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The marine ecosystems at Forsmark and Laxemar-Simpevarp

SR-Site Biosphere

Aquilonius, Karin (Editor)
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December 2010

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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 212, figure 6-60	Wrong numbers in the figure	Figure 6-60 updated with correct numbers

Updated 2013-02

Location	Original text	Corrected text
Page 11, paragraph 4, last line	/SKB 2010c/	/SKB 2011/
Page 15, paragraph 2, line 1	/SKB 2010c/	/SKB 2011/
Page 15, paragraph 3, last line	/SKB 2010e/	/SKB 2010c/
Page 21, paragraph 3, last line	Borgiel and Nilsson, 2006	Reference removed
Page 21, paragraph 3, last line	Ericsson and Engdahl 2004a, b, 2005, 2006/	/Ericsson and Engdahl 2004a, b, 2007, 2008/
Page 29, figure 3-4, figure text	/Ericsson and Engdahl 2006/	/Ericsson and Engdahl 2007/
Page 60, paragraph 4, last line	Ericsson and Engdahl 2006/	Ericsson and Engdahl 2007/
Page 98, last paragraph, line 3	/Engdahl et al. 2007/	/Engdahl et al. 2006/
Page 99, paragraph 4, line 2	/Engdahl et al. 2007/	/Engdahl et al. 2006/
Page 122, paragraph 1 line 4 and 5	/Ericsson and Engdahl 2004a, b, Ericsson and Engdahl 2005, Ericsson and Engdahl 2006/	/Ericsson and Engdahl 2004a, b, 2007, 2008/
Page 138, Table 4-23, line 1	/Ericsson and Engdahl 2004a, b, 2005, 2006/	/Ericsson and Engdahl 2004a, b, 2007, 2008, Engdahl et al. 2006/
Page 138, Tabell 4-23, line 2	/Ericsson and Engdahl 2004a, b, 2005, 2006/	/Ericsson and Engdahl 2004a, b, 2007, 2008, Engdahl et al. 2006/
Page 267, paragraph 4, last line	/SKB 2010a/	/SKB 2010b/
Page 268, paragraph 5, last line	/SKB 2010a/	/SKB 2010b/
Page 268, paragraph 6, line 3	/SKB 2010a/	/SKB 2010b/
Page 274, paragraph 1, last line	/SKB 2010a/	/SKB 2010b/
Page 276, paragraph 1, line 3	/SKB 2010a/	/SKB 2010b/
Page 433, paragraph 3, line 4	/SKB 2010f/	/Brydsten and Strömgren 2004, Strömgren and Brydsten 2008/
Page 437, reference	Borgiel and Nilsson, 2006	Reference removed
Page 439, reference	Ericsson U, Engdahl A, 2005.	Ericsson U, Engdahl A, 2007.
Page 439, reference	Ericsson and Engdahl 2006	Reference removed
Page 439, reference	Ericsson U, Engdahl A, 2007. Oskarshamn site investigation. Surface water sampling at Simpevarp 2005. SKB P-06-155, Svensk Kärnbränslehantering AB.	Ericsson U, Engdahl A, 2008. Oskarshamn site investigation. Monitoring of surface water chemistry 2006. SKB P-08-10, Svensk Kärnbränslehantering AB.
Page 449, reference	SKB 2010c	Reference removed
Page 449, reference	SKB 2010d	Reference removed
Page 449, reference	SKB 2010e.	SKB, 2010c.
Page 449, reference	SKB 2010f	Reference removed
Page 449, reference		New reference SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Updated 2013-08

Location	Original text	Corrected text
Page 8, Content 10.5.6	Aqu_z_regoMid_GL	z_regoMid_gl_basin
Page 394, 10.5.6 Heading	Aqu_z_regoMid_GL	z_regoMid_gl_basin
Page 394, Table 10-10 Heading	Aqu_z_regoMid_GL	z_regoMid_gl_basin
Page 413, 10.11.6 Heading	Aqu_z_regoMid_GL	z_regoMid_gl_basin
Page 413, Table 10-28 Heading	Aqu_z_regoMid_GL	z_regoMid_gl_basin

Summary

The overall objective of this report is to provide a thorough description of the marine ecosystems at the sites Forsmark and Laxemar-Simpevarp, to identify processes in these ecosystems of importance to transfer and accumulation of radionuclides and, finally based on this knowledge, develop parameters to be used for the marine ecosystem in the safety analysis SR-Site.

The report includes a thorough description of the major components in the marine ecosystems in Forsmark and Laxemar-Simpevarp, and covers the following areas: chemical and physical characteristics, climate and meteorology, morphology and regolith, biota in the marine ecosystem, human impact, water exchange and historical evolution at the sites. The site specific characteristics are compared with marine data from the Baltic region. Marine ecosystem modeling and mass balances calculations for carbon and a number of other elements were carried out to further improve the understanding of the marine ecosystems. Important processes for the safety assessment are identified, described and evaluated according to a systematic method. The derivation of marine ecosystem parameters and the resulting parameters is presented. The last chapter of the report aims at summarizing the knowledge of the marine ecosystems at the two areas.

In comparison with the Gulf of Bothnia and the Baltic Proper, salinity is somewhat lower in Forsmark and Laxemar-Simpevarp respectively. The nitrogen and phosphorus levels at the two sites are low to moderately high compared with environmental monitoring data for corresponding areas in the Baltic Sea. In Forsmark, nitrogen seems to be the limiting nutrient during the summer months. In Laxemar-Simpevarp, nitrogen seems to be the limiting nutrient in the outer areas and phosphorus in the inner bays. This coincides with the general conditions in the Bothnian Sea (Forsmark) and the Baltic Proper (Laxemar-Simpevarp). The annual mean water temperature in Forsmark is slightly higher than the mean for the Baltic Sea and slightly lower in Laxemar-Simpevarp. The sea level at Forsmark has since 2003 fluctuated between 0.6 m below and 1.3 m above the mean level, and the corresponding values for Laxemar-Simpevarp are 0.5 and 0.7 m. Due to the gentler slope of the coastline, the sea level fluctuations have a more marked effect in Forsmark, than in the Laxemar-Simpevarp landscape, exhibiting a steeper slope.

In Forsmark the macrophyte vegetation in the photic zone is dominated by red algae and brown filamentous algae. In Laxemar-Simpevarp, the red algae community covers the largest area. The benthic biomass at the bottom sampling sites in Forsmark has been dominated by the Baltic mussel. In Laxemar-Simpevarp the sessile macro fauna attached to hard substrates is completely dominated by the blue mussel in terms of both biomass and abundance. Test fishing in Forsmark and Laxemar-Simpevarp show similar development as in other nearby coastal areas and herring and sprat are the dominant species in offshore areas at both sites. In the inner bays at the sites, perch and pike are the most frequent species.

The biomass in Forsmark is dominated by the primary producers and is focused along the shoreline of the area. On average, the marine area in Forsmark shows a positive Net Ecosystem Production (NEP), although most of the area is heterotrophic. The coastal shallow basins tend to be autotrophic, whereas the more offshore basins are heterothropic. The largest carbon pool in all basins in Forsmark is the abiotic pools (i.e. sediment, DIC and DOC) followed by the macrophytes. The major carbon flux in the ecosystem is the advective flux caused by the movement of sea water. All biotic fluxes are small in comparison with the advective flux. The largest biotic flux is fixation of carbon by primary producers. On average 4% of the initially consumed carbon in the marine ecosystem food web is transferred to the top predators. For nitrogen, phosphorus and thorium, the major pool in the ecosystem is the sediment. For uranium the sediment pool and the dissolved pool are almost equally large, dominant pool for iodine is the dissolved phase.

In Laxemar-Simpevarp the mean biomass is considerable higher than in Forsmark. A major difference between the sites is the high abundances of the blue mussels in the exposed basins with extensive hard-bottoms. The annual mean NEP in the whole marine area in Laxemar-Simpevarp is negative i.e. more carbon is released to the atmosphere than is fixed in biomass. However, not all basins are heterothropic, coastal basins with high macrophyte biomasses are generally autothropic. The largest carbon

pool in the area is the DIC-pool followed by the sediment pool and the filter feeders. Advective flux generates the largest carbon flux in the ecosystem followed by the biotic flux; consumption by filter feeders. Runoff, diffusion, burial and precipitation are generally small fluxes in the area. In average only 0.8% of the carbon initially consumed in the food web reaches the top predators.

Release of heated cooling water is probably the major human impact at the sites. The human impact in general at the two sites is of the same magnitude as in the regions, although the nutrient load is generally greater in the Forsmark region (Uppsala County). Fishery represents mainly a larger-scale impact in both areas.

Hydrodynamic oceanographic models have been applied to Forsmark and Laxemar-Simpevarp in order to describe the residence time of water at present and during long- term development of the areas. The oceanographic models that quantify water exchange in the coastal areas indicate a more rapid residence time of water in the whole marine area in Forsmark. The difference is most likely due to the more enclosed character of the inner bays in Laxemar-Simpevarp. The long-term development of residence time in both areas tends to increase at the rate of the land rise.

The long term development of the marine ecosystems in Forsmark and Laxemar-Simpevarp is driven mainly by two factors: shoreline displacement and climate change. Both has affected Forsmark and Laxemar-Simpevarp since the last deglaciation and is still causing a relatively predictable change in the abiotic and biotic environment. How ecosystem properties may change over long periods of time is exemplified with results from comparisons of ecosystem properties over present-day climate gradients i.e. “substituting time for space”.

A marine ecological model C:N:P model for transport and accumulation of radionuclides is briefly presented to illustrate the spatial and temporal variation in important processes and parameters, in addition to constitute a complement and support assumptions made in the radionuclide model.

A systematic method, an Interaction Matrix (IM), was applied to assure that processes of importance for the safety analysis SR-Site are considered. In total, 51 processes were identified and listed in the IM of which 34 were identified as important to consider in the safety analysis SR-Site. Accordingly, these processes are considered in the parameterization and radionuclide modelling. Calculations of the marine 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 marine 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.

Contents

1 Introduction

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 to roughly 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 (Figure 1-1). 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 /Lindborg (ed) 2008/ (Forsmark) and /Söderbäck and Lindborg 2009/ (Laxemar-Simpevarp).

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). The assessment should focus on potential developments that may lead to a release of radionuclides. SKB launched the project SR-Site to conduct the safety assessment, which is summarised in the SR-Site main report /SKB 2011/.

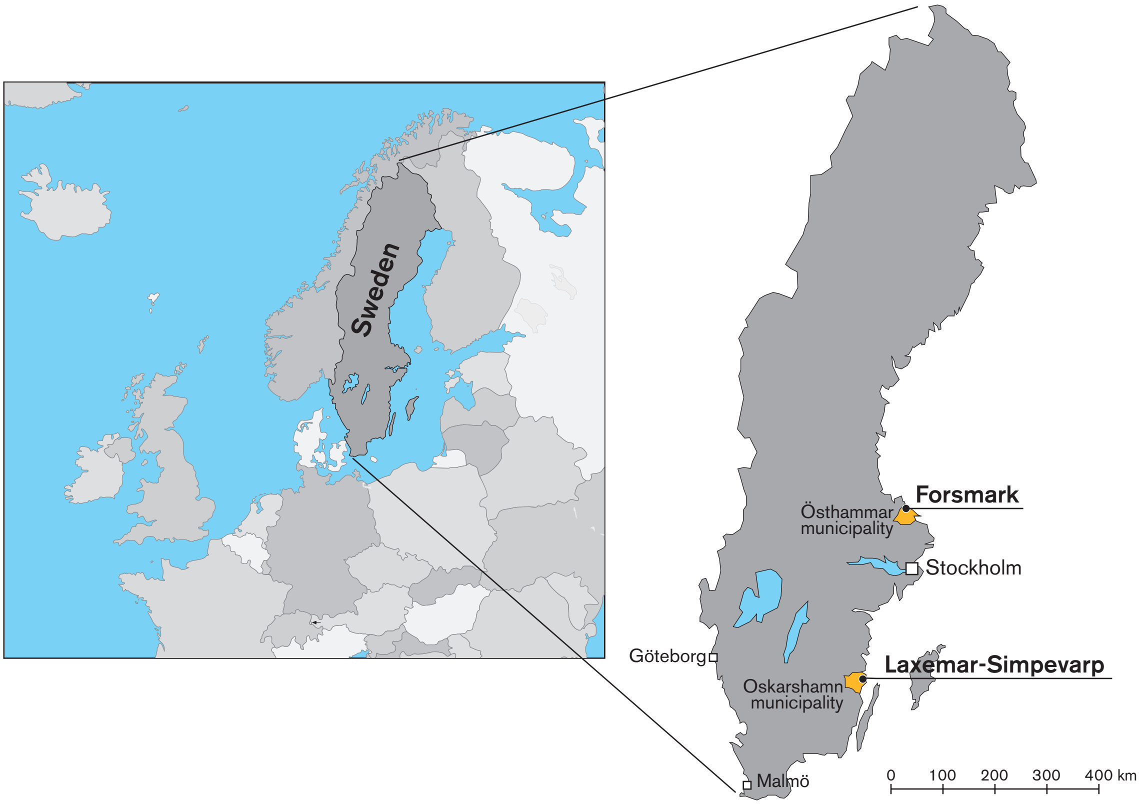

Figure 1-1. *Location of the Forsmark and Laxemar-Simpevarp sites.*

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*. 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. 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 is synthesised in the biosphere synthesis report /SKB 2010a/.

This report is produced within SR-Site Biosphere and summarises the knowledge of the marine ecosystems. Although produced within SR-Site, the intention is that the description of marine systems presented in this report will be used also for future safety assessments. The present report covers the methodology and previously reported input data relating to the site description of the present, historical and future marine ecosystems in the Forsmark and Laxemar-Simpevarp area. However, since Forsmark were selected by the SKB to be the site for the application of building a repository for spent nuclear fuel, Forsmark has been given a more extensive treatment in this report, especially in the Chapters 7–11.

Earlier versions of this report was published in 2008 /Wijnbladh et al. 2008/, and has now been extended with Chapter 9 to 11, and some minor updates and corrections in the earlier chapters. The Chapters 3–6, are based on a first edition of marine ecosystem descriptions /Wijnbladh et al. 2008/. The work in this report has demanded interactions over several disciplines, and several persons involved in SR-Site Biosphere has contributed. The major contributors in alphabetic order, their affiliation and major role in SR-Site Biosphere and in this report are listed in Table 1-1.

Table 1-1. Contributors to this report in alphabetic order. Listing of chapters refers to contributions to the writing of chapters.

Anders Clarhäll, SKB	Site development, Chapter 7
Anders Engqvist, KTH	Physical oceanographical modelling, Chapter 5 and 9
Anders Erichsen, DHI	Ecosystem and radionuclide modelling, Chapter 9
Anders Löfgren, Eco Analytica	Terrestrial ecosystem, Chapter 7,8,10, 11
Anna Hedenström, SGU	Quaternary geology, Chapter 3 and 10
Anna Karlsson, DH	Hydrodynamic modelling, Chapter 9
Anna Nikolopolous, Aquabiota	Parts of Section 4.2 concerning spatial distribution of biomass
Annika Ryegård, WSP	GIS analysis, Chapter 6
Björn Söderbäck, SKB	Historical descriptions
C Borell Lövstedt, DHI	Hydrodynamic modelling , Chapter 9
C Eriksson, DHI	Hydrodynamic modelling , Chapter 9
Emma Bosson, SKB	Surface and near surface hydrology, Chapter 10
Eva Andersson**, Studsvik Nuclear AB	Limnic ecosystems, Chapter 7,8, 10,11
Flemming Möhlenberg, DHI	Ecosystem and radionuclide modelling, Chapter 9
Gustav Sohlenius, SGU	Quaternary geology, land use, regolith chemistry, Chapter 3, 7 and 10
Ida Carlén, Aquabiota	Parts of Section 4.2 concerning spatial distribution of biomass
Johannes Sandeberg, DHI	Ecosystem and radionuclide modelling, Chapter 9
Karin Aquilonius, Studsvik Nuclear AB	Marine ecosystems and editor of this report
Lars Brydsten, Umeå University	Regolith dynamics and lake development, Chapter 7 and 10
Mårten Strömgren, Umeå University	GIS analysis, Chapter 7 and 10
Martin Iseaus, Aquabiota	Parts of Section 4.2 concerning spatial distribution of biomass
Mona Sassner, DHI	Surface hydrology, Chapter 10
Olof Liungman, DHI	Hydrodynamic modelling , Chapter 9
Rikke Closter, DHI	Ecosystem and radionuclide modelling, Chapter 9
Tobias Lindborg*, SKB	Report conformation and general comments
Ulrik Kautsky, SKB	Report conformation and general comments

* project leader SR-Site Biosphere.
** ass. project leader SR-Site Biosphere.

Unless stated otherwise, all photographs in the report were taken by Erik Wijnbladh.

Many improvements on earlier versions of /Wijnbladh et al. 2008/ were suggested by Clare Bradshaw, Department of Systems Ecology, Stockholm University. Many improvements on earlier versions of this report were suggested by: Regina Lindborg (Department of Systems Ecology, Stockholm University), the results of this report do not necessary conform to the opinions of the reviewers.

1.2 Aims

The report has three primary aims:

1. To characterize and describe the marine ecosystems today, in the past and in the future in the Forsmark and Laxemar-Simpevarp areas, and to compare these systems with marine ecosystems in other areas. This includes evaluating and visualizing the major pools, fluxes and sinks of elements in the marine ecosystems in Forsmark and Laxemar-Simpevarp.
2. To describe the human impact on the marine ecosystems in Forsmark and Laxemar-Simpevarp.
3. To identify and describe marine ecosystem processes of importance for transfer and accumulation of radionuclids, and thereby also for radionuclide modelling.
4. To describe the parameterization of the marine ecosystem part of the Radionuclide model (Chapter 10 in /Andersson (ed) 2010/) and how it is linked to the knowledge of ecosystems.

2 This report

This chapter puts the report in a wider context, i.e. in comparison to the overall safety assessment by SKB; SR-Site Biosphere. It provides guidance to the reader on the content of different chapters and definitions of the model area and some terms commonly used in the report.

2.1 This report in a broader context

This report is produced within the biosphere part of SR-Site, SR-Site Biosphere, /SKB 2011/. The hierarchy of the reports produced within the SR-Site biosphere projects is presented in Figure 2-1. To make the safety assessment of the planned repository possible, the SR-Site Biosphere project is divided into a number of subtasks: 1) identify features and processes of importance for modelling radionuclide dynamics of present and future ecosystems in Forsmark, 2) describe the site and predict its future development with respect to identified features and processes, 3) identify and describe areas in the landscape that may be affected by release of radionuclides from the planned repository and 4) calculate radiological exposure to a representative individual of the most exposed group in the future Forsmark landscape, and radiological exposure to the environment. SR-Site Biosphere provides estimates for human exposure, expressed as landscape dose conversion factors (LDFs). The landscape here delimits the regional model area at the sites, comprising various ecosystems.

