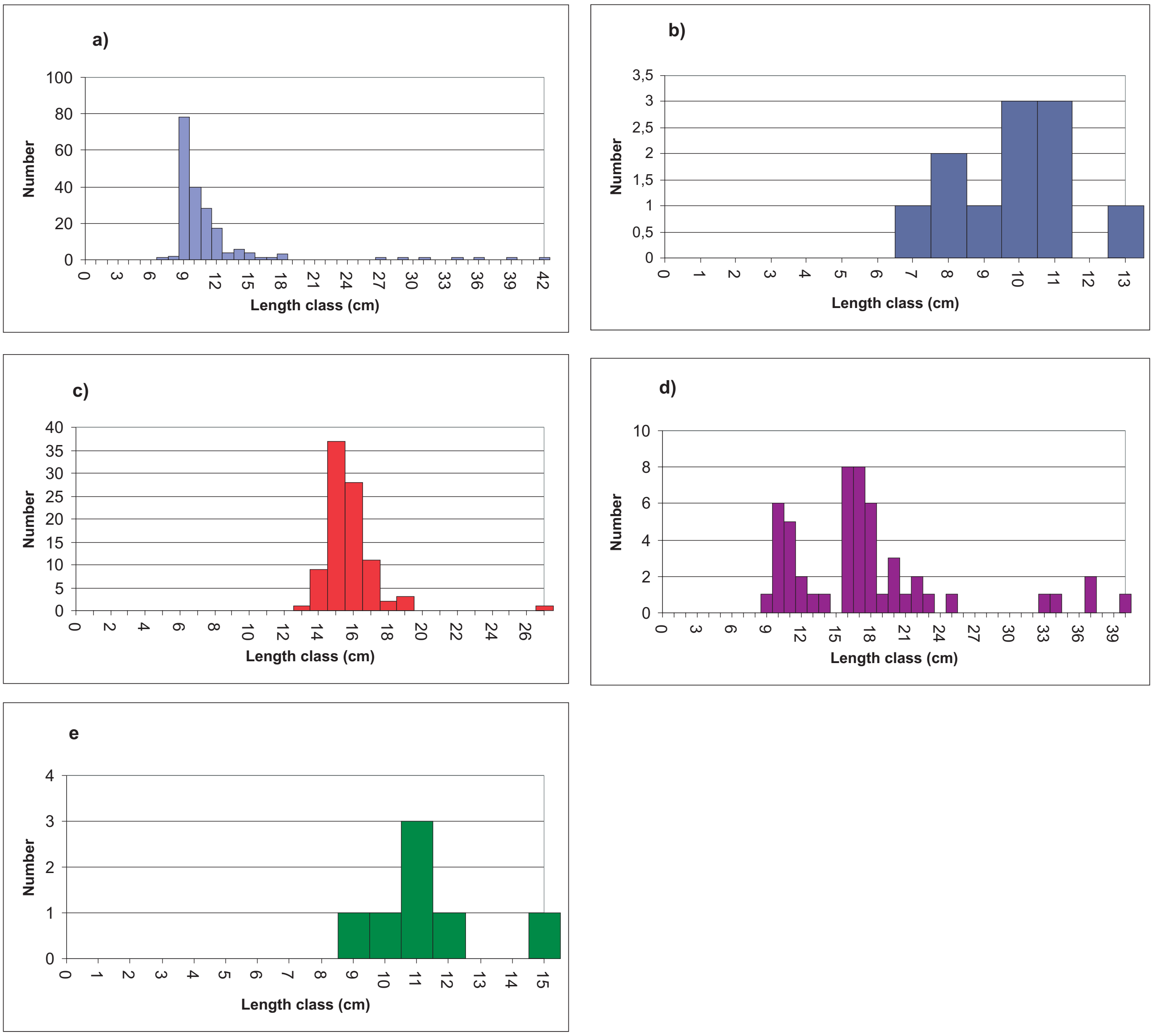


Figure A5-6. *Length frequency distribution for the most common species in Söråmagasinet a) perch, b) ruffe, c) roach, d) bream and e) rudd /data from Engdahl and Ericsson 2004/.*

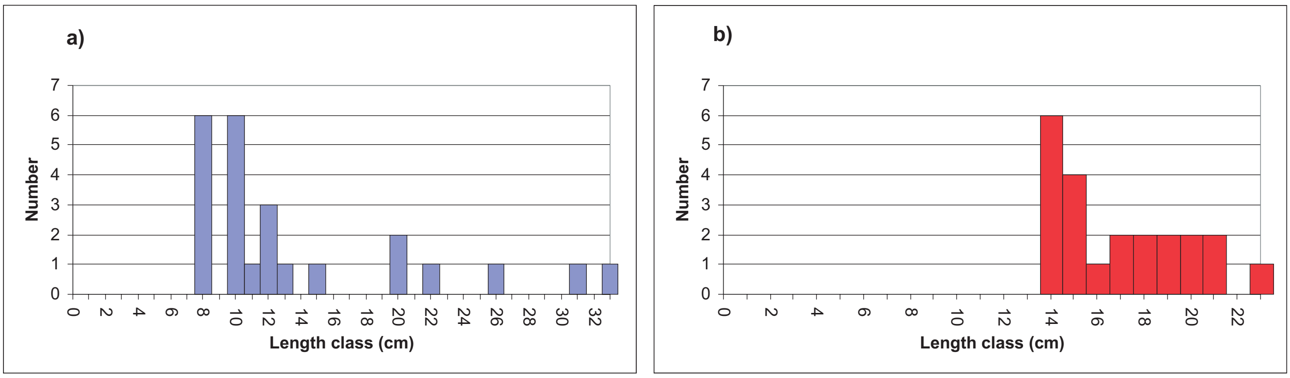


Figure A5-7. *Length frequency distribution for the most common species in Plittorpsgöl a) perch and b) roach. Species with too few replicates (not shown) was pike (n=1) /data from Engdahl and Ericsson 2004/.*

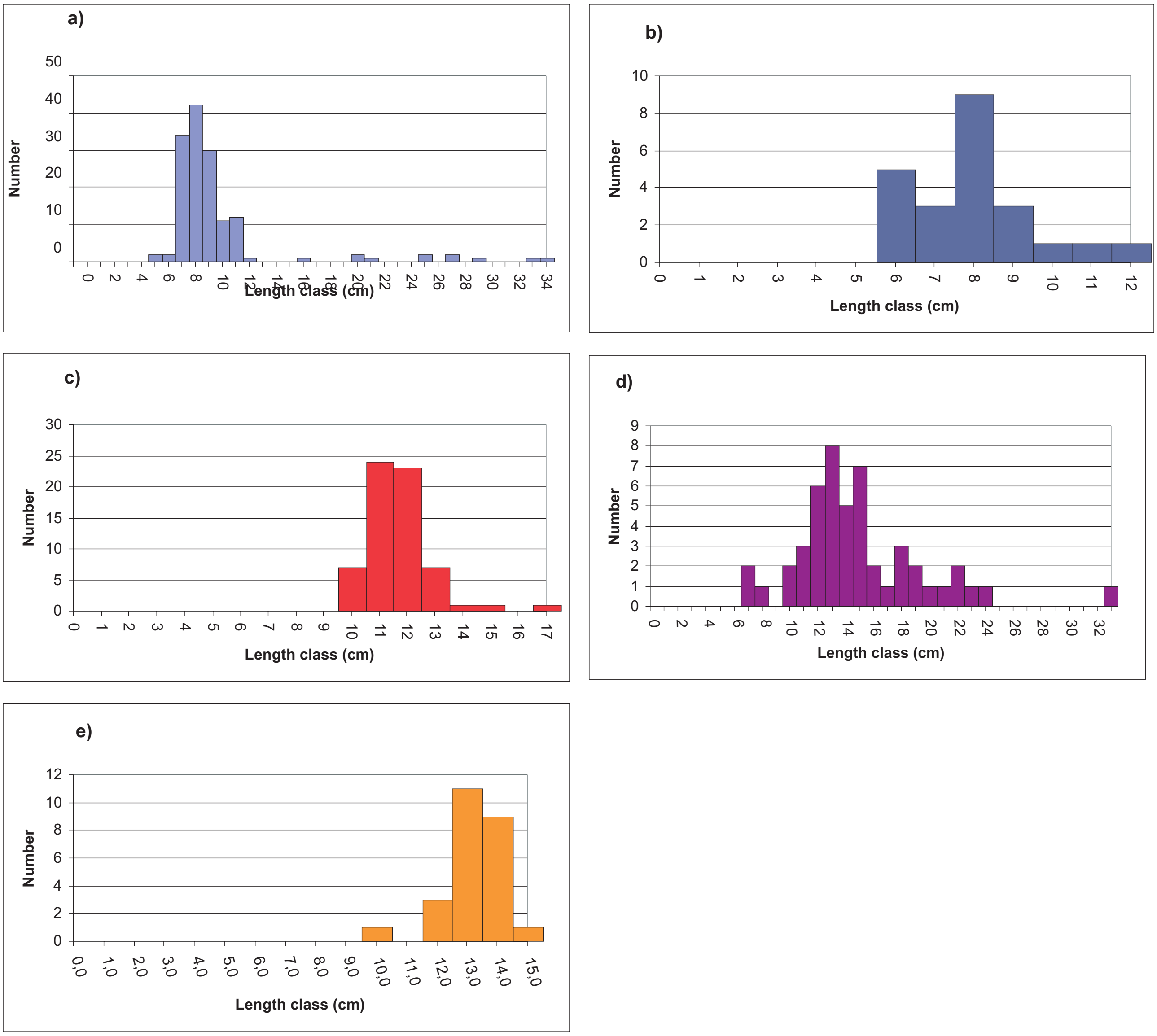


Figure A5-8. *Length frequency distribution for the most common species in Jämsen a) perch, b) ruff, c) roach, d)bream and e) bleak. Species with too few replicates (not shown) were pike (n=2) and rudd (n=1) /data from Engdahl and Ericsson 2004/.*

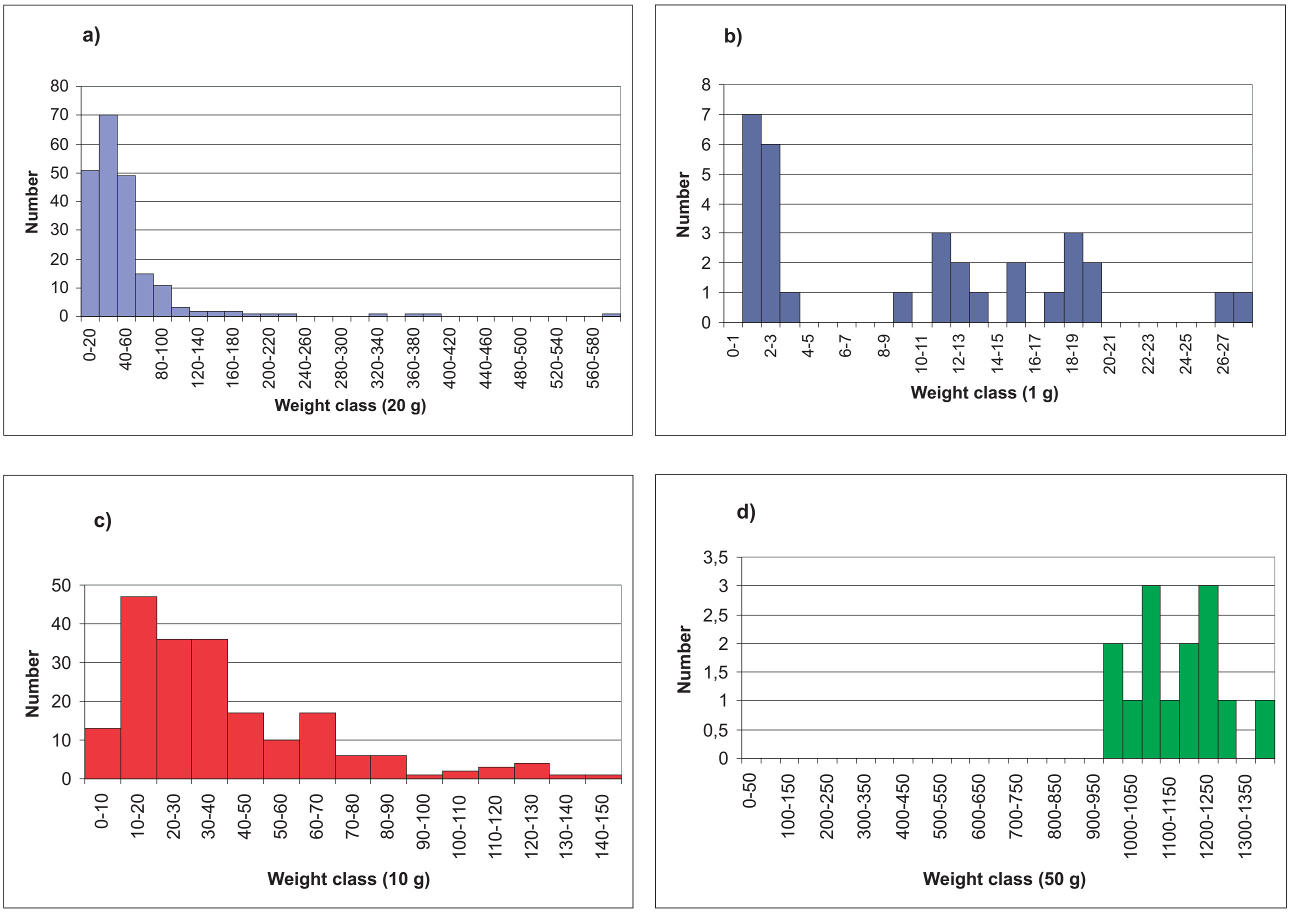


***Figure A5-9.** Weight frequency distribution for the most common species in Bolundsfjärden a) perch, b) ruffe, c) roach and d) tench. Species with too few replicates (not shown) were white bream (n=1), pike (n=3), crucian carp (n=4) and rudd (n=4) /data from Borgiel 2004b/.*

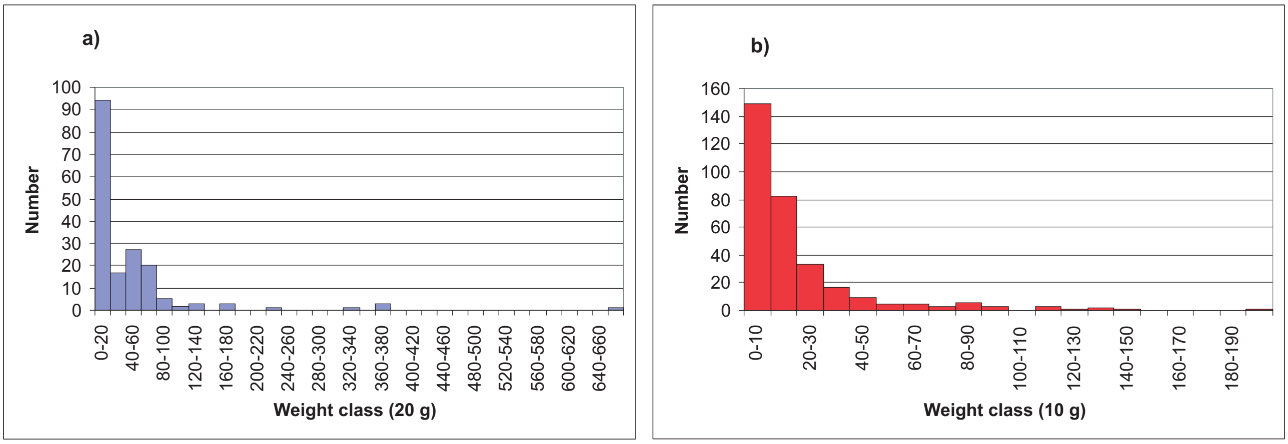


***Figure A5-10.** Weight frequency distribution for the most common species in Eckarfjärden a) perch and b) roach. Species with too few replicates (not shown) were pike (n=2), ruffe (n=1) and tench (n=5) /data from Borgiel 2004b/.*

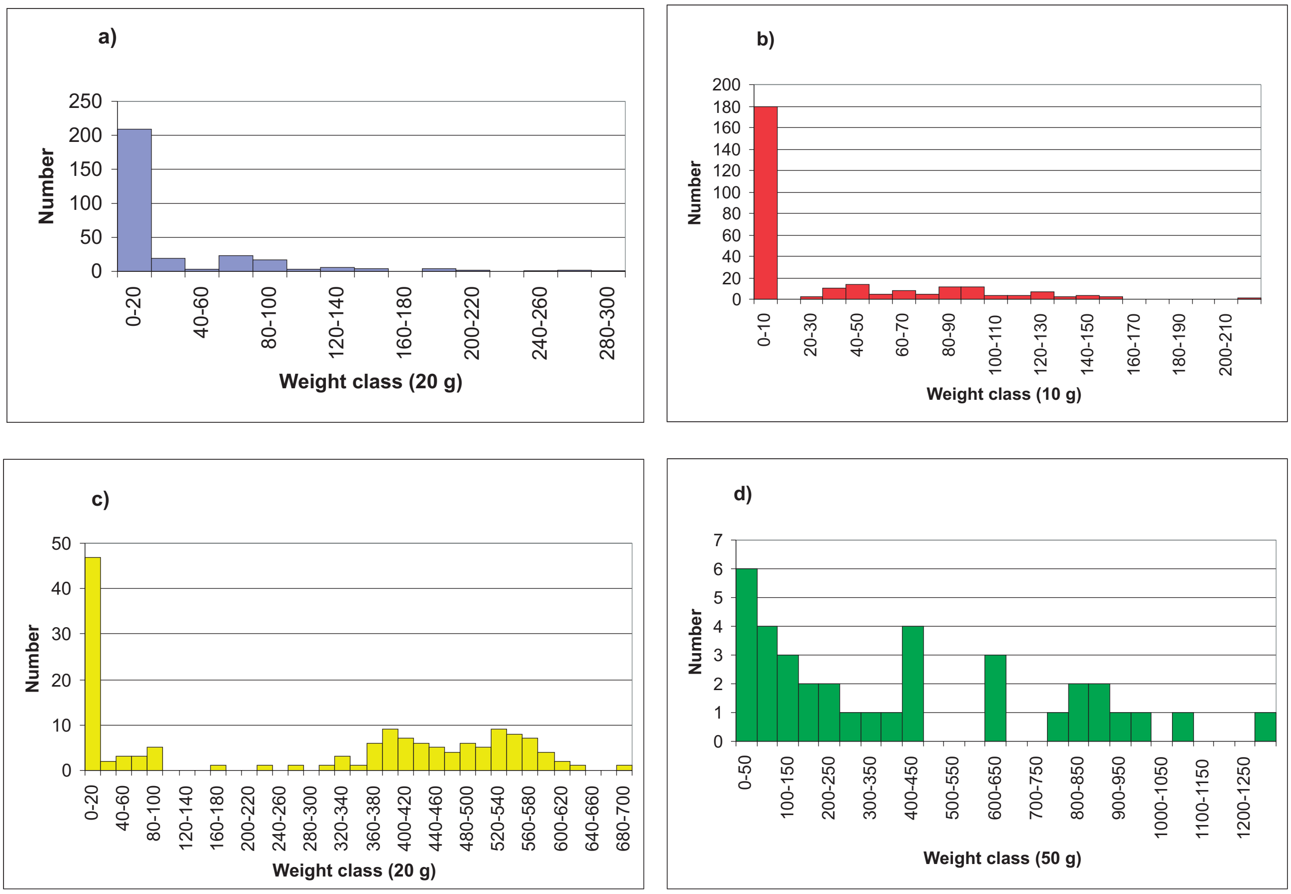


Figure A5-11. *Weight frequency distribution for the most common species in Fiskarfjärden a) perch, b) roach, c) rudd and d) tench. Species with too few replicates (not shown) were pike (n=5) and ruffe (n=1) /data from Borgiel 2004b/.*

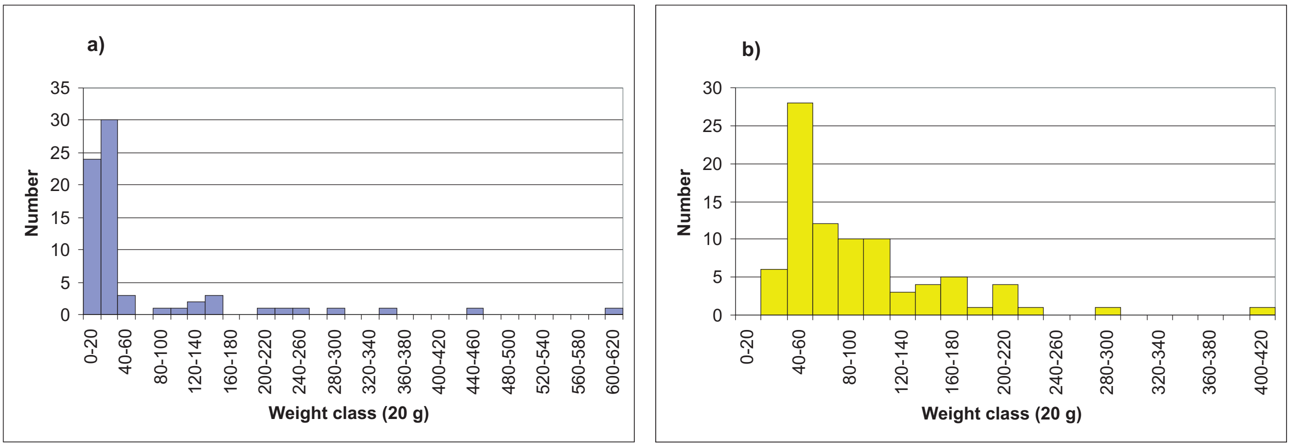


Figure A5-12. *Weight frequency distribution for the most common species in Gunnarsbo-Lillfjärden a) perch and b) rudd. Species with too few replicates (not shown) was roach (n=2) /data from Borgiel 2004b/.*

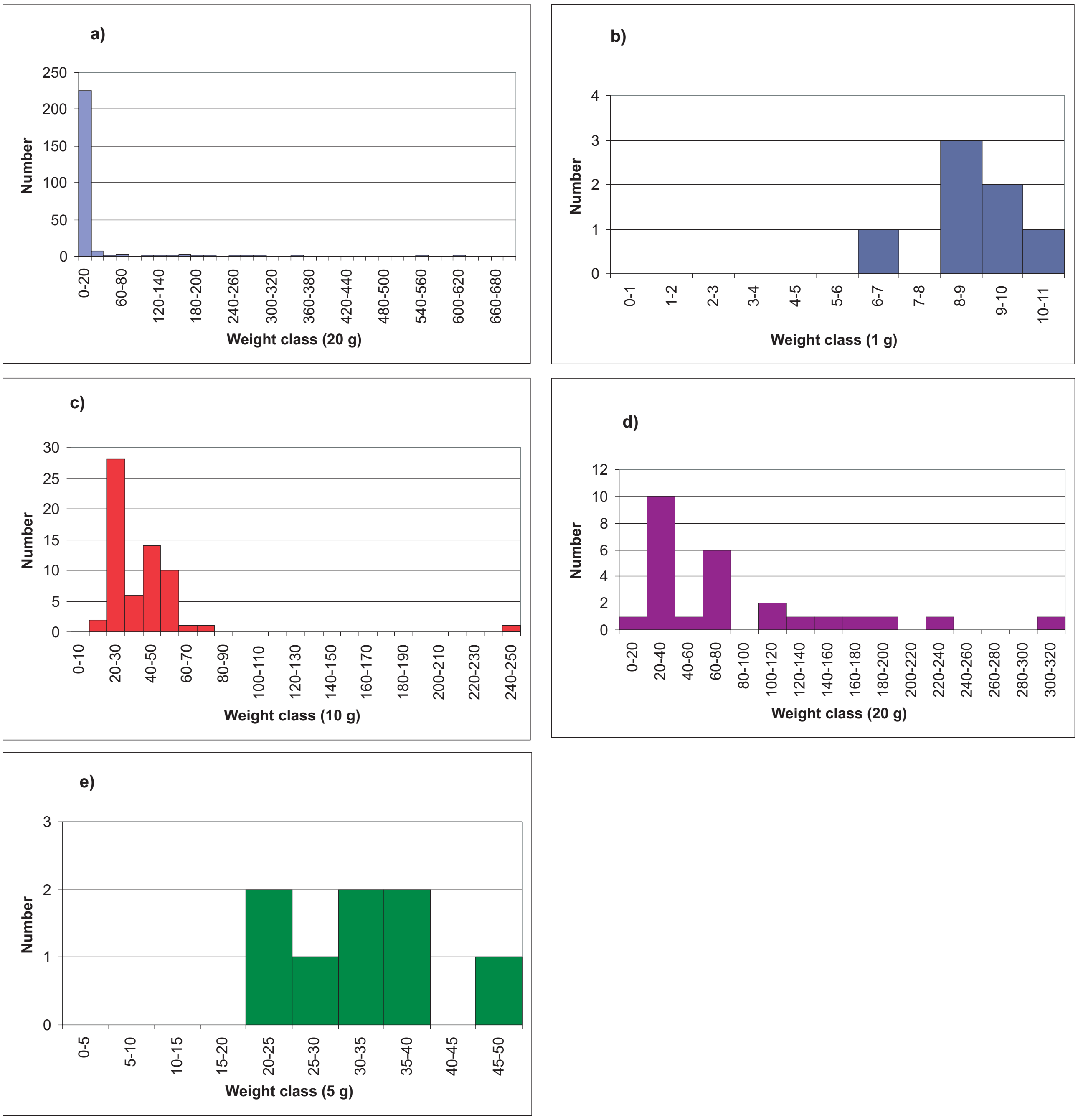


Figure A5-13. *Weight frequency distribution for the most common species in Frisksjön a) perch, b) ruffe, c) roach, d) bream and e)rudd. Species with too few replicates (not shown) was pike (n=2) /data from Engdahl and Ericsson 2004/.*

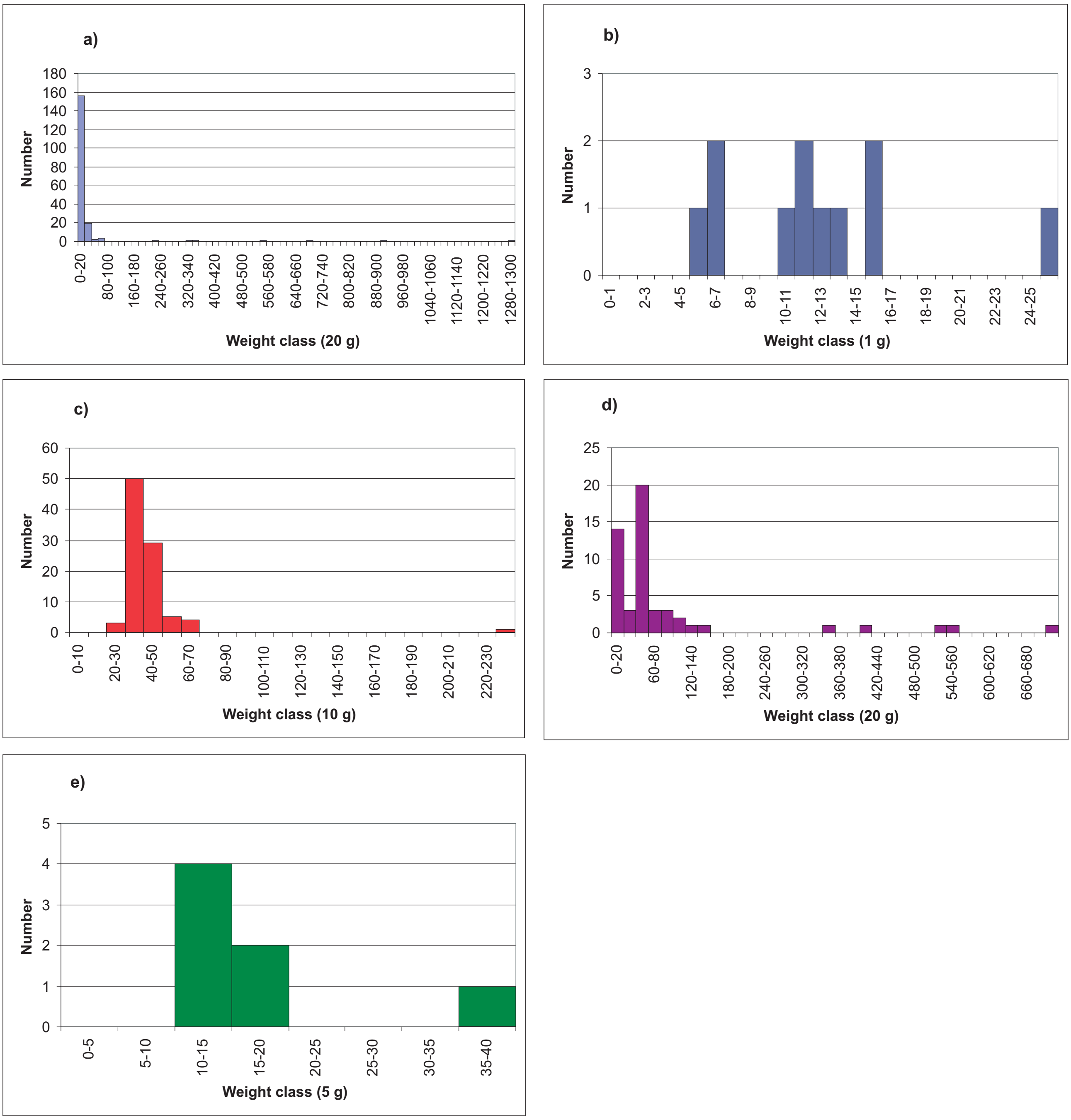


Figure A5-14. *Weight frequency distribution for the most common species in Söråmagasinet a) perch, b) ruffe, c) roach, d) bream and e)rudd /data from Engdahl and Ericsson 2004/.*

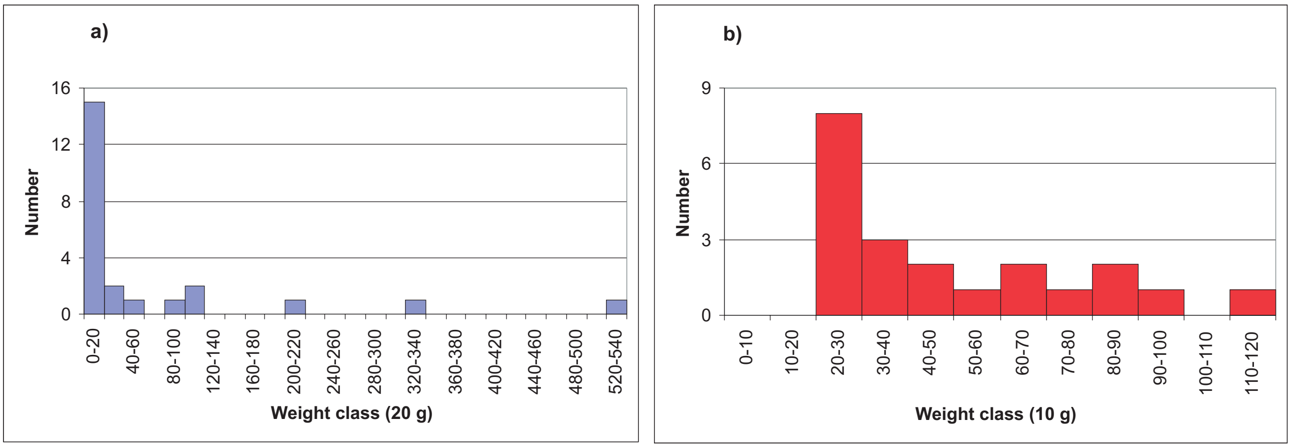


Figure A5-15. *Weight frequency distribution for the most common species in Plittorpsgöl a) perch and b) roach. Species with too few replicates (not shown) was pike (n=1) /data from Engdahl and Ericsson 2004/.*

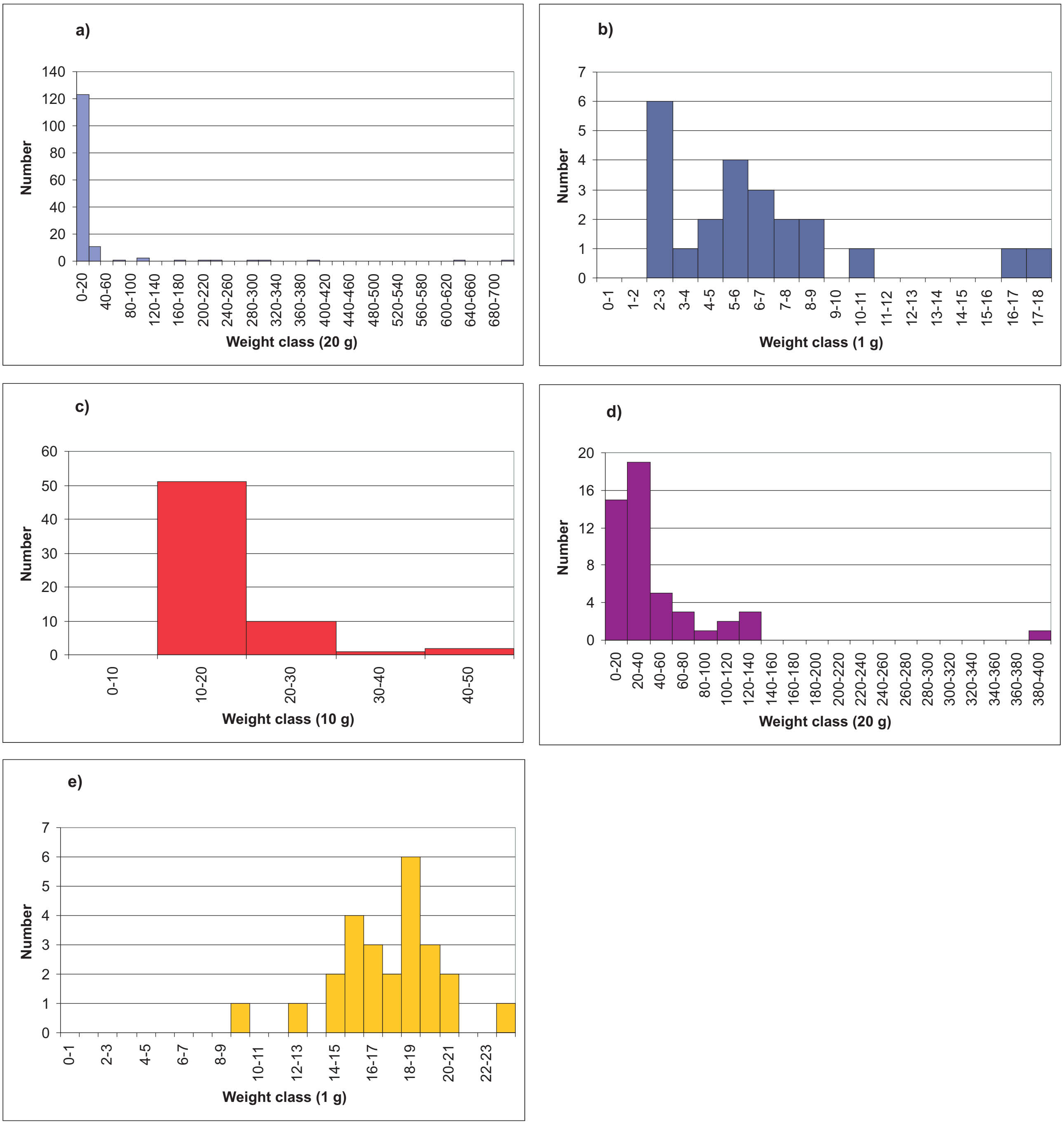


Figure A5-16. *Weight frequency distribution for the most common species in Jämsen a) perch, b) ruffe, c) roach, d) bream and e) bleak. Species with too few replicates (not shown) were pike (n=2) and rudd (n=1) /data from Engdahl and Ericsson 2004/.*

Appendix 6

Available data for models

Data on chemical composition is not available for all functional groups and for all components in the ecosystem. In Table A6-1 and A6-2 follows a description of for which pools data are available in Forsmark and Laxemar-Simpevarp, respectively

Table A6-1. Available data in modelling of lake ecosystems in Forsmark are marked with 1 and data lacking is marked with 0. The major part of data is site-specific, but also some generic data are used. For information of the data, see separate appendices and main report.

	Phyto-plankton	Micrphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter-feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B-fish	Z-fish	P-fish	Dissolved	Particular	Sediment
C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
N	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ag	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Al	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
As	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
B	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	1	1
Ba	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Be	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Br	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ca	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Cd	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ce	1	1	1	0	1	0	1	1	1	1	1	0	0	0	1	1	1
Cl	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0	1	1
Co	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Cr	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Cs	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Cu	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Dy	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Er	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Eu	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
F	1	0	0	0	0	0	1	0	1	1	1	0	0	0	0	1	0

	Phyto-plankton	Micrphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter-feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B-fish	Z-fish	P-fish	Dissolved	Particular	Sediment
Fe	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ga	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Gd	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Hf	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Hg	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ho	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
I	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
K	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
La	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Li	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Lu	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Mg	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Mn	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Mo	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Na	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Nb	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Nd	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ni	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
P	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Pb	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Pr	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Rb	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
S	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sb	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Sc	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Se	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Si	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Sm	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Sn	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Sr	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Ta	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	1	1
Tb	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1

	Phyto-plankton	Micrphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter-feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B-fish	Z-fish	P-fish	Dissolved	Particular	Sediment
Th	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Ti	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Tl	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Tm	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
U	0	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
V	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
W	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Y	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Yb	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Zn	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
Zr	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1

Table A6-2. Available data in modelling of Lake Ecosystem in Laxemar-Simpevarp are marked with 1 and data lacking is marked with 0. The major part of data is site-specific, but also some generic data are used. For information of the data, see separate appendices and main report.

	Phyto-plankton	Microphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter-feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B-fish	Z-fish	P-fish	Dissolved	Particular	Upper sediment (top 1 cm)	Deeper sediment
C	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
N	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
P	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ag	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Al	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
As	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
B	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Ba	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Be	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Br	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ca	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Cd	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ce	1	0	1	0	1	0	1	1	1	1	1	0	0	0	1	1	1	1
Cl	1	0	1	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1
Co	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Cr	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Cs	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Cu	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Dy	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Er	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Eu	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
F	1	0	0	0	0	0	1	0	1	1	1	0	0	0	0	1	0	0
Fe	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ga	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Gd	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Hf	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Hg	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ho	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
I	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
K	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
La	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1

	Phyto-plankton	Microphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter-feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B-fish	Z-fish	P-fish	Dissolved	Particular	Upper sediment (top 1 cm)	Deeper sediment
Li	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Lu	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Mg	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Mn	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Mo	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Na	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Nb	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Nd	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ni	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
P	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Pb	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Pr	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Rb	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
S	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sb	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Sc	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Se	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Si	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Sm	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Sn	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Sr	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Ta	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Tb	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Th	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Ti	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Tl	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Tm	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
U	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
V	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
W	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Y	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Yb	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Zn	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Zr	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1

Appendix 7

Chemical composition of the dissolved fractions of water

Concentrations of a large number of elements have been performed in site investigations for several years and the concentrations of the dissolved phase used in Chapter 6 are presented in Table A7-1. In addition, concentrations of elements dissolved in water (dissolved pool) has been analysed for a large number of elements at one occasion in April 2008. When available, the long-term measurements of elements have been used in Chapter 7 but for elements were long-term data are missing, data from Table A7-2 have been used. When concentrations were below detection limit, half the detection limit has been used in calculations in Chapter 7. In the tables below, the values used in the calculation are presented and the detection limits are given in footnotes.

Table A7-1. Concentrations of elements and macronutrients dissolved in water in lakes in the Forsmark (Labboträsket, Norra bassängen, Bolundsfjärden, Bolundsskogen and Eckarfjärden) and Laxemar-Simpevarp (Frisksjön) during time period 2004-06-01 to 2006-05-31 for Forsmark and 2002-11-20 to 2007-07-24 for Laxemar-Simpevarp. Values represent the mean from the whole sampling periods. When values were below detection limit, half the detection limit was used in the calculation of the mean.

Element	Unit	Labbo-träsket	Norra bassängen	Bolundsfjärden		Eckarfjärden		Bolunds-skogen	Frisksjön	
		Surface	Surface	Bottom	Surface	Bottom	Surface	Surface	Surface	Bottom
Al	µg L^{-1}	74.9		30.71	65.9	66.4	44.3	22.2	213.0	208.2
As	µg L^{-1}	0.509		0.37	1.03	0.33	0.306		0.614	0.618
Ba	µg L^{-1}	25.0		27.6	20.5	21.4	13.2	23.6	14.7	13.8
Br	mg L^{-1}	0.073	0.22	0.929	0.392	0.109	0.047	0.146	0.12	0.121
Ca	mg L^{-1}	69.5	34.9	59.6	47.4	56.0	39.7	65.0	8.08	7.51
Cd	µg L^{-1}	0.004		0.003	0.014	0.001	0.006	0.004	0.014	0.014
Ce	µg L^{-1}	0.059			0.153		0.019	0.117	2.74	2.496
Cl	mg L^{-1}	13.7	78.4	261.3	87.4	6.6	5.8	30.5	13.5	12.8
Co	µg L^{-1}	0.049		0.071	0.073	0.052	0.036	0.079	0.234	0.219
Cr	µg L^{-1}	0.139		0.138	0.143	0.136	0.098	0.138	0.546	0.591
Cs	µg L^{-1}	0.015			0.015		0.015	0.015	0.071	0.173
Cu	µg L^{-1}	0.84		0.535	0.733	0.715	0.479	1.44	2.013	2.062
Dy	µg L^{-1}	0.012			0.019		0.004	0.026	0.144	0.135
Er	µg L^{-1}	0.009			0.015		0.003	0.02	0.094	0.088
Eu	µg L^{-1}	0.006			0.011		0.003	0.01	0.041	0.037
F	mg L^{-1}	0.214	0.23	0.319	0.234	0.184	0.158	0.288	0.779	0.77
Fe	mg L^{-1}	0.05		0.146	0.109	0.06	0.023	0.226	0.847	0.875
Gd	µg L^{-1}	0.012			0.022		0.003	0.028	0.199	0.184
HCO3	mg L^{-1}	213.8	81.9	162.5	133.7	172.4	122.7	193.4	13.9	13.5
Hf	µg L^{-1}	0.005			0.006		0.004	0.01	0.106	0.095
Hg	µg L^{-1}	0.002		0.002	0.002	0.002	0.001	0.001	0.002	0.002
Ho	µg L^{-1}	0.003			0.009		0.003	0.006	0.029	0.028
I	mg L^{-1}	0.008	0.008	0.006	0.007	0.006	0.006	0.009	0.031	0.031
In	µg L^{-1}	0.025			0.043		0.025		0.025	0.025
K	mg L^{-1}	2.11	2.98	8.72	3.76	2.24	1.91	2.05	1.63	1.63
La	µg L^{-1}	0.040			0.101		0.014	0.117	1.33	1.22
Li	mg L^{-1}	0.003	0.002	0.006	0.003	0.004	0.003	0.003	0.002	0.002
Lu	µg L^{-1}	0.004			0.041		0.008	0.003	0.021	0.028
Mg	mg L^{-1}	4.00	6.90	23.0	8.76	3.18	2.92	5.67	2.45	2.42
Mn	mg L^{-1}	0.018		0.05	0.024	0.101	0.016	0.033	0.049	0.058
Mo	µg L^{-1}	0.410		0.482	0.649	0.223	0.247	0.354	1.11	1.08
Na	mg L^{-1}	10.1	37.6	178.4	51.2	6.69	6.49	18.0	10.2	10.1
Nd	µg L^{-1}	0.043			0.08		0.014	0.12	1.48	1.385
Ni	µg L^{-1}	0.424		0.385	0.489	0.315	0.288	0.595	1.566	1.526
Pb	µg L^{-1}	0.085		0.104	0.219	0.051	0.064	0.073	0.736	0.67

Element	Unit	Labbo-träsket	Norra bassängen	Bolundsfjärden		Eckarfjärden		Bolunds-skogen	Frisksjön	
		Surface	Surface	Bottom	Surface	Bottom	Surface	Surface	Surface	Bottom
Pr	µg L^{-1}	0.011			0.027		0.004	0.032	0.373	0.343
Rb	µg L^{-1}	1.79			3.80		2.17	1.78	3.81	3.89
S	mg L^{-1}								4.55	4.29
Sb	µg L^{-1}	0.051			0.126		0.096	0.066	0.157	0.147
Sc	µg L^{-1}	0.025			0.025		0.025	0.025	0.076	0.09
Si	mg/L	5.52	0.033	1.80	1.69	3.01	1.48	6.00	5.06	4.97
Sm	µg L^{-1}	0.009			0.022		0.004	0.025	0.247	0.228
SO4	mg L^{-1}	7.67	17.0	47.6	19.7	6.94	6.02	12.3	13.6	12.8
Sr	mg L^{-1}	0.082	0.107	0.197	0.104	0.06	0.05	0.101	0.039	0.038
Tb	µg L^{-1}	0.018			0.018		0.018	0.006	0.028	0.028
Th	µg L^{-1}	0.01			0.01		0.01	0.01	0.088	0.087
Tl	µg L^{-1}	0.014			0.015		0.014	0.015	0.01	0.009
Tm	µg L^{-1}	0.003			0.009		0.003	0.003	0.014	0.013
U	µg L^{-1}	1.40			2.06		1.17	2.89	0.335	0.324
V	µg L^{-1}	0.223		0.178	0.293	0.196	0.232	0.213	1.30	1.22
Y	µg L^{-1}	0.096			0.109		0.036	0.194	0.933	0.884
Yb	µg L^{-1}	0.009			0.014		0.003	0.021	0.099	0.092
Zn	µg L^{-1}	1.06		4.35	1.08	0.569	1.49	2.36	4.14	3.77
Zr	µg L^{-1}	0.143			0.2		0.094	0.21	0.892	0.938
NH4N	mg L^{-1}	0.01	0.004	0.294	0.035	0.608	0.143	0.014	0.104	0.125
NO3+NO2	mg L^{-1}	0.01	0.001	0.009	0.017	0.009	0.009	0.039	0.197	0.187
N-TOT	mg L^{-1}	0.789	0.921	1.16	0.98	1.68	1.23	0.84	1.07	1.08
P-TOT	mg L^{-1}	0.008	0.014	0.011	0.012	0.008	0.008	0.015	0.024	0.025
PO4-P	mg L^{-1}	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.034	0.002
POP	mg L^{-1}	0.003	0.006	0.004	0.005	0.004	0.004	0.005	0.012	0.012
PON	mg L^{-1}	0.035	0.064	0.036	0.045	0.049	0.054	0.033	0.107	0.102
POC	mg L^{-1}	0.250	0.575	0.263	0.336	0.403	0.431	0.245	0.854	0.825
TOC	mg L^{-1}	17.0	17.2	15.8	17.2	19.2	17.7	19.2	15.6	15.7
DOC	mg L^{-1}	16.9	17.2	15.7	17.0	18.9	17.7	18.8	15.4	15.4
DIC	mg L^{-1}	35.8	13.4	28.5	22.1	29.0	20.2	35.5	2.5	2.80

Table A7-2. Concentrations of elements (mg L^{-1}) dissolved in water in Forsmark and Laxemar-Simpevarp lakes at one occasion in April 2008. When values were below detection limit, half the detection limit is presented in the table and the detection limit is presented in footnotes below.

Element	Forsmark				Laxemar-Simpevarp			
	Bolunds-fjärden	Eckar-fjärden	Labbo-träsk	Mean Forsmark lake	Jämsen	Götemar	Frisksjön	Mean Laxemar lake
Ag	1.0•10^{-6} a)	1.0•10^{-6} a)	1.0•10^{-6} a)	**1.0•10^{-6} a)**	6.0•10^{-6}	1.0•10^{-6} a)	6.0•10^{-6}	**4.3•10^{-6}**
Al	7.7•10^{-3}	8.5•10^{-3}	8.1•10^{-3}	**8.1•10^{-3}**	2.0•10^{-1}	5.2•10^{-2}	2.3•10^{-1}	**1.6•10^{-1}**
As	3.8•10^{-4}	3.6•10^{-4}	3.0•10^{-4}	**3.5•10^{-4}**	2.7•10^{-4}	4.3•10^{-4}	3.7•10^{-4}	**3.6•10^{-4}**
Au	5.0•10^{-7} b)	5.0•10^{-7} b)	5.0•10^{-7} b)	**5.0•10^{-7} b)**	5.0•10^{-7} b)	5.0•10^{-7} b)	2.0•10^{-6}	**1.0•10^{-6}**
B	3.2•10^{-2}	1.0•10^{-2}	8.0•10^{-3}	**1.7•10^{-2}**	1.2•10^{-2}	3.3•10^{-2}	2.2•10^{-2}	**2.2•10^{-2}**
Ba	2.0•10^{-2}	1.6•10^{-2}	2.3•10^{-2}	**2.0•10^{-2}**	1.7•10^{-2}	1.1•10^{-2}	1.4•10^{-2}	**1.4•10^{-2}**
Be	9.0•10^{-6}	5.0•10^{-6}	4.0•10^{-6}	**6.0•10^{-6}**	7.7•10^{-5}	7.4•10^{-5}	2.6•10^{-4}	**1.4•10^{-4}**
Bi	1.0•10^{-6}	5.0•10^{-7} b)	5.0•10^{-7} b)	**6.7•10^{-7}**	4.0•10^{-6}	5.0•10^{-7} b)	4.0•10^{-6}	**2.8•10^{-6}**
Br	4.0•10^{-1}	5.0•10^{-2}	4.0•10^{-2}	**1.6•10^{-1}**	1.2•10^{-1}	2.0•10^{-1}	2.5•10^{-1}	**1.9•10^{-1}**
Ca	49	47	57	**51**	8.0	10	7.8	**8.6**
Cd	7.0•10^{-6}	4.0•10^{-6}	5.0•10^{-6}	**5.3•10^{-6}**	1.3•10^{-5}	1.1•10^{-5}	2.3•10^{-5}	**1.6•10^{-5}**

Element	Forsmark				Laxemar-Simpevarp			
	Bolunds-fjärden	Eckar-fjärden	Labbo-träsk	Mean Forsmark lake	Jämsen	Götemar	Frisksjön	Mean Laxemar lake
Ce	$1.1\cdot10^{-4}$	$6.3\cdot10^{-5}$	$6.0\cdot10^{-5}$	**$7.8\cdot10^{-5}$**	$3.9\cdot10^{-3}$	$4.7\cdot10^{-4}$	$3.4\cdot10^{-3}$	**$2.6\cdot10^{-3}$**
Co	$3.7\cdot10^{-5}$	$3.7\cdot10^{-5}$	$3.9\cdot10^{-5}$	**$3.8\cdot10^{-5}$**	$3.1\cdot10^{-4}$	$2.7\cdot10^{-5}$	$3.7\cdot10^{-4}$	**$2.4\cdot10^{-4}$**
Cr	$1.2\cdot10^{-4}$	$1.1\cdot10^{-4}$	$1.2\cdot10^{-4}$	**$1.2\cdot10^{-4}$**	$3.8\cdot10^{-4}$	$7.2\cdot10^{-5}$	$5.7\cdot10^{-4}$	**$3.4\cdot10^{-4}$**
Cs	$6.8\cdot10^{-5}$	$8.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	**$2.6\cdot10^{-5}$**	$1.8\cdot10^{-5}$	$9.0\cdot10^{-6}$	$1.7\cdot10^{-5}$	**$1.5\cdot10^{-5}$**
Cu	$8.7\cdot10^{-4}$	$8.8\cdot10^{-4}$	$1.4\cdot10^{-3}$	**$1.1\cdot10^{-3}$**	$1.4\cdot10^{-3}$	$1.1\cdot10^{-3}$	$2.6\cdot10^{-3}$	**$1.7\cdot10^{-3}$**
Dy	$4.8\cdot10^{-5}$	$2.2\cdot10^{-5}$	$2.1\cdot10^{-5}$	**$3.0\cdot10^{-5}$**	$3.2\cdot10^{-4}$	$5.4\cdot10^{-5}$	$1.9\cdot10^{-4}$	**$1.9\cdot10^{-4}$**
Er	$2.1\cdot10^{-5}$	$1.5\cdot10^{-5}$	$1.8\cdot10^{-5}$	**$1.8\cdot10^{-5}$**	$2.4\cdot10^{-4}$	$4.9\cdot10^{-5}$	$1.3\cdot10^{-4}$	**$1.4\cdot10^{-4}$**
Eu	$4.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	$4.0\cdot10^{-6}$	**$3.7\cdot10^{-6}$**	$7.5\cdot10^{-5}$	$1.2\cdot10^{-5}$	$5.2\cdot10^{-5}$	**$4.6\cdot10^{-5}$**
Fe	$6.0\cdot10^{-2}$	$2.5\cdot10^{-2}$	$2.8\cdot10^{-2}$	**$3.8\cdot10^{-2}$**	$7.4\cdot10^{-1}$	$3.4\cdot10^{-2}$	$4.8\cdot10^{-1}$	**$4.2\cdot10^{-1}$**
Ga	$5.0\cdot10^{-6}$	$4.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	**$4.0\cdot10^{-6}$**	$5.0\cdot10^{-6}$	$7.0\cdot10^{-6}$	$5.0\cdot10^{-6}$	**$5.7\cdot10^{-6}$**
Gd	$2.7\cdot10^{-5}$	$1.9\cdot10^{-5}$	$2.4\cdot10^{-5}$	**$2.3\cdot10^{-5}$**	$5.4\cdot10^{-4}$	$8.4\cdot10^{-5}$	$3.2\cdot10^{-4}$	**$3.1\cdot10^{-4}$**
Ge	$7.0\cdot10^{-5}$	$4.0\cdot10^{-5}$	$4.0\cdot10^{-5}$	**$5.0\cdot10^{-5}$**	$8.0\cdot10^{-5}$	$5.0\cdot10^{-5}$	$7.0\cdot10^{-5}$	**$6.7\cdot10^{-5}$**
Hf	$1.4\cdot10^{-5}$	$1.3\cdot10^{-5}$	$1.1\cdot10^{-5}$	**$1.3\cdot10^{-5}$**	$4.0\cdot10^{-5}$	$1.1\cdot10^{-5}$	$4.2\cdot10^{-5}$	**$3.1\cdot10^{-5}$**
Hg	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	**$1.0\cdot10^{-6}$ a)**	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	**$1.0\cdot10^{-6}$ a)**
Ho	$7.0\cdot10^{-6}$	$5.0\cdot10^{-6}$	$5.0\cdot10^{-6}$	**$5.7\cdot10^{-6}$**	$7.3\cdot10^{-5}$	$1.5\cdot10^{-5}$	$4.2\cdot10^{-5}$	**$4.3\cdot10^{-5}$**
I	$4.0\cdot10^{-3}$	$4.0\cdot10^{-3}$	$3.0\cdot10^{-3}$	**$3.7\cdot10^{-3}$**	$4.0\cdot10^{-3}$	$1.7\cdot10^{-2}$	$2.5\cdot10^{-2}$	**$1.5\cdot10^{-2}$**
In	$2.5\cdot10^{-5}$ c)	$2.5\cdot10^{-5}$ c)	$2.5\cdot10^{-5}$ c)	**$2.5\cdot10^{-5}$ c)**	$2.5\cdot10^{-5}$ c)	$2.5\cdot10^{-5}$ c)	$2.5\cdot10^{-5}$ c)	**$2.5\cdot10^{-5}$ c)**
Ir	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	**$1.0\cdot10^{-7}$ d)**	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	**$1.0\cdot10^{-7}$ d)**
K	3.3	1.9	2.1	**2.4**	1.3	1.5	1.5	**1.4**
La	$1.0\cdot10^{-4}$	$6.4\cdot10^{-5}$	$7.4\cdot10^{-5}$	**$7.9\cdot10^{-5}$**	$2.3\cdot10^{-3}$	$5.2\cdot10^{-4}$	$1.8\cdot10^{-3}$	**$1.5\cdot10^{-3}$**
Li	$3.0\cdot10^{-3}$	$1.3\cdot10^{-3}$	$1.5\cdot10^{-3}$	**$1.9\cdot10^{-3}$**	$2.1\cdot10^{-3}$	$3.0\cdot10^{-3}$	$2.5\cdot10^{-3}$	**$2.5\cdot10^{-3}$**
Lu	$3.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	**$3.0\cdot10^{-6}$**	$4.7\cdot10^{-5}$	$1.2\cdot10^{-5}$	$2.4\cdot10^{-5}$	**$2.8\cdot10^{-5}$**
Mg	8.3	2.7	2.9	**4.6**	2.2	3.0	2.7	**2.6**
Mn	$3.9\cdot10^{-3}$	$9.9\cdot10^{-3}$	$5.6\cdot10^{-3}$	**$6.5\cdot10^{-3}$**	$7.6\cdot10^{-2}$	$2.9\cdot10^{-3}$	$4.4\cdot10^{-2}$	**$4.1\cdot10^{-2}$**
Mo	$6.2\cdot10^{-4}$	$2.5\cdot10^{-4}$	$6.5\cdot10^{-4}$	**$5.1\cdot10^{-4}$**	$1.1\cdot10^{-4}$	$5.0\cdot10^{-4}$	$9.2\cdot10^{-4}$	**$5.1\cdot10^{-4}$**
Na	50	6.3	6.9	**21**	8.3	11	12	**10**
Nb	$1.0\cdot10^{-5}$	$9.0\cdot10^{-6}$	$9.0\cdot10^{-6}$	**$9.3\cdot10^{-6}$**	$3.0\cdot10^{-5}$	$8.0\cdot10^{-6}$	$3.1\cdot10^{-5}$	**$2.3\cdot10^{-5}$**
Nd	$1.1\cdot10^{-4}$	$8.3\cdot10^{-5}$	$8.5\cdot10^{-5}$	**$9.3\cdot10^{-5}$**	$2.6\cdot10^{-3}$	$4.6\cdot10^{-4}$	$1.9\cdot10^{-3}$	**$1.7\cdot10^{-3}$**
Ni	$5.1\cdot10^{-4}$	$5.0\cdot10^{-4}$	$6.2\cdot10^{-4}$	**$5.4\cdot10^{-4}$**	$1.0\cdot10^{-3}$	$1.2\cdot10^{-3}$	$2.2\cdot10^{-3}$	**$1.5\cdot10^{-3}$**
Os	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	**$1.0\cdot10^{-7}$ d)**	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	$1.0\cdot10^{-7}$ d)	**$1.0\cdot10^{-7}$ d)**
P	$4.1\cdot10^{-3}$	$3.5\cdot10^{-3}$	$4.0\cdot10^{-3}$	**$3.9\cdot10^{-3}$**	$8.9\cdot10^{-3}$	$5.2\cdot10^{-3}$	$9.4\cdot10^{-3}$	**$7.8\cdot10^{-3}$**
Pb	$9.4\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.0\cdot10^{-4}$	**$1.0\cdot10^{-4}$**	$3.7\cdot10^{-4}$	$5.2\cdot10^{-5}$	$5.8\cdot10^{-4}$	**$3.3\cdot10^{-4}$**
Pd	$5.0\cdot10^{-6}$ e)	$5.0\cdot10^{-6}$ e)	$5.0\cdot10^{-6}$ e)	**$5.0\cdot10^{-6}$ e)**	$5.0\cdot10^{-6}$ e)	$5.0\cdot10^{-6}$ e)	$5.0\cdot10^{-6}$ e)	**$5.0\cdot10^{-6}$ e)**
Pr	$2.7\cdot10^{-5}$	$2.0\cdot10^{-5}$	$2.0\cdot10^{-5}$	**$2.2\cdot10^{-5}$**	$6.5\cdot10^{-4}$	$1.2\cdot10^{-4}$	$4.9\cdot10^{-4}$	**$4.2\cdot10^{-4}$**
Pt	$5.0\cdot10^{-7}$ b)	$5.0\cdot10^{-7}$ b)	$5.0\cdot10^{-7}$ b)	**$5.0\cdot10^{-7}$ b)**	$1.0\cdot10^{-6}$ b)	$1.0\cdot10^{-6}$ b)	$2.0\cdot10^{-6}$ b)	**$1.3\cdot10^{-6}$ b)**
Rb	$3.1\cdot10^{-3}$	$2.0\cdot10^{-3}$	$2.0\cdot10^{-3}$	**$2.4\cdot10^{-3}$**	$2.7\cdot10^{-3}$	$3.1\cdot10^{-3}$	$3.2\cdot10^{-3}$	**$3.0\cdot10^{-3}$**
Re	$2.0\cdot10^{-6}$	$1.0\cdot10^{-6}$	$1.0\cdot10^{-6}$	**$1.3\cdot10^{-6}$**	$1.0\cdot10^{-6}$	$3.0\cdot10^{-6}$	$2.0\cdot10^{-6}$	**$2.0\cdot10^{-6}$**
Rh	$5.0\cdot10^{-5}$ f)	$5.0\cdot10^{-5}$ f)	$5.0\cdot10^{-5}$ f)	**$5.0\cdot10^{-5}$ f)**	$5.0\cdot10^{-5}$ f)	$5.0\cdot10^{-5}$ f)	$5.0\cdot10^{-5}$ f)	**$5.0\cdot10^{-5}$ f)**
Ru	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	**$2.5\cdot10^{-6}$ g)**	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	**$2.5\cdot10^{-6}$ g)**
S	8.4	3.5	4.4	**5.4**	3.4	8.0	5.5	**5.6**
Sb	$7.1\cdot10^{-5}$	$7.0\cdot10^{-5}$	$6.0\cdot10^{-5}$	**$6.7\cdot10^{-5}$**	$6.9\cdot10^{-5}$	$9.5\cdot10^{-5}$	$1.3\cdot10^{-4}$	**$9.8\cdot10^{-5}$**
Sc	$3.0\cdot10^{-5}$	$2.7\cdot10^{-5}$	$2.0\cdot10^{-5}$	**$2.6\cdot10^{-5}$**	$1.3\cdot10^{-4}$	$3.2\cdot10^{-5}$	$1.2\cdot10^{-4}$	**$9.4\cdot10^{-5}$**
Se	$1.2\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.2\cdot10^{-4}$	**$1.2\cdot10^{-4}$**	$1.1\cdot10^{-4}$	$1.1\cdot10^{-4}$	$1.4\cdot10^{-4}$	**$1.2\cdot10^{-4}$**
Si	1.2	2.2	3.4	**2.3**	4.1	1.5	6.0	**3.9**
Sm	$2.5\cdot10^{-5}$	$2.0\cdot10^{-5}$	$2.2\cdot10^{-5}$	**$2.2\cdot10^{-5}$**	$5.0\cdot10^{-4}$	$8.4\cdot10^{-5}$	$3.4\cdot10^{-4}$	**$3.1\cdot10^{-4}$**
Sn	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	**$2.5\cdot10^{-6}$ g)**	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	$2.5\cdot10^{-6}$ g)	**$2.5\cdot10^{-6}$ g)**
Sr	$1.4\cdot10^{-1}$	$5.2\cdot10^{-2}$	$7.0\cdot10^{-2}$	**$8.7\cdot10^{-2}$**	$4.7\cdot10^{-2}$	$6.7\cdot10^{-2}$	$4.4\cdot10^{-2}$	**$5.3\cdot10^{-2}$**
Ta	$2.5\cdot10^{-7}$ h)	$2.5\cdot10^{-7}$ h)	$2.5\cdot10^{-7}$ h)	**$2.5\cdot10^{-7}$ h)**	$1.0\cdot10^{-6}$	$2.5\cdot10^{-7}$ h)	$1.0\cdot10^{-6}$	**$7.5\cdot10^{-7}$**
Tb	$7.0\cdot10^{-6}$	$4.0\cdot10^{-6}$	$4.0\cdot10^{-6}$	**$5.0\cdot10^{-6}$**	$6.5\cdot10^{-5}$	$1.1\cdot10^{-5}$	$4.1\cdot10^{-5}$	**$3.9\cdot10^{-5}$**
Te	$2.0\cdot10^{-6}$	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	**$1.3\cdot10^{-6}$**	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	$1.0\cdot10^{-6}$ a)	**$1.0\cdot10^{-6}$ a)**

Element	Forsmark				Laxemar-Simpevarp			
	Bolunds-fjärden	**Eckar-fjärden**	**Labbo-träsk**	**Mean Forsmark lake**	**Jämsen**	**Götemar**	**Frisksjön**	**Mean Laxemar lake**
Th	$3.1\bullet10^{-5}$	$2.6\bullet10^{-5}$	$2.2\bullet10^{-5}$	**$2.6\bullet10^{-5}$**	$8.4\bullet10^{-5}$	$5.2\bullet10^{-5}$	$1.2\bullet10^{-4}$	**$8.5\bullet10^{-5}$**
Ti	$3.2\bullet10^{-4}$	$3.1\bullet10^{-4}$	$4.1\bullet10^{-4}$	**$3.5\bullet10^{-4}$**	$2.0\bullet10^{-3}$	$4.0\bullet10^{-4}$	$1.9\bullet10^{-3}$	**$1.4\bullet10^{-3}$**
Tl	$6.0\bullet10^{-6}$	$4.0\bullet10^{-6}$	$5.0\bullet10^{-6}$	**$5.0\bullet10^{-6}$**	$8.0\bullet10^{-6}$	$8.0\bullet10^{-6}$	$1.0\bullet10^{-5}$	**$8.7\bullet10^{-6}$**
Tm	$3.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	**$2.3\bullet10^{-6}$**	$3.2\bullet10^{-5}$	$8.0\bullet10^{-6}$	$1.7\bullet10^{-5}$	**$1.9\bullet10^{-5}$**
U	$3.7\bullet10^{-3}$	$1.4\bullet10^{-3}$	$2.8\bullet10^{-3}$	**$2.6\bullet10^{-3}$**	$2.5\bullet10^{-4}$	$3.8\bullet10^{-4}$	$3.7\bullet10^{-4}$	**$3.3\bullet10^{-4}$**
V	$1.7\bullet10^{-4}$	$1.7\bullet10^{-4}$	$1.5\bullet10^{-4}$	**$1.6\bullet10^{-4}$**	$6.3\bullet10^{-4}$	$1.3\bullet10^{-4}$	$9.0\bullet10^{-4}$	**$5.5\bullet10^{-4}$**
W	$2.2\bullet10^{-5}$	$3.0\bullet10^{-6}$	$3.0\bullet10^{-6}$	**$9.3\bullet10^{-6}$**	$6.0\bullet10^{-6}$	$5.0\bullet10^{-6}$	$1.4\bullet10^{-5}$	**$8.3\bullet10^{-6}$**
Y	$2.0\bullet10^{-4}$	$1.7\bullet10^{-4}$	$1.6\bullet10^{-4}$	**$1.8\bullet10^{-4}$**	$2.7\bullet10^{-3}$	$5.3\bullet10^{-4}$	$1.4\bullet10^{-3}$	**$1.5\bullet10^{-3}$**
Yb	$2.0\bullet10^{-5}$	$1.8\bullet10^{-5}$	$1.8\bullet10^{-5}$	**$1.9\bullet10^{-5}$**	$2.5\bullet10^{-4}$	$5.7\bullet10^{-5}$	$1.3\bullet10^{-4}$	**$1.5\bullet10^{-4}$**
Zn	$9.2\bullet10^{-4}$	$1.3\bullet10^{-3}$	$1.9\bullet10^{-3}$	**$1.4\bullet10^{-3}$**	$4.4\bullet10^{-3}$	$1.3\bullet10^{-3}$	$4.6\bullet10^{-3}$	**$3.4\bullet10^{-3}$**
Zr	$3.9\bullet10^{-4}$	$3.8\bullet10^{-4}$	$3.9\bullet10^{-4}$	**$3.9\bullet10^{-4}$**	$9.3\bullet10^{-4}$	$2.8\bullet10^{-4}$	$1.1\bullet10^{-3}$	**$7.7\bullet10^{-4}$**

Detection limits (mg L^{-1}):

[a] $< 2\bullet10^{-6}$

[b] $< 1\bullet10^{-6}$

[c] $< 5\bullet10^{-5}$

[d] $< 2\bullet10^{-7}$

[e] $< 1\bullet10^{-5}$

[f] $< 1\bullet10^{-4}$

[g] $< 5\bullet10^{-6}$

[h] $< 5\bullet10^{-7}$

Appendix 8

Chemical composition of the particulate component of water

Concentrations of elements in suspended material (particulate pool) has been analysed for a large number of elements at one occasion in April 2008. The results are presented below. In Chapter 7, values in Table A7-1 have been used to describe the particulate pool of water for all elements except carbon nitrogen and phosphorus. For these three elements long-term analysis are available from the site description in the areas. When concentrations were below detection limit, half the detection limit has been used in calculations in Chapter 7. In the tables below, the values used in the calculation are presented and the detection limit is given in footnotes. When analysing particulate matter, the analysis is dependent on the total amount of an element in the sample and therefore the concentration differs between lakes also when half the detection limit are used as a result of different volumes of filtered water. For some elements, the detection limit was not specified and this sometimes resulted in negative concentration when the filters were subtracted in the analyses, so in those cases the concentration was set to 0.

Table A8-1. Chemical composition of suspended material in Forsmark and Laxemar-Simpevarp lakes from one occasion in April 2008. All values are in g m^{-3}. Values below detection limit are presented as half the detection limit and the detection limit for these elements are given in footnotes below.

	Forsmark				**Laxemar-Simpevarp**			
	Bolunds-fjärden	**Eckar-fjärden**	**Labbo-träsk**	**Mean Forsmark lake**	**Jämsen**	**Götemar**	**Frisksjön**	**Mean Laxemar lake**
Ag	$1.8\bullet10^{-7}$	$2.2\bullet10^{-7}$	$2.0\bullet10^{-7}$	**$2.0\bullet10^{-7}$**	$6.5\bullet10^{-7}$	$1.9\bullet10^{-7}$	$1.1\bullet10^{-6}$	**$6.5\bullet10^{-7}$**
Al	$4.3\bullet10^{-3}$	$3.2\bullet10^{-3}$	$4.1\bullet10^{-3}$	**$3.9\bullet10^{-3}$**	$9.7\bullet10^{-2}$	$6.5\bullet10^{-2}$	$1.7\bullet10^{-1}$	**$1.1\bullet10^{-1}$**
As	$4.1\bullet10^{-6}$	$4.0\bullet10^{-6}$	$2.5\bullet10^{-6}$	**$3.5\bullet10^{-6}$**	$4.7\bullet10^{-5}$	$1.3\bullet10^{-5}$	$7.2\bullet10^{-5}$	**$4.4\bullet10^{-5}$**
Au	$8.2\bullet10^{-8}$ e)	$8.8\bullet10^{-8}$ e)	$4.6\bullet10^{-8}$ e)	**$7.2\bullet10^{-8}$ e)**	$2.2\bullet10^{-7}$ e)	$4.9\bullet10^{-8}$ e)	$2.7\bullet10^{-7}$ e)	**$1.8\bullet10^{-7}$ e)**
B	$3.3\bullet10^{-6}$	0	$5.7\bullet10^{-5}$	**$1.7\bullet10^{-5}$**	$1.9\bullet10^{-5}$	$3.1\bullet10^{-5}$	$4.4\bullet10^{-5}$	**$3.1\bullet10^{-5}$**
Ba	$6.9\bullet10^{-5}$	$9.7\bullet10^{-5}$	$5.9\bullet10^{-5}$	**$7.5\bullet10^{-5}$**	$1.1\bullet10^{-3}$	$5.4\bullet10^{-4}$	$8.4\bullet10^{-4}$	**$8.2\bullet10^{-4}$**
Be	$2.1\bullet10^{-7}$	$1.7\bullet10^{-7}$	$1.7\bullet10^{-7}$	**$1.8\bullet10^{-7}$**	$1.5\bullet10^{-5}$	$1.2\bullet10^{-5}$	$6.3\bullet10^{-5}$	**$3.0\bullet10^{-5}$**
Bi	$4.1\bullet10^{-7}$	$2.5\bullet10^{-7}$	$1.9\bullet10^{-7}$	**$2.8\bullet10^{-7}$**	$2.3\bullet10^{-6}$	$7.8\bullet10^{-7}$	$3.3\bullet10^{-6}$	**$2.1\bullet10^{-6}$**
Br	$4.0\bullet10^{-4}$	$3.2\bullet10^{-4}$	$3.0\bullet10^{-4}$	**$3.4\bullet10^{-4}$**	$8.9\bullet10^{-4}$	$5.4\bullet10^{-4}$	$1.6\bullet10^{-4}$	**$5.3\bullet10^{-4}$**
Ca	$2.1\bullet10^{-2}$	$6.7\bullet10^{-2}$	$1.1\bullet10^{-2}$	**$3.3\bullet10^{-2}$**	$6.2\bullet10^{-2}$	$1.3\bullet10^{-2}$	$4.0\bullet10^{-2}$	**$3.9\bullet10^{-2}$**
Cd	$7.9\bullet10^{-7}$	$1.6\bullet10^{-6}$	$8.8\bullet10^{-7}$	**$1.1\bullet10^{-6}$**	$2.0\bullet10^{-5}$	0	$5.5\bullet10^{-6}$	**$5.8\bullet10^{-6}$**
Ce	$2.3\bullet10^{-5}$	$1.4\bullet10^{-5}$	$8.3\bullet10^{-6}$	**$1.5\bullet10^{-5}$**	$1.6\bullet10^{-3}$	$5.4\bullet10^{-4}$	$1.5\bullet10^{-3}$	**$1.2\bullet10^{-3}$**
Co	$1.7\bullet10^{-6}$	$1.5\bullet10^{-6}$	$1.3\bullet10^{-6}$	**$1.5\bullet10^{-6}$**	$5.2\bullet10^{-5}$	$4.1\bullet10^{-5}$	$4.0\bullet10^{-5}$	**$4.5\bullet10^{-5}$**
Cr	0	$1.1\bullet10^{-5}$	$7.3\bullet10^{-6}$	**$4.8\bullet10^{-6}$**	$8.0\bullet10^{-5}$	$5.1\bullet10^{-5}$	$1.7\bullet10^{-4}$	**$1.0\bullet10^{-4}$**
Cs	$6.6\bullet10^{-7}$	$3.7\bullet10^{-7}$	$5.3\bullet10^{-7}$	**$5.2\bullet10^{-7}$**	$4.6\bullet10^{-6}$	$4.9\bullet10^{-6}$	$8.7\bullet10^{-6}$	**$6.0\bullet10^{-6}$**
Cu	$4.0\bullet10^{-5}$	$3.0\bullet10^{-5}$	$4.6\bullet10^{-5}$	**$3.9\bullet10^{-5}$**	$1.1\bullet10^{-4}$	$6.2\bullet10^{-5}$	$2.5\bullet10^{-4}$	**$1.4\bullet10^{-4}$**
Dy	$1.2\bullet10^{-6}$	$7.9\bullet10^{-7}$	$4.6\bullet10^{-7}$	**$8.2\bullet10^{-7}$**	$8.9\bullet10^{-5}$	$1.9\bullet10^{-5}$	$6.3\bullet10^{-5}$	**$5.7\bullet10^{-5}$**
Er	$7.4\bullet10^{-7}$	$5.3\bullet10^{-7}$	$2.9\bullet10^{-7}$	**$5.2\bullet10^{-7}$**	$6.2\bullet10^{-5}$	$1.4\bullet10^{-5}$	$4.2\bullet10^{-5}$	**$3.9\bullet10^{-5}$**
Eu	$1.8\bullet10^{-7}$	$1.1\bullet10^{-7}$	$6.9\bullet10^{-8}$	**$1.2\bullet10^{-7}$**	$2.0\bullet10^{-5}$	$3.3\bullet10^{-6}$	$1.7\bullet10^{-5}$	**$1.4\bullet10^{-5}$**
Fe	$1.1\bullet10^{-2}$	$3.8\bullet10^{-3}$	$3.8\bullet10^{-3}$	**$6.0\bullet10^{-3}$**	$6.2\bullet10^{-1}$	$6.0\bullet10^{-2}$	$3.7\bullet10^{-1}$	**$3.5\bullet10^{-1}$**
Ga	$1.3\bullet10^{-6}$	$8.1\bullet10^{-7}$	$1.4\bullet10^{-6}$	**$1.2\bullet10^{-6}$**	$1.9\bullet10^{-5}$	$1.4\bullet10^{-5}$	$2.3\bullet10^{-5}$	**$1.8\bullet10^{-5}$**
Gd	$7.4\bullet10^{-7}$	$5.5\bullet10^{-7}$	$3.2\bullet10^{-7}$	**$5.4\bullet10^{-7}$**	$6.6\bullet10^{-5}$	$1.2\bullet10^{-5}$	$4.6\bullet10^{-5}$	**$4.1\bullet10^{-5}$**
Ge	$1.2\bullet10^{-7}$	$3.3\bullet10^{-7}$	$-8.2\bullet10^{-8}$	**$1.2\bullet10^{-7}$**	$2.2\bullet10^{-6}$	$1.4\bullet10^{-6}$	$2.2\bullet10^{-6}$	**$1.9\bullet10^{-6}$**
Hf	$3.3\bullet10^{-7}$	$2.1\bullet10^{-7}$	$3.6\bullet10^{-7}$	**$3.0\bullet10^{-7}$**	$7.0\bullet10^{-6}$	$4.0\bullet10^{-6}$	$1.2\bullet10^{-5}$	**$7.7\bullet10^{-6}$**
Hg	$2.3\bullet10^{-7}$	$1.2\bullet10^{-7}$	$3.6\bullet10^{-7}$	**$2.4\bullet10^{-7}$**	$8.9\bullet10^{-7}$	$2.2\bullet10^{-7}$	$5.9\bullet10^{-7}$	**$5.7\bullet10^{-7}$**
Ho	$2.5\bullet10^{-7}$	$1.9\bullet10^{-7}$	$1.1\bullet10^{-7}$	**$1.8\bullet10^{-7}$**	$2.0\bullet10^{-5}$	$4.2\bullet10^{-6}$	$1.4\bullet10^{-5}$	**$1.3\bullet10^{-5}$**
I	$-8.2\bullet10^{-6}$	$1.8\bullet10^{-4}$	$2.9\bullet10^{-5}$	**$6.7\bullet10^{-5}$**	$3.5\bullet10^{-4}$	$1.5\bullet10^{-4}$	$1.1\bullet10^{-3}$	**$5.2\bullet10^{-4}$**
In	$8.2\bullet10^{-8}$ e)	$8.8\bullet10^{-8}$ e)	$4.6\bullet10^{-8}$ e)	**$7.2\bullet10^{-8}$ e)**	$2.2\bullet10^{-7}$ e)	$4.9\bullet10^{-8}$ e)	$2.7\bullet10^{-7}$ e)	**$1.8\bullet10^{-7}$ e)**