The ecosystem is in most cases the link between radionuclides occurring in the biosphere and the exposure of these to humans and biota. In SR-Site biosphere the landscape were divided into three ecosystems: the limnic, marine and terrestrial ecosystems. This report handles the marine ecosystem in order to fulfil the two initial paragraphs (1 and 2 above) in the subtasks of the SR-Site Biosphere project. Initially the marine ecosystems at the two sites, Forsmark and Laxemar-Simpevarp, is described by summarizing and making interdisciplinary analyses of data from a large number of reports produced during the site investigations. In addition, an interaction matrix is presented (in Chapter 8) illustrating important process interactions in the ecosystems that may influence transport and accumulation in the landscape and how these interactions are considered in the radionuclide modelling. Hence, in the Chapters 7–11, the main focus is on Forsmark due to the outcome in the site selection process /SKB 2010c/.

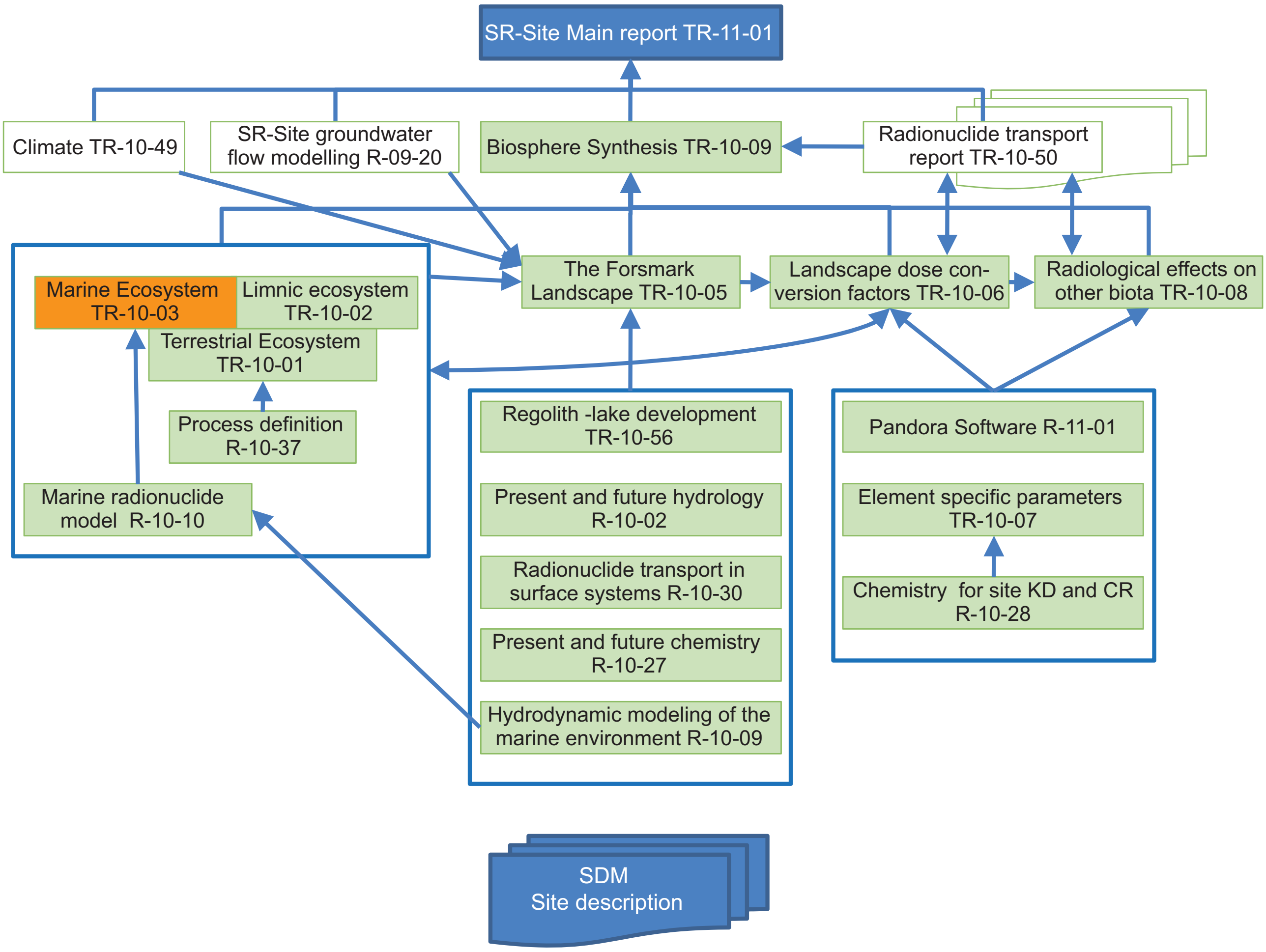

Figure 2-1. *The hierarchy of reports produced in the SR-Site Biosphere project. This report (highlighted in yellow) and its connection with other reports produced within SR-Site Biosphere. Arrows indicate major interactions during project work flow of analysis and results, but interactions have been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

2.2 Contents of the report – a brief overview

Elements are transported and accumulated in the biosphere to different extents depending on the properties of the element and the conditions it is exposed to. The approach used in this report describes a number of different aspects of pools and fluxes of elements in the marine ecosystems of today as well as historical and future aspects regarded as important in the context of modelling radionuclide transfer and accumulation in a developing surface system (i.e. here the ecosystems above the geosphere).

The marine areas in Forsmark and Laxemar-Simpevarp were divided into a number of separate units called basins (see Section 4-1). These delimitations were made in line with the overall strategy of the project (Sr-Site) to assess the long term safety of a deep repository for nuclear waste, e.g. /Lindborg et al. 2006/. Within the assessed time period, a perspective of several thousand years, the landscape will be transformed, largely as a result of ongoing and predicted postglacial shoreline displacement in the area. Due to these processes, marine areas will turn into lakes, and lakes into wetlands and other terrestrial ecosystems, including agricultural areas. Elements in the marine ecosystem basins may thus accumulate in the geographical area and later be integrated in a limnic and eventually a terrestrial system.

The first chapters in this report (Chapter 1–3) provide an overview and a synthesis of site data from the sites. The subsequent chapters (Chapter 4–6) describe different aspects of pools and fluxes of elements that are investigated using site-specific data and literature in order to underpin models describing element transport and accumulation in the marine ecosystems. Chapter 7 describes the long term evolution of the marine ecosystem and Chapter 8 discusses processes and interactions considered. Chapter 9 describes a model for long term development of the oceanography in Forsmark and an alternative way of modeling radionuclides in marine ecosystems. The last part of the report presents the parameterization of marine parameters in the Radionuclide model, Chapter 10 and in Chapter 11 a concluding description of the marine ecosystems in Forsmark and Laxemar-Simpevarp is presented.

Chapter 3, *Descriptions of marine ecosystem characteristics,* describes chemical, physical, biological and climatological characteristics. The sources for this chapter are primarily investigations conducted at the sites, but references are also from other similar studies. Data presented in this chapter is the primary foundation for the model calculations described in the following chapters.

The structure and assumptions made in the ecosystem modeling are described in Chapter 4, *The marine ecosystem – conceptual and quantitative carbon models.* This chapter includes a conceptual description of the marine ecosystem models and mass balance models as well as methods and references for calculations of input data to the models.

A separate chapter (Chapter 5) is assigned to an *Oceanographic model.* It contains a brief description of present oceanographic features of the sites, the methods used and results from the oceanographic modelling.

Chapter 6, *Marine ecosystem – ecosystem models, mass balances and elemental composition,* is the chapter where all ecosystem results are presented. Initially, the modeling results representing the spatial distribution of carbon in the considered marine ecosystems are presented. Then the results of mass balance calculations and the abundance and distribution in the ecosystem of carbon and other elements are presented, and finally five specific basins from each site are described in more detail.

Chapter 7*, Long term evolution of the marine ecosystem,* describes the effect of major forcing factors on the longterm development of marine ecosystems, the historical development and the potential future development of the marine ecosystems in Forsmark and Laxemar-Simpevarp.

Couplings to the interaction matrix (Chapter 8), describes a systematic approach to identify processes of importance for transfer and accumulation of radionuclides in the safety assessment. The processes described in the "Interaction matrix" covered in this report are presented, together with a brief description of how important processes are include in the radionuclide modelling (Chapter 10 in /Andersson 2010/) in SR-site.

Chapter 9, *High-resolution hydrodynamic modelling of the marine environment at Forsmark between 6500 BC and 9000 AD, and complementary ecosystem- and radionuclide models*, includes the description of a high-resolution modelling of the hydrodynamic processes in the marine environment for present conditions and projections between 6500 BC and 9000 AD and in addition, a short presentation of the results from an alternative method to model transfer of radionuclides in a marine ecosystem is included.

In Chapter 10 *Radionuclide model parameterization for the marine ecosystems in Forsmark and Laxemar-Simpevarp*, the definitions and the development of the parameters used in the Radionuclide model (Chapter 10 in /Andersson 2010/) is presented.

Chapter 11, *A concluding description of the marine ecosystems in Forsmark and Laxemar-Simpevarp*, contains a synthesis of the description of the marine ecosystems at the two sites, considering processes of importance for the transfer and accumulation of radionuclides and the long term development of the marine ecosystems.

2.3 Delimitations and definitions

When the two sites are discussed in a general sense 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, modelling at the regional scale. 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 were defined; the Simpevarp subarea and the Laxemar subarea, and preliminary site descriptions were compiled 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 for the sake of clarity and to avoid confusion.

As mentioned earlier in this report, the site description divides the landscape into three ecosystems: the limnic, marine and terrestrial ecosystems. The main 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, water availability to plants and decomposition. 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 borderline between land and water is diffuse and difficult to identify. In most cases, the interface on a freshwater shore is clearly distinguished, covering a transect of a few metres (the littoral zone of a lake), whereas a sea shore, with larger fluctuations in water level, might cover a transect of tens of metres. In the ecosystem models, these zones are classified as wetlands and treated as parts of the terrestrial ecosystem in order to handle all kinds of wetlands in a similar way. The interface zones should be regarded as a transient stage in the succession of sea basins/lakes to land.

The definition of the marine ecosystem in this report is straightforward:

The ecosystem in the area below the water level at mean sea level that is delimited by the lower limit of the shoreline and has an exchange of water with the Baltic Sea, and that is above the bedrock. The uppermost 10 cm of the sediment is included in our definition of the marine ecosystem.

The shoreline sets the boundary between near-sea lakes, not connected to the sea at mean sea level, and the sea. In both Forsmark and Laxemar-Simpevarp, wetlands and small lakes are close to the shore and can be connected to the sea at high water levels. Field studies have been conducted in these areas to confirm the position of the shoreline, see /Brunberg et al. 2004a/ for Forsmark and /Brunberg et al. 2004b/ for the Laxemar-Simpevarp area. The definition of top sediment is discussed further in Section 4.

Some major terms and concepts used in the report are presented below (Table 2-1). The definitions are in accordance with /Chapin et al. 2002/ and /Begon et al. 1996/ unless otherwise stated.

Table 2-1. Definitions for major terms and concepts used in this report and in SR-site.

Concept/term	Definition
abiotic	Non-living physical or chemical component or process.
autotroph	Organism that utilises photosynthesis or chemosynthesis to build up organic carbon.
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	A part of the landscape that potentially will receive radionuclides released from a repository.
biotic	Living ecosystem component or process involving living organisms.
climate cases	SR-Site describes climate cases, which are possible future climate developments at Forsmark.
climate domain	A climatically determined environment with a specific set of characteristic processes of importance for repository safety.
conceptual model	A qualitative description of important components and their interactions.
CR (concentration ratio)	The CR, concentration ratios is used to calculated uptake of radionuclides by biota and is defined as the element-specific concentration ratios between the concentrations biota, and the surrounding media (soil or surface water).
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).
deterministic analysis	Analysis using, for key parameters, single numerical values (taken to have a probability of 1), leading to a single value for the result.
discharge points /area	The area where deep ground water reaches the ground surface.

Concept/term	Definition
dose	Dose, as used in SR-site refers to the mean annual dose of the most exposed group. The calculated dose accounts for retention of radionuclides in the human body and exposure from daughter radionuclides, as well as radiation sensitivities of different tissues and organs.
dose rates to biota	Dose rates for biota represents mean absorbed dose rates in the whole body of a given radionuclide and are expressed uGy h^{-1}.
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 model	Conceptual or numerical representation of an ecosystem, divided into compartments, and its included processes.
effective dose	(or effective dose equivalent). A measure of dose designed to reflect the risk associated with the dose, calculated as the weighted sum of the dose equivalents in the different tissues of the body.
ERICA tool	Computer software used to obtain activity concentrations and radiological effects on different types of non-human biota.
exposure	The act or condition of being subject to irradiation. (Exposure should not be used as a synonym for dose. Dose is a measure of the effects of exposure.)External exposure. Exposure to radiation from a source outside the body. Internal exposure. Exposure to radiation from a source within the body.
flux	Flow of energy or material from one pool to another.
food web	Group of organisms that are linked together by the transfer of energy and nutrients that originates from the same source.
functional group	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.
GPP (gross primary production)	Total fixation of carbon by photosynthesis (cf. net primary production, NPP).
heterotroph	Organism that uses organic compounds produced by autotrophs.
hydrodynamic model	The hydrodynamic model gives outputs of annual mean flows between adjacent marine basins and water retention time for each individual basin.
hydrological model	Hydrological modelling performes simulation of surface and near surface water flow. Each model run have different environmental settings as input parameters The hydrological modelling utilises GIS, as well as MIKE SHE and ConnectFlow as numerical modelling tools.
infilling	Infill describes the combined processes of sedimentation and organogenic deposition turning lakes into wetlands.
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.
Kd	Soil/liquid partition coefficients are defined as the ratio between the element concentrations in the solid and liquid phases.
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 represent 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 model	The mass balance model calculates the total sum of major sources and sinks for individual chemical elements in the landscape.
most exposed group	In SR-Site, the expression most exposed group refers to the group of individuals subjected to the highest exposure during any time period.
Net ecosystem production (NEP)	The balance between gross primary production and ecosystem respiration.
NPP (net primary production)	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.
Pool	Quantity of energy or material in an ecosystem compartment such as plants or soil.
probabilistic analysis	Mathematical analysis of stochastic (random) events or processes and their consequences.

Concept/term	Definition
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 is included in the radionuclide model, whereas exposure of non-human biota is calculated separately. The radionuclide model utilises PANDORA and Ecolego modelling tools.
RDM (regolith depth model)	The RDM interpolates observation points of analysed vertical distribution of regolith into 3-dimentional regolith extension.
regolith	All matter overlying the bedrock are collectively denominated regolith. This includes both minerogenic and organogenic deposits as well as antropogenic landfills.
respiration	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.
RLDM (coupled regolith-lake development model)	The RLDM is divided into a marine module that predicts the sediment dynamics caused by waves, and a lake module that predicts infilling of lakes. The model forecasts regolith distribution and thickness of different strata at time-steps.
sub-catchment	The drainage area of a biosphere object minus the drainage area of the inlets to the object.
terrestrialisation	The transfer of an aquatic ecosystem (marine or limnic) to a terrestrial ecosystem.
watershed	The drainage area of a biosphere object.

3 Descriptions of marine ecosystem characteristics

3.1 Chemical and physical characteristics

3.1.1 Introduction

The Baltic Sea is a semi-enclosed sea with a large net freshwater supply and a strong permanent halocline at 60–70 m. The Baltic Sea consists of three major sub-basins separated by narrow connections (thresholds/sills), namely from south to north: the Baltic Proper, the Bothnian Sea and the Gulf of Bothnia /Sjöberg 1997/. Forsmark is situated in the Bothnian Sea and Laxemar-Simpevarp in the Baltic Proper.

In the site investigations, seawater has been sampled at Forsmark and Laxemar-Simpevarp, biweekly to monthly, since 2002 and analyzed for chemical and physical parameters. Sampling covers both the inner archipelago and the open sea. Since 2004 the sites have been sampled twelve times a year. Marine sampling sites in Forsmark and Laxemar-Simpevarp are shown in Appendix 1 and 2.

The seawater has been analyzed for a large number of parameters: electrical conductivity, pH, dissolved oxygen, salinity, turbidity, and water temperature. Chemical analyses of major constituents have also been performed: nutrient salts, carbon species, trace metals and isotopes. The surface water sampling and results are described in detail in /Nilsson et al. 2003, Nilsson and Borgiel 2004, 2005, 2007, Ericsson and Engdahl 2004a, b, 2007, 2008/.

In the following sections, data from the site investigations are compared to data from the Baltic in general, with a special focus on the Bothnian Sea and the Baltic Proper. General trends for some chemical and physical parameters are presented below for the Bothnian Sea and the Baltic Proper. These data are mainly taken from SMHI's national environmental monitoring programme and from HELCOM.

3.1.2 Temperature, salinity and oxygen

Temperature, salinity and oxygen are physical background parameters that govern water quality, biodiversity and organism recruitment in a semi-enclosed water body such as the Baltic Sea. The seawater temperature varies seasonally and in between years, and in the past few decades the summer temperature has shown a significant increase /Andersson and Andersson 2006/. The Baltic Sea is a relatively cold sea with a mean temperature of 5°C. Due to the large variations in weather and wind during the year, the surface water temperature in the Baltic Sea varies from winter temperatures near zero to summer temperatures above 20°C. The warmer surface temperature creates a strong thermocline. In the springtime the thermocline is close to the surface, but descends in the summer. In the southern parts of the Baltic, the summer thermocline is normally located at a depth of 20–30 m. In sheltered areas a secondary thermocline at a depth of around 2–3 m can develop, with temperatures above 20°C. Storms that stir up the water break the thermocline in the autumn. In the deeper areas the temperature is fairly constant throughout the year at around 4–6°C.

Baltic surface waters are strongly influenced by discharge of freshwater from land i.e. runoff. Several large rivers discharge into the Baltic, creating a positive freshwater balance. Changes in runoff alter the salinity of surface waters, while inflows through the Sound and the Belt Sea alter the salinity of the deep water. Above the halocline the salinity is low and rather homogenous, and below the halocline there is a pronounced vertical stratification. The narrow and shallow passages between the Baltic Sea and the Kattegat limit the exchange of Baltic Sea water with saline water from the Kattegat. For this reason, salinity decreases from south to north in the Baltic Sea. In the Gulf of Bothnia the salinity is around 3.5 Practical Salinity Unit (psu)[1], in the Bothnian Sea around 5.5 psu and in the Baltic Proper around 7 psu.

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[1] Salinity is a measure of the total amount of dissolved material, or the salt content, in water. Salinity is the number of grams (g) of material in 1,000 g of water. Practical Salinity Units (PSU) are often used to describe salinity: a salinity of 5‰ equals 5 psu.

The Baltic is highly stratified from the surface down to the halocline (60–70 m), from 7 psu above the halocline, increasing to 13 psu at the greatest depths (Baltic Proper). In the Bothnian Sea the salinity below the halocline fluctuates around 6 psu /Samuelsson 1996/. Stratification between the upper and lower layers inhibits surface and deep water mixing, thus preventing the oxygenated surface water from penetrating to great depth while hindering the transfer of phosphorus (which is abundant in the deep water) to the photic zone.