	Forsmark				Laxemar-Simpevarp			
	Bolunds-fjärden	**Eckar-fjärden**	**Labbo-träsk**	**Mean Forsmark lake**	**Jämsen**	**Götemar**	**Frisksjön**	**Mean Laxemar lake**
Ir	$4.1^{-10\ a)}$	$4.4^{-10\ a)}$	$2.3^{-10\ a)}$	**$3.6^{-10\ a)}$**	$1.1\bullet10^{-9\ a)}$	$2.5^{-10\ a)}$	$1.3\bullet10^{-9\ a)}$	**$9.0^{-10\ a)}$**
K	$4.1\bullet10^{-3}$	$8.8\bullet10^{-3}$	$5.6\bullet10^{-2}$	**$2.3\bullet10^{-2}$**	$1.6\bullet10^{-2}$	$1.9\bullet10^{-2}$	$2.5\bullet10^{-2}$	**$2.0\bullet10^{-2}$**
La	$1.6\bullet10^{-5}$	$9.1\bullet10^{-6}$	$7.2\bullet10^{-6}$	**$1.1\bullet10^{-5}$**	$8.9\bullet10^{-4}$	$2.1\bullet10^{-4}$	$7.9\bullet10^{-4}$	**$6.3\bullet10^{-4}$**
Li	$2.5\bullet10^{-6}$	$5.9\bullet10^{-6}$	$2.7\bullet10^{-6}$	**$3.7\bullet10^{-6}$**	$2.7\bullet10^{-5}$	$4.5\bullet10^{-5}$	$4.5\bullet10^{-5}$	**$3.9\bullet10^{-5}$**
Lu	$8.4\bullet10^{-8}$	$6.9\bullet10^{-8}$	$3.4\bullet10^{-8}$	**$6.2\bullet10^{-8}$**	$7.5\bullet10^{-6}$	$2.1\bullet10^{-6}$	$5.1\bullet10^{-6}$	**$4.9\bullet10^{-6}$**
Mg	$2.5\bullet10^{-3}$	$4.2\bullet10^{-3}$	$1.5\bullet10^{-3}$	**$2.7\bullet10^{-3}$**	$1.3\bullet10^{-2}$	$7.2\bullet10^{-3}$	$1.3\bullet10^{-2}$	**$1.1\bullet10^{-2}$**
Mn	$8.7\bullet10^{-4}$	$4.9\bullet10^{-3}$	$2.0\bullet10^{-4}$	**$2.0\bullet10^{-3}$**	$1.3\bullet10^{-2}$	$1.1\bullet10^{-2}$	$5.7\bullet10^{-3}$	**$9.9\bullet10^{-3}$**
Mo	$3.3\bullet10^{-6}$	$2.7\bullet10^{-6}$	$3.4\bullet10^{-6}$	**$3.1\bullet10^{-6}$**	$9.3\bullet10^{-6}$	$6.5\bullet10^{-6}$	$3.6\bullet10^{-5}$	**$1.7\bullet10^{-5}$**
Na	$4.9\bullet10^{-3}$	$7.6\bullet10^{-3}$	$1.6\bullet10^{-3}$	**$4.7\bullet10^{-3}$**	$7.6\bullet10^{-3}$	$8.9\bullet10^{-3}$	$1.7\bullet10^{-2}$	**$1.1\bullet10^{-2}$**
Nb	$9.7\bullet10^{-7}$	$8.1\bullet10^{-7}$	$9.1\bullet10^{-7}$	**$9.0\bullet10^{-7}$**	$3.6\bullet10^{-5}$	$1.3\bullet10^{-5}$	$3.2\bullet10^{-5}$	**$2.7\bullet10^{-5}$**
Nd	$8.7\bullet10^{-6}$	$5.3\bullet10^{-6}$	$3.3\bullet10^{-6}$	**$5.8\bullet10^{-6}$**	$7.5\bullet10^{-4}$	$1.4\bullet10^{-4}$	$6.3\bullet10^{-4}$	**$5.1\bullet10^{-4}$**
Ni	$1.6\bullet10^{-5}$	$1.4\bullet10^{-5}$	$1.0\bullet10^{-5}$	**$1.4\bullet10^{-5}$**	$6.0\bullet10^{-5}$	$4.6\bullet10^{-5}$	$1.3\bullet10^{-4}$	**$7.8\bullet10^{-5}$**
Os	$1.6\bullet10^{-9\ b)}$	$1.8\bullet10^{-9\ b)}$	$9.1^{-10\ b)}$	**$1.4\bullet10^{-9\ b)}$**	$4.5\bullet10^{-9\ b)}$	$9.9^{-10\ b)}$	$5.3\bullet10^{-9\ b)}$	**$3.6\bullet10^{-9\ b)}$**
P	$5.5\bullet10^{-3}$	$5.7\bullet10^{-3}$	$3.4\bullet10^{-3}$	**$4.9\bullet10^{-3}$**	$1.0\bullet10^{-2}$	$4.9\bullet10^{-3}$	$1.3\bullet10^{-2}$	**$9.4\bullet10^{-3}$**
Pb	$4.8\bullet10^{-5}$	$5.8\bullet10^{-5}$	$2.1\bullet10^{-5}$	**$4.2\bullet10^{-5}$**	$3.8\bullet10^{-4}$	$1.2\bullet10^{-4}$	$4.8\bullet10^{-4}$	**$3.3\bullet10^{-4}$**
Pd	$1.6\bullet10^{-6\ f)}$	$1.8\bullet10^{-6\ f)}$	$9.1\bullet10^{-7\ f)}$	**$1.4\bullet10^{-6\ f)}$**	$4.5\bullet10^{-6\ f)}$	$9.9\bullet10^{-7\ f)}$	$5.3\bullet10^{-6\ f)}$	**$3.6\bullet10^{-6\ f)}$**
Pr	$2.6\bullet10^{-6}$	$1.5\bullet10^{-6}$	$9.0\bullet10^{-7}$	**$1.7\bullet10^{-6}$**	$2.0\bullet10^{-4}$	$3.8\bullet10^{-5}$	$1.7\bullet10^{-4}$	**$1.4\bullet10^{-4}$**
Pt	$4.1\bullet10^{-8\ d)}$	$4.4\bullet10^{-8\ d)}$	$2.3\bullet10^{-8\ d)}$	**$3.6\bullet10^{-8\ d)}$**	$1.1\bullet10^{-7\ d)}$	$2.5\bullet10^{-8\ d)}$	$1.3\bullet10^{-7\ d)}$	**$9.0\bullet10^{-8\ d)}$**
Rb	$1.1\bullet10^{-5}$	$1.8\bullet10^{-5}$	$1.2\bullet10^{-5}$	**$1.3\bullet10^{-5}$**	$7.5\bullet10^{-5}$	$1.0\bullet10^{-4}$	$1.4\bullet10^{-4}$	**$1.0\bullet10^{-4}$**
Re	1.6^{-10}	$2.1\bullet10^{-9}$	3.6^{-10}	**8.8^{-10}**	$2.2\bullet10^{-9}$	3.9^{-10}	0	**1.7^{-10}**
Rh	$8.2^{-10\ c)}$	$8.8^{-10\ c)}$	$4.6^{-10\ c)}$	**$7.2^{-10\ c)}$**	$2.2\bullet10^{-8\ c)}$	$4.9\bullet10^{-9\ c)}$	$2.7\bullet10^{-8\ c)}$	**$1.8\bullet10^{-8\ c)}$**
Ru	$4.1\bullet10^{-8\ d)}$	$4.4\bullet10^{-8\ d)}$	$2.3\bullet10^{-8\ d)}$	**$3.6\bullet10^{-8\ d)}$**	$1.1\bullet10^{-7\ d)}$	$2.5\bullet10^{-8\ d)}$	$1.3\bullet10^{-7\ d)}$	**$9.0\bullet10^{-8\ d)}$**
S	$9.9\bullet10^{-3}$	$2.0\bullet10^{-2}$	$5.1\bullet10^{-3}$	**$1.1\bullet10^{-2}$**	$1.9\bullet10^{-2}$	$8.0\bullet10^{-3}$	$3.0\bullet10^{-2}$	**$1.9\bullet10^{-2}$**
Sb	$9.6\bullet10^{-7}$	$2.3\bullet10^{-6}$	$2.7\bullet10^{-6}$	**$2.0\bullet10^{-6}$**	$5.0\bullet10^{-6}$	$1.5\bullet10^{-6}$	$4.8\bullet10^{-6}$	**$3.7\bullet10^{-6}$**
Sc	$1.4\bullet10^{-6}$	$1.5\bullet10^{-6}$	$1.2\bullet10^{-6}$	**$1.4\bullet10^{-6}$**	$2.3\bullet10^{-5}$	$1.1\bullet10^{-5}$	$3.7\bullet10^{-5}$	**$2.4\bullet10^{-5}$**
Se	$8.4\bullet10^{-7}$	$9.5\bullet10^{-7}$	$5.1\bullet10^{-7}$	**$7.7\bullet10^{-7}$**	$3.8\bullet10^{-6}$	$3.2\bullet10^{-6}$	$6.4\bullet10^{-6}$	**$4.5\bullet10^{-6}$**
Si	$3.4\bullet10^{-2}$	$3.3\bullet10^{-2}$	$2.4\bullet10^{-2}$	**$3.0\bullet10^{-2}$**	$2.6\bullet10^{-1}$	$2.2\bullet10^{-1}$	$5.1\bullet10^{-1}$	**$3.3\bullet10^{-1}$**
Sm	$1.6\bullet10^{-6}$	$1.1\bullet10^{-6}$	$6.2\bullet10^{-7}$	**$1.1\bullet10^{-6}$**	$1.4\bullet10^{-4}$	$2.5\bullet10^{-5}$	$1.1\bullet10^{-4}$	**$8.9\bullet10^{-5}$**
Sn	0	$6.5\bullet10^{-7}$	$2.8\bullet10^{-6}$	**$1.0\bullet10^{-6}$**	$1.2\bullet10^{-5}$	$4.0\bullet10^{-6}$	$1.2\bullet10^{-5}$	**$9.1\bullet10^{-6}$**
Sr	$4.9\bullet10^{-5}$	$6.9\bullet10^{-5}$	$2.1\bullet10^{-5}$	**$4.6\bullet10^{-5}$**	$4.2\bullet10^{-4}$	$1.4\bullet10^{-4}$	$3.0\bullet10^{-4}$	**$2.9\bullet10^{-4}$**
Ta	0	0	0	**0**	$8.9\bullet10^{-7}$	$4.9\bullet10^{-7}$	$5.3\bullet10^{-7}$	**$6.4\bullet10^{-7}$**
Tb	$1.9\bullet10^{-7}$	$1.3\bullet10^{-7}$	$7.2\bullet10^{-8}$	**$1.3\bullet10^{-7}$**	$1.4\bullet10^{-5}$	$2.8\bullet10^{-6}$	$1.0\bullet10^{-5}$	**$9.0\bullet10^{-6}$**
Te	$9.6\bullet10^{-8}$	$6.5\bullet10^{-8}$	$3.2\bullet10^{-8}$	**$6.4\bullet10^{-8}$**	$3.9\bullet10^{-7}$	$1.7\bullet10^{-7}$	$6.7\bullet10^{-7}$	**$4.1\bullet10^{-7}$**
Th	$3.3\bullet10^{-6}$	$2.2\bullet10^{-6}$	$1.6\bullet10^{-6}$	**$2.4\bullet10^{-6}$**	$6.2\bullet10^{-5}$	$2.7\bullet10^{-5}$	$8.9\bullet10^{-5}$	**$6.0\bullet10^{-5}$**
Ti	$1.6\bullet10^{-4}$	$1.7\bullet10^{-4}$	$1.6\bullet10^{-4}$	**$1.6\bullet10^{-4}$**	$4.1\bullet10^{-3}$	$1.5\bullet10^{-3}$	$3.5\bullet10^{-3}$	**$3.0\bullet10^{-3}$**
Tl	$2.4\bullet10^{-7}$	$1.8\bullet10^{-7}$	$1.4\bullet10^{-7}$	**$1.9\bullet10^{-7}$**	$1.0\bullet10^{-6}$	$7.9\bullet10^{-7}$	$1.3\bullet10^{-6}$	**$1.0\bullet10^{-6}$**
Tm	$1.0\bullet10^{-7}$	$7.6\bullet10^{-8}$	$3.8\bullet10^{-8}$	**$7.2\bullet10^{-8}$**	$8.4\bullet10^{-6}$	$2.1\bullet10^{-6}$	$5.8\bullet10^{-6}$	**$5.4\bullet10^{-6}$**
U	$1.8\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.8\bullet10^{-6}$	**$2.2\bullet10^{-6}$**	$3.1\bullet10^{-5}$	$3.5\bullet10^{-5}$	$6.8\bullet10^{-5}$	**$4.5\bullet10^{-5}$**
V	$1.0\bullet10^{-5}$	$5.6\bullet10^{-6}$	$7.4\bullet10^{-6}$	**$7.7\bullet10^{-6}$**	$6.2\bullet10^{-4}$	$9.6\bullet10^{-5}$	$6.3\bullet10^{-4}$	**$4.5\bullet10^{-4}$**
W	$9.6\bullet10^{-7}$	$1.0\bullet10^{-6}$	$9.8\bullet10^{-7}$	**$9.8\bullet10^{-7}$**	$4.7\bullet10^{-6}$	$2.0\bullet10^{-6}$	$7.1\bullet10^{-6}$	**$4.6\bullet10^{-6}$**
Y	$7.0\bullet10^{-6}$	$5.1\bullet10^{-6}$	$2.8\bullet10^{-6}$	**$5.0\bullet10^{-6}$**	$5.8\bullet10^{-4}$	$1.3\bullet10^{-4}$	$3.9\bullet10^{-4}$	**$3.6\bullet10^{-4}$**
Yb	$5.1\bullet10^{-7}$	$3.9\bullet10^{-7}$	$2.0\bullet10^{-7}$	**$3.7\bullet10^{-7}$**	$4.4\bullet10^{-5}$	$1.5\bullet10^{-5}$	$3.1\bullet10^{-5}$	**$3.0\bullet10^{-5}$**
Zn	$6.6\bullet10^{-5}$	$1.2\bullet10^{-4}$	$5.5\bullet10^{-5}$	**$8.1\bullet10^{-5}$**	$7.1\bullet10^{-4}$	$3.6\bullet10^{-4}$	$6.4\bullet10^{-4}$	**$5.7\bullet10^{-4}$**
Zr	$1.4\bullet10^{-5}$	$1.4\bullet10^{-5}$	$1.3\bullet10^{-5}$	**$1.4\bullet10^{-5}$**	$2.1\bullet10^{-4}$	$1.3\bullet10^{-4}$	$3.9\bullet10^{-4}$	**$2.4\bullet10^{-4}$**

Detection limits:

a) < 0.005 ng

b) < 0.02 ng

c) < 0.1 ng

d) < 0.5 ng

e) < 1 ng

f) < 20 ng

Appendix 9

Chemical composition in the sediment component

The chemical composition of lake sediments has been investigated (in Forsmark: /Hannu and Karlsson 2006, Strömgren and Brunberg 2006/ and in Laxemar: /Engdahl et al. 2006/). In this appendix the mean concentrations of each element are presented. For the Forsmark lakes data is shown according to the three different sediment layers; gyttja, gyttja clay and clay (Table A9-1). For Laxemar lake (Frisksjön) data is shown for the upper two centimetres and for the rest of the gyttja layer (0.02–4.40 m) (Table A9-2). Data in the tables below are sorted in alphabetical order.

Table A9-1. Chemistry in different sediment layers in lakes in the Forsmark area. The number of analytical results used for calculating the mean values are presented in columns denoted "n". Analytical results reported as below the detection limit has been changed to half the detection limit. The number of values below detection limit is presented in separate columns with detection limits in parenthesis.

	Gyttja			Clay gyttja			Clay		
	Conc (mg/kg dw)	**n**	**Values below detection limit**	**Conc (mg/kg dw)**	**n**	**Values below detection limit**	**Conc (mg/kg dw)**	**n**	**Values below detection limit**
Ag	18.8	5		23.5	1		8.2	3	
Al	6,563.3	5		49,224.9	1		88,922.4	3	
As	3.5	14		7.4	2		7.1	4	
B	41.4	14		33.6	2	1 (20 mg/kg dw)	25.9	4	
Ba	112.1	14		364.5	2		679.3	4	
Be	0.4	14	5 (3–4 mg/kg dw)	2.6	2		2.9	4	
Br	27.7	5		93.8	1		1.7	3	
C*	356,000.0	5		88,000.0	1		10,000.0	5	
Ca	64,751.8	5		12,650.2	1		34,710.6	3	
Cd	0.6	14		0.5	2		0.3	4	
Ce	46.8	14		84.5	2		98.6	4	
Cl	781.0	5		334.0	1		76.6	3	
Co	2.5	16		11.1	3		13.3	5	
Cr	13.7	23	3 (5–8 mg/kg dw)	43.9	3		88.0	5	
Cs	0.8	14		5.9	2		7.7	4	
Cu	26.6	23		30.5	3		35.2	5	
Dy	3.7	14		5.9	2		6.7	4	
Er	2.4	14	1 (1 mg/kg dw)	3.6	2		3.3	4	
Eu	0.5	14	1 (0.05 mg/kg dw)	1.0	2		1.3	4	
Fe	9,100.9	14		30,489.5	2		53,793.7	4	
Ga	0.6	14	13 (1 mg/kg dw)	8.9	2	1 (1 mg/kg dw)	18.1	4	1 (1 mg/kg dw)
Gd	2.0	14	3 (0.04 mg/kg dw)	5.1	2		6.2	4	
Hf	1.5	14		4.1	2		5.2	4	
Hg	0.1	14	2 (0.04–0.1 mg/kg dw)	0.0	2	1 (0.04 mg/kg dw)	0.0	4	3 (0.04 mg/kg dw)
Ho	0.8	14		1.3	2		1.3	4	
I	8.8	5		7.9	1		0.3	3	3 (0.5 mg/kg dw)
K	3,842.6	14		16,396.5	2		31,153.3	4	
La	22.2	14		48.7	2		58.6	4	
Li	11.6	14		141.7	2		438.3	4	
Lu	0.3	14		0.5	2		0.5	4	
Mg	2,511.9	14		7,871.8	2		16,120.5	4	
Mn	246.4	23		303.2	3		556.5	5	
Mo	15.1	14		17.0	2		5.8	4	3 (2 mg/kg dw)
N	28,766.7	3		5,980.0	1			0	
Na	2,242.5	14		7,942.0	2		12,890.5	4	
Nb	3.9	14	1 (0.2 mg/kg dw)	11.0	2		17.0	4	

	Gyttja			Clay gyttja			Clay		
	Conc (mg/kg dw)	n	Values below detection limit	Conc (mg/kg dw)	n	Values below detection limit	Conc (mg/kg dw)	n	Values below detection limit
Nd	22.3	14		41.1	2		45.1	4	
Ni	13.6	23	5 (5–8 mg/kg dw)	28.3	3		36.9	5	
P	477.9	14		637.1	2		792.1	4	
Pb	27.8	14		28.1	2		25.5	4	
Pr	7.9	14		12.8	2		12.8	4	
Rb	32.0	14	5 (2 mg/kg dw)	111.1	2		137.0	4	
S	8,496.4	14		8,489.0	2		1,637.5	4	
Sb	0.5	14		0.7	2		0.6	4	1 (0.02 mg/kg dw)
Sc	2.5	14	2 (0.5–0.8 mg/kg dw)	8.6	2		15.3	4	
Se	1.1	5	3 (1–2 mg/kg dw)	0.5	1	1 (1 mg/kg dw)	0.5	3	3 (1 mg/kg dw)
Si	80,343.2	14		200,791.3	2		244,619.4	4	
Sm	3.7	14	1 (0.4 mg/kg dw)	7.1	2		7.8	4	
Sn	1.6	14	6 (1 mg/kg dw)	2.9	2	1 (1 mg/kg dw)	3.4	4	
Sr	63.8	14		86.5	2		144.2	4	
Ta	0.5	14	2 (0.06 mg/kg dw)	1.0	2		1.5	4	
Tb	0.3	14	6 (0.1 mg/kg dw)	0.9	2		1.0	4	
Th	4.1	14		11.2	2		16.1	4	
Ti	531.4	14		2,254.1	2		4,358.4	4	
Tl	0.4	5		1.7	1		1.1	3	
Tm	0.3	14	3 (0.1 mg/kg dw)	0.4	2		0.7	4	
U	34.7	14		20.2	2		8.9	4	
V	13.9	23		41.5	3		94.7	5	
W	2.3	14	1 (0.4 mg/kg dw)	2.8	2		2.5	4	
Y	12.9	14		26.1	2		34.9	4	
Yb	1.8	14	1 (0.2 mg/kg dw)	2.9	2		3.8	4	
Zn	140.7	23		307.7	3		807.4	5	
Zr	26.6	14		114.0	2		167.8	4	

* Carbon data for clay has been taken from /Hedenström and Risberg 2003/. Data from Eckarfjärden.

Table A9-2. Chemistry in different sediment layers in Frisksjön in the Laxemar-Simpevarp area. The numbers of analytical results used for calculating the mean values are presented in columns denoted "n". Analytical results reported as below the detection limit has been changed to half the detection limit. The number of values which was below detection limit is presented in separate columns with detection limits in parenthesis.

	Sediment 0.00–0.02 m			Sediment 0.02–4.40 m		
	Conc (mg/kg dw)	n	Values below detection limit	Conc (mg/kg dw)	n	Values below detection limit
Ag	0.1	1	1 (0.20)	0.1	11	9 (0.030–0.20 mg/kg dw)
Al	30,170.1	1		23,770.4	11	
As	4.42	1		7.6	11	
B	0.5	1	1 (1.0 mg/kg dw)	0.9	11	11 (1.0–3.0 mg/kg dw)
Ba	181	1		145.3	11	
Be	8.73	1		5.6	11	
Br	8.4	1		82.1	11	
C	170,000	1		179,090.9	11	
Ca	8,147.58	1		8,758.3	11	
Cd	3.47	1		2.3	11	
Ce	222	1		185.0	11	
Cl	352	1		2,763.5	11	

	Sediment 0.00–0.02 m			**Sediment 0.02–4.40 m**		
	Conc (mg/kg dw)	**n**	**Values below detection limit**	**Conc (mg/kg dw)**	**n**	**Values below detection limit**
Co	22.2	1		13.2	11	
Cr	36.6	1		34.1	11	
Cs	2.23	1		1.8	11	
Cu	66.4	1		58.8	11	
Dy	11.7	1		8.7	11	
Er	8.03	1		5.1	11	
Eu	3.57	1		2.7	11	
Fe	30,139.83	1		23,382.0	11	
Ga	67.6	1		8.3	11	8 (1.0 mg/kg dw)
Gd	16.6	1		12.1	11	
Hf	0.826	1		0.7	11	3 (0.10 mg/kg dw)
Hg	0.153	1		0.1	11	4 (0.040 mg/kg dw)
Ho	2.52	1		1.8	11	
I	4.25	1		15.3	11	
K	5,645.36	1		5,502.0	11	
La	116	1		87.0	11	
Li	19.6	1		14.0	11	
Lu	0.988	1		0.8	11	
Mg	3,257.28	1		4,968.2	11	
Mn	261.0402	1		200.3	11	
Mo	3	1	1 (6.0 mg/kg dw)	8.1	11	6 (6.0 mg/kg dw)
N	12,700	1		18,063.6	11	
Na	2,351.823	1		4,943.8	11	
Nb	3	1	1 (6.0 mg/kg dw)	3.0	11	11 (6.0 mg/kg dw)
Nd	119	1		95.5	11	
Ni	52	1		42.8	11	
P	1,557.948	1		1,765.8	11	
Pb	42.7	1		23.3	11	
Pr	32.4	1		24.3	11	
Rb	39.7	1		33.6	11	
S	18,500	1		23,690.9	11	
Sb	0.785	1		0.5	11	
Sc	7.74	1		6.5	11	
Se	1	1	1 (2.0 mg/kg dw)	1.0	11	11 (2.0 mg/kg dw)
Si	192,610	1		186,150.0	11	
Sm	19.3	1		15.2	11	
Sn	10	1	1 (20 mg/kg dw)	10.0	11	11 (20 mg/kg dw)
Sr	66.8	1		94.5	11	
Ta	0.03	1	1 (0.060 mg/kg dw)	0.2	11	7 (0.060 mg/kg dw)
Tb	2.02	1		1.7	11	
Th	9.9	1		7.6	11	
Ti	107.91	1		93.2	11	
Tl	0.605	1		0.4	11	
Tm	1.18	1		0.8	11	
U	13	1		12.8	11	
V	42.5	1		35.3	11	
W	30	1	1 (60 mg/kg dw)	30.0	11	11 (60 mg/kg dw)
Y	83.2	1		61.3	11	
Yb	6.65	1		5.3	11	
Zn	233	1		139.6	11	
Zr	57.8	1		54.6	11	

Appendix 10

Chemical composition of the biotic component

Table A10-1. Chemistry in lake biota in Forsmark used in calculations of pools in Chapter 7. Values are in g gC^{-1}. Data on fish, benthic filter feeders, microphytobenthos and macroalgae Chara sp. are site specific data from /Hannu and Karlsson 2006/. Data on phytoplankton, zooplankton benthic herbivores, benthic detritivores and benthic carnivores are taken from the coastal areas outside Forsmark /Kumblad and Bradshaw 2008/. Chemical composition of benthic omnivores was calculated as a mean of the other functional groups. Chemical composition for benthic herbivores, detritivores, carnivores of 15 elements (Ag, B, Be, Ga, Hf, La, Nb, Sb, Sc, Sn, Sr, Ta, Ti, W and Y) was assumed to be identical to chemical composition of benthic filter feeders. Data on bacterioplankton P, N and S content are from /Fagerbakke 1996/. For benthic bacteria P and N content are from /Kautsky 1995/ and S content are assumed to be identical to bacterioplankton /Fagerbakke 1996/. "–" denotes missing data, and * indicates were half the detection limit is reported. For further explanation of the use of data, see Chapter 7.

Element	Phyto-plankton	Microphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
C	1	1	1	1	1	1	1	1	1	1	1	1	1	1
N	$1.2\bullet10^{-1}$	$9.8\bullet10^{-2}$	$2.6\bullet10^{-2}$	$1.9\bullet10^{-1}$	$2.3\bullet10^{-1}$	$1.8\bullet10^{-1}$	$1.2\bullet10^{-1}$	$2.2\bullet10^{-1}$	$7.9\bullet10^{-2}$	$1.8\bullet10^{-1}$	$1.5\bullet10^{-1}$	$2.6\bullet10^{-1}$	$4.0\bullet10^{-1}$	$3.4\bullet10^{-1}$
P	$7.5\bullet10^{-3}$	$3.0\bullet10^{-3}$	$2.0\bullet10^{-3}$	$4.6\bullet10^{-2}$	$2.2\bullet10^{-2}$	$5.6\bullet10^{-2}$	$1.1\bullet10^{-2}$	$6.9\bullet10^{-3}$	$8.7\bullet10^{-3}$	$2.1\bullet10^{-2}$	$2.7\bullet10^{-2}$	$2.5\bullet10^{-2}$	$2.3\bullet10^{-2}$	$3.1\bullet10^{-2}$
Ag	–	$3.8\bullet10^{-5}$	$2.5\bullet10^{-8}$	–	–	–	$1.2\bullet10^{-6}$	$1.2\bullet10^{-6}$	$1.2\bullet10^{-6}$	$1.2\bullet10^{-6}$	$1.2\bullet10^{-6}$	$1.1\bullet10^{-8*}$	$8.0\bullet10^{-8*}$	$1.2\bullet10^{-8*}$
Al	$1.1\bullet10^{-1}$	$8.4\bullet10^{-3}$	$1.1\bullet10^{-3}$	–	$6.8\bullet10^{-3}$	–	$2.7\bullet10^{-3}$	$5.6\bullet10^{-4}$	$3.5\bullet10^{-3}$	$2.0\bullet10^{-6}$	$1.7\bullet10^{-3}$	$2.3\bullet10^{-7}$	$2.4\bullet10^{-6}$	$1.2\bullet10^{-7}$
As	$7.0\bullet10^{-5}$	$3.5\bullet10^{-6}$	$7.0\bullet10^{-7}$	–	$5.5\bullet10^{-5}$	–	$1.5\bullet10^{-5}$	$5.8\bullet10^{-6}$	$1.1\bullet10^{-5}$	$1.8\bullet10^{-5}$	$1.3\bullet10^{-5}$	$1.8\bullet10^{-7}$	$1.0\bullet10^{-7}$	$1.8\bullet10^{-7}$
B	–	$5.7\bullet10^{-5}$	$2.8\bullet10^{-5}$	–	–	–	$5.1\bullet10^{-6}$	$5.1\bullet10^{-6}$	$5.1\bullet10^{-6}$	$5.1\bullet10^{-6}$	$5.1\bullet10^{-6}$	$3.7\bullet10^{-8}$	$2.9\bullet10^{-7}$	$3.5\bullet10^{-8}$
Ba	$2.7\bullet10^{-4}$	$2.2\bullet10^{-4}$	$4.5\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	$1.1\bullet10^{-3*}$	$1.7\bullet10^{-4}$	$2.2\bullet10^{-4}$	$4.1\bullet10^{-4}$	$1.1\bullet10^{-6*}$	$2.0\bullet10^{-6*}$	$2.9\bullet10^{-7*}$
Be	–	$3.7\bullet10^{-7}$	$9.5\bullet10^{-8}$	–	–	–	$7.4\bullet10^{-8}$	$7.4\bullet10^{-8}$	$7.4\bullet10^{-8}$	$7.4\bullet10^{-8}$	$7.4\bullet10^{-8}$	$5.7\bullet10^{-8}$	$4.0\bullet10^{-7}$	$5.8\bullet10^{-8}$
Br	$7.6\bullet10^{-3}$	$3.3\bullet10^{-5}$	$4.5\bullet10^{-5}$	–	$3.1\bullet10^{-2}$	–	$6.7\bullet10^{-4}$	$1.3\bullet10^{-4}$	$1.8\bullet10^{-4}$	$2.8\bullet10^{-4}$	$3.2\bullet10^{-4}$	$2.8\bullet10^{-5}$	$1.9\bullet10^{-5}$	$2.0\bullet10^{-5}$
Ca	$2.2\bullet10^{-2}$	$1.4\bullet10^{-1}$	$7.7\bullet10^{-1}$	–	$2.1\bullet10^{-1}$	–	$5.7\bullet10^{-1}$	$2.4\bullet10^{-1}$	1.5	$3.4\bullet10^{-1}$	$6.7\bullet10^{-1}$	$4.8\bullet10^{-3}$	$9.0\bullet10^{-3}$	$1.1\bullet10^{-2}$
Cd	$1.4\bullet10^{-6}$	$7.2\bullet10^{-7}$	$2.1\bullet10^{-7}$	–	$1.1\bullet10^{-5}$	–	$4.7\bullet10^{-6}$	$1.0\bullet10^{-5}$	$8.6\bullet10^{-7}$	$5.1\bullet10^{-6}$	$5.3\bullet10^{-6}$	$3.4\bullet10^{-9*}$	$1.7\bullet10^{-8*}$	$3.5\bullet10^{-9*}$
Ce	$5.2\bullet10^{-8}$	$5.9\bullet10^{-5}$	$3.6\bullet10^{-6}$	–	$8.4\bullet10^{-6}$	–	$1.9\bullet10^{-7}$	$2.3\bullet10^{-6}$	$1.9\bullet10^{-6}$	$1.0\bullet10^{-7}$	$1.1\bullet10^{-6}$	–	–	–
Cl	$3.7\bullet10^{-1}$	$1.4\bullet10^{-3}$	$3.2\bullet10^{-3}$	–	–	–	$1.8\bullet10^{-2}$	$6.6\bullet10^{-3}$	$1.1\bullet10^{-2}$	$1.3\bullet10^{-2}$	$1.2\bullet10^{-2}$	$3.9\bullet10^{-3}$	$1.1\bullet10^{-2}$	$2.5\bullet10^{-3}$
Co	$9.2\bullet10^{-6}$	$2.6\bullet10^{-6}$	$1.0\bullet10^{-6}$	–	$3.9\bullet10^{-6}$	–	$1.9\bullet10^{-6}$	$2.2\bullet10^{-6}$	$1.7\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$1.2\bullet10^{-8}$	$3.9\bullet10^{-8}$	$5.8\bullet10^{-9}$
Cr	$3.5\bullet10^{-5}$	$1.3\bullet10^{-5}$	$2.1\bullet10^{-6}$	–	$2.4\bullet10^{-5}$	–	$2.3\bullet10^{-6}$	$2.1\bullet10^{-6}$	$3.0\bullet10^{-6}$	$3.0\bullet10^{-6}$	$2.6\bullet10^{-6}$	$1.1\bullet10^{-8*}$	$1.1\bullet10^{-7*}$	$1.2\bullet10^{-8*}$
Cs	$2.8\bullet10^{-6}$	$4.1\bullet10^{-7}$	$9.4\bullet10^{-8}$	–	$7.6\bullet10^{-7}$	–	$2.4\bullet10^{-7}$	$6.3\bullet10^{-8}$	$3.2\bullet10^{-7}$	$2.6\bullet10^{-7}$	$2.2\bullet10^{-7}$	$1.4\bullet10^{-7}$	$7.9\bullet10^{-8}$	$3.3\bullet10^{-7}$
Cu	$1.3\bullet10^{-4}$	$3.7\bullet10^{-5}$	$4.9\bullet10^{-5}$	–	$4.7\bullet10^{-4}$	–	$9.7\bullet10^{-5}$	$4.5\bullet10^{-5}$	$1.3\bullet10^{-4}$	$1.5\bullet10^{-4}$	$1.1\bullet10^{-4}$	$2.0\bullet10^{-6}$	$2.8\bullet10^{-6}$	$1.2\bullet10^{-6}$
Dy	$2.8\bullet10^{-9}$	$8.4\bullet10^{-6}$	$3.8\bullet10^{-7}$	–	$6.5\bullet10^{-7}$	–	$1.3\bullet10^{-8}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$6.9\bullet10^{-9}$	$6.0\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Er	$1.6\bullet10^{-9}$	$4.5\bullet10^{-6}$	$2.6\bullet10^{-7}$	–	$3.7\bullet10^{-7}$	–	$6.9\bullet10^{-9}$	$7.0\bullet10^{-8}$	$5.5\bullet10^{-8}$	$3.8\bullet10^{-9}$	$3.4\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Eu	$1.2\bullet10^{-9}$	$8.8\bullet10^{-7}$	$1.3\bullet10^{-7}$	–	$1.1\bullet10^{-7}$	–	$2.1\bullet10^{-9}$	$1.8\bullet10^{-7}$	$2.6\bullet10^{-8}$	$1.1\bullet10^{-9}$	$5.3\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$

Element	Phyto-plankton	Microphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
F	$5.6\bullet10^{-3}$	–	–	–	–	–	$1.2\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	$1.2\bullet10^{-4}$	$9.3\bullet10^{-5}$	–	–	–
Fe	$2.1\bullet10^{-2}$	$1.0\bullet10^{-2}$	$1.5\bullet10^{-3}$	–	$4.9\bullet10^{-3}$	–	$1.6\bullet10^{-3}$	$6.3\bullet10^{-3}$	$4.7\bullet10^{-3}$	$1.6\bullet10^{-3}$	$3.5\bullet10^{-3}$	$3.5\bullet10^{-5}$	$3.2\bullet10^{-5}$	$1.1\bullet10^{-5}$
Ga	–	$1.3\bullet10^{-6*}$	$2.3\bullet10^{-7}$	–	–	–	$1.4\bullet10^{-7}$	$1.4\bullet10^{-7}$	$1.4\bullet10^{-7}$	$1.4\bullet10^{-7}$	$1.4\bullet10^{-7}$	$4.5\bullet10^{-9*}$	$2.8\bullet10^{-8*}$	$4.6\bullet10^{-9*}$
Gd	$3.5\bullet10^{-9}$	$6.4\bullet10^{-6}$	$3.6\bullet10^{-7}$	–	$6.8\bullet10^{-7}$	–	$1.6\bullet10^{-8}$	$1.4\bullet10^{-7}$	$1.7\bullet10^{-7}$	$8.9\bullet10^{-9}$	$8.3\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Hf	–	$2.8\bullet10^{-6}$	$3.6\bullet10^{-8}$	–	–	–	$1.5\bullet10^{-8}$	$1.5\bullet10^{-8}$	$1.5\bullet10^{-8}$	$1.5\bullet10^{-8}$	$1.5\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$3.0\bullet10^{-9}$	$2.3\bullet10^{-10*}$
Hg	$3.2\bullet10^{-7}$	$1.8\bullet10^{-7}$	$2.8\bullet10^{-8}$	–	$1.4\bullet10^{-6}$	–	$1.1\bullet10^{-7}$	$9.4\bullet10^{-7}$	$2.2\bullet10^{-7}$	$8.6\bullet10^{-8}$	$3.4\bullet10^{-7}$	$2.0\bullet10^{-6}$	$6.3\bullet10^{-7}$	$5.9\bullet10^{-6}$
Ho	$1.2\bullet10^{-9}$	$2.5\bullet10^{-6}$	$8.1\bullet10^{-8}$	–	$1.4\bullet10^{-7}$	–	$2.4\bullet10^{-9}$	$2.4\bullet10^{-8}$	$2.0\bullet10^{-8}$	$1.3\bullet10^{-9}$	$1.2\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
I	$8.6\bullet10^{-5}$	$1.6\bullet10^{-5}$	$2.7\bullet10^{-5}$	–	$1.7\bullet10^{-4}$	–	$4.9\bullet10^{-5}$	$1.3\bullet10^{-5}$	$9.1\bullet10^{-6}$	$1.5\bullet10^{-5}$	$2.2\bullet10^{-5}$	$4.5\bullet10^{-7}$	$6.3\bullet10^{-7}$	$9.4\bullet10^{-7}$
K	$5.2\bullet10^{-2}$	$4.4\bullet10^{-3}$	$7.2\bullet10^{-4}$	–	$1.5\bullet10^{-1}$	–	$1.0\bullet10^{-2}$	$7.3\bullet10^{-3}$	$7.1\bullet10^{-3}$	$1.7\bullet10^{-2}$	$1.0\bullet10^{-2}$	$4.2\bullet10^{-2}$	$3.1\bullet10^{-2}$	$4.2\bullet10^{-2}$
La	–	$3.7\bullet10^{-5}$	$2.7\bullet10^{-6}$	–	–	–	$1.9\bullet10^{-6}$	$1.9\bullet10^{-6}$	$1.9\bullet10^{-6}$	$1.9\bullet10^{-6}$	$1.9\bullet10^{-6}$	$2.5\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$9.3\bullet10^{-10}$
Li	$4.8\bullet10^{-5}$	$2.2\bullet10^{-6}$	$1.7\bullet10^{-6}$	–	$2.3\bullet10^{-5}$	–	$3.2\bullet10^{-6}$	$7.2\bullet10^{-7}$	$2.8\bullet10^{-6}$	$4.2\bullet10^{-6}$	$2.7\bullet10^{-6}$	$2.5\bullet10^{-7}$	$1.7\bullet10^{-7}$	$1.7\bullet10^{-7}$
Lu	$1.2\bullet10^{-9}$	$7.8\bullet10^{-7}$	$3.8\bullet10^{-8}$	–	$5.6\bullet10^{-8}$	–	$1.0\bullet10^{-9}$	$1.4\bullet10^{-8}$	$7.3\bullet10^{-9}$	$5.8\bullet10^{-10}$	$5.7\bullet10^{-9}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Mg	$4.3\bullet10^{-2}$	$3.5\bullet10^{-3}$	$8.0\bullet10^{-3}$	–	$6.3\bullet10^{-2}$	–	$7.7\bullet10^{-3}$	$4.2\bullet10^{-3}$	$2.6\bullet10^{-3}$	$2.0\bullet10^{-2}$	$8.7\bullet10^{-3}$	$2.8\bullet10^{-3}$	$3.7\bullet10^{-3}$	$3.5\bullet10^{-3}$
Mn	$2.6\bullet10^{-3}$	$7.6\bullet10^{-4}$	$3.8\bullet10^{-4}$	–	$4.0\bullet10^{-4}$	–	$3.7\bullet10^{-4}$	$2.5\bullet10^{-2}$	$1.4\bullet10^{-4}$	$2.3\bullet10^{-4}$	$6.4\bullet10^{-3}$	$1.2\bullet10^{-6}$	$3.2\bullet10^{-6}$	$3.0\bullet10^{-6}$
Mo	$1.9\bullet10^{-6}$	$2.5\bullet10^{-5}$	$5.4\bullet10^{-7}$	–	$6.0\bullet10^{-6}$	–	$7.9\bullet10^{-7}$	$1.1\bullet10^{-6}$	$1.1\bullet10^{-6}$	$6.7\bullet10^{-7}$	$9.1\bullet10^{-7}$	$5.1\bullet10^{-8}$	$8.0\bullet10^{-8}$	$1.8\bullet10^{-8}$
Na	$2.8\bullet10^{-1}$	$2.4\bullet10^{-3}$	$9.1\bullet10^{-4}$	–	$4.5\bullet10^{-1}$	–	$3.4\bullet10^{-2}$	$3.5\bullet10^{-2}$	$2.4\bullet10^{-2}$	$3.8\bullet10^{-2}$	$3.3\bullet10^{-2}$	$7.9\bullet10^{-3}$	$5.5\bullet10^{-3}$	$5.4\bullet10^{-3}$
Nb	–	$4.2\bullet10^{-6}$	$2.0\bullet10^{-7}$	–	–	–	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$8.1\bullet10^{-10}$	$1.7\bullet10^{-9}$	$7.5\bullet10^{-10}$
Nd	$2.2\bullet10^{-8}$	$4.1\bullet10^{-5}$	$2.3\bullet10^{-6}$	–	$4.4\bullet10^{-6}$	–	$9.6\bullet10^{-8}$	$9.6\bullet10^{-7}$	$9.3\bullet10^{-7}$	$5.3\bullet10^{-8}$	$5.1\bullet10^{-7}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Ni	$3.3\bullet10^{-5}$	$1.3\bullet10^{-5}$	$4.4\bullet10^{-6}$	–	$2.9\bullet10^{-5}$	–	$5.8\bullet10^{-6}$	$2.5\bullet10^{-6}$	$3.0\bullet10^{-6}$	$5.3\bullet10^{-6}$	$4.1\bullet10^{-6}$	$2.3\bullet10^{-8*}$	$1.7\bullet10^{-7*}$	$2.3\bullet10^{-8*}$
Pb	$6.3\bullet10^{-5}$	$4.3\bullet10^{-5}$	$6.4\bullet10^{-6}$	–	$4.2\bullet10^{-5}$	–	$2.5\bullet10^{-6}$	$1.1\bullet10^{-5}$	$5.1\bullet10^{-6}$	$2.5\bullet10^{-6}$	$5.3\bullet10^{-6}$	$2.3\bullet10^{-8*}$	$1.7\bullet10^{-7*}$	$2.3\bullet10^{-8*}$
Pr	$5.8\bullet10^{-9}$	$8.3\bullet10^{-6}$	$5.7\bullet10^{-7}$	–	$1.1\bullet10^{-6}$	–	$2.6\bullet10^{-8}$	$2.5\bullet10^{-7}$	$2.5\bullet10^{-7}$	$1.4\bullet10^{-8}$	$1.4\bullet10^{-7}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Rb	$7.1\bullet10^{-5}$	$2.8\bullet10^{-5}$	$2.1\bullet10^{-6}$	–	$9.3\bullet10^{-5}$	–	$9.5\bullet10^{-6}$	$7.5\bullet10^{-6}$	$9.9\bullet10^{-6}$	$9.9\bullet10^{-6}$	$9.2\bullet10^{-6}$	$4.7\bullet10^{-5}$	$3.5\bullet10^{-5}$	$5.1\bullet10^{-5}$
S	$4.1\bullet10^{-2}$	$2.7\bullet10^{-2}$	$9.5\bullet10^{-3}$	$1.8\bullet10^{-2}$	$1.1\bullet10^{-1}$	$1.8\bullet10^{-2}$	$1.3\bullet10^{-2}$	$2.4\bullet10^{-2}$	$6.9\bullet10^{-3}$	$2.4\bullet10^{-2}$	$1.7\bullet10^{-2}$	$2.4\bullet10^{-2}$	$2.8\bullet10^{-2}$	$2.8\bullet10^{-2}$
Sb	–	$8.1\bullet10^{-7}$	$1.0\bullet10^{-5}$	–	–	–	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$2.3\bullet10^{-9*}$	$2.7\bullet10^{-8}$	$2.3\bullet10^{-9*}$
Sc	–	$2.2\bullet10^{-6}$	$5.5\bullet10^{-7}$	–	–	–	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$5.4\bullet10^{-9}$	$1.7\bullet10^{-9}$	$7.8\bullet10^{-9}$
Se	$2.8\bullet10^{-6}$	$2.6\bullet10^{-6*}$	$8.3\bullet10^{-7}$	–	$2.4\bullet10^{-5}$	–	$2.3\bullet10^{-6}$	$5.9\bullet10^{-6}$	$2.3\bullet10^{-6}$	$1.7\bullet10^{-6}$	$3.1\bullet10^{-6}$	$1.1\bullet10^{-6}$	$2.9\bullet10^{-7}$	$7.3\bullet10^{-7}$
Si	$7.9\bullet10^{-1}$	$1.0\bullet10^{-1}$	$2.5\bullet10^{-2}$	–	$2.3\bullet10^{-1}$	–	$1.7\bullet10^{-2}$	$6.5\bullet10^{-3}$	$1.1\bullet10^{-2}$	$1.6\bullet10^{-2}$	$1.3\bullet10^{-2}$	$1.9\bullet10^{-4}$	$7.9\bullet10^{-4}$	$1.9\bullet10^{-4}$
Sm	$4.0\bullet10^{-9}$	$6.0\bullet10^{-6}$	$4.2\bullet10^{-7}$	–	$8.7\bullet10^{-7}$	–	$1.7\bullet10^{-8}$	$1.7\bullet10^{-7}$	$1.7\bullet10^{-7}$	$9.5\bullet10^{-9}$	$9.3\bullet10^{-8}$	$2.3\bullet10^{-10*}$	$1.7\bullet10^{-9*}$	$2.3\bullet10^{-10*}$
Sn	–	$7.0\bullet10^{-6}$	$2.9\bullet10^{-7}$	–	–	–	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-8*}$	$8.0\bullet10^{-8*}$	$1.2\bullet10^{-8*}$
Sr	–	$1.2\bullet10^{-4}$	$5.4\bullet10^{-4}$	–	–	–	$3.6\bullet10^{-4}$	$3.6\bullet10^{-4}$	$3.6\bullet10^{-4}$	$3.6\bullet10^{-4}$	$3.6\bullet10^{-4}$	$2.6\bullet10^{-6}$	$5.8\bullet10^{-6}$	$3.2\bullet10^{-6}$

Element	Phyto-plankton	Microphyto-benthos	Macro-algae	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
Ta	–	$4.4 \cdot 10^{-7}$	$3.8 \cdot 10^{-8}$	–	–	–	$9.8 \cdot 10^{-9}$	$9.8 \cdot 10^{-9}$	$9.8 \cdot 10^{-9}$	$9.8 \cdot 10^{-9}$	$9.8 \cdot 10^{-9}$	$8.7 \cdot 10^{-9}$	$8.0 \cdot 10^{-9}$	$7.5 \cdot 10^{-9}$
Tb	$1.2 \cdot 10^{-9}$	$1.5 \cdot 10^{-6}$	$5.9 \cdot 10^{-8}$	–	$1.1 \cdot 10^{-7}$	–	$2.3 \cdot 10^{-9}$	$2.0 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$1.2 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$2.3 \cdot 10^{-10*}$	$1.7 \cdot 10^{-9*}$	$2.9 \cdot 10^{-10*}$
Th	$7.9 \cdot 10^{-6}$	$6.7 \cdot 10^{-6}$	$1.7 \cdot 10^{-7}$	–	$1.3 \cdot 10^{-6}$	–	$9.9 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$	$1.1 \cdot 10^{-6}$	$6.7 \cdot 10^{-7}$	$7.2 \cdot 10^{-7}$	$4.5 \cdot 10^{-9*}$	$2.8 \cdot 10^{-8*}$	$4.6 \cdot 10^{-9*}$
Ti	$1.0 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	$4.1 \cdot 10^{-5}$	–	$2.6 \cdot 10^{-4}$	–	$7.9 \cdot 10^{-5}$	$1.4 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$	$7.4 \cdot 10^{-5}$	$6.8 \cdot 10^{-5}$	$5.8 \cdot 10^{-7}$	$1.3 \cdot 10^{-7}$	$8.5 \cdot 10^{-7}$
Tl	–	$2.7 \cdot 10^{-7}$	$5.7 \cdot 10^{-8}$	–	–	–	$3.3 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-8*}$	$8.0 \cdot 10^{-8}$	$1.5 \cdot 10^{-8*}$
Tm	$1.2 \cdot 10^{-9}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-8}$	–	$5.6 \cdot 10^{-8}$	–	$1.0 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$7.2 \cdot 10^{-9}$	$5.8 \cdot 10^{-10}$	$4.9 \cdot 10^{-9}$	$2.3 \cdot 10^{-10*}$	$1.7 \cdot 10^{-9*}$	$2.3 \cdot 10^{-10*}$
U	–	$9.6 \cdot 10^{-5}$	$2.8 \cdot 10^{-6}$	–	$7.8 \cdot 10^{-7}$	–	$7.8 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$7.8 \cdot 10^{-7}$	$3.0 \cdot 10^{-9}$	$3.8 \cdot 10^{-9}$	$9.3 \cdot 10^{-10}$
V	$3.9 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$	$2.6 \cdot 10^{-6}$	–	$8.9 \cdot 10^{-6}$	–	$3.6 \cdot 10^{-6}$	$9.9 \cdot 10^{-7}$	$4.6 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	$1.4 \cdot 10^{-8*}$	$8.0 \cdot 10^{-8*}$	$1.2 \cdot 10^{-8*}$
W	–	$7.1 \cdot 10^{-6}$	$8.7 \cdot 10^{-8}$	–	–	–	$8.5 \cdot 10^{-8}$	$8.5 \cdot 10^{-8}$	$8.5 \cdot 10^{-8}$	$8.5 \cdot 10^{-8}$	$8.5 \cdot 10^{-8}$	$4.5 \cdot 10^{-9*}$	$2.8 \cdot 10^{-8*}$	$4.6 \cdot 10^{-9*}$
Y	–	$1.7 \cdot 10^{-5}$	$2.9 \cdot 10^{-6}$	–	–	–	$8.0 \cdot 10^{-7}$	$8.0 \cdot 10^{-7}$	$8.0 \cdot 10^{-7}$	$8.0 \cdot 10^{-7}$	$8.0 \cdot 10^{-7}$	$2.6 \cdot 10^{-10*}$	$6.9 \cdot 10^{-9*}$	$2.3 \cdot 10^{-10*}$
Yb	$1.5 \cdot 10^{-9}$	$3.7 \cdot 10^{-6}$	$2.5 \cdot 10^{-7}$	–	$3.4 \cdot 10^{-7}$	–	$6.0 \cdot 10^{-9}$	$7.6 \cdot 10^{-8}$	$4.5 \cdot 10^{-8}$	$3.3 \cdot 10^{-9}$	$3.3 \cdot 10^{-8}$	$2.3 \cdot 10^{-10*}$	$1.7 \cdot 10^{-9*}$	$2.3 \cdot 10^{-10*}$
Zn	$2.0 \cdot 10^{-3}$	$1.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	–	$2.4 \cdot 10^{-3}$	–	$1.2 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$4.7 \cdot 10^{-4}$	$3.3 \cdot 10^{-5}$	$1.4 \cdot 10^{-4*}$	$1.2 \cdot 10^{-4*}$
Zr	$8.6 \cdot 10^{-5}$	$2.8 \cdot 10^{-5}$	$1.4 \cdot 10^{-6}$	–	$1.1 \cdot 10^{-5}$	–	$9.3 \cdot 10^{-6}$	$6.7 \cdot 10^{-7}$	$1.5 \cdot 10^{-5}$	$7.1 \cdot 10^{-6}$	$8.1 \cdot 10^{-6}$	$5.7 \cdot 10^{-9}$	$1.3 \cdot 10^{-7}$	$5.8 \cdot 10^{-9}$

Table A10-2. Chemistry in lake biota in Lake Frisksjön, in the Laxemar area. Values are in g gC^{-1}. Data on fish, benthic filter feeders and macrophytes are lake specific data from /Engdalh et al. 2006/. Data on phytoplankton, zooplankton benthic herbivores, benthic detritivores and benthic carnivores are taken from the coastal areas outside Forsmark /Kumblad and Bradshaw 2008/. Chemical composition of benthic omnivores was calculated as a mean of the other functional groups. Chemical composition for benthic herbivores, detritivores, carnivores of 15 elements (Ag, B, Be, Ga, Hf, La, Nb, Sb, Sc, Sn, Sr, Ta, Ti, W and Y) was assumed to be identical to chemical composition of benthic filter feeders. Data on bacterioplankton P, N and S content are from /Fagerbakke 1996/. For benthic bacteria P and N content are from /Kautsky 1995/ and S content are assumed to be identical to bacterioplankton /Fagerbakke 1996/. "–" denotes missing data, and * indicates were half the detection limit is reported. For further explanation of use of data, see Chapter 7.

Element	Phyto-plankton	Macrophytes	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
C	1	1	1	1	1	1	1	1	1	1	1	1	1
N	$1.2\bullet10^{-1}$	$5.0\bullet10^{-2}$	$1.9\bullet10^{-1}$	$2.3\bullet10^{-1}$	$1.8\bullet10^{-1}$	$1.2\bullet10^{-1}$	$2.1\bullet10^{-1}$	$7.9\bullet10^{-2}$	$1.8\bullet10^{-1}$	$1.5\bullet10^{-1}$	$3.3\bullet10^{-1}$	$4.0\bullet10^{-1}$	$3.0\bullet10^{-1}$
P	$9.1\bullet10^{-3}$	$6.9\bullet10^{-3}$	$4.6\bullet10^{-2}$	$3.8\bullet10^{-2}$	$5.6\bullet10^{-2}$	$1.1\bullet10^{-2}$	$7.4\bullet10^{-2}$	$9.1\bullet10^{-3}$	$8.4\bullet10^{-3}$	$2.7\bullet10^{-2}$	$3.1\bullet10^{-2}$	$2.3\bullet10^{-2}$	$2.8\bullet10^{-2}$
Ag	–	$2.4\bullet10^{-8}$	–	–	–	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$2.4\bullet10^{-7}$	$1.6\bullet10^{-8}$	$8.0\bullet10^{-8}$	$1.6\bullet10^{-8}$
Al	$1.1\bullet10^{-1}$	$4.1\bullet10^{-4}$	–	$6.8\bullet10^{-3}$	–	$2.7\bullet10^{-3}$	$1.3\bullet10^{-3}$	$3.5\bullet10^{-3}$	$2.0\bullet10^{-6}$	$1.9\bullet10^{-3}$	$1.2\bullet10^{-6}$	$2.4\bullet10^{-6}$	$2.1\bullet10^{-6}$
As	$7.0\bullet10^{-5}$	$1.1\bullet10^{-6}$	–	$5.5\bullet10^{-5}$	–	$1.5\bullet10^{-5}$	$1.6\bullet10^{-5}$	$1.1\bullet10^{-5}$	$1.8\bullet10^{-5}$	$1.5\bullet10^{-5}$	$1.1\bullet10^{-7}$	$1.0\bullet10^{-7}$	$6.7\bullet10^{-8}$
B	–	$7.7\bullet10^{-5}$	–	–	–	$9.5\bullet10^{-6}$	$9.5\bullet10^{-6}$	$9.5\bullet10^{-6}$	$9.5\bullet10^{-6}$	$9.5\bullet10^{-6}$	$2.1\bullet10^{-6}$	$2.9\bullet10^{-7}$	$2.0\bullet10^{-6}$
Ba	$2.7\bullet10^{-4}$	$2.5\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	$1.3\bullet10^{-3}$	$1.7\bullet10^{-4}$	$2.2\bullet10^{-4}$	$4.5\bullet10^{-4}$	$2.6\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.3\bullet10^{-7}$
Be	–	$2.0\bullet10^{-7}$	–	–	–	$2.9\bullet10^{-6}$	$2.9\bullet10^{-6}$	$2.9\bullet10^{-6}$	$2.9\bullet10^{-6}$	$2.9\bullet10^{-6}$	$8.6\bullet10^{-8}$	$4.0\bullet10^{-7}$	$8.3\bullet10^{-8}$
Br	$7.6\bullet10^{-3}$	$1.5\bullet10^{-4}$	–	$3.1\bullet10^{-2}$	–	$6.7\bullet10^{-4}$	$4.1\bullet10^{-4}$	$1.8\bullet10^{-4}$	$2.8\bullet10^{-4}$	$3.8\bullet10^{-4}$	$4.9\bullet10^{-5}$	$1.9\bullet10^{-5}$	$4.2\bullet10^{-5}$
Ca	$2.2\bullet10^{-2}$	$6.6\bullet10^{-2}$	–	$2.1\bullet10^{-1}$	–	$5.7\bullet10^{-1}$	$1.2\bullet10^{-1}$	1.5	$3.4\bullet10^{-1}$	$6.4\bullet10^{-1}$	$6.3\bullet10^{-3}$	$9.0\bullet10^{-3}$	$4.5\bullet10^{-3}$
Cd	$1.4\bullet10^{-6}$	$1.3\bullet10^{-7}$	–	$1.1\bullet10^{-5}$	–	$4.7\bullet10^{-6}$	$1.2\bullet10^{-5}$	$8.6\bullet10^{-7}$	$5.1\bullet10^{-6}$	$5.6\bullet10^{-6}$	$4.7\bullet10^{-9}$*	$1.7\bullet10^{-8}$*	$3.9\bullet10^{-9}$*
Ce	$5.2\bullet10^{-8}$	$8.7\bullet10^{-6}$	–	$8.4\bullet10^{-6}$	–	$1.9\bullet10^{-7}$	$1.3\bullet10^{-4}$	$1.9\bullet10^{-6}$	$1.0\bullet10^{-7}$	$3.3\bullet10^{-5}$	–	–	–
Cl	$3.7\bullet10^{-1}$	$2.8\bullet10^{-2}$	–	–	–	$1.8\bullet10^{-2}$	$3.8\bullet10^{-2}$	$1.1\bullet10^{-2}$	$1.3\bullet10^{-2}$	$2.0\bullet10^{-2}$	$3.4\bullet10^{-3}$	$1.1\bullet10^{-2}$	$5.5\bullet10^{-3}$
Co	$9.2\bullet10^{-6}$	$1.7\bullet10^{-6}$	–	$3.9\bullet10^{-6}$	–	$1.9\bullet10^{-6}$	$4.0\bullet10^{-6}$	$1.7\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.4\bullet10^{-6}$	$1.9\bullet10^{-8}$	$3.9\bullet10^{-8}$	$2.4\bullet10^{-8}$
Cr	$3.5\bullet10^{-5}$	$4.7\bullet10^{-7}$	–	$2.4\bullet10^{-5}$	–	$2.3\bullet10^{-6}$	$2.7\bullet10^{-6}$	$3.0\bullet10^{-6}$	$3.0\bullet10^{-6}$	$2.8\bullet10^{-6}$	$2.4\bullet10^{-8}$	$1.1\bullet10^{-7}$	$3.7\bullet10^{-8}$
Cs	$2.8\bullet10^{-6}$	$1.5\bullet10^{-7}$	–	$7.6\bullet10^{-7}$	–	$2.4\bullet10^{-7}$	$1.6\bullet10^{-7}$	$3.2\bullet10^{-7}$	$2.6\bullet10^{-7}$	$2.5\bullet10^{-7}$	$4.8\bullet10^{-7}$	$7.9\bullet10^{-8}$	$2.6\bullet10^{-6}$
Cu	$1.3\bullet10^{-4}$	$6.2\bullet10^{-6}$	–	$4.7\bullet10^{-4}$	–	$9.7\bullet10^{-5}$	$2.0\bullet10^{-5}$	$1.3\bullet10^{-4}$	$1.5\bullet10^{-4}$	$9.9\bullet10^{-5}$	$1.4\bullet10^{-6}$	$2.8\bullet10^{-6}$	$1.5\bullet10^{-6}$
Dy	$2.8\bullet10^{-9}$	$2.0\bullet10^{-7}$	–	$6.5\bullet10^{-7}$	–	$1.3\bullet10^{-8}$	$2.3\bullet10^{-6}$	$1.1\bullet10^{-7}$	$6.9\bullet10^{-9}$	$6.1\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$1.3\bullet10^{-9}$
Er	$1.6\bullet10^{-9}$	$1.2\bullet10^{-7}$	–	$3.7\bullet10^{-7}$	–	$6.9\bullet10^{-9}$	$1.0\bullet10^{-6}$	$5.5\bullet10^{-8}$	$3.8\bullet10^{-9}$	$2.7\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$1.0\bullet10^{-8}$
Eu	$1.2\bullet10^{-9}$	$8.9\bullet10^{-8}$	–	$1.1\bullet10^{-7}$	–	$2.1\bullet10^{-9}$	$1.2\bullet10^{-6}$	$2.6\bullet10^{-8}$	$1.1\bullet10^{-9}$	$3.1\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$3.6\bullet10^{-10}$
F	$5.6\bullet10^{-3}$	–	–	–	–	$1.2\bullet10^{-4}$	–	$1.2\bullet10^{-4}$	$1.2\bullet10^{-4}$	$1.2\bullet10^{-4}$	–	–	–
Fe	$2.1\bullet10^{-2}$	$1.1\bullet10^{-3}$	–	$4.9\bullet10^{-3}$	–	$1.6\bullet10^{-3}$	$1.5\bullet10^{-2}$	$4.7\bullet10^{-3}$	$1.6\bullet10^{-3}$	$5.8\bullet10^{-3}$	$1.6\bullet10^{-5}$	$3.2\bullet10^{-5}$	$1.6\bullet10^{-5}$
Ga	–	$4.2\bullet10^{-8}$	–	–	–	$1.3\bullet10^{-7}$	$1.3\bullet10^{-7}$	$1.3\bullet10^{-7}$	$1.3\bullet10^{-7}$	$1.3\bullet10^{-7}$	$7.4\bullet10^{-9}$	$2.8\bullet10^{-8}$	$6.7\bullet10^{-9}$

Element	Phyto-plankton	Macrophytes	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
Gd	$3.5\bullet10^{-9}$	$2.5\bullet10^{-7}$	–	$6.8\bullet10^{-7}$	–	$1.6\bullet10^{-8}$	$4.5\bullet10^{-6}$	$1.7\bullet10^{-7}$	$8.9\bullet10^{-9}$	$1.2\bullet10^{-6}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$3.6\bullet10^{-10}$
Hf	–	$1.8\bullet10^{-8}$	–	–	–	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$4.2\bullet10^{-8}$	$1.5\bullet10^{-9}$	$3.0\bullet10^{-9}$	$3.6\bullet10^{-10}$
Hg	$3.2\bullet10^{-7}$	$9.7\bullet10^{-9}$	–	$1.4\bullet10^{-6}$	–	$1.1\bullet10^{-7}$	$3.9\bullet10^{-7}$	$2.2\bullet10^{-7}$	$8.6\bullet10^{-8}$	$2.0\bullet10^{-7}$	$1.1\bullet10^{-6}$	$6.3\bullet10^{-7}$	$5.4\bullet10^{-6}$
Ho	$1.2\bullet10^{-9}$	$4.0\bullet10^{-8}$	–	$1.4\bullet10^{-7}$	–	$2.4\bullet10^{-9}$	$4.0\bullet10^{-7}$	$2.0\bullet10^{-8}$	$1.3\bullet10^{-9}$	$1.1\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$1.7\bullet10^{-9}$
I	$8.6\bullet10^{-5}$	$2.5\bullet10^{-5}$	–	$1.7\bullet10^{-4}$	–	$4.9\bullet10^{-5}$	$1.9\bullet10^{-5}$	$9.1\bullet10^{-6}$	$1.5\bullet10^{-5}$	$2.3\bullet10^{-5}$	$3.3\bullet10^{-6}$	$6.3\bullet10^{-7}$	$8.4\bullet10^{-6}$
K	$5.2\bullet10^{-2}$	$4.8\bullet10^{-2}$	–	$1.5\bullet10^{-1}$	–	$1.0\bullet10^{-2}$	$8.7\bullet10^{-3}$	$7.1\bullet10^{-3}$	$1.7\bullet10^{-2}$	$1.1\bullet10^{-2}$	$4.8\bullet10^{-2}$	$3.1\bullet10^{-2}$	$5.0\bullet10^{-2}$
La	–	$3.2\bullet10^{-6}$	–	–	–	$1.1\bullet10^{-4}$	$1.1\bullet10^{-4}$	$1.1\bullet10^{-4}$	$1.1\bullet10^{-4}$	$1.1\bullet10^{-4}$	$2.7\bullet10^{-9}$	$1.7\bullet10^{-9}$	$5.7\bullet10^{-9}$
Li	$4.8\bullet10^{-5}$	$5.1\bullet10^{-7}$	–	$2.3\bullet10^{-5}$	–	$3.2\bullet10^{-6}$	$9.4\bullet10^{-7}$	$2.8\bullet10^{-6}$	$4.2\bullet10^{-6}$	$2.8\bullet10^{-6}$	$4.7\bullet10^{-8}$	$1.7\bullet10^{-7}$	$3.9\bullet10^{-8}$
Lu	$1.2\bullet10^{-9}$	$1.7\bullet10^{-8}$	–	$5.6\bullet10^{-8}$	–	$1.0\bullet10^{-9}$	$1.3\bullet10^{-7}$	$7.3\bullet10^{-9}$	$5.8\bullet10^{-10}$	$3.4\bullet10^{-8}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$3.6\bullet10^{-10}$
Mg	$4.3\bullet10^{-2}$	$5.4\bullet10^{-3}$	–	$6.3\bullet10^{-2}$	–	$7.7\bullet10^{-3}$	$3.6\bullet10^{-3}$	$2.6\bullet10^{-3}$	$2.0\bullet10^{-2}$	$8.5\bullet10^{-3}$	$4.7\bullet10^{-3}$	$3.7\bullet10^{-3}$	$4.0\bullet10^{-3}$
Mn	$2.6\bullet10^{-3}$	$1.6\bullet10^{-3}$	–	$4.0\bullet10^{-4}$	–	$3.7\bullet10^{-4}$	$1.3\bullet10^{-2}$	$1.4\bullet10^{-4}$	$2.3\bullet10^{-4}$	$3.4\bullet10^{-3}$	$4.0\bullet10^{-6}$	$3.2\bullet10^{-6}$	$1.4\bullet10^{-6}$
Mo	$1.9\bullet10^{-6}$	$1.6\bullet10^{-6}$	–	$6.0\bullet10^{-6}$	–	$7.9\bullet10^{-7}$	$3.1\bullet10^{-6}$	$1.1\bullet10^{-6}$	$6.7\bullet10^{-7}$	$1.4\bullet10^{-6}$	$3.1\bullet10^{-8}$	$8.0\bullet10^{-8}$	$2.4\bullet10^{-8}$
Na	$2.8\bullet10^{-1}$	$1.7\bullet10^{-2}$	–	$4.5\bullet10^{-1}$	–	$3.4\bullet10^{-2}$	$2.4\bullet10^{-2}$	$2.4\bullet10^{-2}$	$3.8\bullet10^{-2}$	$3.0\bullet10^{-2}$	$5.4\bullet10^{-3}$	$5.5\bullet10^{-3}$	$5.5\bullet10^{-3}$
Nb	–	$4.3\bullet10^{-8}$	–	–	–	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.1\bullet10^{-7}$	$1.4\bullet10^{-9}$	$1.7\bullet10^{-9}$	$4.8\bullet10^{-10}$
Nd	$2.2\bullet10^{-8}$	$2.5\bullet10^{-6}$	–	$4.4\bullet10^{-6}$	–	$9.6\bullet10^{-8}$	$4.8\bullet10^{-5}$	$9.3\bullet10^{-7}$	$5.3\bullet10^{-8}$	$1.2\bullet10^{-5}$	$1.5\bullet10^{-9}$	$1.7\bullet10^{-9}$	$3.0\bullet10^{-9}$
Ni	$3.3\bullet10^{-5}$	$2.9\bullet10^{-6}$	–	$2.9\bullet10^{-5}$	–	$5.8\bullet10^{-6}$	$4.5\bullet10^{-6}$	$3.0\bullet10^{-6}$	$5.3\bullet10^{-6}$	$4.6\bullet10^{-6}$	$5.3\bullet10^{-8}$	$1.7\bullet10^{-7}$	$3.6\bullet10^{-8}$
P	$1.2\bullet10^{-2}$	$6.9\bullet10^{-3}$	–	$1.3\bullet10^{-1}$	–	$1.2\bullet10^{-2}$	$7.4\bullet10^{-2}$	$9.6\bullet10^{-3}$	$1.9\bullet10^{-2}$	$2.9\bullet10^{-2}$	$3.1\bullet10^{-2}$	$2.3\bullet10^{-2}$	$2.8\bullet10^{-2}$
Pb	$6.3\bullet10^{-5}$	$1.3\bullet10^{-6}$	–	$4.2\bullet10^{-5}$	–	$2.5\bullet10^{-6}$	$6.6\bullet10^{-6}$	$5.1\bullet10^{-6}$	$2.5\bullet10^{-6}$	$4.2\bullet10^{-6}$	$3.5\bullet10^{-8}$	$1.7\bullet10^{-7}$	$3.6\bullet10^{-8}$
Pr	$5.8\bullet10^{-9}$	$6.8\bullet10^{-7}$	–	$1.1\bullet10^{-6}$	–	$2.6\bullet10^{-8}$	$1.4\bullet10^{-5}$	$2.5\bullet10^{-7}$	$1.4\bullet10^{-8}$	$3.6\bullet10^{-6}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$1.2\bullet10^{-9}$
Rb	$7.1\bullet10^{-5}$	$8.1\bullet10^{-5}$	–	$9.3\bullet10^{-5}$	–	$9.5\bullet10^{-6}$	$2.0\bullet10^{-5}$	$9.9\bullet10^{-6}$	$9.9\bullet10^{-6}$	$1.2\bullet10^{-5}$	$1.2\bullet10^{-4}$	$3.5\bullet10^{-5}$	$2.5\bullet10^{-4}$
S	$4.1\bullet10^{-2}$	$9.5\bullet10^{-3}$	$1.8\bullet10^{-2}$	$1.1\bullet10^{-1}$	$1.8\bullet10^{-2}$	$1.3\bullet10^{-2}$	$2.4\bullet10^{-2}$	$6.9\bullet10^{-3}$	$2.4\bullet10^{-2}$	$1.7\bullet10^{-2}$	$3.0\bullet10^{-2}$	$2.8\bullet10^{-2}$	$3.0\bullet10^{-2}$
Sb	–	$4.0\bullet10^{-8}$	–	–	–	$6.4\bullet10^{-8}$	$6.4\bullet10^{-8}$	$6.4\bullet10^{-8}$	$6.4\bullet10^{-8}$	$6.4\bullet10^{-8}$	$3.5\bullet10^{-9}$	$2.7\bullet10^{-8}$	$3.6\bullet10^{-9}$
Sc	–	$1.1\bullet10^{-7}$	–	–	–	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$2.0\bullet10^{-6}$	$1.5\bullet10^{-9}$	$1.7\bullet10^{-9}$	$1.7\bullet10^{-9}$
Se	$2.8\bullet10^{-6}$	$5.8\bullet10^{-7}$	–	$2.4\bullet10^{-5}$	–	$2.3\bullet10^{-6}$	$5.1\bullet10^{-6}$	$2.3\bullet10^{-6}$	$1.7\bullet10^{-6}$	$2.8\bullet10^{-6}$	$1.9\bullet10^{-6}$	$2.9\bullet10^{-7}$	$2.8\bullet10^{-6}$
Si	$7.9\bullet10^{-1}$	$5.4\bullet10^{-3}$	–	$2.3\bullet10^{-1}$	–	$1.7\bullet10^{-2}$	$7.1\bullet10^{-3}$	$1.1\bullet10^{-2}$	$1.6\bullet10^{-2}$	$1.3\bullet10^{-2}$	$4.3\bullet10^{-4}$	$7.9\bullet10^{-4}$	$2.3\bullet10^{-4}$
Sm	$4.0\bullet10^{-9}$	$4.0\bullet10^{-7}$	–	$8.7\bullet10^{-7}$	–	$1.7\bullet10^{-8}$	$6.9\bullet10^{-6}$	$1.7\bullet10^{-7}$	$9.5\bullet10^{-9}$	$1.8\bullet10^{-6}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$2.3\bullet10^{-9}$

Element	Phyto-plankton	Macrophytes	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic herbivores	Benthic filter feeders	Benthic detrivores	Benthic carnivores	Benthic omnivores	B fish	Z fish	P fish
Sn	–	$8.1\bullet10^{-8}$	–	–	–	$7.9\bullet10^{-8}$	$7.9\bullet10^{-8}$	$7.9\bullet10^{-8}$	$7.9\bullet10^{-8}$	$7.9\bullet10^{-8}$	$1.6\bullet10^{-8}$*	$8.0\bullet10^{-8}$*	$1.6\bullet10^{-8}$*
Sr	–	$7.1\bullet10^{-5}$	–	–	–	$4.1\bullet10^{-4}$	$4.1\bullet10^{-4}$	$4.1\bullet10^{-4}$	$4.1\bullet10^{-4}$	$4.1\bullet10^{-4}$	$6.3\bullet10^{-6}$	$5.8\bullet10^{-6}$	$3.9\bullet10^{-6}$
Ta	–	$1.2\bullet10^{-8}$	–	–	–	$7.9\bullet10^{-9}$	$7.9\bullet10^{-9}$	$7.9\bullet10^{-9}$	$7.9\bullet10^{-9}$	$7.9\bullet10^{-9}$	$2.7\bullet10^{-9}$	$8.0\bullet10^{-9}$	$8.7\bullet10^{-9}$
Tb	$1.2\bullet10^{-9}$	$3.3\bullet10^{-8}$	–	$1.1\bullet10^{-7}$	–	$2.3\bullet10^{-9}$	$5.0\bullet10^{-7}$	$2.1\bullet10^{-8}$	$1.2\bullet10^{-9}$	$1.3\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$2.4\bullet10^{-9}$
Th	$7.9\bullet10^{-6}$	$1.3\bullet10^{-7}$	–	$1.3\bullet10^{-6}$	–	$9.9\bullet10^{-7}$	$6.6\bullet10^{-7}$	$1.1\bullet10^{-6}$	$6.7\bullet10^{-7}$	$8.5\bullet10^{-7}$	$7.4\bullet10^{-9}$	$2.8\bullet10^{-8}$	$6.7\bullet10^{-9}$
Ti	$1.0\bullet10^{-3}$	$5.5\bullet10^{-6}$	–	$2.6\bullet10^{-4}$	–	$7.9\bullet10^{-5}$	$1.6\bullet10^{-5}$	$1.0\bullet10^{-4}$	$7.4\bullet10^{-5}$	$6.8\bullet10^{-5}$	$3.0\bullet10^{-7}$	$1.3\bullet10^{-7}$	$1.0\bullet10^{-7}$
Tl	–	$8.7\bullet10^{-8}$	–	–	–	$2.6\bullet10^{-8}$	$2.6\bullet10^{-8}$	$2.6\bullet10^{-8}$	$2.6\bullet10^{-8}$	$2.6\bullet10^{-8}$	$1.6\bullet10^{-8}$	$8.0\bullet10^{-8}$	$4.4\bullet10^{-8}$
Tm	$1.2\bullet10^{-9}$	$1.7\bullet10^{-8}$	–	$5.6\bullet10^{-8}$	–	$1.0\bullet10^{-9}$	$1.2\bullet10^{-7}$	$7.2\bullet10^{-9}$	$5.8\bullet10^{-10}$	$3.3\bullet10^{-8}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$8.6\bullet10^{-10}$
U	–	$4.4\bullet10^{-7}$	–	$2.4\bullet10^{-6}$	–	$2.4\bullet10^{-6}$	$2.4\bullet10^{-6}$	$2.4\bullet10^{-6}$	$2.4\bullet10^{-6}$	$2.4\bullet10^{-6}$	$5.3\bullet10^{-9}$	$3.8\bullet10^{-9}$	$2.7\bullet10^{-10}$
V	$3.9\bullet10^{-5}$	$1.7\bullet10^{-6}$	–	$8.9\bullet10^{-6}$	–	$3.6\bullet10^{-6}$	$3.6\bullet10^{-6}$	$4.6\bullet10^{-6}$	$3.4\bullet10^{-6}$	$3.8\bullet10^{-6}$	$1.4\bullet10^{-7}$	$8.0\bullet10^{-8}$	$1.6\bullet10^{-8}$
W	–	$6.2\bullet10^{-8}$	–	–	–	$1.2\bullet10^{-7}$	$1.2\bullet10^{-7}$	$1.2\bullet10^{-7}$	$1.2\bullet10^{-7}$	$1.2\bullet10^{-7}$	$3.1\bullet10^{-9}$	$2.8\bullet10^{-8}$	$7.1\bullet10^{-10}$
Y	–	$1.5\bullet10^{-6}$	–	–	–	$2.3\bullet10^{-5}$	$2.3\bullet10^{-5}$	$2.3\bullet10^{-5}$	$2.3\bullet10^{-5}$	$2.3\bullet10^{-5}$	$1.5\bullet10^{-9}$	$6.9\bullet10^{-9}$	$2.1\bullet10^{-9}$
Yb	$1.5\bullet10^{-9}$	$1.1\bullet10^{-7}$	–	$3.4\bullet10^{-7}$	–	$6.0\bullet10^{-9}$	$7.9\bullet10^{-7}$	$4.5\bullet10^{-8}$	$3.3\bullet10^{-9}$	$2.1\bullet10^{-7}$	$3.5\bullet10^{-10}$	$1.7\bullet10^{-9}$	$1.6\bullet10^{-9}$
Zn	$2.0\bullet10^{-3}$	$4.4\bullet10^{-5}$	–	$2.4\bullet10^{-3}$	–	$1.2\bullet10^{-4}$	$3.7\bullet10^{-4}$	$2.1\bullet10^{-4}$	$1.6\bullet10^{-4}$	$2.2\bullet10^{-4}$	$4.7\bullet10^{-5}$	$1.4\bullet10^{-4}$	$3.4\bullet10^{-5}$
Zr	$8.6\bullet10^{-5}$	$6.5\bullet10^{-7}$	–	$1.1\bullet10^{-5}$	–	$9.3\bullet10^{-6}$	$2.1\bullet10^{-6}$	$1.5\bullet10^{-5}$	$7.1\bullet10^{-6}$	$8.4\bullet10^{-6}$	$1.2\bullet10^{-7}$	$1.3\bullet10^{-7}$	$8.3\bullet10^{-9}$

Appendix 11

Pools of elements per unit area

The mass of elements per (g m^{-2}) in the average Forsmark and Laxemar-Simpevarp lake is presented in Table A11-1 and A11-2, respectively. “–“ indicates missing data. References to how the pools of element in different components are calculated are presented in Chapter 7.

Table A11-1. Pools of elements (g $m^{-2)}$ in the average Forsmark Lake.

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zooplankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Sediment	Total
As	$2.7\bullet10^{-6}$	$2.9\bullet10^{-5}$	–	$3.3\bullet10^{-6}$	–	$7.6\bullet10^{-6}$	$1.5\bullet10^{-7}$	$1.7\bullet10^{-4}$	$3.6\bullet10^{-6}$	$1.3\bullet10^{0}$	$1.3\bullet10^{0}$
B	–	$8.3\bullet10^{-4}$	–	–	–	$2.7\bullet10^{-6}$	$3.2\bullet10^{-8}$	$2.1\bullet10^{-5}$	$2.0\bullet10^{-6}$	$6.0\bullet10^{0}$	$6.0\bullet10^{0}$
Sb	–	$2.4\bullet10^{-4}$	–	–	–	$2.2\bullet10^{-8}$	$2.1\bullet10^{-9}$	$8.9\bullet10^{-5}$	$1.3\bullet10^{-6}$	$1.3\bullet10^{-1}$	$1.3\bullet10^{-1}$
Se	$1.1\bullet10^{-7}$	$2.8\bullet10^{-5}$	–	$1.4\bullet10^{-6}$	–	$1.3\bullet10^{-6}$	$8.3\bullet10^{-7}$	$1.1\bullet10^{-5}$	$7.9\bullet10^{-7}$	$1.3\bullet10^{-1}$	$1.3\bullet10^{-1}$
Si	$3.1\bullet10^{-2}$	$9.4\bullet10^{-1}$	–	$1.4\bullet10^{-2}$	–	$7.3\bullet10^{-3}$	$1.6\bullet10^{-4}$	$1.7\bullet10^{0}$	$3.0\bullet10^{-2}$	$4.4\bullet10^{4}$	$4.4\bullet10^{4}$
Ag	–	$1.4\bullet10^{-4}$	–	–	–	$6.1\bullet10^{-7}$	$1.0\bullet10^{-8}$	$9.0\bullet10^{-7}$	$1.8\bullet10^{-7}$	$2.4\bullet10^{0}$	$2.4\bullet10^{0}$
Al	$4.1\bullet10^{-3}$	$5.5\bullet10^{-2}$	–	$4.0\bullet10^{-4}$	–	$7.0\bullet10^{-4}$	$1.9\bullet10^{-7}$	$4.6\bullet10^{-2}$	$3.5\bullet10^{-3}$	$1.5\bullet10^{4}$	$1.5\bullet10^{4}$
Ba	$1.0\bullet10^{-5}$	$1.1\bullet10^{-2}$	–	$7.0\bullet10^{-6}$	–	$1.6\bullet10^{-4}$	$7.7\bullet10^{-7}$	$1.9\bullet10^{-2}$	$7.2\bullet10^{-5}$	$1.1\bullet10^{2}$	$1.1\bullet10^{2}$
Be	–	$3.5\bullet10^{-6}$	–	–	–	$3.8\bullet10^{-8}$	$5.0\bullet10^{-8}$	$6.7\bullet10^{-6}$	$1.8\bullet10^{-7}$	$5.0\bullet10^{-1}$	$5.0\bullet10^{-1}$
Ca	$8.5\bullet10^{-4}$	$1.8\bullet10^{1}$	–	$1.2\bullet10^{-2}$	–	$3.3\bullet10^{-1}$	$5.0\bullet10^{-3}$	$4.6\bullet10^{1}$	$3.5\bullet10^{-2}$	$8.4\bullet10^{3}$	$8.5\bullet10^{3}$
Cd	$5.4\bullet10^{-8}$	$7.3\bullet10^{-6}$	–	$6.8\bullet10^{-7}$	–	$2.5\bullet10^{-6}$	$2.9\bullet10^{-9}$	$5.8\bullet10^{-6}$	$9.8\bullet10^{-7}$	$7.1\bullet10^{-2}$	$7.1\bullet10^{-2}$
Co	$3.5\bullet10^{-7}$	$3.3\bullet10^{-5}$	–	$2.3\bullet10^{-7}$	–	$1.0\bullet10^{-6}$	$8.8\bullet10^{-9}$	$5.5\bullet10^{-5}$	$1.5\bullet10^{-6}$	$2.3\bullet10^{0}$	$2.3\bullet10^{0}$
Cr	$1.4\bullet10^{-6}$	$9.5\bullet10^{-5}$	–	$1.4\bullet10^{-6}$	–	$1.4\bullet10^{-6}$	$1.0\bullet10^{-8}$	$6.9\bullet10^{-5}$	$3.7\bullet10^{-6}$	$1.5\bullet10^{1}$	$1.5\bullet10^{1}$
Cs	$1.1\bullet10^{-7}$	$3.6\bullet10^{-6}$	–	$4.5\bullet10^{-8}$	–	$1.3\bullet10^{-7}$	$1.4\bullet10^{-7}$	$1.3\bullet10^{-5}$	$4.9\bullet10^{-7}$	$1.3\bullet10^{0}$	$1.3\bullet10^{0}$
Cu	$4.8\bullet10^{-6}$	$1.2\bullet10^{-3}$	–	$2.8\bullet10^{-5}$	–	$6.5\bullet10^{-5}$	$1.5\bullet10^{-6}$	$5.6\bullet10^{-4}$	$3.3\bullet10^{-5}$	$6.9\bullet10^{0}$	$6.9\bullet10^{0}$
Fe	$8.2\bullet10^{-4}$	$7.2\bullet10^{-2}$	–	$2.9\bullet10^{-4}$	–	$1.5\bullet10^{-3}$	$2.5\bullet10^{-5}$	$8.6\bullet10^{-2}$	$7.1\bullet10^{-3}$	$9.0\bullet10^{3}$	$9.0\bullet10^{3}$
Ga	–	$1.0\bullet10^{-5}$	–	–	–	$7.4\bullet10^{-8}$	$4.0\bullet10^{-9}$	$4.1\bullet10^{-6}$	$1.0\bullet10^{-6}$	$2.9\bullet10^{0}$	$2.9\bullet10^{0}$
Hf	–	$1.2\bullet10^{-5}$	–	–	–	$8.1\bullet10^{-9}$	2.1^{-10}	$4.6\bullet10^{-6}$	$2.6\bullet10^{-7}$	$8.9\bullet10^{-1}$	$8.9\bullet10^{-1}$
Hg	$1.2\bullet10^{-8}$	$1.3\bullet10^{-6}$	–	$8.4\bullet10^{-8}$	–	$1.2\bullet10^{-7}$	$2.3\bullet10^{-6}$	$1.8\bullet10^{-6}$	$1.7\bullet10^{-7}$	$7.9\bullet10^{-3}$	$7.9\bullet10^{-3}$
K	$2.0\bullet10^{-3}$	$3.2\bullet10^{-2}$	–	$9.0\bullet10^{-3}$	–	$6.6\bullet10^{-3}$	$3.5\bullet10^{-2}$	$4.0\bullet10^{0}$	$5.5\bullet10^{-3}$	$5.1\bullet10^{3}$	$5.1\bullet10^{3}$
Li	$1.9\bullet10^{-6}$	$4.7\bullet10^{-5}$	–	$1.4\bullet10^{-6}$	–	$1.7\bullet10^{-6}$	$1.9\bullet10^{-7}$	$3.5\bullet10^{-3}$	$3.4\bullet10^{-6}$	$7.0\bullet10^{1}$	$7.0\bullet10^{1}$