The salinity of the surface water (0–10 m) of the Bothnian Sea and the Baltic Proper has decreased in recent decades /Samuelsson 1996, Andersson and Andersson 2007/.

Statistics on temperature, pH, conductivity, salinity, oxgen and light penetration are shown in Tables 3-1 (Forsmark) and 3-2 (Laxemar-Simpevarp) and compared with data from the environmental monitoring programmes in the same areas /SKVF 2007, KVF 2007/.

Forsmark

In Forsmark the annual mean water temperature is 7.9°C, the mean summer and winter temperatures are 15.9°C and 2.2°C respectively. The sample points included in the site investigations are in relation to the rest of the Baltic considered as relatively shallow areas where the deep thermocline is undeveloped. No evident secondary thermocline in the shallow more sheltered samplings points can be seen in Forsmark.

The parameters do not vary significantly between sampling sites in Forsmark except for salinity where a gradient of freshwater influence can be seen from the inner bays (PFM[2]00065, PFM00064) to the sampling sites further out (PFM0063, PFM00062). The mean salinity in the outer sampling site (PFM000082) 4.6 psu and the SKVF sites located even further offshore has a mean of 5.1 psu.

In comparison with the Gulf of Bothnia, the salinity in the Forsmark area (shallow bays near coast water) is somewhat lower, probably due to freshwater runoff from the land.

Laxemar-Simpevarp

The annual mean water temperature in the Laxemar-Simpevarp area is 7.2°C, while the mean summer and winter temperatures are 10.8°C and 4.5°C, respectively. The fact that the annual mean temperature in Forsmark is higher than Laxemar-Simpevarp, is most probably an effect of shallower sampling sites in Forsmark. Compared with the rest of the Baltic, the sampling points included in the site investigations are relatively shallow areas where the deep thermocline is undeveloped. No evident secondary thermocline in the shallow more sheltered samplings points can be seen in Laxemar-Simpevarp area.

The parameters do not vary significantly between sampling sites in Laxemar-Simpevarp except for salinity and light penetration. The mean salinity in the inner bays (PSM[3]002062, PSM002064), is somewhat lower than at the more offshore sites (PSM002060 and PSM002061). The most offshore sampling site PSM002060 has a mean salinity in accordance with the environmental monitoring in the area, 6.8 psu /KVF 2007/. The light penetration in the bays is low, however the mean for the whole area is largely influenced by the values from the offshore site PSM0002060 (mean light penetration 23 m).

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[2] PFM00000 is sampling number form the site investigation program, and the letters denote Point Forsmark Modelarea.

[3] PSM00000 is sampling number form the site investigation program, and the letters denote Point Simpevarp Modelarea.

Table 3-1. Descriptive statistics for temperature, salinity, conductivity, pH oxygen and light penetration at all sampling sites in Forsmark (PFM00062, PFM00063, PFM00064, PFM00065, PFM00082), from May 2002 until August 2006, in comparison with data from the national surveillance program during 2002–2005, in the Forsmark area, supplied by Svealands KustvattenVårdsFörbund (SKVF 2007).

	Mean	Median	Std. Dev.	Min	Max	25%-tile	75%-tile	N	SKVF 2002–2005
Water Temperature (C°)	7.9	6.1	6.7	–0.4	23.2	1.4	14	739	9.2
pH	7.9	7.9	0.3	6.9	8.9	7.8	8.1	731	7.9[1]
Conductivity (mS/m)	810	860	150	46	960	810	900	739	515[1]
Salinity (psu)	4.5	4.8	0.9	0.2	5.4	4.5	5	737	5.1
Oxygen (mg/l)	10.8	10.7	8.6	9.4	12.7	10.3	13.3	739	10.5
Sample depth (m)	4.2	4.1	1.6	0.9	7.3			743	19
Light penetration (m)	2.7	2.8	1.3	0.3	6.4	1.4	3.8	192	4.6

[1] /Gustavson et al. 2000/.

Table 3-2. Statistics on temperature, salinity, conductivity, pH and oxygen at all sampling sites in Laxemar-Simpevarp (PSM PSM002060, PSM002061, PSM002062, PSM002063 and PSM002064), from May 2002 to August 2006, compared with data from the national monitoring programme 2001–2007 in the Simpevarp area, supplied by Kalmar läns Kustvattenvårdsförbund (KVF).

	Mean	Median	Std. Dev.	Min	Max	25%-tile	75%-tile	N	KVF 2001–2007
Water Temperature (C°)	7.2	6.0	5.1	–0.2	24	3.2	9.8	2,764	8.3
pH	7.7	7.8	0.4	6.6	9	7.5	8.0	2,577	–
Conductivity (mS/m)	1,130	1,160	110	200	1,300	1,100	1,200	2,700	–
Salinity (psu)	6.4	6.6	0.7	1.0	8	6.2	6.8	2,700	6.8
Oxygen (mg/l)	10.0	11.0	3.4	0.1	15	9	12	2,761	7.8
Sample depth (m)	9.4	7.0	7.6	0.5	30	3	14	2,634	8.3
Light penetration (m)	5.5	3.9	4.0	1	23	2.7	8	206	8.7

3.1.3 Nutrients and carbon

Quantitatively, the three most important nutrient elements are nitrogen (chiefly as nitrate, NO_3^-), phosphorus (as phosphate PO_4^{3-}) and for those species that require it for construction of their skeleton, dissolved silica (SiO_2 for brevity, but mainly as $Si(OH)_4$. These nutrients are heavily utilized in the photic zone, where their availability can limit primary production, and they can be almost totally depleted in surface waters. Consumption and decomposition of organic matter sinking from surface waters return the nutrients to solution.

Inorganic nutrients, phosphate, nitrite, nitrate and silicate show clear annual cycles in the Baltic /Andersson and Andersson 2006/. In the winter when the uptake of biological nutrients is low, nutrient concentrations increase and reach maximum winter values, just before the onset of the spring bloom. In the spring and summer, most of the nutrients are taken up by plankton, and the concentration of the limiting inorganic component normally falls below the detection limit. The winter concentrations of nutrients in the surface layer normally vary as follows: phosphate from 15.5 µg L^{-1} in Skagerrak to 1.9 µg L^{-1} in the Gulf of Bothnia, with somewhat higher values in the Sound and in the Åland Sea. Nitrite and nitrate concentrations range from 42 µg L^{-1} in the Åland Sea to 70 µg L^{-1} in Skagerrak with higher concentrations of up to 98 µg L^{-1} in the Sound, the Northern Baltic proper and in the Gulf of Bothnia /Andersson and Andersson 2006/. Total fractions of phosphate and nitrogen (tot-P and tot-N) also show an annual cycle in the surface layer, although it is not as pronounced as for the inorganic fractions. Tot-N and tot-P does also remain at a rather high level throughout the year. In the Baltic proper and in areas with sporadic water exchange, no typical variations occur over a year. In these areas, variations in nutrient concentrations are more closely linked to water exchange than seasonal variation /Andersson and Andersson 2006/.

In the Bothnian Sea (data from four stations), there are generally negative long term trends for P-tot and generally a positive trend for tot-N parameters. In the Western Gotland Basin (represented by two stations), there are generally positive long term trends for tot-P and tot-N parameters /Andersson and Andersson 2006/.

POC can be an indirect rough measure of biomass, but consists of both dead and living material. The amount of carbon, particulate and dissolved organic (POC and DOC) and dissolved inorganic (DIC) in the Baltic is also strongly affected by runoff and precipitation.

Analyzed parameters reflecting the nutrient load in the coastal ecosystem at the sites are presented in Tables 3-3 (Forsmark) and 3-4 (Laxemar-Simpevarp).

Table 3-3. Statistics on nutrients and carbon at all sampling sites in Forsmark (PFM00062, PFM00063, PFM00064, PFM00065, PFM00082), from May 2002 to August 2006 compared with environmental monitoring data from the same area in the Baltic. Note that the monitoring data is from further offshore than the samples in this study.

	Mean	Median	Std. dev.	Min	Max	N	25%-tile	75%-tile	Ref. from the Baltic
N-tot (µg/l)	472	325	387	218	2,750	267	273	490	269[1]
NO_3 (µg/l)	7	1	25	1	63	20	3	9	781
NO_2 (µg/l)	2	2	3	0	14	73	1	3	
NO_3+NO_2 (µg/l)	92	7	232	0	1,648	274	1	72	29[1]
NH_4 (ug/l)	13	3	26	0	185	274	2	10	4.81
NO_3+NO_2+ NH_4 (**DIN**)(µg/l)	101	12	244	0	1,710	286	2	71	0–158[1]
PON (µg/l)	65	53	45	11	317	263	35	77	
P-tot (µg/l**)**	17	15	8	7	59	267	11	21	12.4[1]
PO_4 (**DIP**)((µg/l)	2	1	2	1	13	274	1	2	1.12, 2.6[1]
POP (µg/l)	10	8	6	1	46	267	6	13	
SIO_2 (µg/l)	751	469	919	98	5,510	273	287	716	493[1], 1,010[2]. 36–557[3]
POC (µg/l)	427	335	293	80	2,170	260	230	514	20.2 (uM) [2]
TOC (mg/l)	5	4	4	1	20	270	4	5	306 (uM) [2]
DOC (mg/l)	5	4	3	1	21	270	3	5	190 (uM) [2]
DIC (mg/l)	11	12	5	0.3	27	269	8	14	14–18 ug/kg[4]
N/P[5]	61	52	31	26	215	267	44	64	23[1]
C/N[5]	14	14	7	1	65	267	10	17	
C/P[5]	783	710	16	1	3,113	267	552	938	
DIN/DIP[5]	80	17	169	1	1,108	274	5	83	

1. /SVKF 2007/.
2. /Gustafsson 2000/.
3. /HELCOM 2007/.
4. /Thomas and Schneider 1999/.
5. Molar ratio.

Table 3-4. Statistics for nutrients and carbon at all sampling sites in Laxemar-Simpevarp (PSM002060, PSM002061, PSM002062[1], PSM002064), from May 2002 to December 2006 compared with environmental monitoring data from the same area in the Baltic. Note that the monitoring data is from further offshore than the samples in this study.

	Mean	Median	Std. dev.	Min.	Max.	N	25%-tile	75%-tile	Ref. from the Baltic
N-tot (µg/l)	487	455	206	220	1,410	446	315	598	294 ug/l[2]
NO$_3$ (µg/l)	99	84	100	0.3	523	38	31	128	17 ug/l[2]
NO$_2$ (ug/l)	4	3	4	0.2	23	111	0.8	6	2.8 ug/l[2]
NO$_3$+NO$_2$ (ug/l)	52	21	75	0.2	587	448	0.8	81	42–70
NH$_4$ (ug/l)	45	9	98	1	687	448	2	40	4.2 ug/l[2]
NO$_3$+NO$_2$+ NH$_4$ (**DIN**) (ug/l)	83	23	124	0.8	690	448	2	125	
PON (ug/l)	63	49	53	5	348	439	24	90	
P-tot (ug/l)	29	23	28	12	376	448	20	27	28 ug/l[2] 84–98
PO$_4$ (**DIP**) ug/l)	9	5	14	1	181	448	2	12	19 ug/l[2]
POP (ug/l)	13	9	22	1	198	441	5	13	
SIO$_2$ (ug/l)	1,100	579	1,197	32	7,130	448	344	1,380	84–1,344 ug/l[2]
POC (ug/l)	436	330	386	21	2,430	437	160	573	
TOC (mg/l)	6	5	3	3	26	450	4	7	59 ug/l[2]
DOC (mg/l)	6	5	3	2	26	449	4	7	
DIC (mg/l)	15	16	3	4	22	448	14	17	
N/P[3]	44	41	20	0	107	448	29	59	16–150[2]
C/N[3]	15	15	3	5	23	446	13	17	
C/P[3]	654	571	335	30	1,944	448	430	820	
DIN/DIP3	69	12	209	18	3,894	448	3	71	

1. The location of PSM002062 in Borholmsfjärden has been changed to a slightly deeper site, PSM007097, since May 2005, but in the calculations the site was considered the same as PSM002062.

2. Kalmar läns kustvattenvårdförbund (KVF), mean values during 2001–2007.

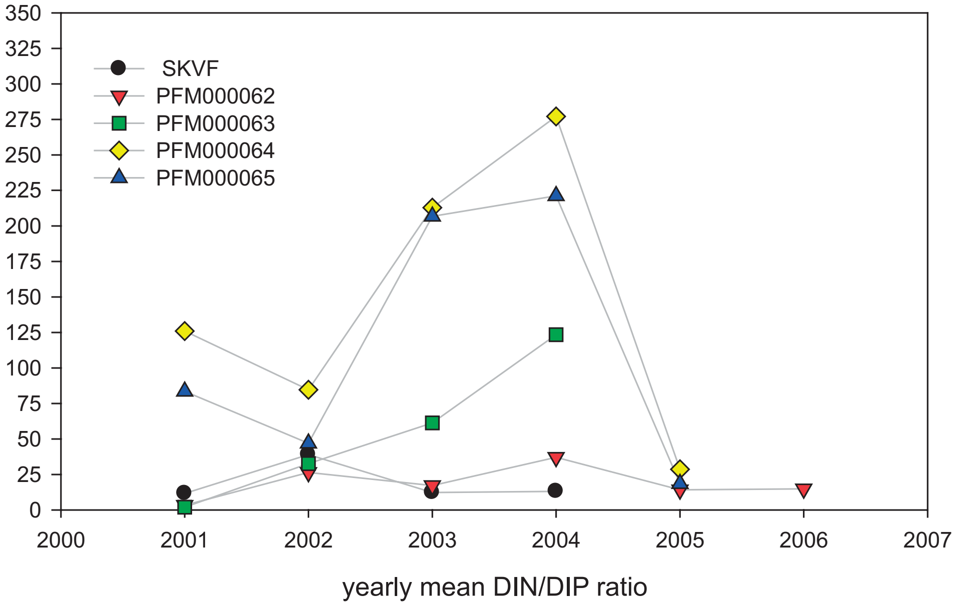
3. Molar ratio.

Forsmark

In the Baltic Sea the inorganic ratio N/P is normally below 16 (molar ratio), except in the Bothnian Bay where it can be as high as 150. In the site investigation area at Forsmark, the ratio has been between 26 and 215, with a annual mean of 61, which suggest that phosphorus is the limiting nutrient in this ecosystem. Although, looking at the seasonality during a year instead (Figure 3-1), the DIN/DIP ratio is very low during summer months, suggesting that during this period N is the limiting nutrient. This is also supported by the blooms of nitrogen fixating cyanobacteria occurring in the area from time to time during summer. In comparison with Swedish Environmental Quality Criteria (EQC) /Naturvårdsverket 1999/ the mean and median values of total nitrogen concentration measured in Forsmark are regarded as low to moderately high, and the corresponding values for total phosphorus are regarded as low. The inorganic fractions of nitrogen (NH$_4$, NO$_3$ and NO$_2$) and phosphorus (PO$_4$) are also regarded as low in comparison with Swedish EQC.

General trends in the same area of the Baltic (SMHI data) are positive for dissolved inorganic nitrogen (DIN) and negative for total phosphorus (P-tot) /Andersson and Andersson 2006/.

No seasonal change in carbon concentrations is evident in the coastal area of Forsmark, Figure 3-2.



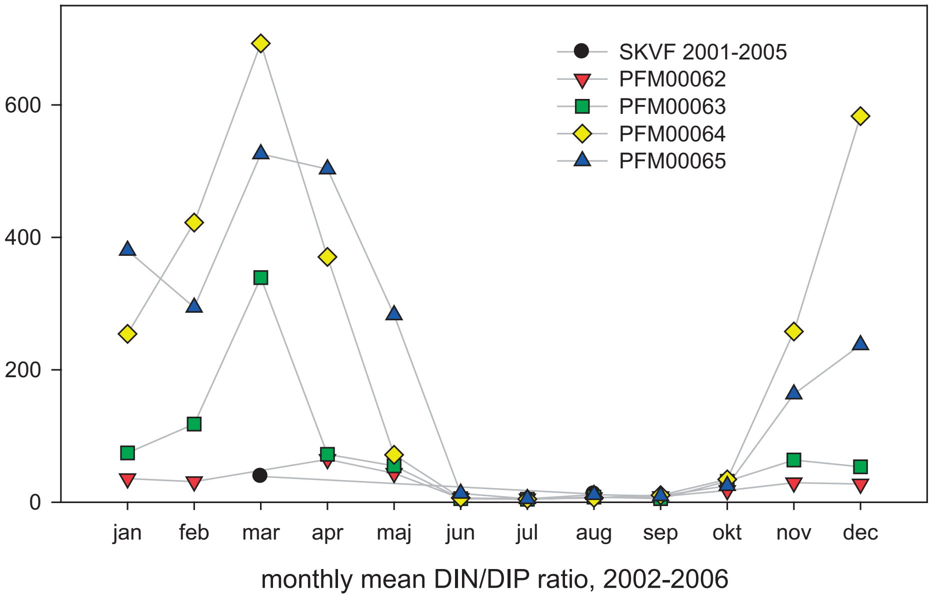


Figure 3-1. *Yearly mean (upper graph) and monthly mean (bottom graph) for the molar DIN/DIP ratio at PFM00062, PFM0006, PFM0006, PFM00064 and PFM00065 in Forsmark /Nilsson and Borgiel 2007/ and from national environmental monitoring in the area /SKVF 2007/ (only sampling points sampled at leastonce a month are included), see also Table 3-3.*

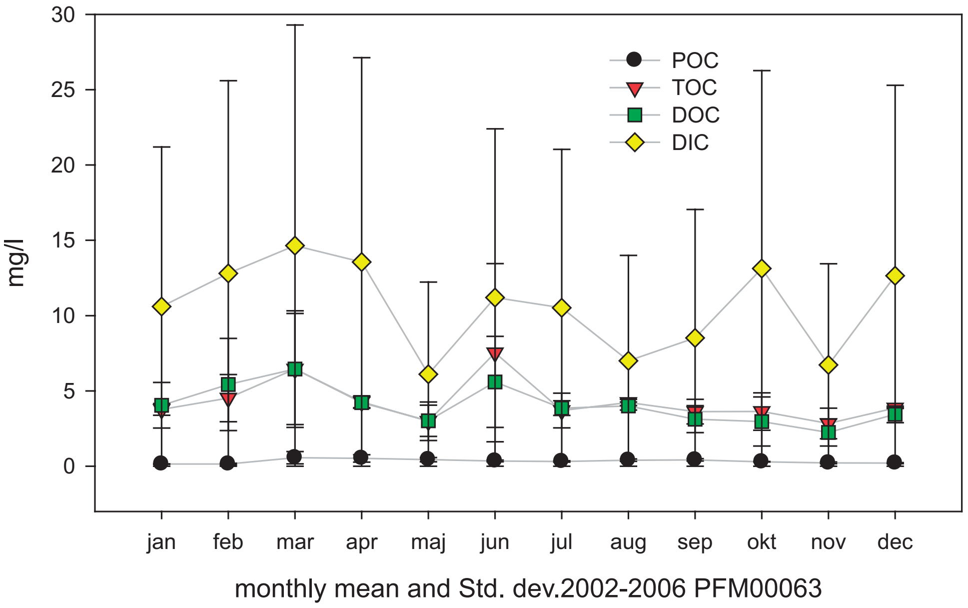


Figure 3-2. *Monthly mean and standard deviation for DIC, DOC, POC and TOC at PFM00063 in 2002–2006 in Forsmark /Nilsson and Borgiel 2007.*