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zooplankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Sediment	Total
Mg	1.6•10^{-3}	1.9•10^{-1}	–	3.8•10^{-3}	–	6.3•10^{-3}	2.4•10^{-3}	9.3•10^{0}	2.8•10^{-3}	2.7•10^{3}	2.7•10^{3}
Mn	9.8•10^{-5}	1.1•10^{-2}	–	2.4•10^{-5}	–	1.7•10^{-3}	1.3•10^{-6}	4.1•10^{-2}	2.2•10^{-3}	1.1•10^{2}	1.1•10^{2}
Mo	7.4•10^{-8}	1.1•10^{-4}	–	3.6•10^{-7}	–	4.4•10^{-7}	3.7•10^{-8}	3.9•10^{-4}	2.8•10^{-6}	1.6•10^{0}	1.6•10^{0}
Na	1.1•10^{-2}	2.9•10^{-2}	–	2.7•10^{-2}	–	1.8•10^{-2}	6.1•10^{-3}	6.1•10^{1}	5.3•10^{-3}	2.2•10^{3}	2.2•10^{3}
Nb	–	2.0•10^{-5}	–	–	–	5.6•10^{-8}	6.7^{-10}	8.6•10^{-6}	8.2•10^{-7}	2.9•10^{0}	2.9•10^{0}
Ni	1.3•10^{-6}	1.5•10^{-4}	–	1.7•10^{-6}	–	2.4•10^{-6}	2.0•10^{-8}	3.5•10^{-4}	1.4•10^{-5}	6.5•10^{0}	6.5•10^{0}
Pb	2.4•10^{-6}	3.0•10^{-4}	–	2.5•10^{-6}	–	2.1•10^{-6}	2.0•10^{-8}	1.1•10^{-4}	4.6•10^{-5}	5.5•10^{0}	5.5•10^{0}
Rb	2.7•10^{-6}	1.5•10^{-4}	–	5.5•10^{-6}	–	5.0•10^{-6}	3.9•10^{-5}	2.8•10^{-3}	1.2•10^{-5}	2.3•10^{1}	2.3•10^{1}
Sc	–	2.0•10^{-5}	–	–	–	1.3•10^{-7}	4.8•10^{-9}	2.2•10^{-5}	1.3•10^{-6}	2.5•10^{0}	2.5•10^{0}
Sn	–	3.3•10^{-5}	–	–	–	5.6•10^{-8}	1.0•10^{-8}	2.2•10^{-6}	2.3•10^{-7}	6.2•10^{-1}	6.2•10^{-1}
Sr	–	1.3•10^{-2}	–	–	–	1.9•10^{-4}	2.3•10^{-6}	4.9•10^{-2}	5.1•10^{-5}	2.6•10^{1}	2.7•10^{1}
Ta	–	2.5•10^{-6}	–	–	–	5.1•10^{-9}	7.0•10^{-9}	2.2•10^{-7}	–	2.5•10^{-1}	2.5•10^{-1}
Ti	3.9•10^{-5}	2.7•10^{-3}	–	1.5•10^{-5}	–	3.9•10^{-5}	5.2•10^{-7}	2.8•10^{-4}	1.5•10^{-4}	7.2•10^{2}	7.2•10^{2}
Tl	–	2.3•10^{-6}	–	–	–	1.7•10^{-7}	1.1•10^{-8}	1.3•10^{-5}	1.9•10^{-7}	2.1•10^{-1}	2.1•10^{-1}
V	1.5•10^{-6}	1.0•10^{-4}	–	5.3•10^{-7}	–	1.8•10^{-6}	1.2•10^{-8}	2.0•10^{-4}	7.6•10^{-6}	1.6•10^{1}	1.6•10^{1}
W	–	2.9•10^{-5}	–	–	–	4.4•10^{-8}	4.0•10^{-9}	1.3•10^{-5}	8.7•10^{-7}	5.0•10^{-1}	5.0•10^{-1}
Y	–	1.3•10^{-4}	–	–	–	4.2•10^{-7}	2.7^{-10}	3.2•10^{-5}	5.6•10^{-6}	6.2•10^{0}	6.2•10^{0}
Zn	7.9•10^{-5}	5.8•10^{-1}	–	1.5•10^{-4}	–	9.5•10^{-3}	2.3•10^{-1}	1.9•10^{-3}	7.9•10^{-5}	1.3•10^{2}	1.4•10^{2}
Zr	3.3•10^{-6}	1.4•10^{-4}	–	6.8•10^{-7}	–	4.4•10^{-6}	5.7•10^{-9}	1.4•10^{-4}	1.3•10^{-5}	2.8•10^{1}	2.8•10^{1}
Ce	2.0•10^{-9}	3.0•10^{-4}	–	5.0•10^{-7}	–	4.0•10^{-7}	–	9.1•10^{-5}	1.7•10^{-5}	1.8•10^{1}	1.8•10^{1}
Dy	1.1^{-10}	4.0•10^{-5}	–	3.9•10^{-8}	–	2.2•10^{-8}	2.0^{-10}	1.2•10^{-5}	9.4•10^{-7}	1.2•10^{0}	1.2•10^{0}
Er	6.0^{-11}	2.3•10^{-5}	–	2.2•10^{-8}	–	1.2•10^{-8}	2.0^{-10}	9.1•10^{-6}	5.9•10^{-7}	6.4•10^{-1}	6.4•10^{-1}
Eu	4.4^{-11}	6.3•10^{-6}	–	6.7•10^{-9}	–	1.1•10^{-8}	2.0^{-10}	6.9•10^{-6}	1.4•10^{-7}	2.3•10^{-1}	2.3•10^{-1}
Gd	1.4^{-10}	3.2•10^{-5}	–	4.0•10^{-8}	–	3.2•10^{-8}	2.0^{-10}	1.3•10^{-5}	6.0•10^{-7}	1.1•10^{0}	1.1•10^{0}
Ho	4.4^{-11}	1.1•10^{-5}	–	8.4•10^{-9}	–	4.4•10^{-9}	2.0^{-10}	6.0•10^{-6}	2.0•10^{-7}	2.5•10^{-1}	2.5•10^{-1}
La	–	2.0•10^{-4}	–	–	–	1.0•10^{-6}	3.3^{-10}	1.3•10^{-5}	1.2•10^{-5}	1.0•10^{1}	1.0•10^{1}
Lu	4.4^{-11}	3.8•10^{-6}	–	3.4•10^{-9}	–	1.9•10^{-9}	2.0^{-10}	2.5•10^{-5}	7.0•10^{-8}	1.0•10^{-1}	1.0•10^{-1}
Nd	8.3^{-10}	2.0•10^{-4}	–	2.6•10^{-7}	–	1.9•10^{-7}	2.0^{-10}	5.0•10^{-5}	6.6•10^{-6}	8.3•10^{0}	8.3•10^{0}
Pr	2.2^{-10}	4.4•10^{-5}	–	6.7•10^{-8}	–	5.0•10^{-8}	2.0^{-10}	1.7•10^{-5}	1.9•10^{-6}	2.4•10^{0}	2.4•10^{0}
Sm	1.5^{-10}	3.2•10^{-5}	–	5.2•10^{-8}	–	3.4•10^{-8}	2.0^{-10}	1.3•10^{-5}	1.3•10^{-6}	1.4•10^{0}	1.4•10^{0}

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zooplankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Sediment	Total
Tb	4.4^{-11}	$6.8\bullet10^{-6}$	–	$6.7\bullet10^{-9}$	–	$4.1\bullet10^{-9}$	2.1^{-10}	$1.5\bullet10^{-5}$	$1.5\bullet10^{-7}$	$1.8\bullet10^{-1}$	$1.8\bullet10^{-1}$
Tm	4.4^{-11}	$5.4\bullet10^{-6}$	–	$3.4\bullet10^{-9}$	–	$1.7\bullet10^{-9}$	2.0^{-10}	$5.5\bullet10^{-6}$	$8.2\bullet10^{-8}$	$1.2\bullet10^{-1}$	$1.2\bullet10^{-1}$
Yb	5.7^{-11}	$2.0\bullet10^{-5}$	–	$2.0\bullet10^{-8}$	–	$1.1\bullet10^{-8}$	2.0^{-10}	$1.0\bullet10^{-5}$	$4.2\bullet10^{-7}$	$6.8\bullet10^{-1}$	$6.8\bullet10^{-1}$
Br	$2.9\bullet10^{-4}$	$1.1\bullet10^{-3}$	–	$1.8\bullet10^{-3}$	–	$1.7\bullet10^{-4}$	$2.2\bullet10^{-5}$	$3.6\bullet10^{-1}$	$3.3\bullet10^{-4}$	$2.8\bullet10^{0}$	$3.1\bullet10^{0}$
C	$3.9\bullet10^{-2}$	$2.6\bullet10^{1}$	$4.8\bullet10^{-2}$	$6.0\bullet10^{-2}$	$3.7\bullet10^{0}$	$5.2\bullet10^{-1}$	$8.3\bullet10^{-1}$	$3.7\bullet10^{1}$	$3.2\bullet10^{-1}$	$1.9\bullet10^{4}$	$1.9\bullet10^{4}$
Cl	$1.4\bullet10^{-2}$	$7.7\bullet10^{-2}$	–	–	–	$6.7\bullet10^{-3}$	$3.1\bullet10^{-3}$	$9.5\bullet10^{1}$	–	$1.9\bullet10^{1}$	$1.1\bullet10^{2}$
F	$2.2\bullet10^{-4}$	–	–	–	–	$5.7\bullet10^{-5}$	–	$2.5\bullet10^{-1}$	–	–	$2.5\bullet10^{-1}$
I	$3.3\bullet10^{-6}$	$6.5\bullet10^{-4}$	–	$9.9\bullet10^{-6}$	–	$1.1\bullet10^{-5}$	$4.5\bullet10^{-7}$	$5.8\bullet10^{-3}$	$6.2\bullet10^{-5}$	$5.4\bullet10^{-1}$	$5.4\bullet10^{-1}$
N	$4.7\bullet10^{-3}$	$9.5\bullet10^{-1}$	$9.0\bullet10^{-3}$	$1.4\bullet10^{-2}$	$6.6\bullet10^{-1}$	$8.0\bullet10^{-2}$	$2.3\bullet10^{-1}$	$1.0\bullet10^{0}$	$5.0\bullet10^{-2}$	$2.3\bullet10^{3}$	$2.3\bullet10^{3}$
P	$2.9\bullet10^{-4}$	$5.5\bullet10^{-2}$	$2.2\bullet10^{-3}$	$1.3\bullet10^{-3}$	$2.1\bullet10^{-1}$	$8.9\bullet10^{-3}$	$2.2\bullet10^{-2}$	$6.6\bullet10^{-3}$	$4.8\bullet10^{-3}$	$1.5\bullet10^{2}$	$1.5\bullet10^{2}$
S	$1.6\bullet10^{-3}$	$3.1\bullet10^{-1}$	$8.5\bullet10^{-4}$	$6.6\bullet10^{-3}$	$6.4\bullet10^{-2}$	$9.7\bullet10^{-3}$	$2.0\bullet10^{-2}$	$6.6\bullet10^{0}$	$1.2\bullet10^{-2}$	$7.5\bullet10^{2}$	$7.6\bullet10^{2}$
Th	$3.0\bullet10^{-7}$	$2.9\bullet10^{-5}$	–	$7.5\bullet10^{-8}$	–	$3.9\bullet10^{-7}$	$4.0\bullet10^{-9}$	$9.0\bullet10^{-6}$	$3.1\bullet10^{-6}$	$2.7\bullet10^{0}$	$2.7\bullet10^{0}$
U	–	$4.3\bullet10^{-4}$	–	$4.7\bullet10^{-8}$	–	$4.1\bullet10^{-7}$	$2.2\bullet10^{-9}$	$1.6\bullet10^{-3}$	$1.7\bullet10^{-6}$	$3.1\bullet10^{0}$	$3.1\bullet10^{0}$

Table A11-2. Pools of elements (g m^{-2}) in Frisksjön in Laxemar-Simpevarp.

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Upper sediment	Lower sediment	Total Sediment	Total
As	$3.9\bullet10^{-5}$	$1.2\bullet10^{-8}$	–	$1.2\bullet10^{-5}$	–	$1.8\bullet10^{-5}$	$5.3\bullet10^{-8}$	$7.4\bullet10^{-4}$	$1.4\bullet10^{-4}$	$6.5\bullet10^{-3}$	$1.8\bullet10^{1}$	$1.8\bullet10^{1}$	$3.6\bullet10^{1}$
B	–	$8.7\bullet10^{-7}$	–	–	–	$9.8\bullet10^{-6}$	$1.2\bullet10^{-6}$	$4.4\bullet10^{-2}$	$8.7\bullet10^{-5}$	$7.4\bullet10^{-4}$	$1.5\bullet10^{0}$	$1.5\bullet10^{0}$	$3.0\bullet10^{0}$
Sb	–	4.5^{-10}	–	–	–	$6.6\bullet10^{-8}$	$2.5\bullet10^{-9}$	$3.0\bullet10^{-4}$	$9.6\bullet10^{-6}$	$1.2\bullet10^{-3}$	$5.3\bullet10^{-1}$	$5.3\bullet10^{-1}$	$1.1\bullet10^{0}$
Se	$1.6\bullet10^{-6}$	$6.5\bullet10^{-9}$	–	$5.4\bullet10^{-6}$	–	$1.8\bullet10^{-6}$	$1.4\bullet10^{-6}$	$2.8\bullet10^{-4}$	$1.3\bullet10^{-5}$	$1.5\bullet10^{-3}$	$1.5\bullet10^{0}$	$1.5\bullet10^{0}$	$3.1\bullet10^{0}$
Si	$4.4\bullet10^{-1}$	$6.1\bullet10^{-5}$	–	$5.1\bullet10^{-2}$	–	$1.6\bullet10^{-2}$	$2.1\bullet10^{-4}$	$1.0\bullet10^{1}$	$1.2\bullet10^{1}$	$2.8\bullet10^{2}$	$2.7\bullet10^{5}$	$2.7\bullet10^{5}$	$5.5\bullet10^{5}$
Ag	–	2.7^{-10}	–	–	–	$2.5\bullet10^{-7}$	$1.0\bullet10^{-8}$	$1.2\bullet10^{-5}$	$2.2\bullet10^{-6}$	$1.5\bullet10^{-4}$	$5.5\bullet10^{-2}$	$5.5\bullet10^{-2}$	$1.1\bullet10^{-1}$
Al	$5.9\bullet10^{-2}$	$4.6\bullet10^{-6}$	–	$1.5\bullet10^{-3}$	–	$5.5\bullet10^{-4}$	$1.0\bullet10^{-6}$	$4.2\bullet10^{-1}$	$3.4\bullet10^{-1}$	$4.5\bullet10^{1}$	$2.8\bullet10^{4}$	$2.8\bullet10^{4}$	$5.5\bullet10^{4}$
Ba	$1.5\bullet10^{-4}$	$2.8\bullet10^{-6}$	–	$2.6\bullet10^{-5}$	–	$2.2\bullet10^{-4}$	$8.8\bullet10^{-7}$	$2.9\bullet10^{-2}$	$1.7\bullet10^{-3}$	$2.7\bullet10^{-1}$	$1.7\bullet10^{2}$	$1.7\bullet10^{2}$	$3.5\bullet10^{2}$

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Upper sediment	Lower sediment	Total Sediment	Total
Be	–	$2.3\bullet10^{-9}$	–	–	–	$3.0\bullet10^{-6}$	$5.5\bullet10^{-8}$	$5.2\bullet10^{-4}$	$1.3\bullet10^{-4}$	$1.3\bullet10^{-2}$	$4.1\bullet10^{0}$	$4.1\bullet10^{0}$	$8.2\bullet10^{0}$
Ca	$1.2\bullet10^{-2}$	$7.4\bullet10^{-4}$	–	$4.7\bullet10^{-2}$	–	$5.4\bullet10^{-1}$	$3.3\bullet10^{-3}$	$1.6\bullet10^{1}$	$8.1\bullet10^{-2}$	$1.2\bullet10^{1}$	$1.3\bullet10^{4}$	$1.3\bullet10^{4}$	$2.6\bullet10^{4}$
Cd	$7.7\bullet10^{-7}$	$1.5\bullet10^{-9}$	–	$2.6\bullet10^{-6}$	–	$4.6\bullet10^{-6}$	$2.8\bullet10^{-9}$	$2.8\bullet10^{-5}$	$1.1\bullet10^{-5}$	$5.1\bullet10^{-3}$	$2.3\bullet10^{0}$	$2.3\bullet10^{0}$	$4.7\bullet10^{0}$
Co	$5.1\bullet10^{-6}$	$1.9\bullet10^{-8}$	–	$8.8\bullet10^{-7}$	–	$2.1\bullet10^{-6}$	$1.3\bullet10^{-8}$	$4.5\bullet10^{-4}$	$8.1\bullet10^{-5}$	$3.3\bullet10^{-2}$	$9.5\bullet10^{0}$	$9.5\bullet10^{0}$	$1.9\bullet10^{1}$
Cr	$1.9\bullet10^{-5}$	$5.3\bullet10^{-9}$	–	$5.3\bullet10^{-6}$	–	$3.1\bullet10^{-6}$	$1.9\bullet10^{-8}$	$1.1\bullet10^{-3}$	$3.4\bullet10^{-4}$	$5.4\bullet10^{-2}$	$4.6\bullet10^{1}$	$4.6\bullet10^{1}$	$9.2\bullet10^{1}$
Cs	$1.6\bullet10^{-6}$	$1.7\bullet10^{-9}$	–	$1.7\bullet10^{-7}$	–	$2.8\bullet10^{-7}$	$8.7\bullet10^{-7}$	$2.4\bullet10^{-4}$	$1.7\bullet10^{-5}$	$3.3\bullet10^{-3}$	$2.3\bullet10^{0}$	$2.3\bullet10^{0}$	$4.7\bullet10^{0}$
Cu	$6.9\bullet10^{-5}$	$7.0\bullet10^{-8}$	–	$1.1\bullet10^{-4}$	–	$1.6\bullet10^{-4}$	$8.7\bullet10^{-7}$	$4.1\bullet10^{-3}$	$5.0\bullet10^{-4}$	$9.8\bullet10^{-2}$	$8.4\bullet10^{1}$	$8.4\bullet10^{1}$	$1.7\bullet10^{2}$
Fe	$1.2\bullet10^{-2}$	$1.2\bullet10^{-5}$	–	$1.1\bullet10^{-3}$	–	$2.2\bullet10^{-3}$	$9.7\bullet10^{-6}$	$1.7\bullet10^{0}$	$7.4\bullet10^{-1}$	$4.5\bullet10^{1}$	$2.6\bullet10^{4}$	$2.6\bullet10^{4}$	$5.1\bullet10^{4}$
Ga	–	4.7^{-10}	–	–	–	$1.3\bullet10^{-7}$	$4.6\bullet10^{-9}$	$1.0\bullet10^{-5}$	$4.6\bullet10^{-5}$	$1.0\bullet10^{-1}$	$4.5\bullet10^{0}$	$4.6\bullet10^{0}$	$9.3\bullet10^{0}$
Hf	–	2.0^{-10}	–	–	–	$4.3\bullet10^{-8}$	5.9^{-10}	$2.0\bullet10^{-4}$	$2.4\bullet10^{-5}$	$1.2\bullet10^{-3}$	$4.8\bullet10^{-1}$	$4.8\bullet10^{-1}$	$9.7\bullet10^{-1}$
Hg	$1.8\bullet10^{-7}$	1.1^{-10}	–	$3.2\bullet10^{-7}$	–	$1.1\bullet10^{-7}$	$1.9\bullet10^{-6}$	$3.2\bullet10^{-6}$	$1.2\bullet10^{-6}$	$2.3\bullet10^{-4}$	$6.7\bullet10^{-2}$	$6.7\bullet10^{-2}$	$1.3\bullet10^{-1}$
K	$2.9\bullet10^{-2}$	$5.4\bullet10^{-4}$	–	$3.4\bullet10^{-2}$	–	$1.6\bullet10^{-2}$	$2.9\bullet10^{-2}$	$3.3\bullet10^{0}$	$5.0\bullet10^{-2}$	$8.3\bullet10^{0}$	$8.3\bullet10^{3}$	$8.4\bullet10^{3}$	$1.7\bullet10^{4}$
Li	$2.7\bullet10^{-5}$	$5.7\bullet10^{-9}$	–	$5.2\bullet10^{-6}$	–	$4.1\bullet10^{-6}$	$2.8\bullet10^{-8}$	$4.3\bullet10^{-3}$	$9.0\bullet10^{-5}$	$2.9\bullet10^{-2}$	$1.6\bullet10^{1}$	$1.6\bullet10^{1}$	$3.2\bullet10^{1}$
Mg	$2.4\bullet10^{-2}$	$6.1\bullet10^{-5}$	–	$1.4\bullet10^{-2}$	–	$1.8\bullet10^{-2}$	$2.6\bullet10^{-3}$	$4.9\bullet10^{0}$	$2.7\bullet10^{-2}$	$1.5\bullet10^{-3}$	$9.5\bullet10^{3}$	$9.5\bullet10^{3}$	$1.9\bullet10^{4}$
Mn	$1.4\bullet10^{-3}$	$1.8\bullet10^{-5}$	–	$9.0\bullet10^{-5}$	–	$2.3\bullet10^{-4}$	$1.7\bullet10^{-6}$	$1.1\bullet10^{-1}$	$1.1\bullet10^{-2}$	$3.9\bullet10^{-1}$	$1.9\bullet10^{2}$	$1.9\bullet10^{2}$	$3.9\bullet10^{2}$
Mo	$1.1\bullet10^{-6}$	$1.8\bullet10^{-8}$	–	$1.4\bullet10^{-6}$	–	$7.6\bullet10^{-7}$	$1.7\bullet10^{-8}$	$2.2\bullet10^{-3}$	$7.3\bullet10^{-5}$	$4.4\bullet10^{-3}$	$1.6\bullet10^{1}$	$1.6\bullet10^{1}$	$3.2\bullet10^{1}$
Na	$1.5\bullet10^{-1}$	$1.9\bullet10^{-4}$	–	$1.0\bullet10^{-1}$	–	$3.7\bullet10^{-2}$	$3.3\bullet10^{-3}$	$2.0\bullet10^{1}$	$3.4\bullet10^{-2}$	$3.5\bullet10^{0}$	$1.1\bullet10^{4}$	$1.1\bullet10^{4}$	$2.2\bullet10^{4}$
Nb	–	4.9^{-10}	–	–	–	$1.2\bullet10^{-7}$	5.8^{-10}	$6.2\bullet10^{-5}$	$6.3\bullet10^{-5}$	$4.4\bullet10^{-3}$	$4.6\bullet10^{0}$	$4.6\bullet10^{0}$	$9.2\bullet10^{0}$
Ni	$1.8\bullet10^{-5}$	$3.2\bullet10^{-8}$	–	$6.4\bullet10^{-6}$	–	$5.1\bullet10^{-6}$	$2.9\bullet10^{-8}$	$3.1\bullet10^{-3}$	$2.6\bullet10^{-4}$	$7.7\bullet10^{-2}$	$5.4\bullet10^{1}$	$5.4\bullet10^{1}$	$1.1\bullet10^{2}$
Pb	$3.5\bullet10^{-5}$	$1.5\bullet10^{-8}$	–	$9.5\bullet10^{-6}$	–	$3.0\bullet10^{-6}$	$2.3\bullet10^{-8}$	$1.4\bullet10^{-3}$	$9.7\bullet10^{-4}$	$6.3\bullet10^{-2}$	$1.8\bullet10^{1}$	$1.8\bullet10^{1}$	$3.6\bullet10^{1}$
Rb	$3.9\bullet10^{-5}$	$9.1\bullet10^{-7}$	–	$2.1\bullet10^{-5}$	–	$1.0\bullet10^{-5}$	$1.1\bullet10^{-4}$	$7.7\bullet10^{-3}$	$2.7\bullet10^{-4}$	$5.9\bullet10^{-2}$	$4.4\bullet10^{1}$	$4.4\bullet10^{1}$	$8.8\bullet10^{1}$
Sc	–	$1.2\bullet10^{-9}$	–	–	–	$2.1\bullet10^{-6}$	9.4^{-10}	$1.7\bullet10^{-4}$	$7.4\bullet10^{-5}$	$1.1\bullet10^{-2}$	$7.6\bullet10^{0}$	$7.6\bullet10^{0}$	$1.5\bullet10^{1}$
Sn	–	9.1^{-10}	–	–	–	$8.2\bullet10^{-8}$	$1.0\bullet10^{-8}$	$5.0\bullet10^{-6}$	$2.3\bullet10^{-5}$	$1.5\bullet10^{-2}$	$1.5\bullet10^{1}$	$1.5\bullet10^{1}$	$3.1\bullet10^{1}$
Sr	–	$8.0\bullet10^{-7}$	–	–	–	$4.2\bullet10^{-4}$	$3.1\bullet10^{-6}$	$7.7\bullet10^{-2}$	$6.0\bullet10^{-4}$	$9.9\bullet10^{-2}$	$1.7\bullet10^{2}$	$1.7\bullet10^{2}$	$3.4\bullet10^{2}$
Ta	–	1.4^{-10}	–	–	–	$8.2\bullet10^{-9}$	$3.4\bullet10^{-9}$	$2.0\bullet10^{-6}$	$1.1\bullet10^{-6}$	$4.4\bullet10^{-5}$	$1.2\bullet10^{-1}$	$1.2\bullet10^{-1}$	$2.4\bullet10^{-1}$
Ti	$5.6\bullet10^{-4}$	$6.2\bullet10^{-8}$	–	$5.8\bullet10^{-5}$	–	$8.1\bullet10^{-5}$	$1.2\bullet10^{-7}$	$3.8\bullet10^{-3}$	$7.1\bullet10^{-3}$	$1.6\bullet10^{-1}$	$1.2\bullet10^{2}$	$1.3\bullet10^{2}$	$2.5\bullet10^{2}$
Tl	–	9.9^{-10}	–	–	–	$2.7\bullet10^{-8}$	$1.8\bullet10^{-8}$	$1.9\bullet10^{-5}$	$2.6\bullet10^{-6}$	$8.9\bullet10^{-4}$	$4.7\bullet10^{-1}$	$4.7\bullet10^{-1}$	$9.3\bullet10^{-1}$
V	$2.2\bullet10^{-5}$	$1.9\bullet10^{-8}$	–	$2.0\bullet10^{-6}$	–	$3.8\bullet10^{-6}$	$4.7\bullet10^{-8}$	$2.5\bullet10^{-3}$	$1.3\bullet10^{-3}$	$6.3\bullet10^{-2}$	$4.3\bullet10^{1}$	$4.3\bullet10^{1}$	$8.5\bullet10^{1}$
W	–	7.0^{-10}	–	–	–	$1.3\bullet10^{-7}$	$1.6\bullet10^{-9}$	$2.8\bullet10^{-5}$	$1.4\bullet10^{-5}$	$4.4\bullet10^{-2}$	$4.6\bullet10^{1}$	$4.6\bullet10^{1}$	$9.2\bullet10^{1}$
Y	–	$1.7\bullet10^{-8}$	–	–	–	$2.4\bullet10^{-5}$	$1.2\bullet10^{-9}$	$1.8\bullet10^{-3}$	$7.8\bullet10^{-4}$	$1.2\bullet10^{-1}$	$6.0\bullet10^{1}$	$6.0\bullet10^{1}$	$1.2\bullet10^{2}$

Element	Phyto-plankton	Benthic primary producers	Bacterio-plankton	Zoo-plankton	Benthic bacteria	Benthic fauna	Fish	Dissolved	Particulate	Upper sediment	Lower sediment	Total Sediment	Total
Zn	$1.1\cdot10^{-3}$	$5.6\cdot10^{-4}$	–	$5.5\cdot10^{-4}$	–	$1.7\cdot10^{-4}$	$1.9\cdot10^{-1}$	$7.9\cdot10^{-3}$	$1.3\cdot10^{-3}$	$9.8\cdot10^{-3}$	$1.2\cdot10^{2}$	$1.2\cdot10^{2}$	$2.5\cdot10^{2}$
Zr	$4.7\cdot10^{-5}$	$7.3\cdot10^{-9}$	–	$2.6\cdot10^{-6}$	–	$8.6\cdot10^{-6}$	$3.9\cdot10^{-8}$	$1.8\cdot10^{-3}$	$7.7\cdot10^{-4}$	$1.9\cdot10^{1}$	$7.2\cdot10^{1}$	$9.1\cdot10^{1}$	$1.8\cdot10^{2}$
Ce	$2.9\cdot10^{-8}$	$9.8\cdot10^{-8}$	–	$1.9\cdot10^{-6}$	–	$3.8\cdot10^{-7}$	–	$5.2\cdot10^{-3}$	$3.1\cdot10^{-3}$	$3.3\cdot10^{-1}$	$1.7\cdot10^{2}$	$1.7\cdot10^{2}$	$3.4\cdot10^{2}$
Dy	$1.6\cdot10^{-9}$	$2.3\cdot10^{-9}$	–	$1.5\cdot10^{-7}$	–	$2.2\cdot10^{-8}$	5.1^{-10}	$2.8\cdot10^{-4}$	$1.3\cdot10^{-4}$	$1.7\cdot10^{-2}$	$8.5\cdot10^{0}$	$8.5\cdot10^{0}$	$1.7\cdot10^{1}$
Er	8.6^{-10}	$1.4\cdot10^{-9}$	–	$8.2\cdot10^{-8}$	–	$1.2\cdot10^{-8}$	$3.0\cdot10^{-9}$	$1.8\cdot10^{-4}$	$8.3\cdot10^{-5}$	$1.2\cdot10^{-2}$	$5.0\cdot10^{0}$	$5.0\cdot10^{0}$	$1.0\cdot10^{1}$
Eu	6.4^{-10}	$1.0\cdot10^{-9}$	–	$2.5\cdot10^{-8}$	–	$5.0\cdot10^{-9}$	2.3^{-10}	$7.7\cdot10^{-5}$	$3.4\cdot10^{-5}$	$5.3\cdot10^{-3}$	$1.1\cdot10^{0}$	$1.1\cdot10^{0}$	$2.3\cdot10^{0}$
Gd	$1.9\cdot10^{-9}$	$2.8\cdot10^{-9}$	–	$1.5\cdot10^{-7}$	–	$3.4\cdot10^{-8}$	2.3^{-10}	$3.8\cdot10^{-4}$	$9.2\cdot10^{-5}$	$2.5\cdot10^{-2}$	$1.1\cdot10^{1}$	$1.1\cdot10^{1}$	$2.3\cdot10^{1}$
Ho	6.4^{-10}	4.5^{-10}	–	$3.2\cdot10^{-8}$	–	$4.3\cdot10^{-9}$	6.2^{-10}	$5.7\cdot10^{-5}$	$2.8\cdot10^{-5}$	$3.7\cdot10^{-3}$	$1.7\cdot10^{0}$	$1.7\cdot10^{0}$	$3.4\cdot10^{0}$
La	–	$3.6\cdot10^{-8}$	–	–	–	$1.2\cdot10^{-4}$	$2.4\cdot10^{-9}$	$2.6\cdot10^{-3}$	$1.6\cdot10^{-3}$	$1.7\cdot10^{-1}$	$7.8\cdot10^{1}$	$7.8\cdot10^{1}$	$1.6\cdot10^{2}$
Lu	6.4^{-10}	2.0^{-10}	–	$1.3\cdot10^{-8}$	–	$1.6\cdot10^{-9}$	2.3^{-10}	$4.9\cdot10^{-5}$	$1.0\cdot10^{-5}$	$1.5\cdot10^{-3}$	$8.2\cdot10^{-1}$	$8.2\cdot10^{-1}$	$1.6\cdot10^{0}$
Nd	$1.2\cdot10^{-8}$	$2.8\cdot10^{-8}$	–	$9.8\cdot10^{-7}$	–	$1.9\cdot10^{-7}$	$1.3\cdot10^{-9}$	$2.9\cdot10^{-3}$	$6.3\cdot10^{-5}$	$1.8\cdot10^{-1}$	$8.8\cdot10^{1}$	$8.8\cdot10^{1}$	$1.8\cdot10^{2}$
Pr	$3.2\cdot10^{-9}$	$7.7\cdot10^{-9}$	–	$2.5\cdot10^{-7}$	–	$5.1\cdot10^{-8}$	4.7^{-10}	$7.2\cdot10^{-4}$	$3.4\cdot10^{-4}$	$4.8\cdot10^{-2}$	$2.2\cdot10^{1}$	$2.2\cdot10^{1}$	$4.4\cdot10^{1}$
Sm	$2.2\cdot10^{-9}$	$4.5\cdot10^{-9}$	–	$2.0\cdot10^{-7}$	–	$3.5\cdot10^{-8}$	7.9^{-10}	$4.8\cdot10^{-4}$	$6.8\cdot10^{-4}$	$2.9\cdot10^{-2}$	$1.3\cdot10^{1}$	$1.3\cdot10^{1}$	$2.7\cdot10^{1}$
Tb	6.4^{-10}	3.8^{-10}	–	$2.5\cdot10^{-8}$	–	$4.4\cdot10^{-9}$	8.2^{-10}	$5.5\cdot10^{-5}$	$2.0\cdot10^{-5}$	$3.0\cdot10^{-3}$	$1.6\cdot10^{0}$	$1.6\cdot10^{0}$	$3.2\cdot10^{0}$
Tm	6.4^{-10}	1.9^{-10}	–	$1.3\cdot10^{-8}$	–	$1.6\cdot10^{-9}$	3.8^{-10}	$2.7\cdot10^{-5}$	$1.2\cdot10^{-5}$	$1.7\cdot10^{-3}$	$8.1\cdot10^{-1}$	$8.1\cdot10^{-1}$	$1.6\cdot10^{0}$
Yb	8.1^{-10}	$1.3\cdot10^{-9}$	–	$7.6\cdot10^{-8}$	–	$1.0\cdot10^{-8}$	6.0^{-10}	$1.9\cdot10^{-4}$	$6.2\cdot10^{-5}$	$9.8\cdot10^{-3}$	$5.2\cdot10^{0}$	$5.3\cdot10^{0}$	$1.1\cdot10^{1}$
Br	$4.2\cdot10^{-3}$	$1.7\cdot10^{-6}$	–	$6.9\cdot10^{-3}$	–	$2.8\cdot10^{-4}$	$2.7\cdot10^{-5}$	$2.4\cdot10^{-1}$	$3.2\cdot10^{-4}$	$1.2\cdot10^{-2}$	$2.3\cdot10^{2}$	$2.3\cdot10^{2}$	$4.7\cdot10^{2}$
C	$5.5\cdot10^{-1}$	$1.1\cdot10^{-2}$	$5.2\cdot10^{-2}$	$2.2\cdot10^{-1}$	$5.3\cdot10^{0}$	$1.0\cdot10^{0}$	$6.0\cdot10^{-1}$	$3.6\cdot10^{1}$	$1.7\cdot10^{0}$	$2.5\cdot10^{2}$	$2.6\cdot10^{5}$	$2.6\cdot10^{5}$	$5.2\cdot10^{5}$
Cl	$2.0\cdot10^{-1}$	$3.2\cdot10^{-4}$	–	–	–	$1.3\cdot10^{-2}$	$2.7\cdot10^{-3}$	$2.6\cdot10^{1}$	–	$5.2\cdot10^{-1}$	$7.8\cdot10^{3}$	$7.8\cdot10^{3}$	$1.6\cdot10^{4}$
F	$3.1\cdot10^{-3}$	–	–	–	–	$1.3\cdot10^{-4}$	–	$1.5\cdot10^{0}$	–	–	–	–	$1.6\cdot10^{0}$
I	$4.8\cdot10^{-5}$	$2.8\cdot10^{-7}$	–	$3.7\cdot10^{-5}$	–	$1.5\cdot10^{-5}$	$3.4\cdot10^{-6}$	$6.2\cdot10^{-2}$	$2.1\cdot10^{-3}$	$6.3\cdot10^{-3}$	$4.2\cdot10^{1}$	$4.2\cdot10^{1}$	$8.3\cdot10^{1}$
N	$6.7\cdot10^{-2}$	$5.6\cdot10^{-4}$	$9.6\cdot10^{-3}$	$5.1\cdot10^{-2}$	$9.6\cdot10^{-1}$	$1.7\cdot10^{-1}$	$1.9\cdot10^{-1}$	$6.1\cdot10^{-1}$	$2.1\cdot10^{-1}$	$1.9\cdot10^{1}$	$3.1\cdot10^{4}$	$3.1\cdot10^{4}$	$6.1\cdot10^{4}$
P	$5.1\cdot10^{-3}$	$7.8\cdot10^{-5}$	$2.4\cdot10^{-3}$	$8.5\cdot10^{-3}$	$3.0\cdot10^{-1}$	$8.8\cdot10^{-3}$	$1.8\cdot10^{-2}$	$3.6\cdot10^{-2}$	$2.6\cdot10^{-2}$	$2.3\cdot10^{0}$	$2.2\cdot10^{3}$	$2.2\cdot10^{3}$	$4.4\cdot10^{3}$
S	$2.3\cdot10^{-2}$	$1.1\cdot10^{-4}$	$9.1\cdot10^{-4}$	$2.5\cdot10^{-2}$	$9.3\cdot10^{-2}$	$2.3\cdot10^{-2}$	$1.8\cdot10^{-2}$	$8.8\cdot10^{0}$	$6.0\cdot10^{-2}$	$2.7\cdot10^{1}$	$3.7\cdot10^{4}$	$3.7\cdot10^{4}$	$7.5\cdot10^{4}$
Th	$4.4\cdot10^{-6}$	$1.4\cdot10^{-9}$	–	$2.8\cdot10^{-7}$	–	$7.6\cdot10^{-7}$	$4.6\cdot10^{-9}$	$1.8\cdot10^{-4}$	$1.8\cdot10^{-4}$	$1.5\cdot10^{-2}$	$8.7\cdot10^{0}$	$8.7\cdot10^{0}$	$1.7\cdot10^{1}$
U	–	$4.9\cdot10^{-9}$	–	$5.5\cdot10^{-7}$	–	$2.5\cdot10^{-6}$	$1.7\cdot10^{-9}$	$6.6\cdot10^{-4}$	$1.4\cdot10^{-4}$	$1.9\cdot10^{-2}$	$1.9\cdot10^{1}$	$1.9\cdot10^{1}$	$3.9\cdot10^{1}$

Appendix 12

Fluxes of elements

Fluxes of elements are described in Chapter 5 and 7. Range of carbon fluxes into and out of the 5 lakes in Chapter 5 are presented in Table A12-1. Fluxes into and out of the 5 lakes in Forsmark and one lake in Laxemar-Simpevarp (Frisksjön) for a number of elements are presented in Table A12-2 below. In Table A12-3 and A12-4, values of atmospheric deposition are presented. Details of how fluxes were calculated are presented in Chapter 7. For carbon, more detailed mass balances are described in Chapter 5 for Bolundsfjärden, Eckarfjärden and Frisksjön.

Table A12-1. Calculated carbon influxes and outfluxes (minimum, maximum and best guess) to/from Eckarfjärden, Bolundsfjärden, Gunnarsbo-Lillfjärden, and Labboträsk in Forsmark and to/from Frisksjön in Laxemar-Simpevarp. All values are in kgC lake^{-1} year $^{-1}$.

Lake	DIC inflow	TOC inflow	Atmospheric deposition	CO2 gas exchange	DIC Outflow	TOC Outflow	Sediment accumulation	Bird consumption
Eckarfjärden								
min	9,732	3,272	158	-264	6,316	5,336	339	1
max	11,123	3,753	434	-1,236	7,219	6,119	15,083	676
best guess	10,427	3,512	233	-928	6,767	5,727	3,649	326
Bolundsfjärden								
min	27,942	19,551	340	-2,592	27,874	18,917	728	2
max	35,999	25,456	931	-3,157	36,113	24,794	32,367	1,451
best guess	31,971	22,502	501	-2,848	31,993	21,855	8,988	700
Gunnarsbo-Lillfjärden								
min	26,654	13,088	15	1,361	26,214	13,088	32	1
max	26,654	13,088	41	1,361	26,214	13,088	1,434	676
best guess	26,654	13,088	22	1,361	26,214	13,088	371	31
Labboträsk								
min	16,528	7,698	2	400	18,959	8,313	4	0,01
max	21,772	10,792	5	506	23,108	10,625	176	8
best guess	19,150	9,245	3	448	21,033	9,469	45	4
Frisksjön								
min	388	6,498	86	1,883	364	2,754	2,665	0,1
max	5,047	13,476	236	6,026	1,205	5,390	10,848	283
best guess	1,082	8,272	193	4,478	800	4,299	8,009	93

Table A12-2. Fluxes to/from lakes in Forsmark and Laxemar-Simpevarp. Eckarfjärden, Bolundsfjärden, Gällsboträsket, Norra Bassängen and Puttan are lakes in the Forsmark area, and the average Forsmark lake is mean values for the 5 lakes. Frisksjön represent the Laxemar-Simpevarp area. Fluxes are in g lake^{-1} year^{-1}.

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
C	In through water	13,939,532	54,473,472	17,624,951	55,636,066	1,918,721	28,135,548	9,354,653
	In from atmosphere	233,308	500,683	10,771	39,198	32,807	163,355	193,283
	Out through water	12,494,644	53,848,483	17,005,475	55,298,689	1,558,525	28,040,938	5,099,212
	Accumulation	3,649,303	8,987,988	224,355	816,457	683,349	3,402,518	8,009,020
N	In through water	370,882	1,087,329	223,000	1,314,000	48,000	608,642	584,814
	In from atmosphere	67,872	145,653	3,133	11,403	9,544	47,521	65,798
	Out through water	370,932	1,207,728	222,882	1,323,098	47,612	634,450	424,463
	Accumulation	392,682	842,703	18,129	65,974	55,218	274,941	803,029
P	In through water	3,033	10,782	4,600	13,600	400	6,483	17,173
	In from atmosphere	2,292	4,919	106	385	322	1,605	2,762
	Out through water	3,049	12,792	4,632	13,660	418	6,910	7,974
	Accumulation	6,523	13,999	301	1,096	917	4,567	97,090
Ag	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	257	551	12	43	36	180	5
Al	In through water							184,033
	In from atmosphere	3	7	0.2	1	0.5	2	2
	Out through water							100,165
	Accumulation	89,593	192,269	4,136	15,052	12,598	62,730	1,416,810
As	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	48	103	2	8	7	33	210
B	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	566	1,214	26	95	80	396	38
Ba	In through water	8,018	21,812	8,304	23,446	811	12,478	13,420
	In from atmosphere							
	Out through water	5,723	21,665	7,887	23,440	566	11,856	13,420

Element	Flux (g year⁻¹)	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
	Accumulation	1,530	3,283	71	257	215	1,071	8,665
Be	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	5	11	0	1	1	4	404
Br	In through water							
	In from atmosphere	263	565	12	44	37	184	8,558
	Out through water							
	Accumulation	378	810	17	63	53	264	1,050
Ca	In through water	19,091,100	51,932,521	19,773,000	64,935,000	1,932,000	31,532,724	3,940,331
	In from atmosphere	31,617	67,850	1,460	5,312	4,374	22,123	43,077
	Out through water	13,626,689	51,583,198	18,779,658	55,809,089	1,346,436	28,229,014	3,940,331
	Accumulation	883,901	1,896,868	40,807	148,503	124,292	618,874	439,516
Cd	In through water	0.4	10	1	12	0.3	5	26
	In from atmosphere							
	Out through water	0.4	11	1	12	0.3	5	14
	Accumulation	8	17	0	1	1	6	153
Ce	In through water	7	23	8	29	1	13	587
	In from atmosphere							
	Out through water	7	27	8	29	1	14	319
	Accumulation	639	1,372	30	107	90	448	12,274
Cl	In through water	1,629,657	22,201,954	6,289,000	89,588,000	1,494,000	24,240,522	3,484,357
	In from atmosphere	96,958	208,074	4,476	16,290	13,634	67,887	76,514
	Out through water	1,629,812	85,752,495	6,288,777	89,859,150	1,493,967	37,004,840	3,484,357
	Accumulation	10,661	22,879	492	1,791	1,499	7,465	38,741
Co	In through water	15	51	17	66	2	30	316
	In from atmosphere							
	Out through water	15	60	17	66	2	32	172
	Accumulation	35	74	2	6	5	24	977
Cr	In through water	126	437	148	563	19	259	473
	In from atmosphere							
	Out through water	126	517	148	567	19	275	219
	Accumulation	188	403	9	32	26	131	1,875

Element	Flux (g year⁻¹)	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
Cs	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	10	23	0	2	1	7	103
Cu	In through water	267	727	277	782	27	416	1,329
	In from atmosphere							
	Out through water	191	722	263	781	19	395	724
	Accumulation	363	778	17	61	51	254	3,142
Dy	In through water	6	19	7	25	1	11	152
	In from atmosphere							
	Out through water	6	23	7	25	1	12	152
	Accumulation	50	107	2	8	7	35	573
Er	In through water	4	15	5	19	1	9	100
	In from atmosphere							
	Out through water	4	18	5	19	1	9	100
	Accumulation	33	70	2	5	5	23	345
Eu	In through water	0.1	6	0	7	0.1	3	37
	In from atmosphere							
	Out through water	0.1	7	0	7	0.1	3	37
	Accumulation	7	14	0	1	1	5	182
F	In through water							
	In from atmosphere							7,267
	Out through water							
	Accumulation							
Fe	In through water	37,425	129,257	43,734	166,658	5,725	76,560	588,670
	In from atmosphere	3,404	7,305	157	572	915	2,471	3,871
	Out through water	37,425	153,002	43,734	167,713	5,725	81,520	272,273
	Accumulation	124,233	266,605	5,735	20,872	17,469	86,983	1,431,293
Ga	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	8	18	0	1	1	6	983
Gd	In through water	6	19	7	25	1	11	200

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
	In from atmosphere							
	Out through water	6	23	7	25	1	12	200
	Accumulation	27	59	1	5	4	19	805
Hf	In through water	6	17	7	15	1	9	46
	In from atmosphere							
	Out through water	3	13	6	15	0	7	21
	Accumulation	20	43	1	3	3	14	52
Hg	In through water	1	2	1	2	0	1	1
	In from atmosphere							
	Out through water	1	2	1	2	0	1	1
	Accumulation	1	2	0.04	0.1	0.1	1	7
Ho	In through water	1	5	2	6	0	3	32
	In from atmosphere							
	Out through water	1	6	2	6	0	3	32
	Accumulation	11	24	1	2	2	8	118
I	In through water	2,023	6,987	2,364	9,009	309	4,138	4,537
	In from atmosphere	53	113	2	9	7	37	31
	Out through water	2,023	8,270	2,364	9,066	309	4,406	3,424
	Accumulation	120	258	6	20	17	84	258
K	In through water	712,900	2,189,250	724,000	3,904,000	73,000	1,520,630	429,889
	In from atmosphere	18,443	39,579	851	3,099	2,593	12,913	37,012
	Out through water	712,429	3,723,021	723,876	3,927,248	73,083	1,831,931	429,889
	Accumulation	52,454	112,568	2,422	8,813	7,376	36,727	271,145
La	In through water	25	87	30	113	4	52	1,252
	In from atmosphere							
	Out through water	25	103	30	113	4	55	1,252
	Accumulation	303	651	14	51	43	212	5,875
Li	In through water	712	3,390	724	3,905	73	1,761	
	In from atmosphere	0	0	0	0	0	0	150
	Out through water	712	3,723	724	3,927	73	1,832	
	Accumulation	158	339	7	27	22	111	868
Lu	In through water	0.4	9	1	11	0.3	4	17
	In from atmosphere							
	Out through water	0.4	10	1	11	0.3	5	17

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
	Accumulation	4	9	0	1	1	3	51
Mg	In through water	856,880	3,692,030	1,701,000	8,481,000	148,000	2,975,782	874,785
	In from atmosphere	8,642	18,546	399	1,429	1,215	6,046	13,365
	Out through water	857,290	8,193,406	1,701,163	8,503,909	148,248	3,880,803	874,785
	Accumulation	34,289	73,585	1,583	5,761	4,822	24,008	184,906
Mn	In through water	11,126	38,428	13,002	49,547	1,702	22,761	0
	In from atmosphere	2,467	5,294	114	414	347	1,727	1,444
	Out through water	11,126	45,487	13,002	49,861	1,702	24,236	0
	Accumulation	3,348	7,185	155	563	471	2,344	12,931
Mo	In through water	128	610	130	703	13	317	247
	In from atmosphere							
	Out through water	128	670	130	707	13	330	186
	Accumulation	206	443	10	35	29	145	281
Na	In through water	2,003,152	17,936,737	3,616,000	56,545,000	1,302,000	16,280,578	2,055,802
	In from atmosphere	56,910	122,130	2,627	9,561	8,003	39,846	106,203
	Out through water	2,003,723	54,061,516	3,612,554	57,774,973	1,302,219	23,750,997	2,055,802
	Accumulation	30,611	65,693	1,413	5,143	4,305	21,433	140,082
Nb	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	53	115	2	9	8	37	150
Nd	In through water	6	19	7	25	1	11	1,321
	In from atmosphere							
	Out through water	6	23	7	25	1	12	1,321
	Accumulation	305	655	14	51	43	214	6,338
Ni	In through water	76	494	106	563	10	250	1,525
	In from atmosphere							
	Out through water	76	541	106	565	10	260	830
	Accumulation	186	399	9	31	26	130	2,481
Pb	In through water	9	220	16	259	6	102	
	In from atmosphere							
	Out through water	9	243	16	260	6	107	
	Accumulation	379	814	18	64	53	265	1,721

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
Pr	In through water	26	91	31	117	4	54	329
	In from atmosphere							
	Out through water	26	108	31	118	4	57	329
	Accumulation	107	230	5	18	15	75	
Rb	In through water	620	2,949	630	3,397	64	1,532	850
	In from atmosphere							
	Out through water	620	3,239	630	3,417	64	1,594	850
	Accumulation	436	937	20	73	61	306	1,863
S	In through water	2,553,160	4,390,937	1,316,408	20,860,000	127,981	5,849,697	4,704,939
	In from atmosphere	52,695	113,084	2,433	8,853	7,410	36,895	35,428
	Out through water	944,857	6,686,217	1,316,408	6,991,057	127,981	3,213,304	4,704,939
	Accumulation	115,981	248,898	5,355	194,86	16,309	81,206	1,129,631
Sb	In through water	19	92	20	105	2	48	
	In from atmosphere							
	Out through water	19	101	20	106	2	49	
	Accumulation	7	16	0	1	1	5	30
Sc	In through water	0	0	0	0	0	0	66
	In from atmosphere	0	0	0	0	0	0	0
	Out through water	0	0	0	0	0	0	66
	Accumulation	34	72	2	6	5	23	389
Se	In through water	0	0	0	0	0	0	0
	In from atmosphere	0	0	0	0	0	0	0
	Out through water	0	0	0	0	0	0	0
	Accumulation	15	31	1	2	2	10	50
Si	In through water	1,744,406	4,473,285	1,767,000	5,682,000	190,000	2,771,338	3,561,195
	In from atmosphere	1,581	3,393	73	266	222	1,107	3,352
	Out through water	842,005	3,577,086	1,548,471	3,947,457	87,949	2,000,594	1,938,281
	Accumulation	1,096,733	2,353,608	50,633	184,261	154,220	767,891	9,375,140
Sm	In through water	1	4	1	5	0	2	229
	In from atmosphere							
	Out through water	1	5	1	5	0	3	229
	Accumulation	51	109	2	9	7	36	1,023
Sn	In through water							

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
	In from atmosphere							
	Out through water							
	Accumulation	22	48	1	4	3	16	502
Sr	In through water	23,216	101,478	25,517	138,000	5,702	58,783	19,054
	In from atmosphere	887	1,904	41	149	125	621	519
	Out through water	15,152	100,184	28,481	133,464	3,583	56,173	19,054
	Accumulation	871	1,869	40	146	122	610	3,994
Ta	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	6	14	0	1	1	4	12
Tb	In through water	1	21	2	25	1	10	22
	In from atmosphere							
	Out through water	1	23	2	25	1	10	12
	Accumulation	4	9	0	1	1	3	110
Th	In through water	6	19	7	25	1	11	52
	In from atmosphere	0.001	0.002	0.00004	0.0002	0.0001	0.001	0.001
	Out through water	6	23	7	25	1	12	28
	Accumulation	56	120	3	9	8	39	470
Ti	In through water							8
	In from atmosphere							
	Out through water							4
	Accumulation	7,254	15,567	335	1,219	1,020	5,079	5,073
Tl	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	6	12	0	1	1	4	27
Tm	In through water	0.2	6	0.4	7	0.2	3	14
	In from atmosphere							
	Out through water	0.2	6	0.4	7	0.2	3	14
	Accumulation	4	10	0.2	1	1	3	55
U	In through water	977	2,645	1,012	2,822	99	1,511	281
	In from atmosphere							

Element	Flux (g year^{-1})	Eckarfjärden	Bolundsfjärden	Gällsboträsket	Norra Bassängen	Puttan	Average Forsmark Lake	Frisksjön
	Out through water	687	2,606	959	2,820	68	1,428	130
	Accumulation	474	1,017	22	80	67	332	652
V	In through water	55	191	65	246	8	113	590
	In from atmosphere							
	Out through water	55	226	65	248	8	120	273
	Accumulation	189	406	9	32	27	133	2,086
W	In through water							
	In from atmosphere							
	Out through water							
	Accumulation	31	66	1	5	4	22	1,505
Y	In through water	48	166	56	214	7	98	1,108
	In from atmosphere							
	Out through water	48	196	56	215	7	105	1,108
	Accumulation	176	378	8	30	25	123	4,021
Yb	In through water	5	16	5	20	1	9	103
	In from atmosphere							
	Out through water	5	19	5	21	1	10	103
	Accumulation	24	52	1	4	3	17	339
Zn	In through water	556	1,921	650	2,477	85	1,138	3,996
	In from atmosphere							
	Out through water	556	2,274	650	2,493	85	1,212	2,175
	Accumulation	1,920	4,120	89	323	270	1,344	9,773
Zr	In through water	159	407	161	364	17	222	972
	In from atmosphere	0	0	0	0	0	0	0
	Out through water	77	326	141	359	8	182	451
	Accumulation	363	778	17	61	51	254	3,035

Table A12-3. Values of atmospheric deposition (dry deposition and/or precipitation) used in mass balance models of Forsmark lakes. Data from 1) /Tröjbom and Söderbäck 2006b/, 2) /Phil-Karlsson et al. 2003/, 3) /Tyler and Olsson 2006/, 4) Sicada October 2007.

Element	Precipitation (mm year^{-1})	Deposition (g m^{-2} year^{-1})	Reference	Comment
C	559	1.25775	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
N	559	0.36	2	Precipitation, Site data only includes data from 1 sampling occasion and therefore generic data is used. Station Jädraås
P	559	0.012158	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
U	559	0.000002	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
Th	559	0.000005	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
I	559	0.00028	1	Precipitation, Based on two measurements at the site that both were below the detection limit of 1µg/l. Half the detection limit was assumed to be the deposition, which was in the lower range of the iodine deposition interval reported by /Sheppard et al. 2002/
Al	559	1.76E–05	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Br	559	0.001398	1	Precipitation, Based on 12 measurements at the site that all were below the detection limit of 5µg/l. Half the detection limit was assumed to be the deposition
Ca	559	0.1677	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Cl	559	0.51428	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Fe	559	0.018056	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Mg	559	0.045838	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
K	559	0.097825	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Si	559	0.008385	1	Precipitation, Based on one measurements at the site that was below the detection limit of 30µg/l. Half the detection limit was assumed to be the deposition
Na	559	0.30186	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
S	559	0.2795	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564)
Mn	559	0.013085	4	Precipitation, Based on site investigation in Laxemar-Simpevarp but with precipitation amounts for Forsmark
Sr	559	0.004705	4	Precipitation, Based on site investigation in Laxemar-Simpevarp but with precipitation amounts for Forsmark

Table A12-4. Values of atmospheric deposition (dry deposition and/or precipitation) used in mass balance models of Frisksjön in Laxemar-Simpevarp. Data from 1) /Phil-Karlsson et al. 2008/, 2) /Knape 2001/, 3) /Tyler and Olsson 2006/, 4) /Tröjbom and Söderbäck 2006b/, 5) Sicada October 2007.

Element	Precipitation (mm year^{-1})	Deposition (g m^{-2} year^{-1})	Reference	Comment
C	600	1.88	1	Precipitation, generic data from station Rockneby in Kalmar län mean 2000–20007
N	600	0.64	1	Precipitation, generic data from station Rockneby in Kalmar län mean 2000–20007
P	600	0,027	2	Generic data from Äspö
U	600	0.000002	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
Th	600	0.000005	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
I	600	0.0003	4	Precipitation, Based on two measurements in Forsmark that both were below the detection limit of 1µg/l. Half the detection limit was assumed to be the deposition, which was in the lower range of the interval reported by /Sheppard et al. 2002/. Corrected for precipitation amount in Laxemar-Simpevarp
Al	600	1.89E–05	4	Precipitation, Based on site investigation in Forsmark but with precipitation amounts for Laxemar-Simpevarp
Br	600	0.083246	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=105, Sep 2002–Oct 2007
Ca	600	0.419	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Cl	600	0.744231	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=104, Sep 2002–Oct 2007. 1 outlier was removed from the original dataset
Fe	600	0.037649	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Mg	600	0.13	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
K	600	0.36	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Si	600	0.0326	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Na	600	1.033	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
S	600	0.3446	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Mn	600	0.014045	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=29, Sep 2002–Oct 2007
Sr	600	0.00505	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007
Li	600	0.00146	5	Precipitation, Based on 30 measurements at the site that was below the detection limit, half the detection limit was used in the estimate, Sep 2002–Nov 2017
F	600	0.070686	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007

Appendix 13

Equations in the radionuclide model for the biosphere

In this Appendix the equations included in the Radionuclide Model for the biosphere are presented. Firstly, a model overview is given including the conceptual model, the differential equations and the transfer rate coefficients; secondly a report generated by the software tool Ecolego is presented including all the detailed equations used in the model.

Model overview

The Radionuclide Model for the biosphere is a compartment model consisting of a System of 10 Ordinary Differential Equations (ODEs). Each ODE represents the rate of change of the radionuclide inventory (Bq) in a model compartment, as a function of the radionuclide fluxes (Bq/y) from and to this compartment, and of radioactive decay and in-growth of progeny. The ODE of a compartment (*k*) has the following general form:

$$\frac{\mathrm{dA_k^j}}{\mathrm{dt}} = \mathrm{F^j_{out\ to\ k}} - \mathrm{F^j_{k\ to\ out}} + \sum\nolimits_\mathrm{i} \mathrm{F^j_{i\ to\ k}} - \sum\nolimits_\mathrm{i} \mathrm{F^j_{k\ to\ i}} - \lambda^\mathrm{j} \cdot \mathrm{A^j_k} + \mathrm{ingrowth^j}$$

$$\mathrm{F^j_{k\ to\ out}} = TC^j_{k\ to\ out} \cdot \mathrm{A^j_k}$$

$$\mathrm{F^j_{i\ to\ k}} = TC^j_{i\ to\ k} \cdot \mathrm{A^j_i}$$

$$\mathrm{F^j_{k\ to\ i}} = TC^j_{k\ to\ i} \cdot \mathrm{A^j_k}$$

where,

A^j_k is in inventory of the *j-th* radionuclide in compartment k (Bq).

λ^j is the decay constant for the *j-th* radionuclide (year^{-1}).

Ingrowth ^{j} is the in-growth of the *j-th* radionuclide from decay of the parents (Bq·year^{-1}).

$\mathrm{F^j_{out\ to\ k}}$ is the inflow of the *j-th* radionuclide from outside the system to *k-th* compartment (Bq·year^{-1}).

$\mathrm{F_{k\ to\ out}}$ is the outflow of the *j-th* radionuclide from *k-th* compartment out from the system (Bq·year^{-1}).

$\mathrm{F^j_{i\ to\ k}}$ is the flux of the *j-th* radionuclide from *i-th* to *k-th* compartment (Bq·year^{-1}).

$\mathrm{F^j_{k\ to\ i}}$is the flux of the *j-th* radionuclide from *k-th* to *i-th* compartment (Bq·year^{-1}).

$\mathrm{TC^j_{k\ to\ out}}$ is the transfer rate coefficient of the *j-th* radionuclide from *k-th* compartment out from the system (year^{-1}).

$\mathrm{TC^j_{k\ to\ i}}$ is the transfer rate coefficient of the *j-th* radionuclide from *k-th* to *i-th* compartment (year^{-1}).

$\mathrm{TC^j_{i\ to\ k}}$ is the transfer rate coefficient rate of the *j-th* radionuclide from *i-th* to *k-th* compartment (year^{-1}).

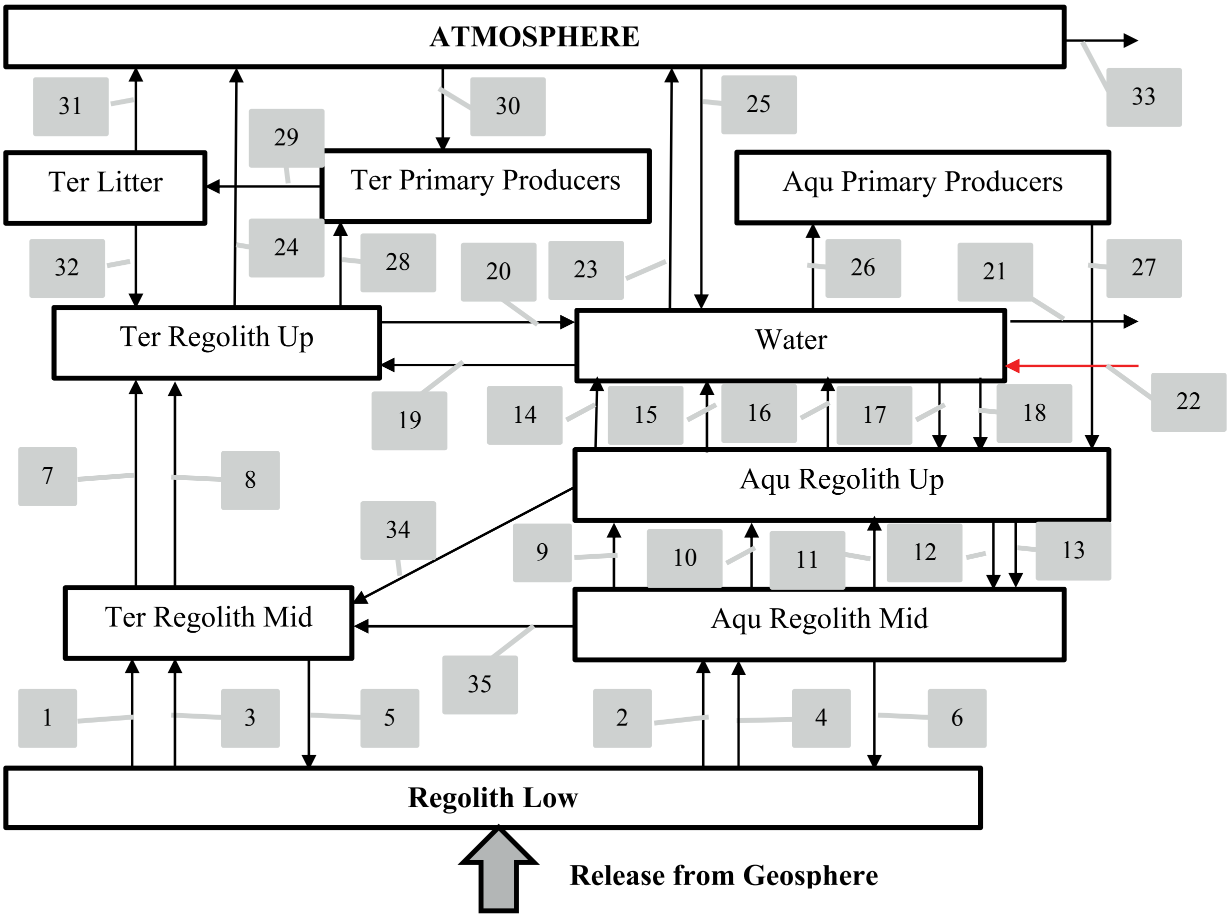


Figure A-1. *Conceptual representation of the Radionuclide Model for the biosphere. The boxes represent model compartments and the black arrows represent radionuclide fluxes calculated with Transfer Rate Coefficients. The red arrow represents inflows with surface waters from adjacent biosphere objects.*

Transfer rate coefficients (TC)

The transfer rate coefficients, *TC*, represent the fraction of the inventory in one compartment that is transferred to other compartments and out from the biosphere object. The different fluxes included in the model are represented with arrows in Figure A-1.

The parameters used in the equations of *TCs* are listed in Appendix B and are shown below in **bold**.

Regolith_Low to Ter_Regolith_ Mid and Aqu_ Regolith_ Mid

1 The equation for the *TC* of the *j-th* radionuclide from Regolith_Low to Ter_Regolith_Mid by advection (arrow 1 in Figure A-1) is:

$$TC^j = adv\_low\_mid \cdot \frac{fract\_Mire}{z\_regoLow \cdot \boldsymbol{poro\_regoLow} \cdot R^j\_regoLow}$$

where,

adv_low_mid (m/y) equals ***Sea_adv_low_mid*** for time < ***threshold_start***

adv_low_mid (m/y) equals ***Lake_adv_low_mid*** for time > ***threshold_stop***

adv_low_mid (m/y) is calculated with a linear equation going from ***Sea_adv_low_mid*** to ***Lake_adv_low_mid*** for times between ***threshold_start*** and ***threshold_stop***

fract_Mire (unitless) equals zero for time < ***threshold_start***

fract_Mire (unitless) equals ***Lake_fract_Mire*** for time > ***threshold_stop***

fract_Mire (unitless) is calculated with a linear equation going from zero to ***Lake_fract_Mire*** for times between ***threshold_start*** and ***threshold_stop***

z_regoLow (m) equals ***Sea_z_regoLow*** for time < ***threshold_start***

z_regoLow (m) equals ***Lake_z_regoLow*** for time > ***threshold_stop***

z_regoLow (m) is calculated with a linear equation going from ***Sea_z_regoLow*** to ***Lake_z_regoLow*** for times between ***threshold_start*** and ***threshold_stop***

R^j*_regoLow* (unitless) is the retardation factor for the *j-th* radionuclide in the *Regolith_Low* compartment

$$R^j\_regoLow = 1.0 + \boldsymbol{kD\_regoLow^j} \cdot \frac{\boldsymbol{dens\_regoLow}}{\boldsymbol{poro\_regoLow}}$$

2 The equation for the *TC* of the *j-th* radionuclide from Regolith_Low to Aqu_Regolith_Mid by advection (arrow 2 in Figure A-1) is:

$$TC^j = adv\_low\_mid \cdot \frac{1 - fract\_Mire}{z\_regoLow \cdot \boldsymbol{poro\_regoLow} \cdot R^j\_regoLow}$$

3 The equation for the *TC* of the *j-th* radionuclide from Regolith_Low to Ter_Regolith_Mid by diffusion (arrow 3 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{z\_regoLow^2 \cdot R^j\_regoLow} \cdot \frac{\boldsymbol{Ter\_area\_obj}}{\boldsymbol{Ter\_area\_obj} + \boldsymbol{Aqu\_area\_obj}}$$

4 The equation for the *TC* of the *j-th* radionuclide from Regolith_Low to Aqu_Regolith_Mid by diffusion (arrow 4 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{z\_regoLow^2 \cdot R^j\_regoLow} \cdot \frac{\boldsymbol{Aqu\_area\_obj}}{\boldsymbol{Ter\_area\_obj} + \boldsymbol{Aqu\_area\_obj}}$$

Ter_Regolith_ Mid and Aqu_ Regolith_ Mid to Regolith_Low

5 The equation for the *TC* of the *j-th* radionuclide from Ter_Regolith_Mid to Regolith_Low by diffusion (arrow 5 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{Ter\_z\_regoMid^2 \cdot R^j\_Ter\_regoMid}$$

where,

Ter_z_regoMid (m) is the sum of ***Ter_z_regoMid_pg*** and ***Aqu_z_regoMid_gl_lake***

R^j_Ter_regoMid (unitless) is the retardation factor for the *j-th* radionuclide in the *Ter_Regolith_Mid* compartment

$$R^j\_Ter\_regoMid = 1.0 + \boldsymbol{Ter\_kD\_regoMid^j} \cdot \frac{Ter\_dens\_regoMid}{Ter\_poro\_regoMid}$$

$$Ter\_dens\_regoMid = \frac{\boldsymbol{Ter\_z\_regoMid\_pg} \cdot \boldsymbol{Ter\_dens\_regoMid\_pg} + \boldsymbol{z\_rego\_Mid\_gl\_basin} \cdot \boldsymbol{Ter\_dens\_regoMid\_gl}}{Ter\_z\_regoMid}$$

$$Ter\_poro\_regoMid = \frac{\boldsymbol{Ter\_z\_regoMid\_pg} \cdot \boldsymbol{Ter\_poro\_regoMid\_pg} + \boldsymbol{z\_rego\_Mid\_gl\_basin} \cdot \boldsymbol{Ter\_poro\_regoMid\_gl}}{Ter\_z\_regoMid}$$

6 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Mid to Regolith_Low by diffusion (arrow 6 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{Aqu\_z\_regoMid^2 \cdot R^j\_Aqu\_regoMid}$$

where,

Aqu_z_regoMid (m) is the sum of ***Agu_z_regoMid_pg*** and *Aqu_z_regoMid_gl*

Aqu_z_regoMid_gl (m) equals ***z_regoMid_gl_basin*** for time < ***threshold_start***

Aqu_z_regoMid_gl (m) equals ***Aqu_z_regoMid_gl_lake*** for time > ***threshold_stop***

*Aqu_z_regoMid*_gl (m) is calculated with a linear equation going from ***z_regoMid_gl_basin*** to ***Aqu_z_regoMid_gl_lake*** for times between ***threshold_start*** and ***threshold_stop***

R^j *_Aqu_regoMid* (unitless) is the retardation factor for the *j-th* radionuclide in the *Ter_Regolith_Mid* compartment

$$R^j\_Aqu\_regoMid = 1.0 + Aqu\_kD\_regoMid^j \cdot \frac{Aqu\_dens\_regoMid}{Aqu\_poro\_regoMid}$$

where,

Aqu_kD_regoMid ^{j} (m^3/kg dw) equals ***Sea_kD_regoMid*** for time < ***threshold_start***

Aqu_kD_regoMid ^{j} (m^3/kg dw) equals ***Lake_kD_regoMid*** for time > ***threshold_stop***

Aqu_kD_regoMid ^{j} (m^3/kg dw) is calculated with a linear equation going from ***Sea_kD_regoMid*** to ***Lake_kD_regoMid*** for times between ***threshold_start*** and ***threshold_stop***

$$Aqu\_dens\_regoMid = \frac{\boldsymbol{Aqu\_z\_regoMid\_pg} \cdot \boldsymbol{Aqu\_dens\_regoMid\_pg} + Aqu\_z\_rego\_Mid\_gl \cdot \boldsymbol{Aqu\_dens\_regoMid\_gl}}{Aqu\_z\_regoMid}$$

$$Aqu\_poro\_regoMid = \frac{\boldsymbol{Aqu\_z\_regoMid\_pg} \cdot \boldsymbol{Aqu\_poro\_regoMid\_pg} + Aqu\_z\_rego\_Mid\_gl \cdot \boldsymbol{Aqu\_poro\_regoMid\_gl}}{Aqu\_z\_regoMid}$$

Ter_Regolith_Mid to Ter_Regolith_Up

7 The equation for the *TC* of the *j-th* radionuclide from Ter_Regolith_Mid to Ter_Regolith_Up by advection (arrow 7 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff} \cdot \boldsymbol{Ter\_adv\_mid\_up\_norm}}{\boldsymbol{Ter\_area\_obj} \cdot Ter\_z\_regoMid \cdot Ter\_poro\_regoMid \cdot R^j\_Ter\_regoMid}$$

8 The equation for the *TC* of the *j-th* radionuclide from Ter_Regolith_Mid to Ter_Regolith_Up by diffusion (arrow 8 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{Ter\_z\_regoMid^2 \cdot R^j\_Ter\_regoMid}$$

Aqu_Regolith_Mid to Aqu_Regolith_Up

9 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Mid to Aqu_Regolith_Up by advection (arrow 9 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff} \cdot Aqu\_adv\_mid\_up\_norm}{\boldsymbol{Aqu\_area\_object} \cdot Aqu\_z\_regoMid \cdot Aqu\_poro\_regoMid. R^j\_Aqu\_regoMid}$$

$$+\frac{adv\_low\_mid \cdot (1 - fract\_Mire) \cdot (\boldsymbol{Ter\_area\_object} + \boldsymbol{Aqu\_area\_object})}{\boldsymbol{Aqu\_area\_object} \cdot Aqu\_z\_regoMid \cdot Aqu\_poro\_regoMid \cdot R^j\_Aqu\_regoMid}$$

where,

Aqu_adv_mid_up_norm (unitless) equals zero for time < ***threshold_start***

Aqu_adv_mid_up_norm (unitless) equals ***Lake_Aqu_adv_mid_up_norm*** for time > ***threshold_stop***

Aqu_adv_mid_up_norm (unitless) is calculated with a linear equation going from zero to ***Lake_Aqu_adv_mid_up_norm*** for times between ***threshold_start*** and ***threshold_stop***

10 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Mid to Aqu_Regolith_Up by diffusion (arrow 10 in Figure A-1) is:

$$TC^j = 2.0 \cdot \frac{\boldsymbol{diffcoef^j}}{Aqu\_z\_regoMid^2 \cdot R^j\_Aqu\_regoMid}$$

11 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Mid to Aqu_Regolith_Up by erosion of sediments (arrow 11 in Figure A-1) is:

$$TC^j = -\frac{\boldsymbol{growth\_rego}}{Aqu\_z\_regoMid}$$

If ***growth_rego*** *is negative and zero otherwise*

Aqu_Regolith_Up to Aqu_Regolith_Mid

12 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Up to Aqu_Regolith_Mid by advection (arrow 12 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff} \cdot Aqu\_adv\_mid\_up\_norm}{\boldsymbol{Aqu\_area\_object} \cdot Aqu\_z\_regoUp \cdot \boldsymbol{Aqu\_poro\_regoUp} \cdot R^j\_Aqu\_regoUp}$$

where,

Aqu_z_regoUp (m) equals ***Sea_z_regoUp*** for time < ***threshold_start***

Aqu_z_regoUp (m) equals ***Lake_z_regoUp*** for time > ***threshold_stop***

Aqu_z_regoUp (m) is calculated with a linear equation going from ***Sea_z_regoUp*** to ***Lake_z_regoUp*** for times between ***threshold_start*** and ***threshold_stop***

$R^j\_Aqu\_regoUp$ (unitless) is the is the retardation factor for the *j-th* radionuclide in the *Aqu_Regolith_Up* compartment

$$R^j\_Aqu\_regoUp = 1.0 + Aqu\_kD\_regoUp^j \cdot \frac{\boldsymbol{Aqu\_dens\_regoUp}}{\boldsymbol{Aqu\_poro\_regoUp}}$$

where,

$\mathit{Aqu\_kD\_regoUp}^{j}$ (m^3/kg dw) equals ***Sea_kD_regoUp*** for time < ***threshold_start***

$\mathit{Aqu\_kD\_regoUp}^{j}$ (m^3/kg dw) equals ***Lake_kD_regoUp*** for time > ***threshold_stop***

$\mathit{Aqu\_kD\_regoUp}^{j}$ (m^3/kg dw) is calculated with a linear equation going from ***Sea_kD_regoUp*** to ***Lake_kD_regoUp*** for times between ***threshold_start*** and ***threshold_stop***

13 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Up to Aqu_Regolith_Mid by sedimentation (arrow 13 in Figure A-1) is:

$$TC^{j} = \frac{\boldsymbol{growth\_rego}}{Aqu\_z\_regoMid}$$

If ***growth_rego*** *is positive and zero otherwise*

Aqu_Regolith_Up to Water

14 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Up to Water by advection (arrow 14 in Figure A-1) is:

$$TC^{j} = \frac{\boldsymbol{area\_subcatch}\cdot\boldsymbol{runoff}\cdot Aqu\_adv\_mid\_up\_norm}{\boldsymbol{Aqu\_area\_object}\cdot Aqu\_z\_regoUp\cdot\boldsymbol{Aqu\_poro\_regoUp}\cdot R^{j}\_Aqu\_regoUp}$$

$$+\frac{adv\_low\_mid\cdot(1-fract\_Mire)\cdot(\boldsymbol{Ter\_area\_object}+\boldsymbol{Aqu\_area\_object})}{\boldsymbol{Aqu\_area\_object}\cdot Aqu\_z\_regoUp\cdot\boldsymbol{Aqu\_poro\_regoUp}\cdot R^{j}\_Aqu\_regoUp}$$

15 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Up to Water by diffusion (arrow 15 in Figure A-1) is:

$$TC^{j} = 2.0\cdot\frac{\boldsymbol{diffcoef^{j}}}{Aqu\_z\_regoUp^{2}\cdot R^{j}\_Aqu\_regoUp}$$

16 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Up to Water by resuspension (arrow 16 in Figure A-1) is:

$$TC^{j} = \boldsymbol{res\_rate}\cdot\frac{Aqu\_kD\_regoUp}{Aqu\_z\_regoUp\cdot\boldsymbol{Aqu\_poro\_regoUp}\cdot R^{j}\_Aqu\_regoUp}$$

Water to Aqu_Regolith_Up

17 The equation for the *TC* of the *j-th* radionuclide from Water to Aqu_Regolith_Up by advection (arrow 17 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff} \cdot Aqu\_adv\_mid\_up\_norm}{\boldsymbol{Aqu\_area\_object} \cdot \boldsymbol{depth\_aver} \cdot R^j\_Water}$$

where,

R^j_Water (unitless) is the is the retardation factor for the *j-th* radionuclide in the *WATER compartment*

$$R^j_{Water} = 1.0 + kD\_PM^j \cdot Aqu\_conc\_PM^j$$

where,

kD_PM^j (m^3/kg dw) equals ***Sea_kD_PM*** for time < ***threshold_start***

kD_PM^j (m^3/kg dw) equals ***Lake_kD_PM*** for time > ***threshold_stop***

kD_PM^j (m^3/kg dw) is calculated with a linear equation going from ***Sea_kD_PM*** to ***Lake_kD_PM*** for times between ***threshold_start*** and ***threshold_stop***

$Aqu\_conc\_PM^j$ (kg dw /m^3) equals ***Sea_conc_PM*** for time < ***threshold_start***

$Aqu\_conc\_PM^j$ (kg dw /m^3) equals ***Lake_conc_PM*** for time > ***threshold_stop***

$Aqu\_conc\_PM^j$ (kg dw /m^3) is calculated with a linear equation going from ***Sea_conc_PM*** to ***Lake_conc_PM*** for times between ***threshold_start*** and ***threshold_stop***

18 The equation for the *TC* of the *j-th* radionuclide from Water to Aqu_Regolith_Up by sedimentation (arrow 18 in Figure A-1) is:

$$TC^j = \boldsymbol{sed\_rate} \cdot \frac{kD\_PM^j}{\boldsymbol{depth\_aver} \,.\, R^j\_Water}$$

Water to Ter_Regolith_Up

19 The equation for the *TC* of the *j-th* radionuclide from Water to Ter_Regolith_Up by advection (arrow 19 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{Flooding\_coef} \cdot \boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff}}{\boldsymbol{depth\_aver} \cdot \boldsymbol{Aqu\_area\_obj}}$$

Ter_Regolith_Up to Water

20 The equation for the *TC* of the *j-th* radionuclide from Ter_Regolith_Up to Water by advection (arrow 20 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff} + \boldsymbol{Flooding\_coef} \cdot \boldsymbol{area\_subcatch} \cdot \boldsymbol{runoff}}{\boldsymbol{Ter\_area\_obj} \cdot \boldsymbol{Ter\_poro\_regoUp} \cdot \boldsymbol{Ter\_z\_regoUp} \cdot R^j\_Ter\_regoUp}$$

where,

$R^j\_Ter\_regoUp$ (unitless) is the is the retardation factor for the *j-th* radionuclide in the *Ter_Regolith_Up* compartment

$$R^j\_Ter\_regoUp = 1.0 + \boldsymbol{Ter\_kD\_regoUp^j} \cdot \frac{\boldsymbol{Ter\_dens\_regoUp}}{\boldsymbol{Ter\_poro\_regoUp}}$$

Water to downstream biosphere objects

21 The equation for the *TC* of the *j-th* radionuclide from Water to downstream biosphere objects by advection (arrow 21 in Figure A-1) is:

For time < ***threshold_start***

$$TC^j = \frac{1.0}{\boldsymbol{wat\_ret}}$$

For time ≥ ***threshold_start***

$$TC^j = \frac{\boldsymbol{area\_wshed} \cdot \boldsymbol{runoff}}{\boldsymbol{depth\_aver} \cdot \boldsymbol{Aqu\_area\_obj}}$$

Backflux to Water during Sea stage

22 The equation for the *back flux* of the *j-th* radionuclide to the WATER compartment from a connected Sea object *X* (arrow 22 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{depth\_aver} \cdot \boldsymbol{Aqu\_area\_object}}{\boldsymbol{depth\_aver\_X} \cdot \boldsymbol{Aqu\_aver\_X} \cdot \boldsymbol{wat\_ret}}$$

This *TC* is multiplied by the radionuclide inventory in the WATER compartment of the Sea object *X* to obtain the flux to the WATER compartment of the biosphere object of interest.