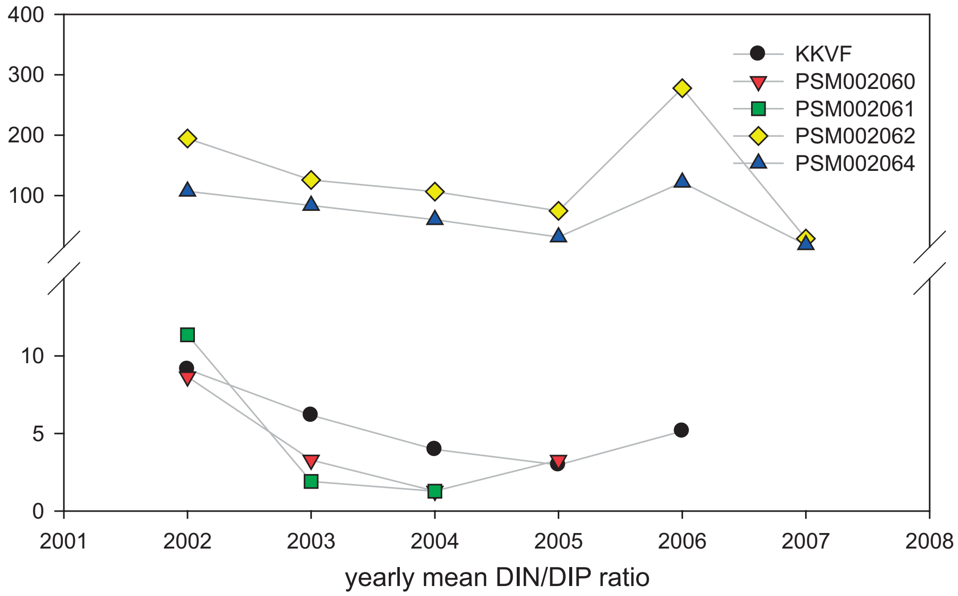
Laxemar-Simpevarp

In Laxemar-Simpevarp nutrient and carbon concentrations differ between the bays (PSM002062, PSM002064) and the outer sampling sites (PSM002060, PSM002061), with higher nutrient concentrations in the bays. Concentrations and trends at the outer sampling sites were similar to environmental monitoring data for the area /KVF 2007/. Data for the whole area is presented in Table 3-4 and comparison between the various sampling sites is shown in Figure 3-3 and 3-4. General trends for the nearby area in the Baltic (the Baltic Proper), are positive for dissolved inorganic nitrogen (DIN) and for total phosphorus (P-tot) /Andersson and Andersson 2006/.

The DIN/DIP ratio is generally higher in bays in this regional area /KVF 2007/, which can also be seen in Laxemar-Simpevarp (Figures 3-3 and 3-4), where the coastal sampling stations show higher ratios. The seasonality in the DIN/DIP ratio is more pronounced in the outer sampling stations. It seems like phosphorus is the limiting nutrient in the bays and nitrogen in the more off -shore areas.

In comparison with Swedish Environmental Quality Criteria (EQC) /Naturvårdsverket 1999/, the mean and median values for total nitrogen concentration measured in Laxemar-Simpevarp are regarded as low to moderately high, and the corresponding values for total phosphorus are regarded as low. The inorganic fractions of nitrogen (NO_3 and NO_2) and phosphorus (PO_4) are also regarded as low in comparison with Swedish EQC. Mean concentrations of PO_4 are, however, in the range for high values according to the Swedish EQC.

The variation of carbon concentration in coastal waters in the Laxemar-Simpevarp areas is highly dependent on runoff from land and shows no significant seasonality, Figure 3-4.



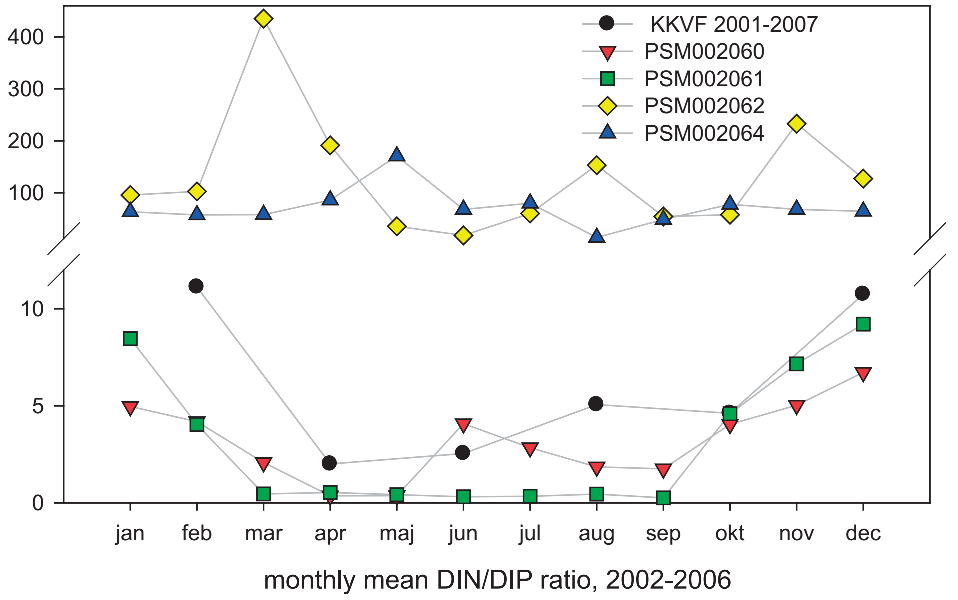


Figure 3-3. *Yearly mean (upper graph) and monthly mean (bottom graph) for molar DIN/DIP ratio at (PSM002060, PSM002061, PSM002062, PSM002064) in Laxemar-Simpevarp during 2002–2006 and at a sampling site near Laxemar-Simpevarp in the environmental monitoring programme /KVF 2007/.*

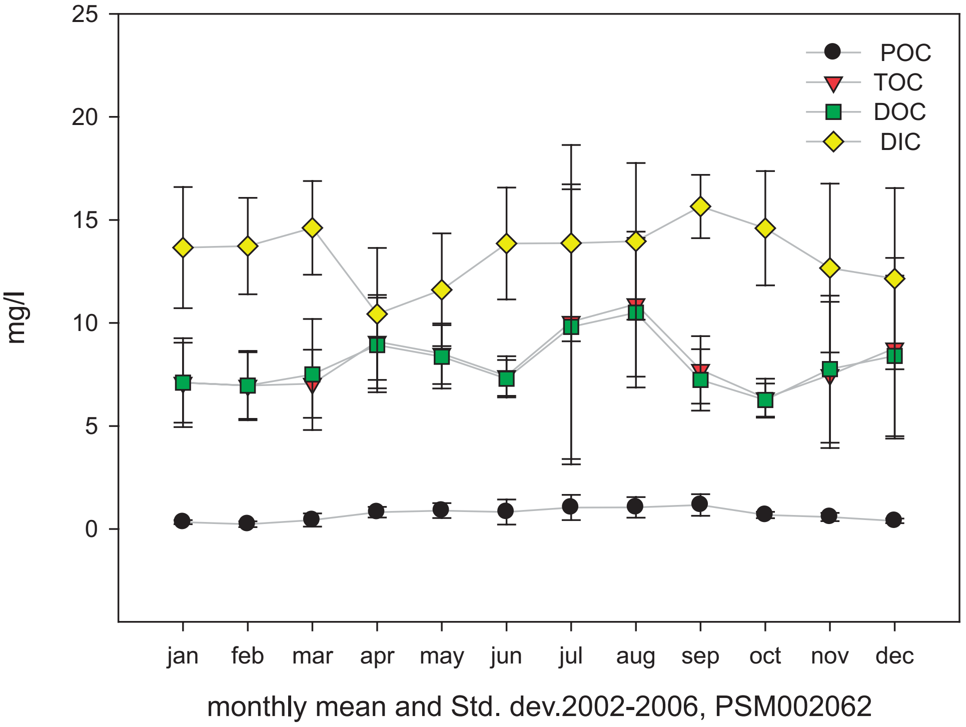


Figure 3-4. *Monthly mean for the DIC, DOC, POC and TOC at PSM002062, in Laxemar-Simpevarp, 2002–2006. /Ericsson and Engdahl 2007/.*

3.1.4 Major and minor constituents

Major constituents of seawater are those ions that occur in concentrations greater than 1 part per million (1×10^{-6}) ppm by weight. They account for over 99.9% of the salinity of seawater, which is generally defined as the sum of all the ions in seawater. The remainders of the ions present in seawater, are in the form of minor and trace constituents. The distinction between the two is somewhat ill-defined, but normally minor constituents are considered to be those with concentrations of between 1×10^{-6} and 1×10^{-9} by weight, and trace constituents to be those elements with concentrations of less than 1×10^{-9} by weight (1 part per billion or ppb).

Most of the major constituents exhibit conservative behaviour that is their concentrations in seawater are not significantly changed by the biological or chemical reactions that take place in seawater. Exceptions to the conservative behaviour among the major constituents are carbon (C), calcium (Ca) and silicon (Si).

The basic water analysis include the major constituents Na, K, Ca, Mg, Sr, S, SO_4^{2-}, Cl^-, Si and HCO_3^- as well as the minor constituents Fe, Li, Mn, F^-, I^- and HS^-. A selection of parameters is shown in Tables 3-5 (Forsmark) and 3-6 (Laxemar-Simpevarp), compared with data from other studies in the same or adjacent areas. Most major and minor constituents measured in the site investigations are of the same order of magnitude as reported elsewhere, which supports the accuracy of site investigation data.

Forsmark and Laxemar-Simpevarp

Statistics for some major and minor constituents of seawater, sampled in Forsmark and Laxemar-Simpevarp, are presented in Table 3-5 (Forsmark) and 3-6 (Laxemar-Simpevarp). The concentrations are generally of the same order of magnitude as reported elsewhere.

3.1.5 Trace constituents – Forsmark and Laxemar-Simpevarp

In contrast to most major constituents, nearly all of the minor and trace dissolved constituents exhibit non-conservative behaviour, i.e. their concentrations are significantly changed by biological and chemical reactions in seawater.

Table 3-5. Statistics for some major and minor constituents in seawater at all sampling sites in Forsmark (PFM00062, PFM00063, PFM00064, PFM00065, PFM00082), from May 2002 to August 2006.

	Mean	Median	Std. Dev.	Min.	Max.	N	75%-tile	25%-tile	Other studies
Na (mg/l)	1,300	1,400	290	70	1,600	262	1,500	1,400	1,040–2,230[1]
K (mg/l)	50	50	10	4	60	262	60	50	38.1–137[1]
Ca (mg/l)	70	70	6	40	90	262	80	70	49.7–101[1]
Mg (mg/l)	160	170	40	10	200	262	180	160	126–436[1]
HCO_3 (mg/l)	80	80	20	60	220	268	80	70	28[4]
Cl (mg/l)	2,500	2,600	550	120	3,000	270	2,700	2,500	1.95×10^{4}[4]
SO_4 (mg/l)	350	370	80	50	790	270	130	110	9.05×10^{2}[4]
Fe (µg/l)[2]	80	20	190	0.4	1,200	85	60	10	< 500–700[1]
Mn (µg/l)[2]	10	4	20	0.02	90	84	60	10	2–3[1]
Li (µg/l)	20	20	6	3	40	253	30	20	180[4]
Sr (µg/l)[2]	980	1,000	200	100	1,300	262	1,000	980	566–2,560[3]
I (µg/l)	10	9	8	4	80	195	12	9	60[4]

1. /Porcelli et al. 1997/.
2. Some (in some cases all) of the reported values from analyses were below the detection limit and reported as < values. To calculate a mean value these results were divided by 2.
3. /Andersson et al. 1992/.
4. /Bearman 2005/. Average value for all oceans.

Table 3-6. Statistics for some major and minor constituents in seawater at all sampling sites in Laxemar-Simpevarp (PSM002060, PSM002061, PSM002062[1], PSM002064), from October 2002 to December 2006.

	Mean	Median	Std. Dev.	Min.	Max.	N	75%-tile	25%-tile	Other studies
Na (mg/l)	1,800	1,900	330	280	2,300	415	2,000	1,700	1,040–2,230[2]
K (mg/l)	70	70	10	10	90	415	80	60	38.1–137[2]
Ca (mg/l)	90	90	10	20	110	415	100	80	49.7–101[2]
Mg (mg/l)	210	230	40	30	270	415	240	200	126–436[2]
HCO_3 (mg/l)	90	90	20	20	120	415	90	80	28[5]
Cl (mg/l)	3,300	3,500	640	260	4,100	415	3,700	3,000	1.95×10^{4}[5]
SO_4 (mg/l)	470	500	90	50	620	415	530	430	9.05×10^{2}[5]
Fe (µg/l)[3]	80	20	190	1	2,900	414	70	10	< 500–700[2]
Mn (µg/l)[3]	420	5	600	0.5	84,000	414	20	2	2–3[2]
Li (µg/l)	30	30	9	9	50	414	30	30	180[5]
Sr (µg/l)	1,300	1,400	240	240	1,800	415	1,500	1,300	566–2,560[4]
I (µg/l)	20	10	7	7	40	81	20	10	60[5]

1. The location of PSM002062 in Borholmsfjärden has been changed to a slightly deeper site, PSM007097 since May 2005, but in the calculations the site was considered the same as PSM002062.
2. /Porcelli et al. 1997/.
3. Some (in some cases all) of the reported values from analyses were the below detection limit and reported as < values. To calculate a mean value these results were divided by 2.
4. /Andersson et al. 1992/.
5. /Bearman 2005/. Average value for all oceans.

Concentrations of trace constituents in the Baltic Sea are higher than in the North Atlantic (regarded as less influenced by human impact), and in general concentrations of dissolved and particle-bound cadmium (Cd), lead (Pb) and zinc (Zn) are higher in the western Baltic Sea, while the concentrations of dissolved copper (Cu) and total mercury (Hg) are slightly elevated in the Baltic Proper compared with the rest of the Baltic /Pohl and Hennings 2003, HELCOM 2003/.

In contrast to uranium, which can be dissolved easily during weathering and transported as an ion, thorium is almost insoluble and is to a large extent transported in the particulate phase. Dissolved uranium in oxygen-saturated waters from the Baltic Sea correlates very well with salinity and thus shows a general conservative behaviour /Andersson et al. 1995/.

Concentrations of trace constituents from the site investigations are shown in Tables 3-7 (Forsmark) and 3-8 (Laxemar-Simpevarp), compared with (if found) other reported values from the Baltic. Some of the analyzed trace constituents at the sites are higher than reported values for the Baltic in general (Cd, Pb and Cu I Forsmark for example), probably due to the anthropogenic influence in the area.

3.1.6 Isotopes – Forsmark and Laxemar-Simpevarp

The results of the site investigations regarding U-, Th-, Rn and Ra-isotopes are presented in Tables 3-9 (Forsmark) and 3-10 (Laxemar-Simpevarp) and when possible (due to available data) are compared to other reported values from the Baltic. U-238 and Th-232 seem to be slightly higher in the Forsmark area than in the Baltic. In Laxemar-Simpevarp all values for U and Th were below detection limit and thus it is difficult to compare results.

3.2 Climate and meteorology

Climatological parameters such as precipitation and atmospheric deposition, ice cover and runoff are presented in this section. Water temperature at the sites is presented in the previous section, 3.1.2.

The Baltic marine area is located within the west wind zone where cyclones coming from the west or southwest dominate the weather. Periodically, cyclones from a more southerly direction enter the region. The temperature climate of the region is largely coupled to the latitude of the main cyclonic tracks, although cloud cover also plays an important role, especially in the winter.

Winds of storm force, i.e. at least 25 ms^{-1}, are almost exclusively associated with deep cyclones that form west of Scandinavia and mainly occur from September to March.

The water mass of the Baltic marine area has a strong impact on the local climate in the region, in particular influencing air temperature, precipitation, cloud cover, irradiation and winds, and in coastal areas leading to pronounced gradients /HELCOM 2002/.

Table 3-7. Statistics for some trace constituents at all sampling sites i Forsmark (PFM00062, PFM00063, PFM00064, PFM00065, PFM00082), from May 2002 to August 2006, compared with reported concentrations from the Baltic Sea in general /HELCOM 2007/.

ng/l	Mean	Median	Standard Deviation	Minimum	Maximum	N	Other studies
Hg[1]	2	1	2	1	10	58	5–6
Cd[1]	30	16	60	2	390	58	12–16
Pb[1]	300	100	600	10	3,100	58	12–20
Cu	1,500	830	3,200	200	24,700	58	500–700
Zn[1]	5,000	1,700	14,000	580	106,000	58	600–1,000
U[1]	1,000	760	580	550	2,700	50	3,200[2]
Th[1]	80	50	60	10	320	50	10[2]

1. Some (in some cases all) of the reported values from analyses were below the detection limit and reported as < values. To calculate a mean value these results were divided by 2.

2. /Bearman 2005/. Average value for all oceans.

Table 3-8. Statistics for some trace constituents at all sampling sites in Laxemar-Simpevarp (PSM002060, PSM002061, PSM002062,1 PSM002064) from May 2002 to August 2006, compared with reported concentrations from the Baltic Sea in general /HELCOM 2007/.

ng/l	Mean	Median	Standard Deviation	Minimum	Maximum	N	Other studies
Hg[2]	1	1	0.3	1	2.2	29	5–6
Cd[2]	20	10	10	10	40	29	12–16
Pb[2]	190	50	200	50	640	29	12–20
Cu[2]	760	750	320	100	1,560	29	500–700
Zn[2] (ug/l)	4	3	5	1	28	29	0.6–1.0
U	770	750	110	560	1,140	29	3,200[3]
Th	90	100	20	10	100	29	10[3]

1. The location of PSM002062 in Borholmsfjärden has been changed to a slightly deeper site, PSM007097, since May 2005, but in the calculations the site was considered the same as PSM002062.
2. Some (in some cases all) of the reported values from analyses were below the detection limit and reported as < values. To calculate a mean value these results were divided by 2.
3. /Bearman 2005/. Average value for all oceans.

3.2.1 Precipitation and atmospheric deposition

In the winter, most of the precipitation is frontal (i.e. falls in connection with fronts), especially inland. In the summer, around half of the precipitation can be characterized as convective and is commonly greater inland than at sea. Winds are closely related to the cyclones and the pressure gradient around these systems.

In general, the precipitation over the Baltic Sea is greater in the south than in the north, and it is also often greater closer to the coast than further out to sea. Despite their locations, Forsmark is situated in an area with a somewhat higher precipitation (600–700 mm y^{-1}) than Laxemar-Simpevarp (600 mm y^{-1}) /Sjöberg 1997/.

Table 3-9. Statistics for some isotopes at all sampling sites in Forsmark (PFM00062, PFM00063, PFM00064, PFM00065, PFM00082), from May 2002 to August 2006, compared with reported concentrations from the Baltic Sea in general.

(mBq/kg)	Mean	Median	Std. dev.	Min	Max	N	Other studies
U-238[1]	31	25	23	7	100	14	10–14[2]
U-235[1]	25	25	0	25	25	12	0.32–0.36[3]
U-234[1]	32	25	23	9	100	14	10–12.2[3]
Th-230[1]	27	25	23	0.25	100	14	40–4 400[3]
Th-232[1]	25	25	0	25	25	12	0.2–0.9[2]
Rn-222 (Bq/l)[1]	0.2	0.2	0.2	0.03	0.6	14	
Ra-226 (Bq/l)[1]	0.1	0.1	0.1	0.03	0.4	14	2–3[2]

1. Some (in some cases all) of the reported values from analyses were below the detection limit and reported as < values. To calculate a mean value these results were divided by 2.
2. /Porcelli et al. 2001/.
3. /Szefer 2002/.

Table 3-10. Statistics for some isotopes at all sampling sites in Laxemar-Simpevarp (PSM002060, PSM002061, PSM0020627, PSM002064, from May 2002 to August 2006, compared with reported concentrations from the Baltic Sea in general.

(mBq/kg)	Mean	Median	Std. dev.	Min	Max	N	Other studies
U-238[1]	25	25	0	25	25	8	10–14[2]
U-235 [1]	25	25	0	25	25	8	0.32–0.36[3]
U-234[1]	25	25	0	25	25	8	10–12.2[3]
Th-230[1]	25	25	0	25	25	8	40–4,400[3]
Th-232[1]	25	25	0	25	25	8	0.2–0.9 [2]
Rn-222 (Bq/l)[1]	0.2	0.1	0.2	0.008	1	8	
Ra-226 (Bq/l)[1]	0.08	0.03	0.1	0.008	0.4	8	2–3[2]

1. Some (in some cases all) of the reported values from analyses were below the detection limit and reported as < values. To calculate a mean value these results were divided by 2.

2. /Porcelli et al. 2001/.

3. /Szefer 2002/.

Forsmark

The regional mean annual precipitation in the Forsmark area has been estimated as 559 mm for the period 1961–1990 /Johansson and Öhman 2008/. 25–30% of the annual precipitation falls in the form of snow. The average monthly precipitation for the period June 2003–May 2007 is presented in Figure 3-5.

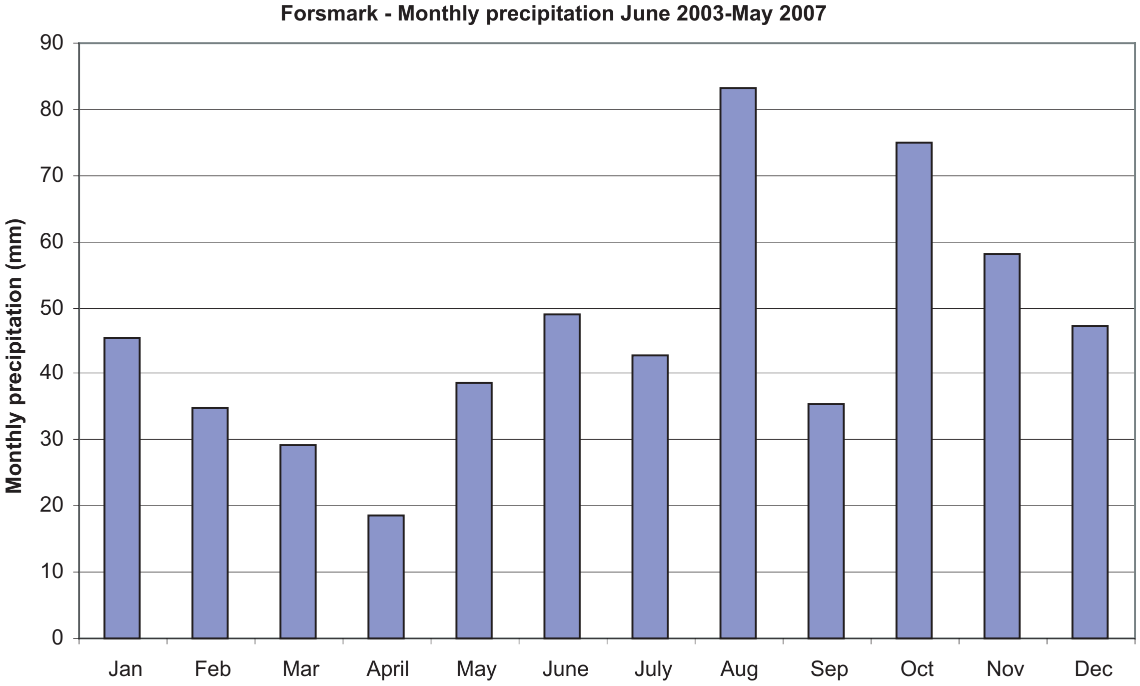


Figure 3-5. *Mean monthly precipitation (mm), June 2003–May 2007 in Laxemar-Simpevarp. From /Juston et al. 2007/.*

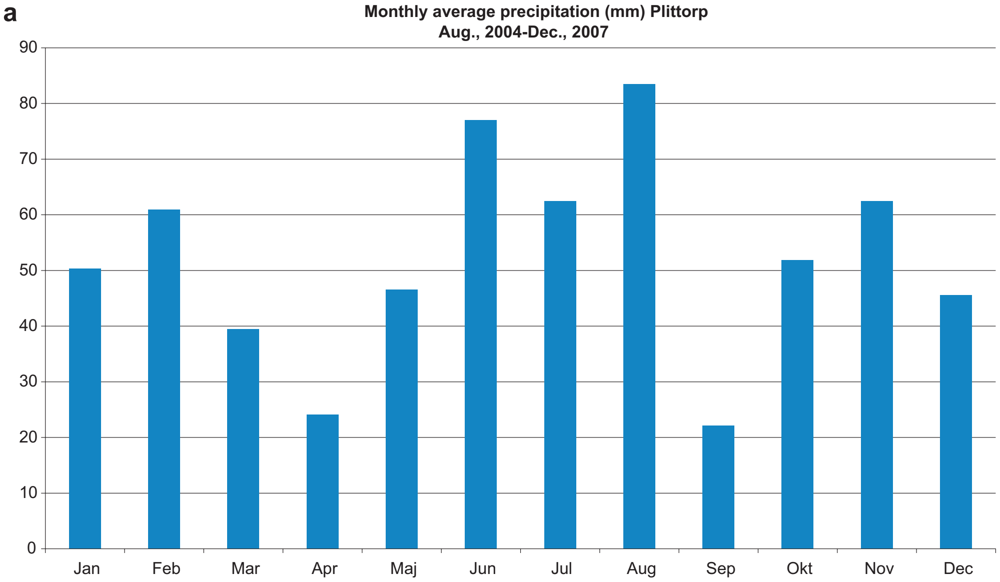
Laxemar-Simpevarp

The annual average precipitation at Äspö during the site investigation period was c. 520 mm, while the corresponding average for Plittorp was c. 620 mm for the period 2003–2007 /Werner et al. 2008/. The monthly precipitation for the period august 2004 to December 2007 at the two meteoro-logical sampling stations in Laxemar-Simpevarp (for location see Appendix 2) is presented in Figure 3-6 a and b. Considering the common data period for the Äspö and Plittorp stations (2005–2007), the accumulated precipitation was c. 7% higher at Plittorp compared with Äspö.

3.2.2 Ice cover

Forsmark

The ice cover measurements were made on Lake Eckarfjärden and on a bay of the Baltic close to the Forsmark harbour. The Baltic Sea bay froze approximately a month later than Eckarfjärden, but had an ice break-up approximately at the same time as the lake. On average the Baltic Sea bay was covered with ice 98 days/season. The ice cover measurements are summarized in Table 3-11. For more details on the recordings, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.



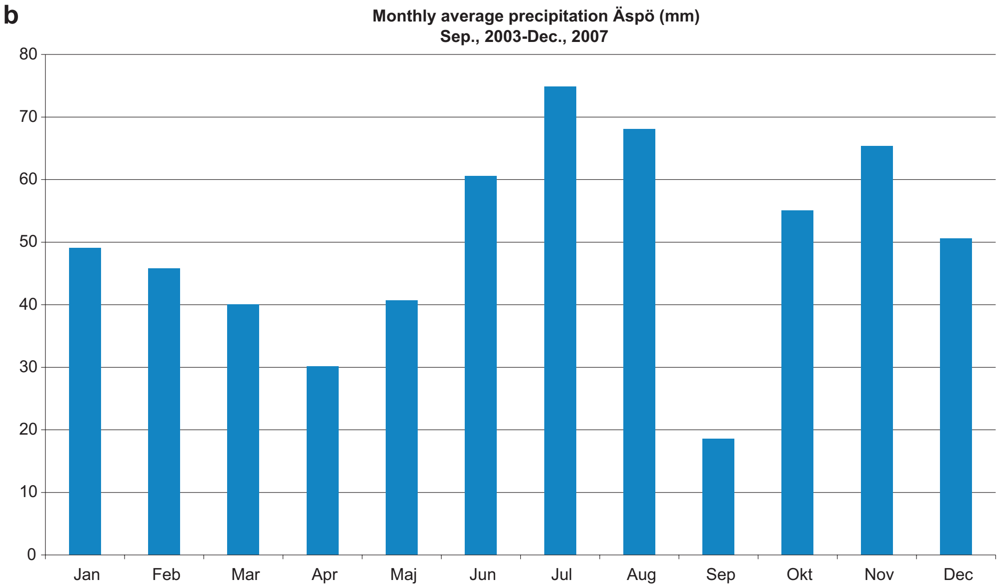


Figure 3-6 a and b. *Monthly precipitation (mm) in Laxemar-Simpevarp, August 2004–December 2007 at Plittorpsgöl (a) and Äspö (b). From /Werner et al. 2008/.*

Table 3-11. Ice cover at Forsmark 2002/03–2006/07.

Baltic Sea bay at Forsmark harbour (AFM000072 and AFM001172)			
Winter period	**Period with observed ice (calendar)**		**Period with observed ice (days)**
	Ice freeze-up	**Ice break-up**	
2002–2003	2003-01-07	2003-03-31	83
2003–2004	2003-12-17	2004-04-13	120
2004–2005	2004-12-21	2005-01-13	95
	2005-01-17	2005-04-07	
2005–2006	2005-12-12	2006-04-24	133
2006–2007	2007-01-22	2007-03-22	60

Laxemar-Simpevarp

Ice freeze-up/break-up was inspected at three locations in the Baltic Sea: Äspö brygga (ASM100226), Kråkelund yttre (ASM100227), and Kråkelund inre (ASM100228). In addition, inspections were also made in Lake Jämsen (ASM100229). Table 3-12 summarizes these ice freeze-up/break-up data.

In general, the near-coastal sea bays (represented by ASM100226) are ice-covered 1–4 months each winter (from December/January to March/April). The ice conditions further offshore are variable, but generally with an ice cover from January to March.

3.2.3 Runoff from land – Forsmark and Laxemar-Simpevarp

Yearly riverine runoff to the Baltic marine area has fluctuated around 15,000 $m^3 s^{-1}$ since 1950. 1998 was the second wettest year since 1950 with the extreme value of 18,720 $m^3 s^{-1}$. The riverine runoff to the Bothnian Sea (Forsmark site) is lower, around 3,000 $m^3 s^{-1}$, than the riverine runoff to the Baltic Proper (Laxemar-Simpevarp site), around 3,500 $m^3 s^{-1}$ in the investigated time period from 1950–2002 /HELCOM 2002/.

An extensive monitoring programme has been carried out since 2002 in both Forsmark and Laxemar-Simpevarp, where stream discharge has been measured at 10 sites. Data on discharge and conductivity have been logged continuously and water samples for analysis have been collected every second week /Johansson and Juston 2007/. These data have been used to calculated specific figures for runoff for water and for 10 elements from individual catchment areas in Forsmark /Tröjbom and Söderbäck 2006b/, see Table 3-13, and in Laxemar-Simpevarp /Tröjbom and Söderbäck 2006a/, see Table 3-14.

Table 3-12. Summary of observed ice freeze-up/break up in Laxemar-Simpevarp area.

Winter period	Gauging station	Period with observed ice (calendar)	Period with observed ice (days)
2002–2003	ASM100226, (Baltic Sea; Äspö brygga)	2002-12-19–2003-03-27	99
2003–2004		2004-01-07–2004-03-10	62
2004–2005		2004-12-22–2005-01-23	3,263
		2005-01-28–2005-04-01	
2005–2006		2005-12-20–2006-04-18	119
2006–2007		2007-01-29–2007-03-01	31
2002–2007	ASM100227, (Baltic Sea; Kråkelund outer)	No ice	
2002–2003	ASM100228, (Baltic Sea; Kråkelund inner)	2003-01-10–2003-03-21	71
2003–2005		No ice	
2005–2006		2006-01-02–2006-01-12	10,812
		2006-01-26–2006-02-03	
		2006-03-17–2006-03-29	
2006–2007		No ice	

Table 3-13. Mean runoff from all catchments areas in Forsmark /Tröjbom et al. 2007/.

	Mean	Median	Std. dev.	Min	Max	N	Other data from the region
water ($m^3\ y^{-1}\ m^{-2}$)	0.6	0.2	1	0.2	5	43	
C ($gy^{-1}\ m^{-2}$)	10	3	19	2	84	43	3.5–17[1]
N ($gy^{-1}\ m^{-2}$)	0.2	–	–	–	–		0.2
P ($gy^{-1}\ m^{-2}$)	0.01	0.003	0.02	0.001	0.08	43	0.01

1. /Canhem et al. 2004/.

Table 3-14. Mean runoff from all catchments areas in Laxemar-Simpevarp /Tröjbom et al. 2008/.

	Mean	Median	Std. dev.	Min	Max	N	Other data from the region
water ($m^3\ y^{-1}\ m^{-2}$)	0.2	0.2	0.0004	0.2	0.2	19	
C ($gy^{-1}\ m^{-2}$)	3	4	2	0.004	5	19	3.5–17[1]
N ($gy^{-1}\ m^{-2}$)	0.2	0.2	0.1	0.0003	0.3	19	0.1
P ($gy^{-1}\ m^{-2}$)	0.005	0.01	0.004	0.00001	0.01	19	0.003

1. /Canhem et al. 2004/.
2. /SLU, 2008/ (County of Kalmar).

Runoff is greater in Forsmark than in Laxemar-Simpevarp for all parameters except nitrogen (N), which is of the same order of magnitude at both sites. In comparison with other reported runoff values /SLU 2008/, the runoff of C, N and phosphorus (P) is of the same order of magnitude as reported elsewhere.

3.2.4 Irradiation

Global irradiadiance is relatively evenly distributed over Sweden. The greatest differences are between values inland and at sea, with greater irradiation over the sea. This is due to the differences in cloudiness. In the winter time the irradiation pattern is latitude-dependent. Normally, annual global irradiadiance in Sweden varies within 15% of the normal value of 800–1,100 kWh m^{-2} /Sjöberg 1997/.

Forsmark and Laxemar-Simpevarp

Global irradiation was measured every second and mean values for 30 min were recorded continuously for one site in Forsmark: Högmasten /Wern and Jones 2007/ and for one site in Laxemar-Simpevarp area: Äspö /Sjögren et al. 2007/ (Appendix 1 and 2). Daily values in Forsmark vary between 0.30 MJ d^{-1} (in January) and 27 MJ d^{-1} (in July) with a mean of 9.3 MJ d^{-1} (Figure 3-7).

Daily values in Laxemar-Simpevarp vary between 0.30 MJ d^{-1} (in January) and 27 MJ d^{-1} (in July) with a mean of 10.2 MJ d^{-1} (Figure 3-8).

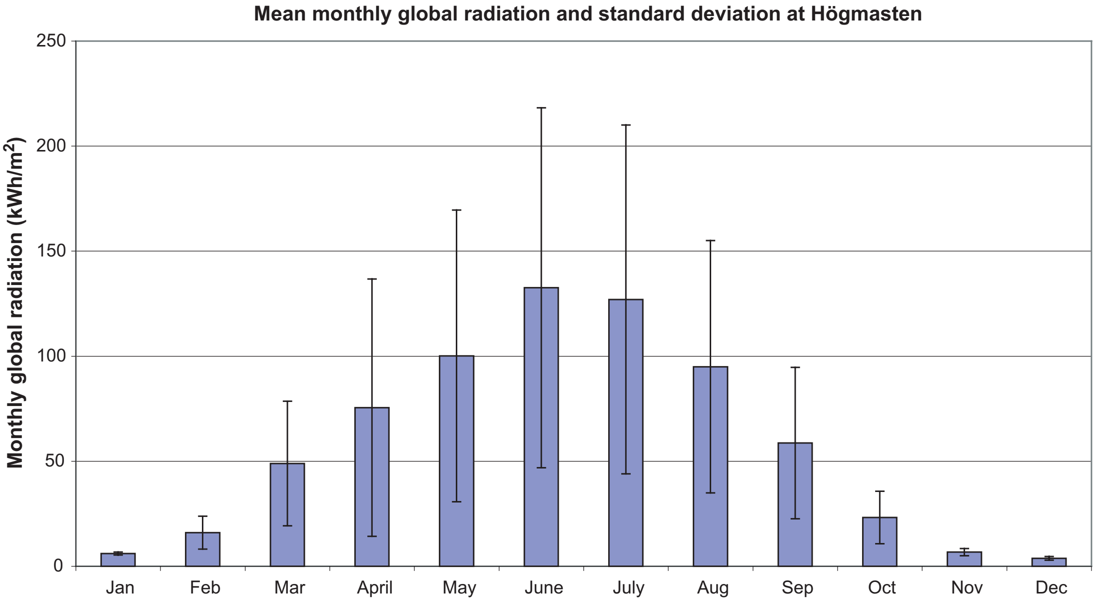


Figure 3-7. *Monthly averages of the global irradiation at Forsmark during 2003–2007, from /Wern and Jones 2007/.*

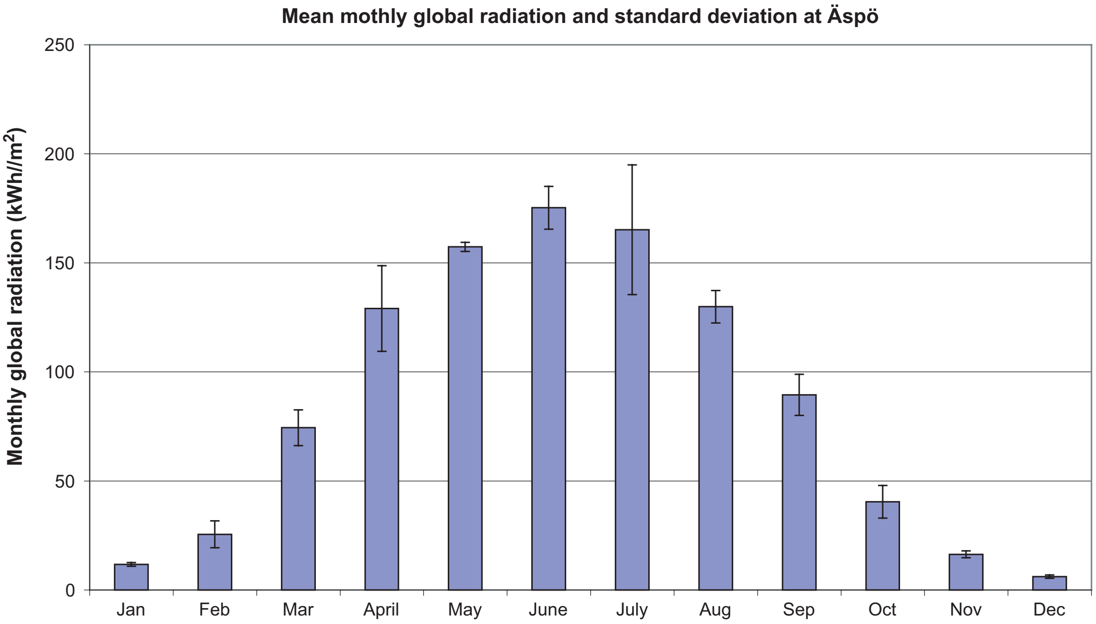


Figure 3-8. *Monthly averages of the global irradiation at Äspö, in the Laxemar-Simpevarp area during 2004–2007, from /Sjögren et al. 2007/.*

3.2.5 Sea level

The sea level in the Baltic Sea and the Gulf of Bothnia is influenced by several factors, of which the long term factors are isostatic (changes due to land uplift) and eustatic (changes due to ocean level rise). Over shorter time periods, seiches (standing waves), freshwater runoff, changes in atmospheric pressure and winds create changes in water level. The variation in sea level is greatest in the autumn and winter, when the strongest winds appear. In the spring and summer, with a more stable weather pattern, the sea level varies to a lesser extent, mainly due to the atmospheric pressure. Tidal effects are small and overshadowed by the other factors. The sea level variations are relative to the mean sea level, which is calculated as a sum of the eustatic and isostatic changes. Annual mean sea level is the mean of measured sea level relative to the zero elevation in the Swedish national elevation system RH70/RHB70.

Forsmark

Since January 2003 sea level has been measured at two sites every hour. The sea level has fluctuated between 0.62 m below and 1.27 m above mean sea level (Figure 3-9). Deviations above 1.0 metre are uncommon and were only recorded on one day (January 2007) during the period from January 2003 to April 2007. Statistics between 2003 and April 2007 at Forsmark are presented in Table 3-15. As the Forsmark coastline has a low-angle slope, a deviation of 0.5 m, which occurs on average every second year, has a marked effect on the landscape, Figure 3-10.

Laxemar-Simpevarp

Since 2004 sea level has been measured every hour /Werner et al. 2008/. The sea level has fluctuated between 0.5 m below and 0.7 m above mean. The narrower deviation range and the steeper general slope make the impact of sea-level variability less marked than in Forsmark, Figure 3-11 and Table 3-16.

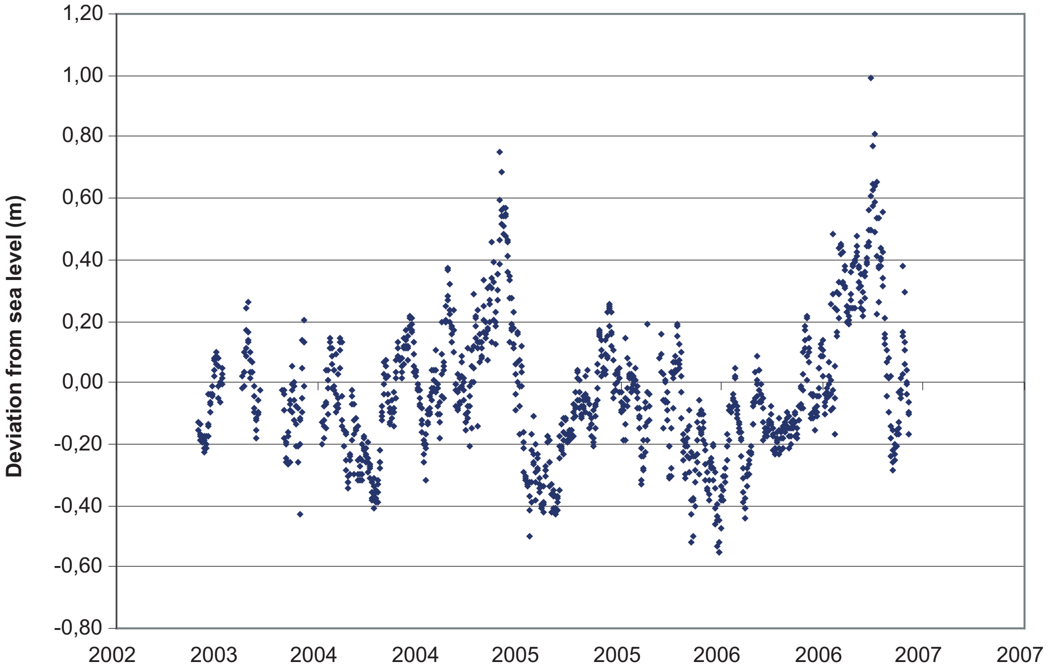


Figure 3-9. Daily means of sea level deviation (m) in Forsmark from January 2003 to April 2007 at the site PFM010039.

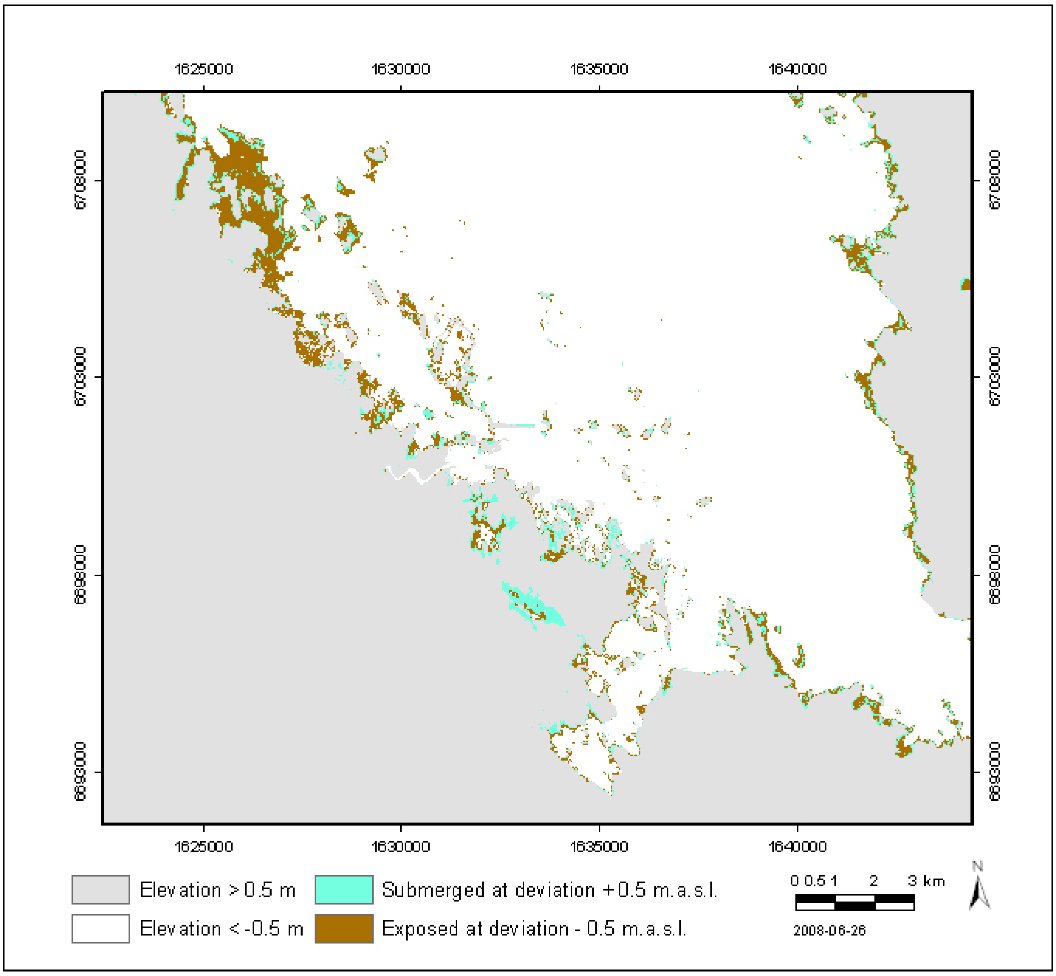


Figure 3-10. *Effects of a 0.5 m increase and of a 0.5 m decrease in sea level in Forsmark. Blue colour indicates area covered by seawater at sea level +0.5 m.a.s.l. (m above sea level), brown colour indicates area exposed to air at –0.5 m.a.s.l.*

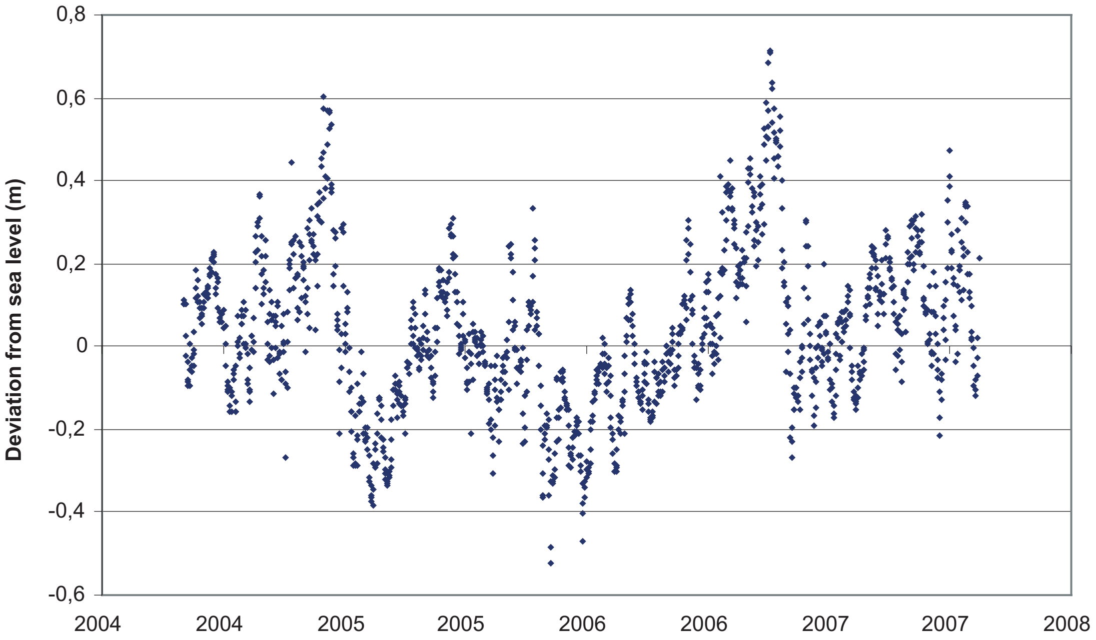


Figure 3-11. *Daily means of sea level deviation (m) in Laxemar-Simpevarp from January 2003 to April 2007 at the site PSM0000371.*

3.3 Morphometry and regolith

The term regolith refers here to all loose materials covering igneous or sedimentary bedrock, e.g. till, gravel, sand, silt and clay, whether glacial or postglacial.

3.3.1 Bathymetry

Both Forsmark and Laxemar-Simpevarp areas have low surface relief (< 25 m) associated with the subcambrian peneplains.

Forsmark

The region of Northern Uppland , including the Forsmark area, is on the peneplain which here includes the flattest parts of Sweden /Magnusson and Lundqvist 1957/. The Forsmark area is situated in a transition zone between flat coast to the north and a zone with fissure terrain and vertical displacements along faultlines to the south. The latter are related to the outline of the north-eastern shore of Öresundsgrepen, with its deeper part, the Gräsö trough.

The smaller-scale morphology of the Forsmark area is governed by a combination of bedrock structure and glacial morphology. The major bedrock lineaments run NW–SE, e.g. the Forsmark and Singö deformation zones, the former underlying the Forsmarksån River and the inner part of Kallrigafjärden Bay, the latter underlying Stånggrundsfjärden Basin. A third distinct lineament runs perpendicular to the other two underlying the major axis of Kallrigafjärden Bay (Figure 3-13).

The combined effect of rapid uplift and low relief has contributed to the formation of the present archipelago, which is relatively narrow despite the shallow depth of the basin depressions. Elevation profiles (Figure 3-13) show the peneplain with its low relative relief (< 10 m) and gentle 1:500 slope towards the NW. The lineaments affect the division of the western part of Öregrundsgrepen into basins with mean depth 8.5 m (marine basins 102–104, 106–108, 110–112, 116–118, 120–121, 123, 126, 134, 145–146, 150 and 152; for basin partitioning, see Section 5.3, Figure 5-2). The rest of Öregrundsgrepen dominated by the Gräsö trough has a mean depth in its eastern part of 19 m (marine basins 100, 105, 109 and 113–115).

Detailed bathymetry surveys have been performed in Forsmark using side scan and multi-beam sonar in deep areas /Elhammer and Sandkvist 2005a/ and single-beam sonar in shallow coastal areas /Brunberg et al. 2004a/. These data, together with older data (e.g. isolines from sea charts) have been compiled into a large point dataset, see Figure 3-14. This dataset, together with a corresponding dataset on land, has been used to perform kriging interpolation to create a digital elevation model (DEM) of high accuracy /Brydsten and Strömgren 2004/, see Figure 4-1, Section 4. The methodology and input data are described in detail in /Brydsten and Strömgren 2004/.

Laxemar-Simpevarp

The Laxemar-Simpevarp area, forming part of the fissure valley terrain of south and central Sweden /Rudberg 1970/, lies east of the peneplain. The relief is low near the coast-line and increases with a 1/400 slope to 25–50 m in the landward part of the area. See Figure 3-15.

Detailed bathymetry surveys were performed using depth soundings /Ingvarson et al. 2004, Elhammer and Sandkvist 2005b/ and a digital elevation model (DEM) of high accuracy was created by /Brydsten and Strömgren 2005/, See Figure 4-2.

Based on the DEM the coastal area off Laxemar-Simpevarp may thus be divided into two parts:

(1) the inner, sheltered bays, notably Bussviken, Granholmsfjärden, Borholmsfjärden and partly sheltered Figeholmsfjärden, and

(2) the exposed coast making up part of the north-western Kalmar sound, with two slightly deeper troughs running N-S and SW-NE.

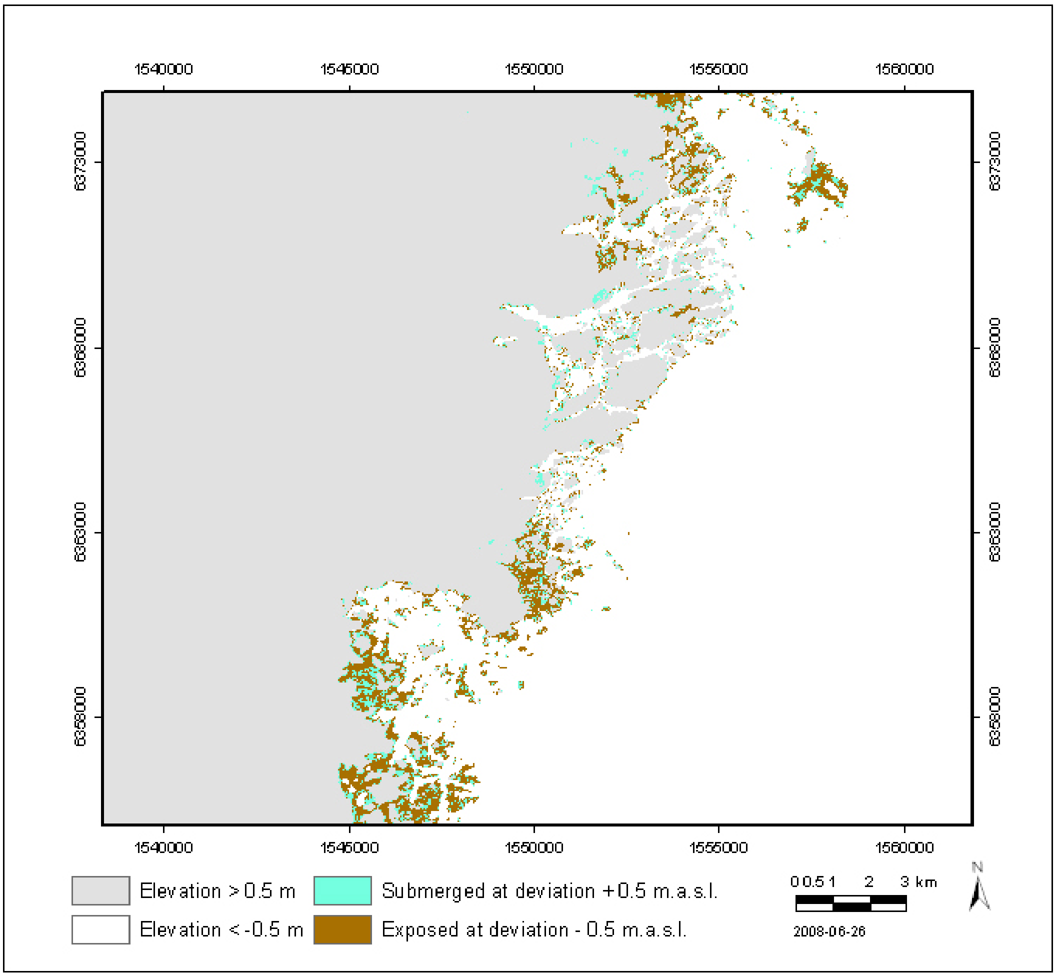


Figure 3-12. *Effects of a 0.5 m increase and of a 0.5 m decrease in sea level in Laxemar-Simpevarp. Blue colour indicates area covered by seawater at sea level 0.5 m.a.s.l. brown colour indicates area exposed to air at –0.5 m.a.s.l.*

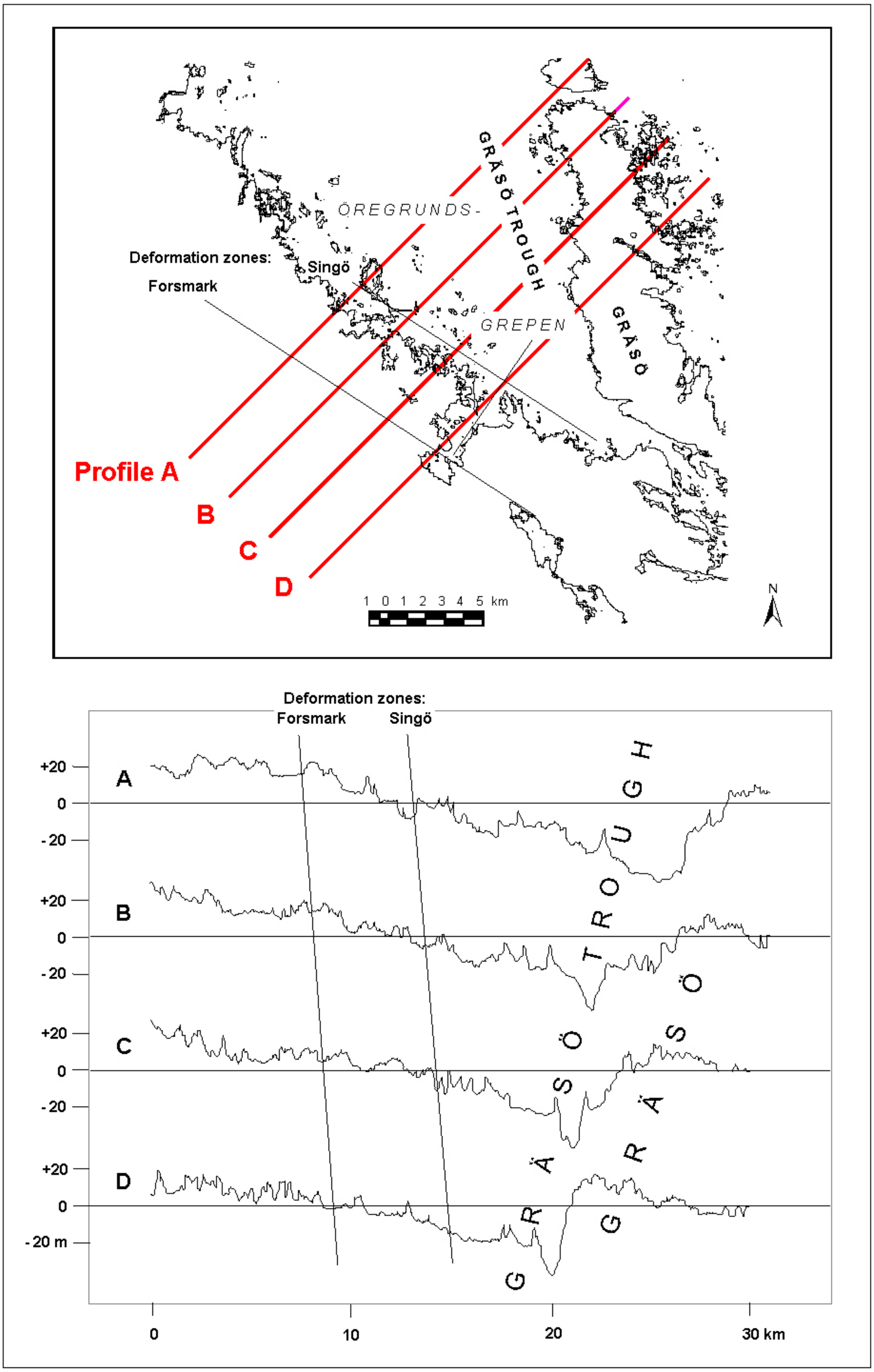


Figure 3-13. *Elevation profiles, 3 km apart, across Öregrundsgrepen through the Forsmark area with the major bedrock lineaments indicated.*

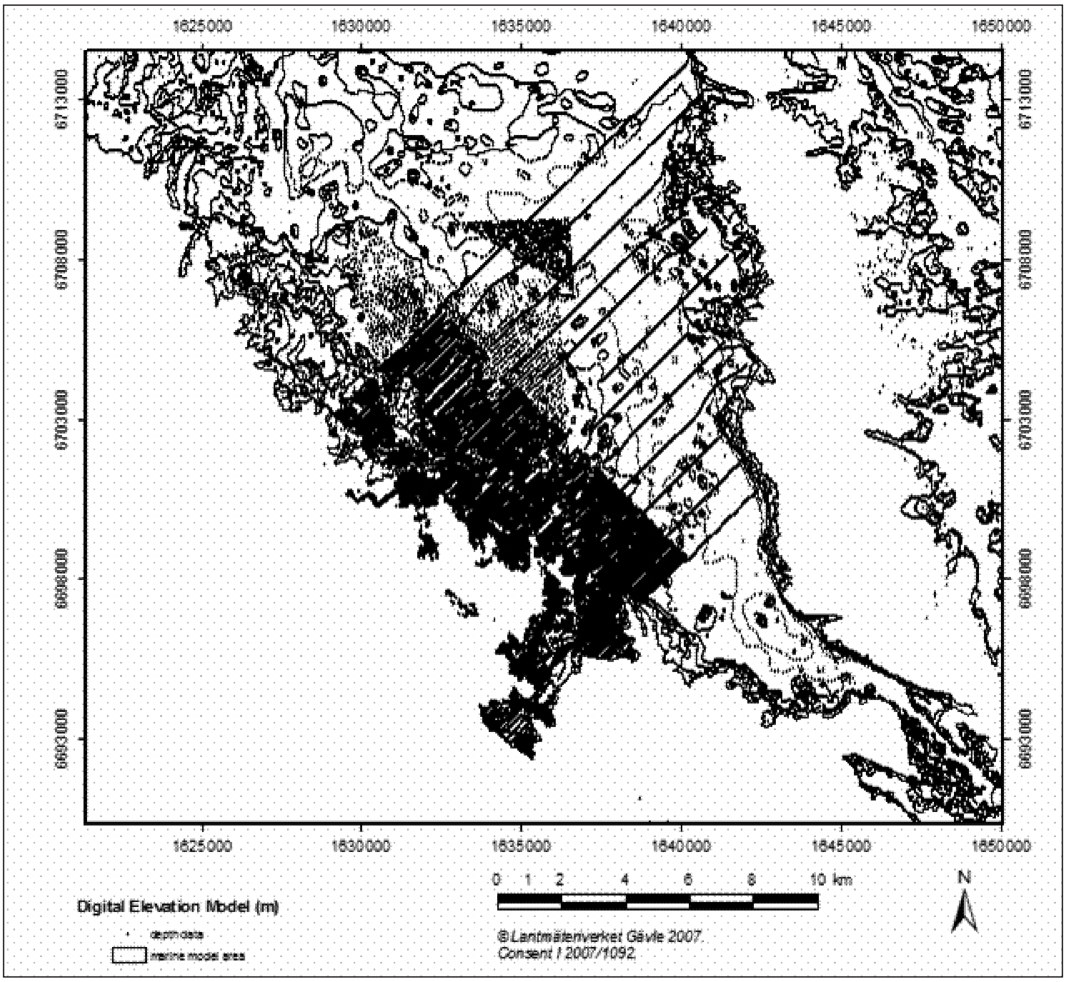


Figure 3-14. *Distribution of point data in the marine area used to generate the digital elevation model (DEM) for the Forsmark area.*

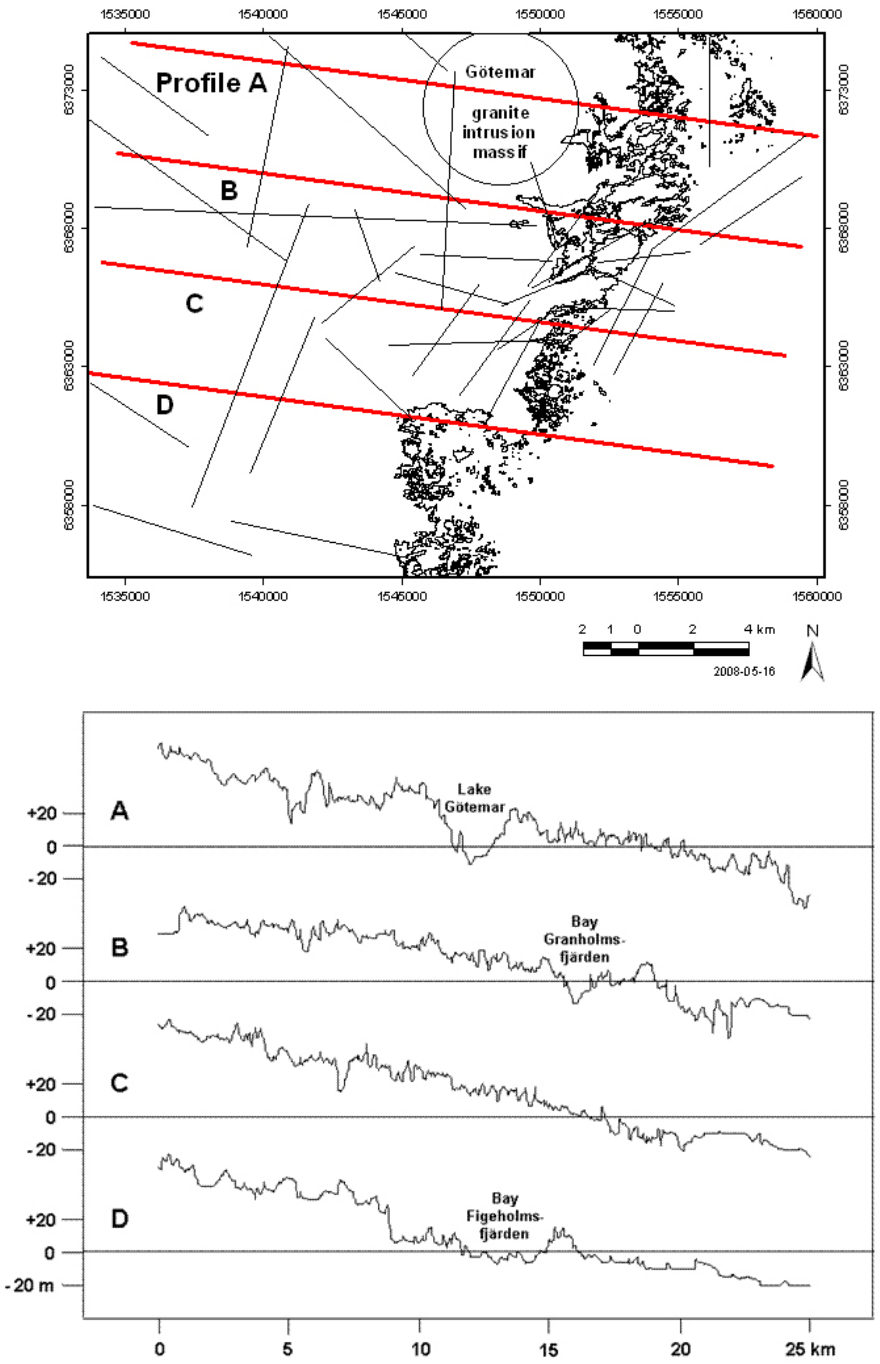


Figure 3-15. Elevation profiles, 4 km apart, across the Laxemar-Simpevarp area with the major bedrock lineaments indicated.

3.3.2 Sediment conditions

Forsmark

Mapping of the distribution and thickness of marine sediments in the Forsmark area was carried out using side-scan sonar, seismics, coring and sampling in areas deeper than 3 m /Elhammar and Sandkvist 2005/ and using probing (for surveying penetration resistance), coring and grab sampling in the shallow lagoonal areas /Ising 2005/. The position of seismic lanes and of stations where cores and grabs were taken and probings made are shown in Figure 3-16.

During glaciations, lineaments are prone to be carved out depending on the flow direction, hydrology and bottom temperature of the ice sheet. Due to the deeper aquatic environment during the latest deglaciation, irregularities and depressions were subsequently filled in and smoothed out in the Forsmark area by deposition of subglacial till, glaciofluvial sediments and subaquatic deposition of varved (heavy) glacial and further transported postglacial clay. Glacifluvial activity formed longitudinal deposits such as the Börstil esker crossing both Kallrigafjärden and Tixelfjärden. The thickness of the glacial clay is shown by the seismic mapping and modelling (Figure 3-17). It is also in the three lineaments and the Gräsö trough that the thickness of the regolith is the greatest, up to 10–20 m (Figure 3-18).

As deposits were raised above sea level, occasional episodes of eustatic sea level rise have resulted at least three times in prolonged periods of shoreline reworking and sheltering, 4600 to 3800 yrs BP, 2500 to 2200 yrs BP and 1100 to 850 yrs BP /Hedenström and Risberg 2003/. However, the longer-term isostatic uplift in the Forsmark area, 6 mm y^{-1}, has been too rapid for shoreline processes to rework sorted glaciofluvial material into any large-scale constructive beach morphologies.

In the coastal zone, final retention of elements through permanent burial takes place at accumulation bottoms, i.e. in marine postglacial fine matter deposits also referred to as A-bottoms or depocenters. Their formation is controlled by input, erosion, resuspension, transport and deposition of fine sediments, i.e. slow-falling aggregates and single particles made up of both organic and fine inorganic matter.

Following deposition of glacial clay in connection with the deglaciation stage, raised till deposits were washed and eroded by wave action during the subsequent isostatic uplift. Coarse materials were then sorted into postglacial gravel and sand layers. Their finer fractions were generally carried further offshore and “focused” towards depressions where they may be deposited as A-bottoms with high organic content (postglacial mud; Figure 3-19). A steady supply of fine particles is contributed from glacial clays being eroded as they approach shallow depth during uplift.

As noted by /Sohlenius et al. 2004/ the Forsmark area has been particularly well exposed to coastal abrasive and transport processes. Cores taken in the present shallow lagoons show glacial clays underlying postglacial clay, but with signs of erosion having taken place since the earliest shoaling phases, and with postglacial clays often missing or otherwise thin. One exception is the area south-east of Lake Fiskarfjärden. Glacial clays throughout the rest of the area are mostly covered by a thin layer of sand or gravel instead of by postglacial silt, clay or gyttja, except in the eastern part of Öregrundsgrepen (Figure 3-20).

The present extent of marine A-bottoms in the Forsmark area is limited. In the western part of Öregrundsgrepen, such bottoms are found only to the north-west of Norra Asphällssundet Basin and in the two lagoonal areas to the south-east: Tixelfjärden and Kallrigafjärden (see map in Appendix 1) /Ising 2005/.

Further offshore, fine sediments are found over larger areas, covering the Gräsö trough and the adjacent broad lineament extending from the Gräsö trough in the direction of Kallrigafjärden.

As for the origin of offshore A-bottom particles, these can originate from both shallow and deeper waters. Cesium-134, sPCB and sDDT measurements in the Stockholm archipelago have shown 6–8 times higher burial rates in the Stockholm archipelago compared to offshore A-bottoms, indicating import of contaminants from open sea to archipelago /Meili et al. 2000/. Such transport in Öregrundsgrepen most likely happens during southerly winds as bottom water and its load of resuspended particles is advected inward along the Gräsö trough.

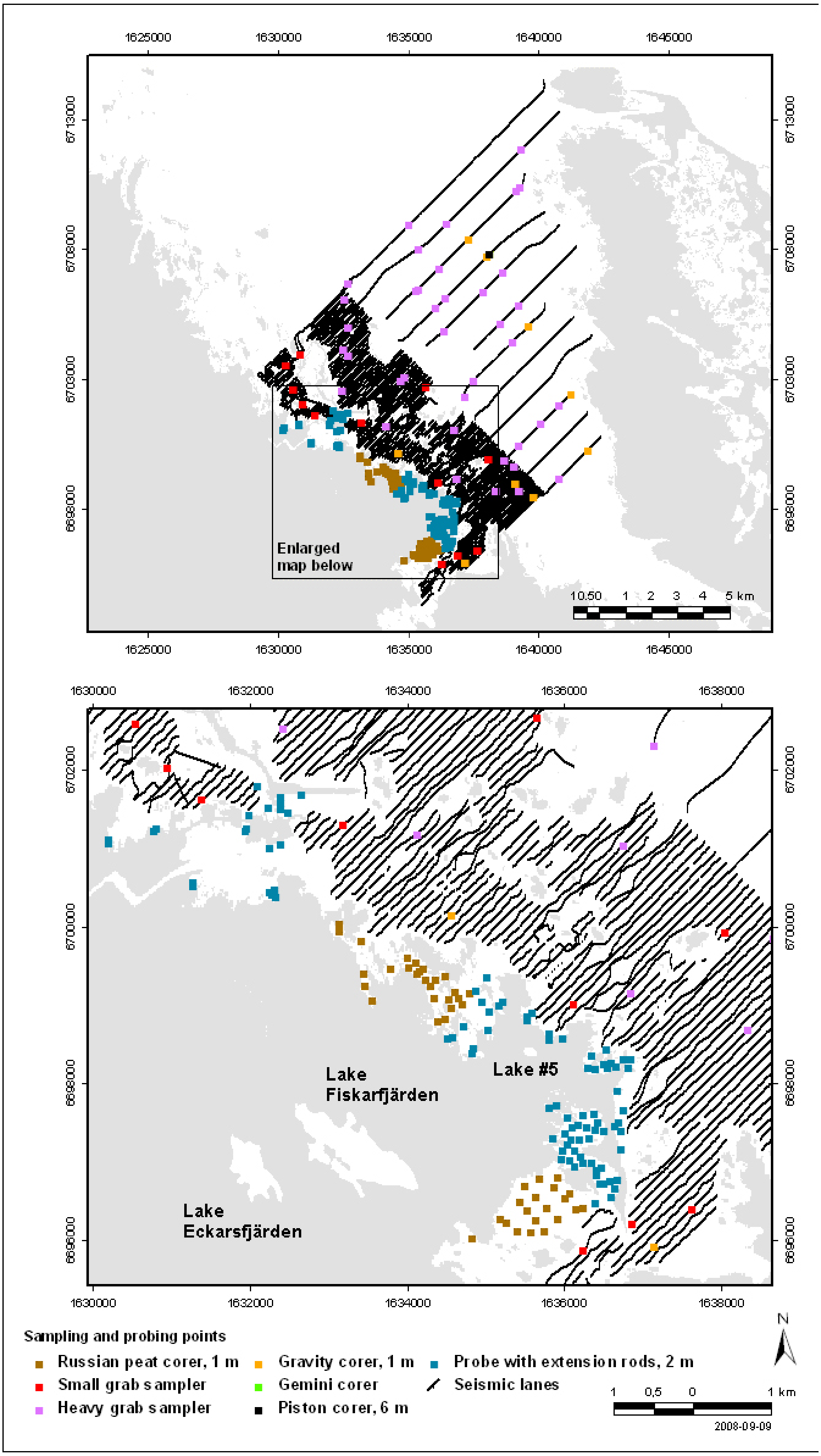


Figure 3-16. *Seismic lanes, sampling and probing points in Forsmark area. Probed hard bottoms are not included.*

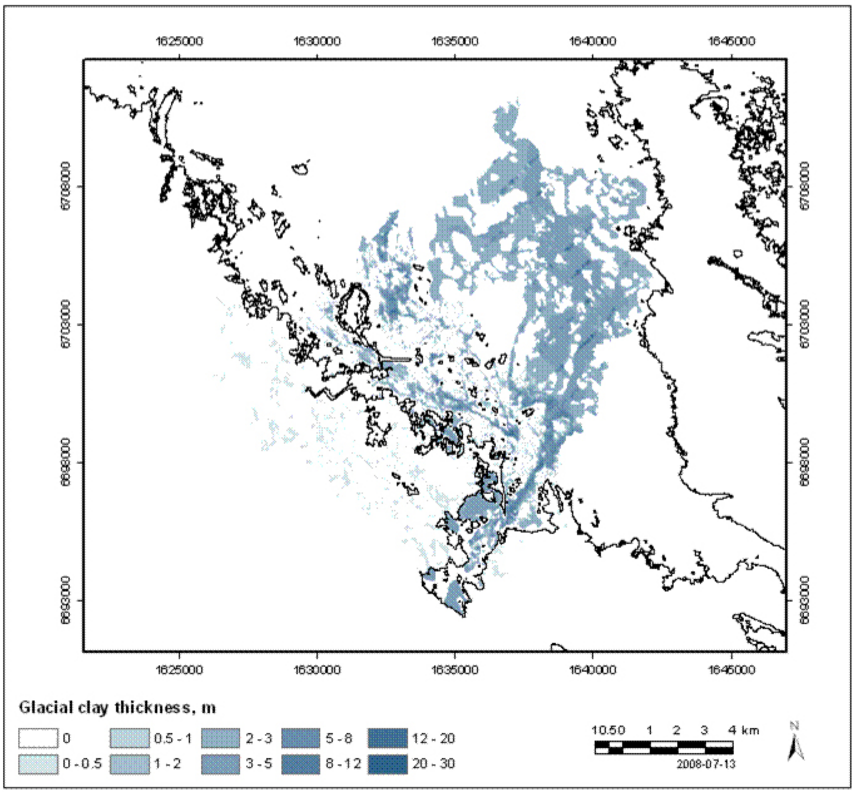


Figure 3-17. *Thickness of the present glacial clay deposits (m) in the Forsmark area as derived through the modeling /Hedenström et al. 2008/ based on coring and seismic investigation data /Elhammar and Sandkvist 2005, Ising 2005/.*

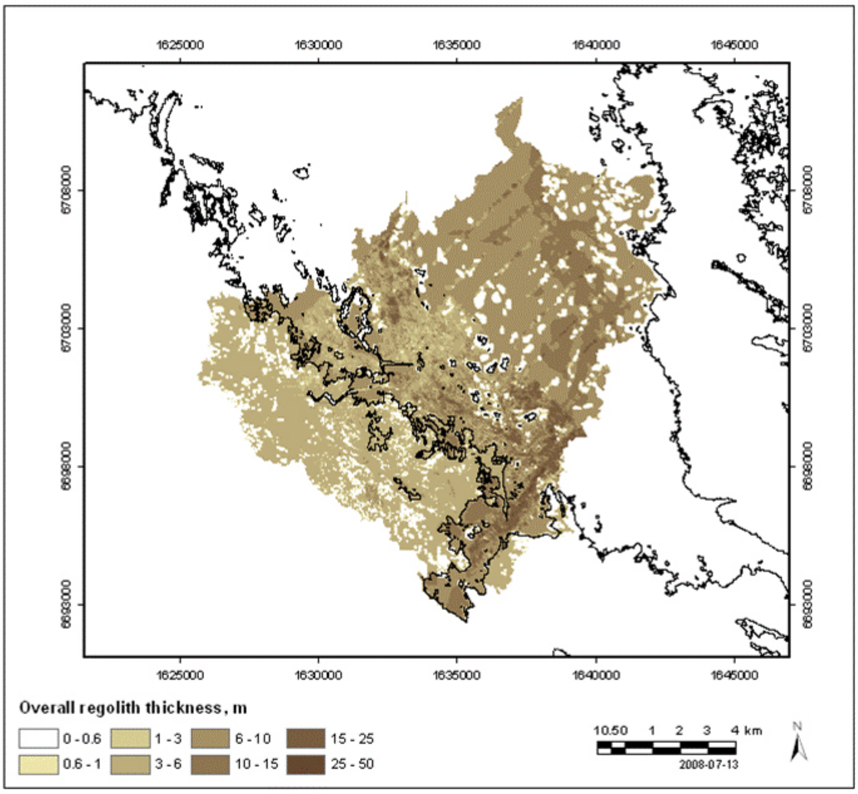


Figure 3-18. *Overall thickness of the present marine regolith (m) in the Forsmark area as derived through the modelling /Hedenström et al. 2008/ based on coring and seismic investigation data /Elhammar and Sandkvist 2005, Ising 2005/.*

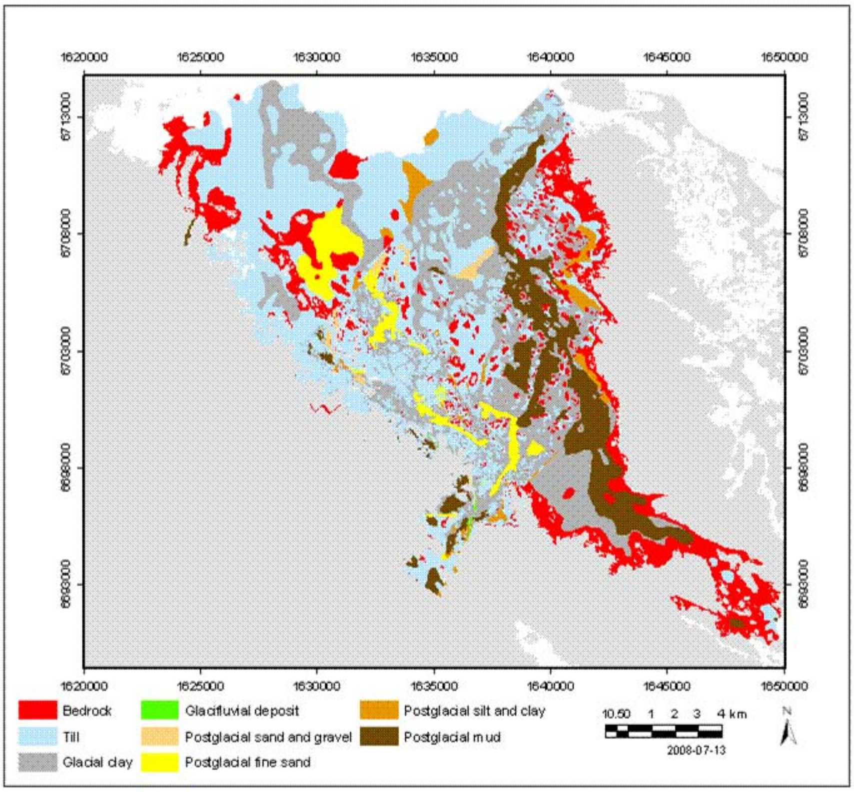


***Figure 3-19.** Overview of the genesis and composition of the dominant fraction of the seabed in the Forsmark area, mapped in the outer regional model area by /Elhammer and Sandkvist 2005a/ and in the shallow-water lagoonal areas by /Ising 2005/, and modelled by /Hedenström 2008/.*

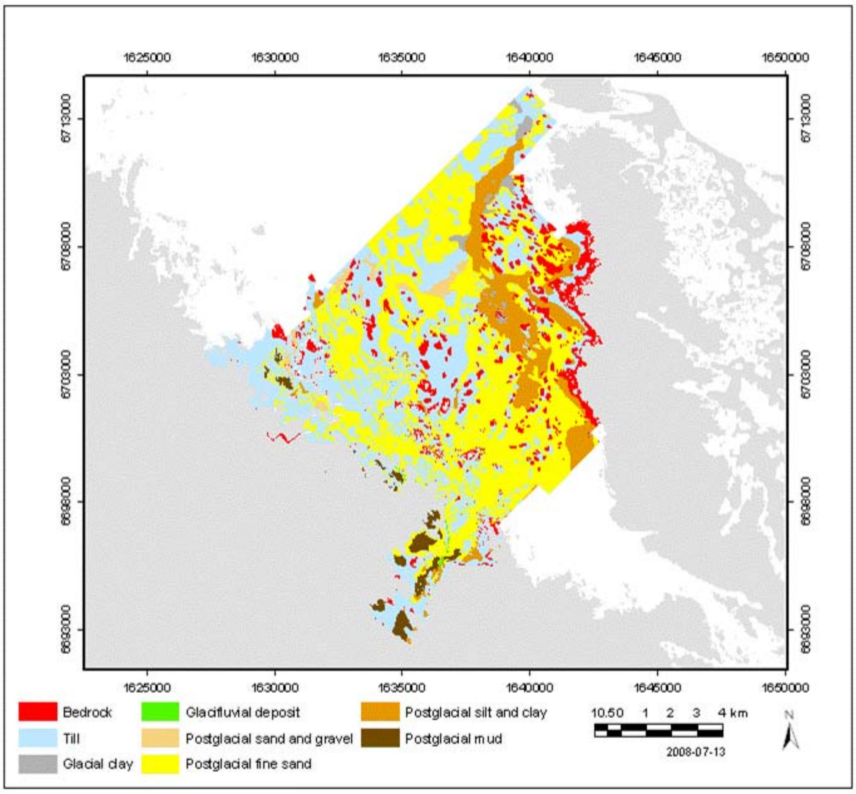


***Figure 3-20.** Overview of the seabed in the Forsmark regional model area, showing the thin, uppermost layer where this differs from the dominant fraction /Elhammer and Sandkvist 2005a, Ising 2005/.*

A-bottom development also shows long-term trends related to uplift. Using a wave-ray model, /Brydsten 1999/ investigated the theoretical extent of fine-matter deposition for 500 year intervals. A function of near-bed velocities caused by incident waves and their resulting long-shore currents, this was expressed and mapped as maximum resuspendable grain size (MRGS). When resulting MRGS histories were compared with actual stratigraphy, an MRGS of 20 µm was identified as a wave energy level roughly dividing bottoms of erosion and transport (ET-bottoms) from A-bottoms. MRGS histories describe how the area's bottoms have experienced diminishing wave energy levels over the last 2000–3000 years, due to increasing sheltering caused by the ongoing shoaling. /Brydsten 1999/ also suggested that such theoretical A-bottom conditions already extend over roughly twice the area actually mapped as fine matter deposits, in which case such mapping is either incomplete or discrepancies result from how the wave incidence is formulated.

Measurements of burial in the Forsmark area originate from:

(1) lake core studies of the earliest postglacial conditions /Hedenström 2003, Hedenström and Risberg 2003/ with sediments accumulating at between 0.2 and 4 (mostly 0.5 to 1.5) mmy^{-1},

(2) /Risberg 2005/ analysis of the 6 m piston core from the outer Gräsö trough (Figure 3-19) which showed carbon burial rates decreasing towards present rates from possibly up to one order of magnitude higher rates prevailing throughout the Holocene climatic optimum, i.e. before the sub-recent sheltering,

(3) /Sternbeck et al. 2006/5 who used ^{210}Pb measurements to estimate recent to sub-recent average mass accumulation rates in Tixelfjärden and Kallrigafjärden at approximately 1,000 gm^{-2} y^{-1} with C and N burial rates at 14 and 1.6 gm^{-2} y^{-1}, respectively.

By comparison, carbon burial rates as measured by /Jonsson et al. 2000/ in the Baltic Proper are moderately high at 10–50 gC m^{-2} y^{-1}.

A-bottoms exposed today are moderately organic fines, showing oxic or suboxic conditions down to a few cm depths.

Laxemar-Simpevarp

As summarized in Figure 3-21 (from /Sohlenius and Hedenström 2008/), the inner sheltered bays were studied by sediment coring and grab sampling /Risberg 2002, Nilsson 2004, Sternbeck et al. 2006/ and by means of echo sounding, side scan sonar and shallow seismics /Ingvarson et al. 2004/. The exposed coast was surveyed by means of side-scan sonar, seismics, sediment coring and grab sampling /Elhammar and Sandkvist 2005b, Ingvarsson et al. 2004/, including analyses of two 5–6 m long piston cores /Kaislahti et al. 2006/. Overall sediment depth and stratigraphy of the regolith were modelled by /Nyman 2005/.

The components of the sediments in the Laxemar-Simpevarp area are more typical of an exposed bedrock-fissure coast, showing mud accumulation in the sheltered bays and bedrock, till and boulders along the exposed coast, where residual glacial clay is found only in two minor troughs, in pockets and in fissures /Ingvarson et al. 2004/. Glaciofluvial material is found along the Tuna esker running N-S in the western part of the area, and in the minor Misterhult and Gässhult esker running NW-SE perpendicular to the coast. The thickness of the clays is shown in Figure 3-22 and the thickness of the overall regolith in Figure 3-23. Furthermore, Figure 3-24 shows the composition of the dominant fraction of the marine bottom while Figure 3-25 shows the composition of an upper thin layer, silt or sand, where this layer differs from that of the bulk, typically the glacial clay.

Carbon sequestration (burial) rates estimated by /Kaislahti et al. 2006/ from one of the two long piston cores taken in the offshore deeper trough running SW-NE from Kråkelund (station PSM002123, depth 40 m) increased during the Holocene from < 5 gC m^{-2} yr^{-1} towards 56 gC m^{-2} yr^{-1} in the sub recent Littorina phase. Rates measured by /Sternbeck et al. 2006/ in the sheltered bays were also high, 74–95 gC m^{-2} yr^{-1} compared to those measured in the same study in sheltered locations in the Forsmark area (14 gC m^{-2} yr^{-1}), as well as those measured by /Jonsson et al. 2000/ in the Baltic Proper (10–50 gC m^{-2} y^{-1}).

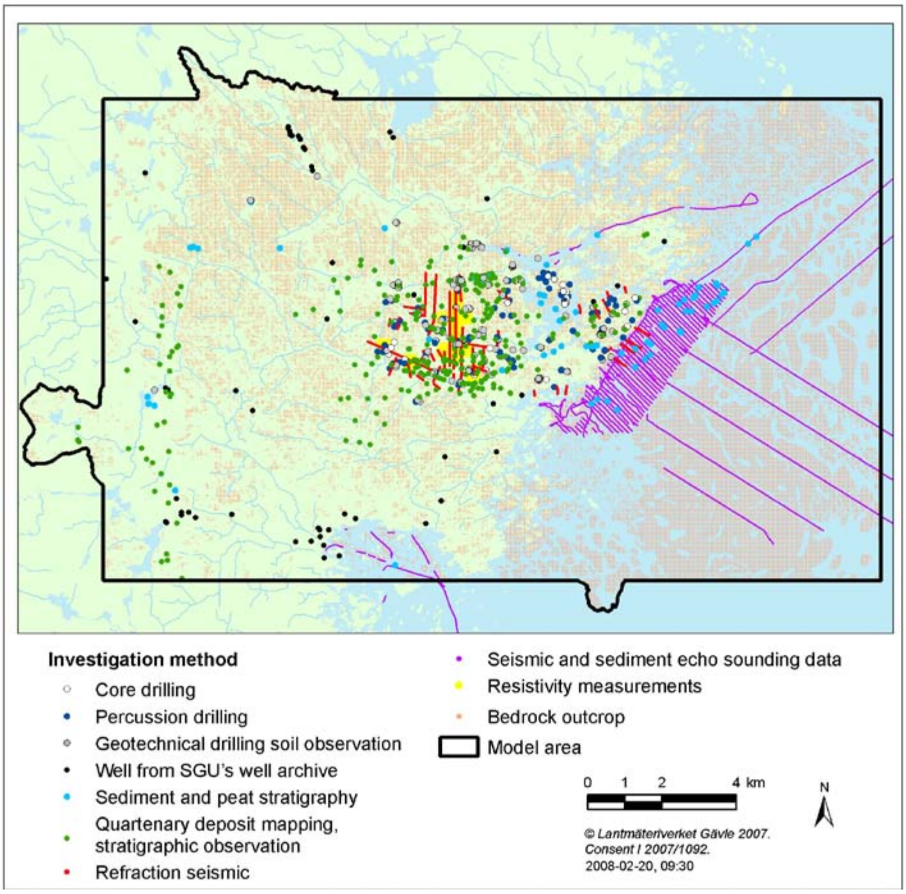


Figure 3-21. *Overview of the main marine seismic lanes (purple) and sampling points (light blue) in the Laxemar-Simpevarp area. From /Sohlenius and Hedenström 2008/.*

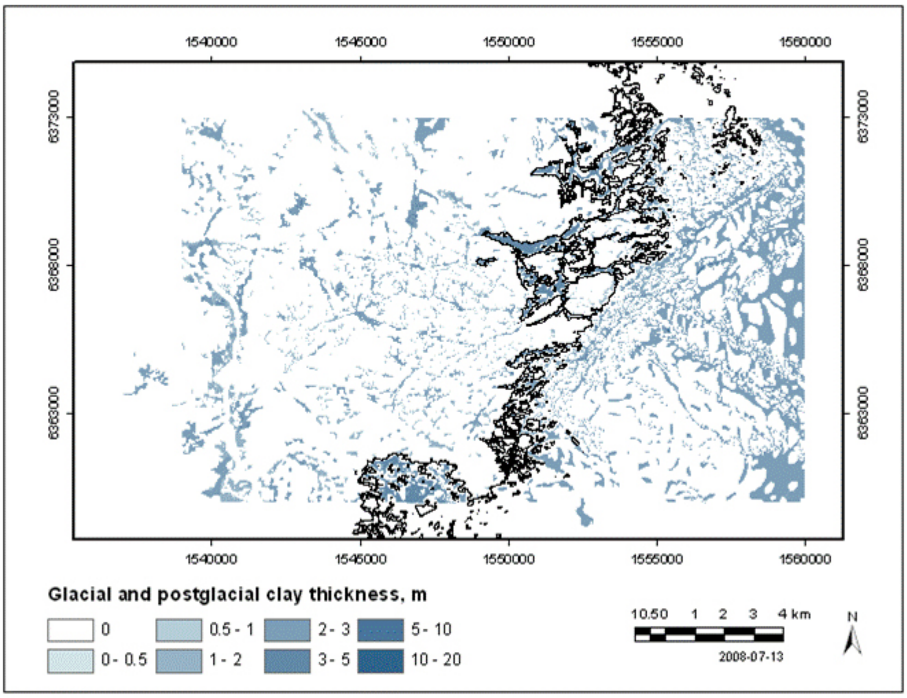


Figure 3-22. *Thickness of the present glacial and postglacial clay deposits in the Laxemar-Simpevarp area, based on data presented and modeled in /Sohlenius and Hedenström 2008/.*