Water to Atmosphere

23 The equation for the *TC* of C-14 from Water to Atmosphere by gas exchange (arrow 23 in Figure A-1) is:

$$TC = \frac{\boldsymbol{Aqu\_degass\_C}}{Aqu\_conc\_DIC \cdot \boldsymbol{depth\_aver}}$$

where,

Aqu_conc_DIC (kgC/m^3) equals ***Sea_conc_DIC*** for time < ***threshold_start***

Aqu_conc_DIC (kgC/m^3)) equals ***Lake_conc_DIC*** for time > ***threshold_stop***

Aqu_conc_DIC (kgC/m^3) is calculated with a linear equation going from ***Sea_conc_DIC*** to ***Lake_conc_DIC*** for times between ***threshold_start*** and ***threshold_stop***

Ter Regolith Up to Atmosphere

24 The equation for the *TC* of C-14 from Ter_Regolith_Up to Atmosphere by gas exchange (arrow 24 in Figure A-1) is:

$$TC = \frac{\boldsymbol{Ter\_degass\_C}}{\boldsymbol{Ter\_z\_regoUp \cdot Ter\_conc\_C\_regoUp}}$$

Atmosphere to Water

25 The equation for the *TC* of C-14 from Atmosphere to Water by gas exchange (arrow 25 in Figure A-1) is:

$$TC = \frac{\boldsymbol{gasUptake\_C}}{\boldsymbol{conc\_C\_atmos \cdot Ter\_z\_mixlay}}$$

Water to Aqu_Primary_Producers

26 The equation for the *TC* of the *j-th* radionuclide (except C-14) from Water to Aqu_Primary_Producers (arrow 26 in Figure A-1) is:

$$TC = \frac{\begin{array}{c}\boldsymbol{Aqu\_prod\_pp\_plank} \cdot \boldsymbol{Aqu\_biom\_pp\_plank} \cdot cR\_pp\_plank^{j} + \boldsymbol{Aqu\_prod\_pp\_ubent} \cdot \boldsymbol{Aqu\_biom\_pp\_ubent} \cdot cR\_pp\_ubent \\ + \boldsymbol{Aqu\_prod\_pp\_macro} \cdot \boldsymbol{Aqu\_biom\_pp\_macro} \cdot cR\_pp\_macro\end{array}}{\boldsymbol{depth\_aver} \,.\, R^{j}\_Water}$$

where,

$cR\_pp\_plank^{j}$ (m^3/kgC) equals ***Sea_cR_pp_plank*** for time < ***threshold_start***

$cR\_pp\_plank^{j}$ (m^3/kgC) equals ***Lake_ cR_pp_plank*** for time > ***threshold_stop***

$cR\_pp\_plank^{j}$ (m^3/kgC) is calculated with a linear equation going from ***Sea_cR_pp_plank*** to ***Lake_ cR_pp_plank*** for times between ***threshold_start*** and ***threshold_stop***

$cR\_pp\_ubent^{j}$ (m^3/kgC) equals ***Sea_cR_pp_ubent*** for time < ***threshold_start***

$cR\_pp\_ubent^{j}$ (m^3/kgC) equals ***Lake_ cR_pp_ubent*** for time > ***threshold_stop***

$cR\_pp\_ubent^{j}$ (m^3/kgC) is calculated with a linear equation going from ***Sea_cR_pp_ubent*** to ***Lake_ cR_pp_ubent*** for times between ***threshold_start*** and ***threshold_stop***

$cR\_pp\_macro^{j}$ (m^3/kgC) equals ***Sea_cR_pp_macro*** for time < ***threshold_start***

$cR\_pp\_macro^{j}$ (m^3/kgC) equals ***Lake_ cR_pp_macro*** for time > ***threshold_stop***

$cR\_pp\_macro^{j}$ (m^3/kgC) is calculated with a linear equation going from ***Sea_cR_pp_macro*** to ***Lake_ cR_pp_macro*** for times between ***threshold_start*** and ***threshold_stop***

26 The equation for the *TC* of C-14 from Water to Aqu_Primary_Producers (arrow 26 in Figure A-1) is:

$$TC = \frac{\begin{gathered}\boldsymbol{Aqu\_prod\_pp\_plank \cdot Aqu\_biom\_pp\_plank + Aqu\_prod\_pp\_ubent \cdot Aqu\_biom\_pp\_ubent}\\ \boldsymbol{+Aqu\_prod\_pp\_macro \cdot Aqu\_biom\_pp\_macro}\end{gathered}}{\boldsymbol{depth\_aver}\ \cdot Aqu\_conc\_DIC\ \cdot R\_Water}$$

where,

Aqu_conc_DIC (kgC/ m^3) equals ***Sea_conc_DIC*** for time < ***threshold_start***

Aqu_conc_DIC (kgC/ m^3) equals ***Lake_conc_DIC*** for time > ***threshold_stop***

Aqu_conc_DIC (kgC/ m^3) is calculated with a linear equation going from ***Sea_conc_DIC*** to ***Lake_ conc_DIC*** for times between ***threshold_start*** and ***threshold_stop***

Aqu_Primary_Producers to Aqu_regolith_Up

27 The equation for the *TC* of the *j-th* radionuclide from Aqu_Primary_Producers to Aqu_Regolith_Up (arrow 27 in Figure A-1) is:

$$TC = \frac{\begin{gathered}\boldsymbol{Aqu\_prod\_pp\_plank \cdot Aqu\_biom\_pp\_plank + Aqu\_prod\_pp\_ubent \cdot Aqu\_biom\_pp\_ubent}\\ \boldsymbol{+Aqu\_prod\_pp\_macro \cdot Aqu\_biom\_pp\_macro}\end{gathered}}{\boldsymbol{Aqu\_biom\_pp\_plank + Aqu\_biom\_pp\_ubent + Aqu\_biom\_pp\_macro}}$$

Ter Regolith_Up to Ter_Primary_Producers

28 The equation for the *TC* of the *j-th* radionuclide (except C-14) from Ter_Regolith Up to Ter_Primary_Producers (arrow 28 in Figure A-1) is:

$$TC^j = \frac{\boldsymbol{Ter\_Biom\_pp \cdot Ter\_prodBiomass\_pp \cdot Ter\_cR\_pp}}{\boldsymbol{Ter\_z\_regoUp \cdot Ter\_dens\_regoUp}}$$

Ter_Primary_Producers to Ter_Litter

29 The equation for the *TC* of the *j-th* radionuclide from Ter_Primary_Producers to Ter_Litter (arrow 29 in Figure A-1) is:

$$TC^j = \boldsymbol{Ter\_prodBiom\_pp}$$

Atmosphere to Ter_Primary_Producers

30 The equation for the *TC* of C-14 from Atmosphere to Ter_Primary_Producers (arrow 30 in Figure A-1) is:

$$TC = \frac{\boldsymbol{Ter\_prodBiom\_pp \cdot Ter\_biom\_pp}}{\boldsymbol{Ter\_z\_mixlay \cdot\ conc\_C\_atmos}}$$

Ter Litter to Atmosphere

31 The equation for the *TC* of C-14 from Ter_Litter to Atmosphere (arrow 31 in Figure A-1) is:

$$TC = \boldsymbol{Ter\_decomp} \cdot \boldsymbol{frac\_C\_atmos}$$

Ter Litter to Ter_Regolith Up

32 The equation for the *TC* of the *j-th* radionuclide (except C-14) from Ter_Litter to Ter_Regolith Up by decomposition (arrow 32 in Figure A-1) is:

$$TC^{j} = \boldsymbol{Ter\_decomp} \cdot \boldsymbol{Ter\_df\_decomp^{j}}$$

32 The equation for the *TC* of C-14 from Ter_Litter to Ter_Regolith Up by decomposition (arrow 32 in Figure A-1) is:

$$TC = \boldsymbol{Ter\_decomp} \cdot (\boldsymbol{1.0} - \boldsymbol{frac\_C\_atmos})$$

Atmosphere out from the biosphere object

33 The equation for the *TC* of C-14 from Atmosphere out from the biosphere object (arrow 33 in Figure A-1) is:

$$TC = \frac{\boldsymbol{vel\_wind}}{log\left(\frac{10.0}{\boldsymbol{Ter\_z\_roughness}}\right)} \cdot \frac{\boldsymbol{Ter\_z\_mixlay}}{\boldsymbol{Ter\_z\_mixlay} - \boldsymbol{Ter\_z\_roughness}} \cdot log\left(\frac{\boldsymbol{Ter\_z\_mixlay}}{\boldsymbol{Ter\_z\_roughness}}\right) - \frac{1}{sqrt\left(\frac{\boldsymbol{Ter\_area\_obj}}{pi}\right)}$$

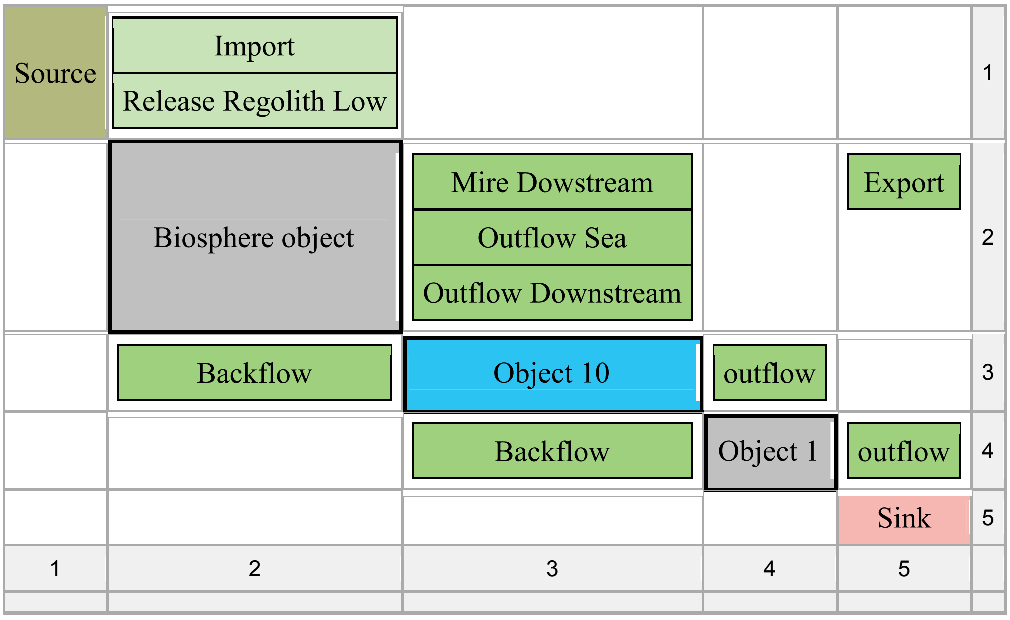
Aqu_Regolith_Mid and Aqu_Regolith_Up to Ter_Regolith Mid

34 35 The equation for the *TC* of the *j-th* radionuclide from Aqu_Regolith_Mid and Aqu_Regolith_Up to Ter_Regolith Mid due to the wetland growth (arrows 34 and 35 in Figure A-1) is:

$$TC^{j} = \boldsymbol{Ter\_growth\_rego}$$

1 Model description generated by Ecolego

1.1 Interaction Matrix



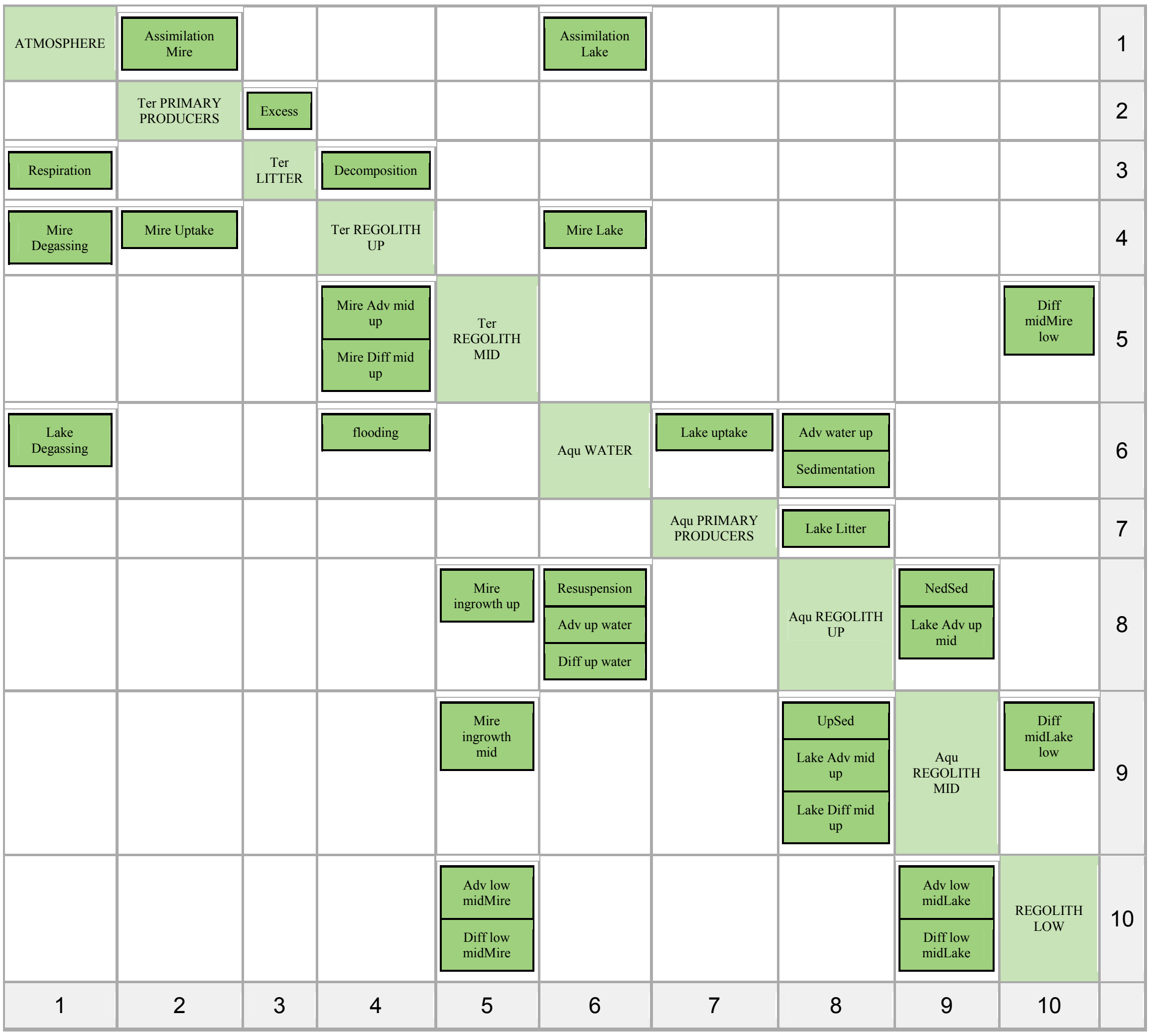
Source	Import Release Regolith Low				1
	Biosphere object	Mire Dowstream Outflow Sea Outflow Downstream		Export	2
	Backflow	Object 10	outflow		3
		Backflow	Object 1	outflow	4
				Sink	5
1	2	3	4	5	

Import	Transfer
Equation	**Unit**
Import from upstream object.	Bq year $^{-1}$

Release_Regolith_Low	Transfer
Equation	**Unit**
Release of radionuclides from the bedrock.	Bq year $^{-1}$

1.2 Biosphere object

Interaction Matrix



ATMOSPHERE	Assimilation Mire				Assimilation Lake					1
	Ter PRIMARY PRODUCERS	Excess								2
Respiration		Ter LITTER	Decomposition							3
Mire Degassing	Mire Uptake		Ter REGOLITH UP		Mire Lake					4
			Mire Adv mid up Mire Diff mid up	Ter REGOLITH MID					Diff midMire low	5
Lake Degassing			flooding		Aqu WATER	Lake uptake	Adv water up Sedimentation			6
						Aqu PRIMARY PRODUCERS	Lake Litter			7
				Mire ingrowth up	Resuspension Adv up water Diff up water		Aqu REGOLITH UP	NedSed Lake Adv up mid		8
				Mire ingrowth mid			UpSed Lake Adv mid up Lake Diff mid up	Aqu REGOLITH MID	Diff midLake low	9
				Adv low midMire Diff low midMire				Adv low midLake Diff low midLake	REGOLITH LOW	10
1	2	3	4	5	6	7	8	9	10	

ATMOSPHERE

Compartment

The lower part of the atmosphere (the troposphere) where released radionuclides are fully mixed (only relevant for C-14).

Differential equation	**Unit**
d ATMOSPHERE /dt = -λ · ATMOSPHERE + Ter_LITTER · Respiration + Ter_REGOLITH_UP · Mire_Degassing + Aqu_WATER · Lake_Degassing - ATMOSPHERE · Assimilation_Mire - ATMOSPHERE · Export - ATMOSPHERE · Assimilation_Lake + ingrowth	Bq

Assimilation_Lake

Transfer rate coefficient corresponding to the assimilation of radionuclides in the WATER compartment by gas uptake (only relevant for C-14)

Transfer Coefficient

Equation

```
if ( have_water AND switcherC )
    gasUptake_C / ( conc_C_atmos · Ter_z_mixlay )
else
   0.0
end
```

Unit

year $^{-1}$

have_water

True (1) if object has a water part at a time point. False (0) otherwise.

Expression

Equation

```
if ( switcherRiver OR (1.0 - time_GE_threshold_end ))
   1.0
else
   0.0
end
```

Unit

unitless

time_GE_threshold_end

True (1) for times after the time point when ingrowth of wetland stops. False (0) otherwise.

Expression

Equation

```
if (time >= threshold_end )
   1.0
else
   0.0
end
```

Unit

unitless

Assimilation_Mire

Transfer rate coefficient corresponding to the assimilation rate of C-14 by primary producers

Transfer Coefficient

Equation

```
if ( time_GE_threshold_start AND switcherC )
    Ter_prodBiom_pp · Ter_biom_pp / conc_C_atmos / Ter_z_mixlay
else
   0.0
end
```

Unit

year $^{-1}$

time_GE_threshold_start

Expression

True (1) for times after the time point when isolation of the bay starts (the bay will become a lake). False (0) otherwise.

Equation

```
if (time >= threshold_start )
   1.0
else
   0.0
end
```

Unit

unitless

Export

Transfer Coefficient

Transfer rate coefficient corresponding to the export of radionuclides from the biosphere object with lateral wind.

Equation	Unit
vel_wind / log(10.0 / Ter_z_roughness) · (Ter_z_mixlay / (Ter_z_mixlay - Ter_z_roughness) · log(Ter_z_mixlay / Ter_z_roughness) - 1.0) / sqrt(Ter_area_obj / pi)	year $^{-1}$

Lake_Degassing

Transfer Coefficient

Transfer rate coefficient corresponding to the loss of radionuclides from the WATER compartment by degassing (only relevant for C-14)

Equation

```
if ( have_water AND switcherC )
    Aqu_degass_C / ( Aqu_conc_DIC · depth_aver )
else
   0.0
end
```

Unit

year $^{-1}$

Aqu_conc_DIC

Expression

Concentration of Dissolved Inorganic Carbon in lake/river or sea water

Equation	Unit
Lake_conc_DIC + (Sea_conc_DIC - Lake_conc_DIC) · threshold_sea_lake	kg C/m ^{3}

threshold_sea_lake

Expression

1 during the sea period: i.e. before threshold_start
0 during the terrestrial period: i.e. after threshold_stop
linearly decreasing from 1 to 0 for times between threshold_start and threshold_stop

Equation	Unit
	unitless

```
if (time < threshold_start )
   1.0
else
   if ( time_G_threshold_stop )
      0.0
   else
      ( threshold_stop - time) / ( threshold_stop - threshold_start )
   end
end
```

time_G_threshold_stop

Expression

True (1) for times after the time point when the isolation of the bay has ended (the bay will become a lake). False (0) otherwise.

Equation	Unit
	unitless

```
if (time > threshold_stop )
   1.0
else
   0.0
end
```

Mire_Degassing

Transfer Coefficient

Transfer rate coefficient corresponding to the loss of radionuclides from the Ter_regoUp compartment due to degassing (only relevant for C-14)

Equation	Unit
	year^{-1}

```
if ( time_GE_threshold_start AND switcherC )
    Ter_degass_C / ( Ter_z_regoUp · Ter_conc_C_regoUp )
else
   0.0
end
```

Respiration

Transfer rate coefficient corresponding to the loss of radionuclides to the atmosphere from the Litter compartment driven by respiration (only relevant for C-14)

Transfer Coefficient

Equation	Unit
	year^{-1}

```
if ( time_GE_threshold_start AND switcherC )
    Ter_decomp · frac_C_atmos
else
   0.0
end
```

Ter_PRIMARY_PRODUCERS

Terrestrial primary producers.

Compartment

Differential equation	Unit
d Ter_PRIMARY_PRODUCERS /dt = -λ · Ter_PRIMARY_PRODUCERS + ATMOSPHERE · Assimilation_Mire + Ter_REGOLITH_UP · Mire_Uptake - Ter_PRIMARY_PRODUCERS · Excess + ingrowth	Bq

Excess

Transfer rate coefficient from primary producers to the Litter compartment.

Transfer Coefficient

Equation	Unit
Ter_prodBiom_pp	year^{-1}

Mire_Uptake

Transfer rate coefficient corresponding to the root uptake of radionuclides (except for C-14) by primary producers

Transfer Coefficient

Equation	Unit
	year^{-1}

```
if ( switcherC )
   0.0
else
    Ter_biom_pp · Ter_prodBiom_pp · Ter_cR_pp / ( Ter_z_regoUp · Ter_dens_regoUp )
end
```

Ter_LITTER

Compartment

Dead plant material overlying the regolith

Differential equation	Unit
d Ter_LITTER /dt = -λ · Ter_LITTER + Ter_PRIMARY_PRODUCERS · Excess - Ter_LITTER · Decomposition - Ter_LITTER · Respiration + ingrowth	Bq

Decomposition

Transfer Coefficient

Transfer rate coefficient from the litter compartment by decomposition.

Equation	Unit
	year^{-1}

```
if ( switcherC )
    Ter_decomp · (1.0 - frac_C_atmos )
else
    Ter_decomp · Ter_df_decomp
end
```

Ter_REGOLITH_UP

Compartment

The upper part of the terrestrial regolith which has the highest biological activity, like the peat in a wetland, or the plowing depth of in cultivated land.

Differential equation	Unit
d Ter_REGOLITH_UP /dt = -λ · Ter_REGOLITH_UP + Ter_LITTER · Decomposition + Ter_REGOLITH_MID · Mire_Adv_mid_up + Ter_REGOLITH_MID · Mire_Diff_mid_up + Aqu_WATER · flooding - Ter_REGOLITH_UP · Mire_Uptake - Ter_REGOLITH_UP · Mire_Degassing - Ter_REGOLITH_UP · Mire_Lake - Ter_REGOLITH_UP · Mire_Dowstream + ingrowth	Bq

Mire_Adv_mid_up

Transfer Coefficient

Advective transfer rate coefficient between the compartments Ter_regoMid and Ter_regoUp.

Equation	Unit
area_subcatch · runoff · Ter_adv_mid_up_norm / (Ter_area_obj · Ter_z_regoMid · Ter_poro_regoMid · Ter_R_regoMid)	year^{-1}

Ter_R_regoMid

Expression

Retention coefficient of the Ter_regoMid compartment

Equation	Unit
1.0 + Ter_kD_regoMid · Ter_dens_regoMid / Ter_poro_regoMid	unitless

Ter_dens_regoMid

Expression

Density of the Ter_regoMid compartment

Equation	Unit
(Ter_z_regoMid_pg · Ter_dens_regoMid_pg + z_regoMid_gl_basin · Ter_dens_regoMid_gl) / Ter_z_regoMid	kg DW/m ^{3}

Ter_z_regoMid

Expression

Thickness of the Ter_regoMid compartment.

Equation

```
if (( Aqu_z_regoMid_gl_lake + Ter_z_regoMid_pg ) = 0.0)
   1.0
else
    Aqu_z_regoMid_gl_lake + Ter_z_regoMid_pg
end
```

Unit

m

Ter_poro_regoMid

Expression

Porosity of the Ter_regoMid compartment.

Equation	Unit
(Ter_z_regoMid_pg · Ter_poro_regoMid_pg + z_regoMid_gl_basin · Ter_poro_regoMid_gl) / Ter_z_regoMid	m ^{3} /m ^{3}

Mire_Diff_mid_up

Transfer Coefficient

Diffusive transfer rate coefficient between the compartments Ter_regoMid and Ter_regoUp.

Equation

```
if ( time_GE_threshold_start )
   2.0 · diffcoef / ( Ter_z_regoMid ^ 2.0 · Ter_R_regoMid )
else
   0.0
end
```

Unit

year $^{-1}$

Mire_Dowstream

Transfer Coefficient

Transfer rate coefficient corresponding to the downstream transport from the compartment Ter_regoUp by surface runoff.

Equation

```
if ( have_water )
   0.0
else
    area_subcatch · runoff / ( Ter_area_obj · Ter_poro_regoUp · Ter_z_regoUp · Ter_R_regoUp )
end
```

Unit

year $^{-1}$

Ter_R_regoUp

Expression

Retardation factor of the Ter_regoUp compartment

Equation	Unit
1.0 + Ter_kD_regoUp · Ter_dens_regoUp / Ter_poro_regoUp	unitless

Mire_Lake

Transfer Coefficient

Transfer rate coefficient from the Ter_regoUp compartment to the WATER compartment during the lake stage.

Equation

```
if ( have_water AND time_GE_threshold_start )
    area_subcatch · runoff · (1.0 + Flooding_coef ) / ( Ter_area_obj · Ter_poro_regoUp · Ter_z_regoUp · Ter_R_regoUp )
else
   0.0
end
```

Unit

year $^{-1}$

Flooding

Transfer Coefficient

Transfer rate coefficient from the WATER compartment to the Ter_regoUp compartment by flooding.

Equation

```
if ( have_water AND time_GE_threshold_start )
    Flooding_coef · area_subcatch · runoff / ( depth_aver · Aqu_area_obj )
else
   0.0
end
```

Unit

year $^{-1}$

Ter_REGOLITH_MID

Compartment

The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. sediments formed in a former seabed / lake bottom environment.

Differential equation	Unit
d Ter_REGOLITH_MID /dt = -λ · Ter_REGOLITH_MID + REGOLITH_LOW · Adv_low_midMire + REGOLITH_LOW · Diff_low_midMire + Aqu_REGOLITH_MID · Mire_ingrowth_mid + Aqu_REGOLITH_UP · Mire_ingrowth_up - Ter_REGOLITH_MID · Diff_midMire_low - Ter_REGOLITH_MID · Mire_Adv_mid_up - Ter_REGOLITH_MID · Mire_Diff_mid_up + ingrowth	Bq

Adv_low_midMire

Transfer Coefficient

Advective transfer rate coefficient from the regoLow compartment to the Ter_regoMid compartment.

Equation	Unit
Adv_low_mid · fract_Mire / (z_regoLow · poro_regoLow · R_regoLow)	year^{-1}

Adv_low_mid

Expression

Advective velocity in the regoLow compartment.

Equation	Unit
Lake_adv_low_mid + (Sea_adv_low_mid - Lake_adv_low_mid) · threshold_sea_lake	m/year

R_regoLow

Expression

Retardation factor of the regoLow compartment

Equation	Unit
1.0 + kD_regoLow · dens_regoLow / poro_regoLow	unitless

fract_Mire

fraction of the upward water flux from the regolith_low compartment that goes to the terrestrial part of the object

Expression

Equation

```
if ( have_water )
    Lake_fract_Mire · (1.0 - threshold_sea_lake )
else
   1.0
end
```

Unit

unitless

z_regoLow

Thickness of the regoLow compartment.

Expression

Equation	Unit
Lake_z_regoLow + (Sea_z_regoLow - Lake_z_regoLow) · threshold_sea_lake	m

Diff_low_midMire

Diffusive transfer rate coefficient from the regoLow compartment to the Ter_regoMid compartment.

Transfer Coefficient

Equation

```
if ( time_GE_threshold_start )
   2.0 · diffcoef / ( z_regoLow ^ 2.0 · R_regoLow ) · Ter_area_obj / area_obj
else
   0.0
end
```

Unit

$year^{-1}$

area_obj

Total area of the biosphere object.

Expression

Equation

```
if ( time_GE_threshold_start )
    Ter_area_obj + Aqu_area_obj
else
    Aqu_area_obj
end
```

Unit

m^{2}

Diff_midMire_low

Transfer Coefficient

Diffusive transfer rate coefficient from the Ter_regolith_Mid compartment to the regolith_Low compartment.

Equation	Unit
2.0 · diffcoef / (Ter_z_regoMid ^ 2.0 · Ter_R_regoMid)	year $^{-1}$

Mire_ingrowth_mid

Transfer Coefficient

Transfer rate coefficient from the Aqu_regoolith_Mid compartment to the Ter_regoMid compartment by ingrowth of the mire

Equation

```
if ( time_GE_threshold_start )
    Ter_growth_rego
else
   0.0
end
```

Unit

year $^{-1}$

Mire_ingrowth_up

Transfer Coefficient

Transfer rate coefficient from the Aqu_regolith_Up compartment to the Ter_regoMid compartment by ingrowth of the mire

Equation

```
if ( time_GE_threshold_start )
    Ter_growth_rego
else
   0.0
end
```

Unit

year $^{-1}$

Aqu_WATER

Compartment

The surface water (stream, lake, or sea water).

Differential equation	Unit
d Aqu_WATER /dt = -λ • Aqu_WATER + Import + ATMOSPHERE • Assimilation_Lake + Ter_REGOLITH_UP • Mire_Lake + Aqu_REGOLITH_UP • Resuspension + Aqu_REGOLITH_UP • Adv_up_water + Aqu_REGOLITH_UP • Diff_up_water + Aqu_WATER • Backflow - Aqu_WATER • Lake_Degassing - Aqu_WATER • flooding - Aqu_WATER • Adv_water_up - Aqu_WATER • Sedimentation - Aqu_WATER • Lake_uptake - Aqu_WATER • Outflow_Sea - Aqu_WATER • Outflow_Downstream + ingrowth	Bq

Adv_up_water

Transfer Coefficient

Advective transfer rate coefficient from the Agu_regolith_Up compartment to the WATER compartment.

Equation	Unit
area_subcatch • runoff • Aqu_adv_mid_up_norm / (Aqu_area_obj • Aqu_z_regoUp • Aqu_poro_regoUp • Aqu_R_regoUp) + area_obj • Adv_low_mid • (1.0 - fract_Mire) / (Aqu_area_obj • Aqu_z_regoUp • Aqu_poro_regoUp • Aqu_R_regoUp)	year $^{-1}$

Aqu_R_regoUp

Expression

Retardation factor of the Aqu_regolith_Up compartment.

Equation	Unit
1.0 + Aqu_kD_regoUp • Aqu_dens_regoUp / Aqu_poro_regoUp	unitless

Aqu_kD_regoUp

Expression

Kd value of the Aqu_regolith_Up compartment.

Equation	Unit
Lake_kD_regoUp + (Sea_kD_regoUp - Lake_kD_regoUp) • threshold_sea_lake	m ^{3} /kg DW

Aqu_adv_mid_up_norm

Expression

Normalized advective transfer rate coefficient from the Aqu_regolith_Mid compartment to the Aqu_regolith_Up compartment.

Equation	Unit
Lake_Aqu_adv_mid_up_norm • (1.0 - threshold_sea_lake)	unitless

Aqu_z_regoUp

Expression

Thickness of the Aqu_regolith_Up compartment.

Equation	Unit
Lake_z_regoUp + (Sea_z_regoUp - Lake_z_regoUp) • threshold_sea_lake	m

Adv_water_up

Transfer Coefficient

Advective transfer rate coefficient from the Aqu_regolith_Up compartment to the WATER compartment.

Equation	Unit
area_subcatch • runoff • Aqu_adv_mid_up_norm / (Aqu_area_obj • depth_aver • R_water)	year $^{-1}$

R_water

Expression

Retardation factor of the WATER compartment.

Equation	Unit
1.0 + kD_PM • Aqu_conc_PM	unitless

Aqu_conc_PM

Expression

Concentration of suspended particular matter in the WATER compartment.

Equation	Unit
Lake_conc_PM + (Sea_conc_PM - Lake_conc_PM) • threshold_sea_lake	kg DW/m ^{3}

kD_PM

Expression

Kd value for suspended particular matter in the WATER compartment.

Equation	Unit
Lake_kD_PM + (Sea_kD_PM - Lake_kD_PM) • threshold_sea_lake	m ^{3} /kg DW

Diff_up_water

Transfer Coefficient

Diffusive transfer rate coefficient from the Ter_regolith_Up compartment to the WATER compartment.

Equation	Unit
2.0 • diffcoef / (Aqu_z_regoUp ^ 2.0 • Aqu_R_regoUp)	year $^{-1}$

Lake_uptake

Transfer rate coefficient corresponding to the uptake of C-14 by aquatic primary producers.

Transfer Coefficient

Equation	Unit
	year $^{-1}$

```
if ( switcherC )

   ( Aqu_prod_pp_plank • Aqu_biom_pp_plank + Aqu_prod_pp_ubent • Aqu_biom_pp_ubent + Aqu_prod_pp_macro • Aqu_biom_pp_macro ) / ( Aqu_conc_DIC • depth_aver • R_water )

Else

    Aqu_TC_pp / R_water

end
```

Aqu_TC_pp

Transfer rate coefficient corresponding to the uptake of radionuclides (except for C-14) by aquatic primary producers

Expression

Equation	Unit
(Aqu_prod_pp_plank • Aqu_biom_pp_plank • cR_pp_plank + Aqu_prod_pp_ubent • Aqu_biom_pp_ubent • cR_pp_ubent + Aqu_prod_pp_macro • Aqu_biom_pp_macro • cR_pp_macro) / depth_aver	year $^{-1}$

cR_pp_macro

Concentration Ratio for macro algae.

Expression

Equation	Unit
Lake_cR_pp_macro + (Sea_cR_pp_macro - Lake_cR_pp_macro) • threshold_sea_lake	m ^{3} /kg C

cR_pp_plank

Concentration Ratio for plankton.

Expression

Equation	Unit
Lake_cR_pp_plank + (Sea_cR_pp_plank - Lake_cR_pp_plank) • threshold_sea_lake	m ^{3} /kg C

cR_pp_ubent

Concentration Ratio for benthic primary producers.

Expression

Equation	Unit
Lake_cR_pp_ubent + (Sea_cR_pp_ubent - Lake_cR_pp_ubent) • threshold_sea_lake	m^3/kg C

Outflow_Downstream

Transfer rate coefficient corresponding to the transport from the WATER compartment by surface runoff

Transfer Coefficient

Equation	Unit

if (have_water AND time_GE_threshold_start)
area_wshed • runoff / (depth_aver • Aqu_area_obj)
else
0.0
end
	year^{-1}

Outflow_Sea

Transfer rate coefficient corresponding to the transport from the WATER compartment to object 10 during the Sea period.

Transfer Coefficient

Equation	Unit

if (is_sea)
1.0 / wat_ret
else
0.0
end
	year^{-1}

is_sea

True (1) for times before the time point when isolation of the bay starts (the bay will become a lake). False (0) otherwise.

Expression

Equation	Unit

if (time_GE_threshold_start)
0.0
else
1.0
end
	unitless

Resuspension

Transfer rate coefficient from the Aqu_regolith_Up compartment to the WATER compartment by resuspension.

Transfer Coefficient

Equation	Unit
res_rate · Aqu_kD_regoUp / (Aqu_z_regoUp · Aqu_poro_regoUp · Aqu_R_regoUp)	year $^{-1}$

Sedimentation

Transfer rate coefficient from the WATER compartment to the Aqu_regolith_Up compartment by sedimentation.

Transfer Coefficient

Equation	Unit
sed_rate · kD_PM / (depth_aver · R_water)	year $^{-1}$

Aqu_PRIMARY_PRODUCERS

The biotic community in aquatic habitats, comprising both primary producers and consumers

Compartment

Differential equation	Unit
d Aqu_PRIMARY_PRODUCERS /dt = -λ · Aqu_PRIMARY_PRODUCERS + Aqu_WATER · Lake_uptake - Aqu_PRIMARY_PRODUCERS · Lake_Litter + ingrowth	Bq

Lake_Litter

Transfer rate coefficient from the aquatic primary producers to the Aqu_regolith_Up compartment

Transfer Coefficient

Equation	Unit
(Aqu_prod_pp_plank · Aqu_biom_pp_plank + Aqu_prod_pp_ubent · Aqu_biom_pp_ubent + Aqu_prod_pp_macro · Aqu_biom_pp_macro) / Aqu_biom_pp	year $^{-1}$

Aqu_biom_pp

Biomass of aquatic primary producers.

Expression

Equation	Unit
Aqu_biom_pp_macro + Aqu_biom_pp_plank + Aqu_biom_pp_ubent	kg C/m ^{2}

Aqu_REGOLITH_UP

Compartment

The part of the aquatic regolith with highest biological activity, comprising ca 5-10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidizing environment.

Differential equation	Unit
d Aqu_REGOLITH_UP /dt = -λ • Aqu_REGOLITH_UP + Aqu_REGOLITH_MID • UpSed + Aqu_REGOLITH_MID • Lake_Adv_mid_up + Aqu_REGOLITH_MID • Lake_Diff_mid_up + Aqu_PRIMARY_PRODUCERS • Lake_Litter + Aqu_WATER • Adv_water_up + Aqu_WATER • Sedimentation - Aqu_REGOLITH_UP • Mire_ingrowth_up - Aqu_REGOLITH_UP • NedSed - Aqu_REGOLITH_UP • Lake_Adv_up_mid - Aqu_REGOLITH_UP • Resuspension - Aqu_REGOLITH_UP • Adv_up_water - Aqu_REGOLITH_UP • Diff_up_water + ingrowth	Bq

Lake_Adv_mid_up

Transfer Coefficient

Advective transfer rate coefficient from the Aqu_regolith_Up compartment to the Aqu_regolith_Mid compartment.

Equation

```
if ( have_water )

   ( area_subcatch • runoff • Aqu_adv_mid_up_norm + (1.0 - fract_Mire ) • area_obj • Adv_low_mid ) / ( Aqu_area_obj • Aqu_z_regoMid • Aqu_poro_regoMid • Aqu_R_regoMid )
else
   0.0
end
```

Unit

year $^{-1}$

Aqu_R_regoMid

Expression

Retardation factor of the Aqu_regolith_Mid compartment.

Equation	Unit
1.0 + Aqu_kD_regoMid • Aqu_dens_regoMid / Aqu_poro_regoMid	unitless

Aqu_dens_regoMid

Expression

Density of the Aqu_regolith_Mid compartment.

Equation	Unit
(Aqu_z_regoMid_pg • Aqu_dens_regoMid_pg + Aqu_z_regoMid_gl • Aqu_dens_regoMid_gl) / Aqu_z_regoMid	kg DW/m ^{3}

Aqu_z_regoMid

Expression

Thickness of the Aqu_regolith_Mid compartment.

Equation	Unit
Aqu_z_regoMid_pg + Aqu_z_regoMid_gl	m

Aqu_z_regoMid_gl

Expression

Thickness of the glacial clay component of the Aqu_regolith_Mid compartment

Equation	Unit
Aqu_z_regoMid_gl_lake + (z_regoMid_gl_basin - Aqu_z_regoMid_gl_lake) · threshold_sea_lake	m

Aqu_z_regoMid_pg

Expression

Thickness of the post-glacial clay component of the Aqu_regolith_Mid compartment

Equation	Unit
max(Aqu_z_rego_pg - Aqu_z_regoUp , 0.0)	m

Aqu_kD_regoMid

Expression

Kd values of the Aqu_regolith_Mid compartment.

Equation	Unit
Lake_kD_regoMid + (Sea_kD_regoMid - Lake_kD_regoMid) · threshold_sea_lake	m^3/kg DW

Aqu_poro_regoMid

Expression

Porosity of the Aqu_regolith_Mid compartment.

Equation	Unit
(Aqu_z_regoMid_pg · Aqu_poro_regoMid_pg + Aqu_z_regoMid_gl · Aqu_poro_regoMid_gl) / Aqu_z_regoMid	m^3/m^3

Lake_Adv_up_mid

Transfer Coefficient

Advective transfer rate coefficient from the Aqu_regolith_Up compartment to the Aqu_regolith_Mid compartment.

Equation	Unit
area_subcatch · runoff · Aqu_adv_mid_up_norm / (Aqu_area_obj · Aqu_z_regoUp · Aqu_poro_regoUp · Aqu_R_regoUp)	year $^{-1}$

Lake_Diff_mid_up

Transfer Coefficient

Diffusive transfer rate coefficient from the Aqu_regolith_Up compartment to the Aqu_regolith_Mid compartment.

Equation

```
if ( have_water )
   2.0 · diffcoef / ( Aqu_z_regoMid ^ 2.0 · Aqu_R_regoMid )
else
   0.0
end
```

Unit

year $^{-1}$

NedSed

Transfer Coefficient

Transfer rate coefficient from the Aqu_regolith_Up compartment to the Aqu_regolith_Mid compartment due to sediment growth when there is positive net sedimentation.

Equation

```
if ( growth_rego > 0.0)
    growth_rego / Aqu_z_regoUp
else
   0.0
end
```

Unit

year $^{-1}$

UpSed

Transfer Coefficient

Transfer rate coefficient from the Aqu_regolith_Mid compartment to the Aqu_regolith_Up compartment due to reduction of sediment thickness when there is negative net sedimentation.

Equation

```
if ( growth_rego < 0.0 AND have_water )
    - growth_rego / Aqu_z_regoMid
else
   0.0
end
```

Unit

year $^{-1}$

Aqu_REGOLITH_MID

Compartment

The middle part of the regolith in the aquatic part of biosphere objects, usually consisting of glacial and postglacial clay and gyttja.

Differential equation	Unit
d Aqu_REGOLITH_MID /dt = -λ · Aqu_REGOLITH_MID + REGOLITH_LOW · Adv_low_midLake + REGOLITH_LOW · Diff_low_midLake + Aqu_REGOLITH_UP · NedSed + Aqu_REGOLITH_UP · Lake_Adv_up_mid - Aqu_REGOLITH_MID · Mire_ingrowth_mid - Aqu_REGOLITH_MID · Diff_midLake_low - Aqu_REGOLITH_MID · UpSed - Aqu_REGOLITH_MID · Lake_Adv_mid_up - Aqu_REGOLITH_MID · Lake_Diff_mid_up + ingrowth	Bq

Adv_low_midLake

Transfer Coefficient

Advective transfer rate coefficient from the regoLow compartment to the Aqu_regolith_Mid compartment.

Equation **Unit**

```
if ( have_water )
    Adv_low_mid · (1.0 - fract_Mire ) / ( z_regoLow · poro_regoLow · R_regoLow )
else
   0.0
end
```

year $^{-1}$

Diff_low_midLake

Transfer Coefficient

Diffusive transfer rate coefficient from the regoLow compartment t the Aqu_regolith_Mid compartment.

Equation **Unit**

```
if ( have_water )
   2.0 · diffcoef / ( z_regoLow ^ 2.0 · R_regoLow ) · Aqu_area_obj / area_obj
else
   0.0
end
```

year $^{-1}$

Diff_midLake_low

Transfer Coefficient

Diffusive transfer rate coefficient between from the Aqu_regolith_Mid compartment to the regoLow compartment.

Equation **Unit**

```
if ( have_water )
   2.0 · diffcoef / ( Aqu_z_regoMid ^ 2.0 · Aqu_R_regoMid )
else
   0.0
end
```

year $^{-1}$

REGOLITH_LOW Compartment

The lower part of the regolith overlying the bedrock primarily composed of glacial till.

Differential equation	Unit
d REGOLITH_LOW /dt = -λ · REGOLITH_LOW + Release_Regolith_Low + Ter_REGOLITH_MID · Diff_midMire_low + Aqu_REGOLITH_MID · Diff_midLake_low - REGOLITH_LOW · Adv_low_midMire - REGOLITH_LOW · Diff_low_midMire - REGOLITH_LOW · Adv_low_midLake - REGOLITH_LOW · Diff_low_midLake + ingrowth	Bq

1.2.1 Concentration

conc_Aqu_PRIMARY_PRODUCER Expression

Radionuclide concentration in aquatic primary producers.

<table>
<tr><th>Equation</th><th>Unit</th></tr>
<tr><td><pre>
if (have_water)
    Aqu_PRIMARY_PRODUCERS / (Aqu_biom_pp · Aqu_area_obj)
else
   0.0
end
</pre></td><td>Bq/kg C</td></tr>
</table>

conc_ATMOSPHERE Expression

Radionuclide concentration in the ATMOSHERE compartment (only relevant for C-14)

Equation	Unit
ATMOSPHERE / (Ter_z_mixlay · Ter_area_obj) + conc_Ter_REGOLITH_UP · Ter_conc_Dust	Bq/m ^{3}

conc_Ter_PRIMARY_PRODUCER Expression

Radionuclide concentration in the Ter_PRIMARY_PRODUCERS compartment.

Equation	Unit
Ter_PRIMARY_PRODUCERS / (Ter_biom_pp • Ter_area_obj)	Bq/kg C

conc_Ter_REGOLITH_UP

Radionuclide concentration in the Ter_regoUp compartment.

Expression

Equation	Unit
Ter_REGOLITH_UP / (Ter_area_obj • Ter_z_regoUp • Ter_dens_regoUp)	Bq/kg DW

conc_WATER_Aqu

Radionuclide concentration in the WATER compartment.

Expression

Equation — **Unit:** Bq/m^3

```
if ( have_water )
    Aqu_WATER / ( Aqu_area_obj • depth_aver • R_water )
else
   0.0
end
```

time_GE_threshold_agriculture

True (1) for times after the time point when the wetland is 2 m above sea level. False (0) otherwise.

Expression

Equation — **Unit:** unitless

```
if (time >= threshold_agriculture )
   1.0
else
   0.0
end
```

time_GE_threshold_stop

True (1) for times after the time point when the isolation of the bay has concluded. False (0) otherwise.

Expression

Equation — **Unit:** unitless

```
if (time >= threshold_stop )
   1.0
else
   0.0
end
```

conc_SOIL_Agric

Radionuclide concentration in the agricultural soil.

Expression

Equation	Unit

if (time_GE_threshold_agriculture)
conc_SOIL_Agric_IC · conc_SOIL_Agric_exp + conc_SOIL_Agric_irrig · (1.0 - conc_SOIL_Agric_exp) / (lambda + conc_SOIL_Agric_runoffRate)
else
0.0
end
	Bq/kg DW

conc_SOIL_Agric_IC

Initial radionuclide concentration in the agricultural soil.

Expression

Equation	Unit
(Ter_LITTER + Ter_REGOLITH_UP + Agri_z_regoUp / Ter_z_regoMid · Ter_REGOLITH_MID) / (Ter_area_obj · Agri_z_regoUp · Agri_dens_regoUp)	Bq/kg DW

conc_SOIL_Agric_exp

Intermedial equation used in the equation of radionuclide concentration in agricultural soil.

Expression

Equation	Unit
(1.0 - exp(- (lambda + conc_SOIL_Agric_runoffRate) · AverTime)) / ((lambda + conc_SOIL_Agric_runoffRate) · AverTime)	unitless

conc_SOIL_Agric_runoffRate

Transfer rate coefficient corresponding to the transport from the agricultural soil by surface runoff.

Expression

Equation	Unit
runoff / (Agri_z_regoUp · Agri_poro_regoUp · Agri_R_regoUp)	year $^{-1}$

Agri_R_regoUp

Retardation factor of the agricultural soil

Expression

Equation	Unit
1.0 + Ter_kD_regoUp · Agri_dens_regoUp / Agri_poro_regoUp	unitless

Lambda

Decay rate constant.

Expression

Equation	Unit
log(2.0) / halflife	year $^{-1}$

conc_SOIL_Agric_irrig

Radionuclide concentration in agricultural soil resulting from irrigation

Expression

Equation	Unit
vol_irrig · conc_WATER_irrig / (Agri_z_regoUp · Agri_dens_regoUp)	Bq/(kg DW year)

conc_WATER_irrig

Radionuclide concentration in irrigation water.

Expression

Equation	Unit
conc_WATER_Lake	Bq/m ^{3}

conc_WATER_Lake

Radionuclide concentration in the WATER compartment during the lake period.

Expression

Equation	Unit
	Bq/m ^{3}

```
if ( time_GE_threshold_stop )
    conc_WATER_Aqu
else
   0.0
end
```

conc_ATMOSPHERE_Agricultural

Radionuclide concentration in the atmospheric air above the agricultural soil.

Expression

Equation	Unit
conc_SOIL_Agric · Agri_conc_Dust	Bq/m ^{3}

conc_WATER_Well

Expression

Radionuclide concentration in well water.

Equation

```
if ( time_GE_threshold_start )
    release / wellCapac
else
   0.0
end
```

Unit

Bq/m^3

conc_WATER

Expression

Radionuclide concentration in drinking water.

Equation

```
if ( have_water )
   ( conc_WATER_Lake + conc_WATER_Well ) / 2.0
else
   conc_WATER_Well
end
```

Unit

Bq/m^3

conc_SOIL_Mire

Expression

Radionuclide concentration in the Ter_regoUp compartment

Equation

```
if ( time_GE_threshold_start )
    conc_Ter_REGOLITH_UP
else
   0.0
end
```

Unit

Bq/kg DW

conc_crayfish

Expression

Radionuclide concentration in crayfish.

Equation

```
if ( switcherC )
    conc_Aqu_PRIMARY_PRODUCER
else
    conc_WATER_Aqu · cR_crayfish
end
```

Unit

Bq/kg C

cR_crayfish

Expression

Concentration Ratio for limnic crayfish.

Equation	Unit
cR_watToCray_Lake · (1.0 - threshold_sea_lake)	m ^{3} /kg C

conc_fish

Expression

Radionuclide concentration in fish.

Equation	Unit
	Bq/kg C

```
if ( switcherC )
    conc_Aqu_PRIMARY_PRODUCER
else
    conc_WATER_Aqu · cR_fish
end
```

cR_fish

Expression

Concentration Ratio for fish.

Equation	Unit
cR_watToFish_Lake + (cR_watToFish_Sea - cR_watToFish_Lake) · threshold_sea_lake	m ^{3} /kg C

prod_edib_crayfish

Expression

Production of edible crayfish.

Equation	Unit
prod_edib_cray_Lake · (1.0 - threshold_sea_lake)	kg C/(m ^{2} year)

prod_edib_fish

Expression

Production of edible fish.

Equation	Unit
prod_edib_fish_Lake + (prod_edib_fish_Sea - prod_edib_fish_Lake) · threshold_sea_lake	kg C/(m ^{2} year)

conc_Herbiv

Expression

Radionuclide concentration in terrestrial herbivores.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    conc_Diet_Herbiv · cR_foodToHerbiv
end
```

Unit

Bq/kg C

conc_Diet_Herbiv

Expression

Radionuclide concentration in the diet of terrestrial herbivores.

Equation	Unit
frac_mush_Herbiv · conc_mushrooms + (1.0 - frac_mush_Herbiv) · conc_Ter_PRIMARY_PRODUCER	Bq/kg C

conc_mushrooms

Expression

Radionuclide concentration in mushrooms.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    conc_Ter_REGOLITH_UP · cR_soilToMush
end
```

Unit

Bq/kg C

conc_vegetables

Expression

Radionuclide concentration in cultivated vegetables.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    conc_SOIL_Agric · cR_soilToVegetab + conc_WATER_irrig · numb_irrig · leaf_areaIndex · leaf_StoreCapac · coefRetent / prod_edib_vegetab
end
```

Unit

Bq/kg C

conc_meat

Expression

Radionuclide concentration in cow meat.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    ( conc_WATER • ingRate_water_meat + conc_SOIL_Agric • ingRate_soil_Cow + conc_SOIL_Agric • Ter_cR_pp • ingRate_food_meat ) • tC_cowMeat / conc_C_meat
end
```

Unit

Bq/kg C

conc_milk

Expression

Radionuclide concentration in cow milk.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    ( conc_WATER • ingRate_water_milk + conc_SOIL_Agric • ingRate_soil_Cow + conc_SOIL_Agric • Ter_cR_pp • ingRate_food_milk ) • tC_cowMilk / ( densMilk • conc_C_milk )
end
```

Unit

Bq/kg C

conc_roots

Expression

Radionuclide concentration in root crops (tubers).

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    conc_SOIL_Agric · cR_soilToTuber
end
```

Unit

Bq/kg C

conc_cereals

Expression

Radionuclide concentration in cereals.

Equation

```
if ( switcherC )
    conc_Ter_PRIMARY_PRODUCER
else
    conc_SOIL_Agric · cR_soilToCereal
end
```

Unit

Bq/kg C

1.2.2 Dose

LDF

Expression

Landscape Dose Conversion Factor.

Equation	Unit
Dose_ext + Dose_inh + Dose_ing_WATER + Dose_ing_Total	Sv/year

Dose_ext

Expression

Annual effective dose from external irradiation.

Equation

```
if ( time_GE_threshold_agriculture )
   (16.0 / 24.0 · Dose_external_Mire + 8.0 / 24.0 · Dose_external_Agric ) · min(1.0, N )
else
    Dose_external_Mire · min(1.0, N )
end
```

Unit

Sv/year

Dose_external_Agric

Expression

Annual effective dose from external irradiation in agricultural areas.

Equation	Unit
conc_SOIL_Agric · Agri_dens_regoUp · expTime · dosCoef_ext	Sv/year

Dose_external_Mire

Expression

Annual effective dose from external irradiation in wetland areas.

Equation	Unit
conc_SOIL_Mire · Ter_dens_regoUp · expTime · dosCoef_ext	Sv/year

N

Expression

Number of individuals in the most exposed group.

Equation	Unit
Production_Total / ingRate_C	unitless

Dose_inh

Annual effective dose from inhalation.

Expression

Equation	Unit

if (time_GE_threshold_agriculture)
(16.0 / 24.0 · Dose_inh_Mire + 8.0 / 24.0 · Dose_inh_Agric) · min(1.0, N)
else
Dose_inh_Mire · min(1.0, N)
end
	Sv/year

Dose_inh_Agric

Annual effective dose from inhalation in agricultural areas.

Expression

Equation	Unit
conc_ATMOSPHERE_Agricultural · inhalRate · expTime · dosCoef_inhal	Sv/year

Dose_inh_Mire

Annual effective dose from inhalation in wetland areas.

Expression

Equation	Unit
conc_ATMOSPHERE · inhalRate · expTime · dosCoef_inhal	Sv/year

LDF_perm

Landscape Dose Conversion Factors during the permafrost period

Expression

Equation	Unit
Dose_ext_perm + Dose_inh_perm + Dose_ing_WATER_perm + Dose_ing_Total_perm	Sv/year

Dose_ext_perm

Annual effective dose from external irradiation during the permafrost period.

Expression

Equation	Unit
Dose_external_Mire · min(1.0, N_perm)	Sv/year

N_perm

Expression

Number of individuals in the most exposed group during the permafrost period.

Equation	Unit
Production_Total_perm / ingRate_C	unitless

Dose_inh_perm

Expression

Annual effective dose by inhalation during the permafrost period.

Equation	Unit
Dose_inh_Mire · min(1.0, N_perm)	Sv/year

LDF_ter_limnic

Expression

Landscape Dose Conversion Factor for the terrestrial/limnic period.

<table>
<tr><th>Equation</th><th>Unit</th></tr>
<tr><td><pre>
if (time_GE_threshold_agriculture)
    LDF_interglacial
else
   0.0
end
</pre></td><td>Sv/year</td></tr>
</table>

LDF_interglacial

Expression

Landscape Dose Conversion Factor for the interglacial period (base case).

<table>
<tr><th>Equation</th><th>Unit</th></tr>
<tr><td><pre>
if (time <= interglacial_stop)
    LDF
else
   0.0
end
</pre></td><td>Sv/year</td></tr>
</table>

LDF_marine_trans

Expression

Landscape Dose Conversion Factor for the marine/transitional period.

Equation	Unit

if (time_GE_threshold_agriculture)
0.0
else
LDF
end
	Sv/year

LDF_greenhouse

Expression

Landscape Dose Conversion Factor for the greenhouse climate variant.

Equation	Unit

if (time <= greenhouse_stop)
LDF
else
0.0
end
	Sv/year

LDF_permafrost

Expression

Landscape Dose Conversion Factor for the prolonged permafrost variant.

Equation	Unit

if (time <= greenhouse_stop)
LDF_perm
else
0.0
end
	Sv/year

LDF_glacial

Expression

Landscape Dose Conversion Factor for the glacial period.

Equation	Unit

if (time < threshold_start)
LDF
else
0.0
end
	Sv/year

Production_Cereals

Production of cereals in the biosphere object assuming that one fifth of the terrestrial area is used for production of cereals.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_cereal · Ter_area_obj / 5.0
else
   0.0
end
```

Production_Roots

Production of root crops (tubers) in the biosphere object assuming that one fifth of the terrestrial area is used for production of root crops (tubers).

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_tuber · Ter_area_obj / 5.0
else
   0.0
end
```

Production_Vegetables

Production of vegetables in the biosphere object assuming that one fifth of the terrestrial area is used for production of vegetables.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_vegetab · Ter_area_obj / 5.0
else
   0.0
end
```

Production_Milk

Production of milk in the biosphere object assuming that one fifth of the terrestrial area is used for production of fodder.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_milk · prod_fodder · Ter_area_obj / 5.0
else
   0.0
end
```

Production_Game

Production of game in the biosphere object assuming that all terrestrial area is a forest before agriculture is possible and that one fifth of the terrestrial area is forest when agriculture is possible.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_game · Ter_area_obj / 5.0
else
   if ( time_GE_threshold_start )
       prod_edib_game · Ter_area_obj
   else
      0.0
   end
end
```

Production_Meat

Production of meat in the biosphere object assuming that one fifth of the terrestrial area is used for production of fodder.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_meat · prod_fodder · Ter_area_obj / 5.0
else
   0.0
end
```

Production_Mushrooms

Production of mushrooms in the biosphere object assuming that all terrestrial area is a forest before agriculture is possible and that one fifth of the terrestrial area is forest when agriculture is possible.

Expression

Equation	Unit
	kg C/year

```
if ( time_GE_threshold_agriculture )
    prod_edib_mush · Ter_area_obj / 5.0
else
   if ( time_GE_threshold_start )
       prod_edib_mush · Ter_area_obj
   else
      0.0
   end
end
```

Production_Berries

Production of berries in the biosphere object assuming that all terrestrial area is a forest before agriculture is possible and that one fifth of the terrestrial area is forest when agriculture is possible.

Expression

Equation

```
if ( time_GE_threshold_agriculture )
    prod_edib_berry · Ter_area_obj / 5.0
else
   if ( time_GE_threshold_start )
       prod_edib_berry · Ter_area_obj
   else
      0.0
   end
end
```

Production_Fish

Production of fish in the biosphere object in periods when the water depth is sufficient for fish production.

Expression

Equation

```
if ( depth_max >= z_min_prod_edib_fish_Lake )
    prod_edib_fish · Aqu_area_obj
else
   0.0
end
```

Unit

kg C/year

Production_Crayfish

Production of crayfish in the biosphere object in periods when the water depth is sufficient for crayfish production.

Expression

Equation

```
if ( depth_aver >= z_min_prod_edib_crayfish_Lake )
    prod_edib_crayfish · Aqu_area_obj
else
   0.0
end
```

Unit

kg C/year

Production_Total

Expression

Total production of food in the biosphere object.

Equation	Unit
(Production_Berries + Production_Game + Production_Mushrooms) + (Production_Cereals + Production_Meat + Production_Milk + Production_Vegetables + Production_Roots) + (Production_Crayfish + Production_Fish)	kg C/year

Production_Total_perm

Expression

Total production of food in the biosphere object during the permafrost period.

Equation	Unit
Production_Berries + Production_Game + Production_Mushrooms + Production_Fish	kg C/year

Dose_ing_Fish_perm

Expression

Annual effective dose from fish ingestion during the permafrost period

Equation	Unit
ingFoodConstant_perm · conc_fish · Fraction_in_Diet_Fish_perm	Sv/year

ingFoodConstant_perm

Expression

Intermedial equation used to shorten ingestion dose equation for the permafrost period.

Equation	Unit
ingRate_C · dosCoef_ing_food · min(1.0, N_perm)	kg C Sv/(year Bq)

Dose_ing_Berries_perm

Expression

Annual effective dose from ingestion of berries during the permafrost period.

Equation	Unit
ingFoodConstant_perm · conc_Ter_PRIMARY_PRODUCER · Fraction_in_Diet_Berries_perm	Sv/year

Dose_ing_Mushrooms_perm

Expression

Annual effective dose from ingestion of mushrooms during the permafrost period.

Equation	Unit
ingFoodConstant_perm · conc_mushrooms · Fraction_in_Diet_Mushrooms_perm	Sv/year

Dose_ing_Game_perm

Expression

Annual effective dose from ingestion of game during the permafrost period.

Equation	Unit
ingFoodConstant_perm · conc_Herbiv · Fraction_in_Diet_Game_perm	Sv/year

Dose_ing_Cereals

Expression

Annual effective dose from ingestion of cereals.

Equation	Unit
ingFoodConstant · conc_cereals · Fraction_in_diet_Cereals	Sv/year

ingFoodConstant

Expression

Intermedial equation used to shorten ingestion dose equation.

Equation	Unit
ingRate_C · dosCoef_ing_food · min(1.0, N)	kg C Sv/(year Bq)

Dose_ing_Roots

Expression

Annual effective dose from ingestion of root crops.

Equation	Unit
ingFoodConstant · conc_roots · Fraction_in_Diet_Roots	Sv/year

Dose_ing_Vegetables

Expression

Annual effective dose from ingestion of vegetables.

Equation	Unit
ingFoodConstant · conc_vegetables · Fraction_in_Diet_Vegetables	Sv/year

Dose_ing_Milk

Expression

Annual effective dose from ingestion of cow milk.

Equation	Unit
ingFoodConstant · conc_milk · Fraction_in_Diet_Milk	Sv/year

Dose_ing_Meat

Expression

Annual effective dose from ingestion of cow meat.

Equation	Unit
ingFoodConstant · conc_meat · Fraction_in_Diet_Meat	Sv/year

Dose_ing_Game

Expression

Annual effective dose from ingestion of game meat.

Equation	Unit
ingFoodConstant · conc_Herbiv · Fraction_in_Diet_Game	Sv/year

Dose_ing_Mushrooms

Expression

Annual effective dose from ingestion of mushrooms.

Equation	Unit
ingFoodConstant · conc_mushrooms · Fraction_in_Diet_Mushrooms	Sv/year

Dose_ing_Berries

Expression

Annual effective dose from ingestion of berries.

Equation	Unit
ingFoodConstant · conc_Ter_PRIMARY_PRODUCER · Fraction_in_Diet_Berries	Sv/year

Dose_ing_Fish

Expression

Annual effective dose from ingestion of fish.

Equation	Unit
ingFoodConstant · conc_fish · Fraction_in_Diet_Fish	Sv/year

Dose_ing_Crayfish

Expression

Annual effective dose from ingestion of crayfish.

Equation	Unit
ingFoodConstant · conc_crayfish · Fraction_in_Diet_Crayfish	Sv/year

Dose_ing_Total

Expression

Total annual effective dose from food ingestion

Equation	Unit
(Dose_ing_Berries + Dose_ing_Mushrooms + Dose_ing_Game) + (Dose_ing_Meat + Dose_ing_Milk + Dose_ing_Roots + Dose_ing_Vegetables + Dose_ing_Cereals) + (Dose_ing_Crayfish + Dose_ing_Fish)	Sv/year

Dose_ing_WATER_perm

Expression

Annual effective dose from ingestion of water during the permafrost period.

Equation	Unit
ingRate_wat · dosCoef_ing_water · min(1.0, N_perm) · conc_WATER_Lake	Sv/year

Dose_ing_WATER

Expression

Annual effective dose from ingestion of water

Equation	Unit
ingRate_wat · dosCoef_ing_water · min(1.0, N) · conc_WATER	Sv/year

Dose_ing_Total_perm

Expression

Total annual effective dose from food ingestion during the permafrost period.

Equation	Unit
Dose_ing_Berries_perm + Dose_ing_Game_perm + Dose_ing_Mushrooms_perm + Dose_ing_Fish_perm	Sv/year

Fraction_in_Diet_Fish_perm

Expression

Fraction of fish in the diet during the permafrost period.

Equation	Unit
Production_Fish / Production_Total_perm	unitless

Fraction_in_Diet_Berries_perm

Expression

Fraction of berries in the diet during the permafrost period.

Equation	Unit
Production_Berries / Production_Total_perm	unitless

Fraction_in_Diet_Mushrooms_perm

Expression

Fraction of mushrooms in the diet during the permafrost period.

Equation	Unit
Production_Mushrooms / Production_Total_perm	unitless

Fraction_in_Diet_Game_perm

Expression

Fraction of game in the diet during the permafrost period.

Equation	Unit
Production_Game / Production_Total_perm	unitless

Fraction_in_diet_Cereals

Expression

Fraction of cereals in the diet.

Equation	Unit
Production_Cereals / Production_Total	unitless

Fraction_in_Diet_Roots

Expression

Fraction of roots in the diet.

Equation	Unit
Production_Roots / Production_Total	unitless

Fraction_in_Diet_Vegetables

Expression

Fraction of vegetables in the diet.

Equation	Unit
Production_Vegetables / Production_Total	unitless

Fraction_in_Diet_Milk

Expression

Fraction of milk in the diet.

Equation	Unit
Production_Milk / Production_Total	unitless

Fraction_in_Diet_Meat Expression

Fraction of meat in the diet.

Equation	Unit
Production_Meat / Production_Total	unitless

Fraction_in_Diet_Game Expression

Fraction of game meat in the diet.

Equation	Unit
Production_Game / Production_Total	unitless

Fraction_in_Diet_Mushrooms Expression

Fraction of mushrooms in the diet.

Equation	Unit
Production_Mushrooms / Production_Total	unitless

Fraction_in_Diet_Berries Expression

Fraction of berries in the diet.

Equation	Unit
Production_Berries / Production_Total	unitless

Fraction_in_Diet_Fish Expression

Fraction of fish in the diet.

Equation	Unit
Production_Fish / Production_Total	unitless

Fraction_in_Diet_Crayfish

Fraction of crayfish in the diet.

Expression

Equation	Unit
Production_Crayfish / Production_Total	unitless

1.2.3 Activity concentrations used for dose to Biota assessmetns

Marine

ActivityConcentrationWater

Radionuclide concentration in water used to calculate doses to marine biota.

Expression

Equation

```
if ( is_sea )
    conc_WATER_Aqu · 0.0010
else
   0.0
end
```

Unit

Bq/L

ActivityConcentrationSediment_up

Radionuclide concentration in the Aqu_regolith_Up compartment used to calculate doses to marine biota.

Expression

Equation

```
if ( is_sea )
    Aqu_REGOLITH_UP / ( Aqu_area_obj · Aqu_z_regoUp · Aqu_dens_regoUp )
else
   0.0
end
```

Unit

Bq/(kg DW)

ActivityConcentrationSediment_mid

Radionuclide concentration in the Aqu_regolith_Mid compartment used to calculate doses to marine biota.

Expression

Equation

```
if ( is_sea )
    Aqu_REGOLITH_MID / ( Aqu_area_obj · Aqu_z_regoMid · Aqu_dens_regoMid )
else
   0.0
end
```

Unit

Bq/(kg DW)

FreshWater

ActivityConcentrationWater Expression

Radionuclide concentration in water used to calculate doses to freshwater biota.

Equation	Unit
	Bq/L

```
if ( time_GE_threshold_start AND switcherRiver )
    conc_WATER_Aqu · 0.0010
else
   0.0
end
```

ActivityConcentrationSediment_up Expression

Radionuclide concentration in the Aqu_regolith_Up compartment used to calculate doses to freshwater biota.

Equation	Unit
	Bq/(kg DW)

```
if ( time_GE_threshold_start AND switcherRiver )
    Aqu_REGOLITH_UP / ( Aqu_area_obj · Aqu_z_regoUp · Aqu_dens_regoUp )
else
   0.0
end
```

ActivityConcentrationSediment_mid Expression

Radionuclide concentration in the Aqu_regolith_Mid compartment used to calculate doses to freshwater biota.

Equation	Unit
	Bq/m ^{2}

```
if ( time_GE_threshold_start AND switcherRiver )
    Aqu_REGOLITH_MID / ( Aqu_area_obj · Aqu_z_regoMid · Aqu_dens_regoMid )
else
   0.0
end
```

Terrestrial

ActivityConcentrationSoil Expression

Radionuclide concentration in soil used to calculate doses to terrestrial biota.

Equation	Unit
conc_Ter_REGOLITH_UP	Bq/(kg DW)

ActivityConcentrationAir

Expression

Radionuclide concentration in air used to calculate doses to terrestrial biota.

Equation	Unit
conc_ATMOSPHERE	Bq/m^{3}

1.3 Object 10 (Grepen)

Aqu_WATER

Compartment

The surface water (sea water).

Differential equation	Unit
d Aqu_WATER /dt = -λ • Aqu_WATER + Aqu_WATER • Outflow_Sea + Aqu_WATER • Outflow_Downstream + Aqu_WATER • Backflow + Ter_REGOLITH_UP • Mire_Dowstream - Aqu_WATER • outflow - Aqu_WATER • Backflow + ingrowth	Bq

Backflow

Transfer Coefficient

Radionuclide transfer rate coefficient corresponding to the transport from object 10 to the WATER compartment during the Sea period

Equation	Unit
see below	year^{-1}

```
if ( is_sea )
    depth_aver · Aqu_area_obj / ( depth_aver · Aqu_area_obj ) / wat_ret
else
   0.0
end
```

Outflow

Transfer Coefficient

Radionuclide transfer rate coefficient corresponding to the transport from object 10 to object 1.

Equation	Unit
1.0 / wat_ret	year^{-1}

1.4 Object 1 (Baltic Sea)

Aqu_WATER Compartment

The surface water (sea water).

Differential equation	Unit
d Aqu_WATER /dt = $-\lambda \cdot$ Aqu_WATER + Aqu_WATER · outflow - Aqu_WATER · outflow - Aqu_WATER · Backflow + ingrowth	Bq

Backflow Transfer Coefficient

Radionuclide transfer rate coefficient corresponding to the transport from object 1 object 10

Equation	Unit
(depth_aver · Aqu_area_obj) / (depth_aver · Aqu_area_obj) / wat_ret	$year^{-1}$

Outflow Transfer Coefficient

Radionuclide transfer rate coefficient corresponding to the transport from object 1 out from the system (Atlantic Ocean).

Equation	Unit
1.0 / wat_ret	$year^{-1}$

Appendix 14

Parameters in the radionuclide model for the biosphere

Parmeter Name	Description	Unit	Type	Report	Source File
Physical constant					
Half_life	Radionuclide half-life.	year	Nuclide specific	TR-10-07	ParametersES.xls
Landscape geometry					
Aqu_area_obj	Water area in the lake basin.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
area_subcatch	Area of the subcatchment.	m^2	Site Specific	TR-10-05	ParametersSS.xls
area_wshed	Watershed area.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
depth_aver	Average water depth.	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
depth_max	Maximum water depth.	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
growth_rego	Average accumulation rate of sediment calculated for lake and marine bottoms.	m/year	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
res_rate	Resuspension rate.	kg DW/(m^2year)	Site Specific (Time Series)	TR-10-05	ParametersTS.xls
sed_rate	Sedimentation rate.	kg DW/(m^2year)	Site Specific (Time Series)	TR-10-05	ParametersTS.xls
Ter_area_obj	Area with peat in the lake basin.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
threshold_agriculture	Point in time when wetland is 2 m above sea level.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_end	Point in time when ingrowth of wetland stops.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_start	Point in time when lake isolation starts.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_stop	Point in time when lake isolation is completed.	year	Site Specific	TR-10-05	ParametersSS.xls
Regolith					
Agri_z_regoUp	Depth of the agricultural upper regolith layer.	m	Generic	TR-10-01	ParametersUC.xls
Aqu_dens_regoMid_gl	Density of glacial clay in the middle layer of the regolith.	kg DW/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Agri_dens_regoUp	Density of the agricultural upper regolith layer.	kg DW/ m^3	Site Specific	TR-10-01	ParametersSS.xls
Agri_poro_regoUp	Porosity of the agricultural upper regolith layer.	m^3/ m^3	Site Specific	TR-10-01	ParametersSS.xls
Aqu_dens_regoMid_pg	Density of the postglacial sediments in aquatic middle layer of regolith.	kg DW/ m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_dens_regoUp	Density of the aquatic upper layer of the regolith.	kg DW/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoMid_gl	Porosity of the glacial clay in aquatic middle regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoMid_pg	Porosity of postglacial sediments in aquatic middle regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoUp	Porosity of the aquatic upper regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_z_rego_pg	Depth of aquatic postglacial sediments under sea, lake or stream.	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
Aqu_z_regoMid_gl_lake	Average depth of glacial deposits in lake.	m	Site Specific	TR-10-05	ParametersSS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
dens_regoLow	Density of the lower regolith layer (till).	kg DW/m^3	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Lake_z_regoLow	Depth of the lower regolith (till) in the lake/terrestrial stage.	m	Site Specific	TR-10-05	ParametersSS.xls
Lake_z_regoUp	Depth of the upper regolith layer in the lake basin.	m	Site Specific	TR-10-02	ParametersSS.xls
poro_regoLow	Porosit of the lower regolith layer (till).	m^3/m^3	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Sea_z_regoLow	Average depth of glacial till in sea basin.	m	Site Specific	TR-10-05	ParametersSS.xls
Sea_z_regoUp	Depth of the upper regolith layer in sea.	m	Site Specific	TR-10-03	ParametersSS.xls
Ter_dens_regoMid_gl	Density of the glacial clay in terrestrial middle regolith layer.	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_dens_regoMid_pg	Density of the postglacial clay in terrestrial middle regolith layer.	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_dens_regoUp	Density of the terrestrial upper regolith layer (peat).	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_growth_rego	Growth of wetland relative water area.	m^2/ (m^{2}year)	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
Ter_poro_regoMid_gl	Porosity of the glacial clay in terrestrial middle regolith layer.	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_poro_regoMid_pg	Porosity of the post glacial clay in terrestrial middle regolith layer.	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_poro_regoUp	Porosity of the terrestrial upper regolith layer (peat).	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_z_regoMid_pg	Depth of the post glacial clay in terrestrial middle regolith layer (covered by peat).	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
Ter_z_regoUp	Depth of the terrestrial upper regolith layer (peat).	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_all_basins.xls
z_regoMid_gl_basin	Depth of the glacial clay of the aquatic middle layer in the sea basin.	m	Site Specific	TR-10-05	ParametersSS.xls
Aquatic ecosystem					
Aqu_biom_pp_macro	Biomass of macroflora and macrofauna (macroalgae, macrophytes, benthic macrofauna) in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_biom_pp_plank	Biomass of pelagic biota (i.e. phytoplankton bacterioplankton, zooplankton and fish) in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_biom_pp_ubent	Biomass of microphytobenthos and benthic bacteria in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_degass_C	Carbon degassing rate. Release of carbon from lake water surface to atmosphere.	kg C/ (m^{2}year)	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_macro	Net productivity of the benthic macrocommunity, i.e. the net primary production minus respiration of macrofauna and flora, in lake.	year^{-1}	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_plank	Net productivity of the pelagic community, i.e. net primary production by phytoplankton minus respiration by zooplankton, bacterioplankton, and fish, in lake.	year^{-1}	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_ubent	Net productivity of the benthic microscopic community, i.e. net primary production by microphytobenthos minus respiration by benthic bacteria in lake.	year^{-1}	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
gasUptake_C	Uptake of carbon from atmosphere to lake water (mainly CO_2).	kg C/ (m^2year)	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Lake_conc_DIC	Concentration of dissolved inorganic carbon in lake water.	kg C/m^3	Site Specific	TR-10-02	ParametersSS.xls
Lake_conc_PM	Concentration of particulate matter in lake water.	kg DW/m^3	Site Specific	TR-10-02	ParametersSS.xls
prod_edib_cray_Lake	Production of edible crayfish in the lake.	kg C/ (m^2year)	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
prod_edib_fish_Lake	Production of edible fish in the lake.	kg C/ (m^2year)	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
z_min_prod_edib_crayfish_Lake	Minimum lake depth for crayfish production.	m	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
z_min_prod_edib_fish_Lake	Minimum lake depth for production of edible fish.	m	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
prod_edib_fish_Sea	Production of edible fish in the sea.	kg C/ (m^2year)	Site Specific	TR-10-03	PostProcessing ParametersSS.xls
Sea_conc_DIC	Concentration of dissolved inorganic carbon in sea water.	kg C/m^3	Site Specific	TR-10-03	ParametersSS.xls
Sea_conc_PM	Concentration of particulate matter in sea water.	kg DW/m^3	Site Specific	TR-10-03	ParametersSS.xls
Terrestrial Ecosystem					
conc_C_atmos	Concentration of carbon in the atmosphere above the terrestrial ecosystem.	kg C/m^3	Generic	TR-10-01	ParametersUC.xls
frac_C_atmos	Fraction of decomposed carbon that is mineralised (leaving as CO_2 to the atmosphere).	–	Site Specific	TR-10-01	ParametersSS.xls
frac_mush_Herbiv	Fraction of mushrooms in the diet of terrestrial herbivores.	–	Generic	TR-10-01	ParametersUC.xls
prod_edib_berry	Production of edible berries.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_game	Production of edible game meat.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_mush	Production of edible mushrooms.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Ter_biom_pp	Biomass of terrestrial primary producers.	kg C/m^2	Site Specific	TR-10-01	ParametersSS.xls
Ter_conc_C_regoUp	Concentration of dissolved inorganic carbon in the upper terrestrial regolith (peat).	kg C/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_conc_Dust	Concentration of dust in air.	kg DW/m^3	Generic	TR-10-01	ParametersUC.xls
Ter_decomp	Decomposition rate.	1/year	Site Specific	TR-10-01	ParametersES.xls
Ter_degass_C	Degassing rate of dissolved inorganic carbon in the terrestrial ecosystem.	kg C/ m^2 year	Site Specific	TR-10-01	ParametersSS.xls
Ter_prodBiom_pp	Net primary production per unit biomass in the terrestrial ecosystem.	kg C/(kg C year)	Site Specific	TR-10-01	ParametersSS.xls
Ter_z_mixlay	Height of the mixing layer in the terrestrial ecosystem.	m	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Ter_z_roughness	Height above ground below which the wind speed is zero due to vegetation.	m	Generic	TR-10-01	ParametersUC.xls
vel_wind	Wind velocity.	m/year	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Agri_conc_Dust	Concentration of dust in the atmosphere on agricultural land.	kg DW/m^3	Generic	TR-10-01	PostProcessing ParametersSS.xls
conc_C_meat	Concentration of carbon in meat.	kg C/kg FW	Generic	TR-10-07	ParametersUC.xls
conc_C_milk	Concentration of carbon in milk.	kg C/kg FW	Generic	TR-10-07	ParametersUC.xls
densMilk	Density of the milk.	kg FW/l	Generic	TR-10-07	ParametersUC.xls
ingRate_food_meat	Fodder ingestion rate for meat cattle.	kg C/d	Generic	TR-10-07	ParametersUC.xls

Parmeter Name	Description	Unit	Type	Report	Source File
ingRate_food_milk	Fodder ingestion rate for milk producing cattle.	kg C/d	Generic	TR-10-07	ParametersUC.xls
ingRate_soil_Cow	Soil ingestion rate for cattle.	kg DW/d	Generic	TR-10-07	ParametersUC.xls
ingRate_water_meat	Water ingestion rate for meat cattle.	m^3/d	Generic	TR-10-07	ParametersUC.xls
ingRate_water_milk	Water ingestion rate for milk producing cattle.	m^3/d	Generic	TR-10-07	ParametersUC.xls
leaf_areaIndex	Ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows.	m^2/ m^2	Generic	TR-10-01	ParametersUC.xls
leaf_StoreCapac	Storage capacity of intercepted water on leaf surface.	m^3/ m^2	Generic	TR-10-01	ParametersUC.xls
numb_irrig	Number of irrigation events.	$year^{-1}$	Generic	TR-10-01	ParametersUC.xls
prod_edib_cereal	Production of edible cereals.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_meat	Production of edible meat (relative fodder consumption).	kg C/kg C	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_milk	Production of edible milk (relative fodder consumption).	kg C/kg C	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_tuber	Production of edible root crop, e.g. potato.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_vegetab	Production of edible vegetables.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_fodder	Production of fodder on agricultural land.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
vol_irrig	Volume of irrigation water used each year.	m/year	Generic	TR-10-01	ParametersUC.xls
Surface Hydrology and water exchange					
Flooding_coef	Gross lateral flux of water from lake/stream to wetland, normalised by the net lateral flux from wetland to lake/stream.	unitless or (m^3/year)/ (m^3/year)	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
Lake_adv_low_mid	Total advective flux from regoLow (till) to regoMid (glacial and post glacial deposits) for the lake/terrestrial stage.	m/year	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
Lake_Aqu_adv_mid_up_norm	Advective flux in the aquatic object between the sediment and the water during lake stage, normalised by the net lateral advective flux from wetland to lake/stream.	–	Site Specific	TR-10-02	ParametersSS.xls
Lake_fract_Mire	Fraction of the upward flux from regoLow (till) that is directed to the terrestrial part of the biosphere object.	–	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
runoff	Total annual runoff.	m/year	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Sea_adv_low_mid	Total advective flux from regoLow (till) to regoMid (glacial and post glacial deposits) for the sea stage.	m/year	Site Specific	TR-10-03	ParametersSS.xls
Ter_adv_mid_up_norm	The advective flux from regoMid (glacial and post glacial deposits) to regoUp (peat) in the terrestrial ecosystem. normalised by the net lateral flux from terrestrial ecosystem to lake/stream.	–	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
wat_ret	Average water retention time in the sea basin.	year	Site Specific (Time Series)	TR-10-03	Water_retention.xls
wellCapac	The water volume capacity of a well.	m^3/year	Site Specific	TR-10-01	PostProcessing ParametersSS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
Distribution coefficients and diffusivity					
kD_regoLow	Distribution coefficient for lower regolith layer (till).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Lake_kD_PM	Distribution coefficient for particulate matter in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersSS.xls
Lake_kD_regoMid	Distribution coefficient for particulate matter in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Lake_kD_regoUp	Distribution coefficient for the middle regolith layer in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_PM	Distribution coefficient for particulate matter in sea.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_regoMid	Distribution coefficient for the middle regolith layer in sea (glacial clay and post glacial sediments combined).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_regoUp	Distribution coefficient for the upper regolith layer in sea.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Ter_kD_regoMid	Distribution coefficient for the terrestrial middle regolith layer (glacial clay and post glacial sediments combined).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Ter_kD_regoUp	Distribution coefficient for the terrestrial upper regolith layer (peat).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
diffcoef	Diffusion coefficient.	m^2/year	Element Specific	TR-10-07	ParametersES.xls
Concentration ratios, retention and release					
cR_foodToHerbiv	Concentration ratio from food to terrestrial herbivores.	kg C/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToCereal	Concentration ratio from soil to cereals.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToMush	Concentration ratio from soil to mushrooms.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToTuber	Concentration ratio from soil to tubers.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToVegetab	Concentration ratio from soil to vegetables.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToCray_Lake	Concentration ratio from water to crustacean in the lake.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToFish_Lake	Concentration ratio from water to fish in the lake.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToFish_Sea	Concentration ratio from water to fish in the sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_macro	Concentration ratio from water to macrophytes/macroalgae in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_plank	Concentration ratio from water to macrophytes/macroalgae in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_ubent	Concentration ratio from water to phytoplankton in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_macro	Concentration ratio from water to macrophytes/macroalgae in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_plank	Concentration ratio from water to phytoplankton in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_ubent	Concentration ratio from water to microphytobenthos in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
tC_cowMeat	Transfer coefficient from intake of radionuclides in fodder and water to cow meat.	d/kg FW	Element Specific	TR-10-07	ParametersES.xls

Parmeter Name	Description	Unit	Type	Report	Source File
tC_cowMilk	Transfer coefficient from intake of radionuclides in fodder and water to cow milk.	d/l	Element Specific	TR-10-07	ParametersES.xls
Ter_cR_pp	Concentration ratio for terrestrial primary producers.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
coefRetent	Fraction of leaf intercepted radionuclides that is adsorbed to edible parts of vegetables during irrigation.	–	Element Specific	TR-10-07	ParametersES.xls
Ter_df_decomp	Discrimination factor during decomposition.	–	Element Specific	TR-10-07	ParametersES.xls
Human characteristics					
AverTime	The time interval over which concentration in agricultural soil is averaged over.	y	Generic	TR-10-07	ParametersUC.xls
expTime	Time spent outdoor (time for exposure from external radiation).	h/year	Generic	TR-10-07	ParametersUC.xls
ingRate_C	Human food ingestion rate.	kg C/year	Generic	TR-10-07	ParametersUC.xls
ingRate_wat	Human water ingestion rate.	m^3/year	Generic	TR-10-07	ParametersUC.xls
inhalRate	Human inhalation rate of volume air.	m^3/h	Generic	TR-10-07	ParametersUC.xls
Dose coefficients					
dosCoef_ext	Dose coefficient from external exposure.	Sv/h*Bq/m^3	Element Specific	TR-10-07	ParametersES.xls
dosCoef_ing_food	Dose coefficient from ingestion of food.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls
dosCoef_ing_water	Dose coefficient from ingestion of water.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls
dosCoef_inhal	Dose coefficient from inhalation.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls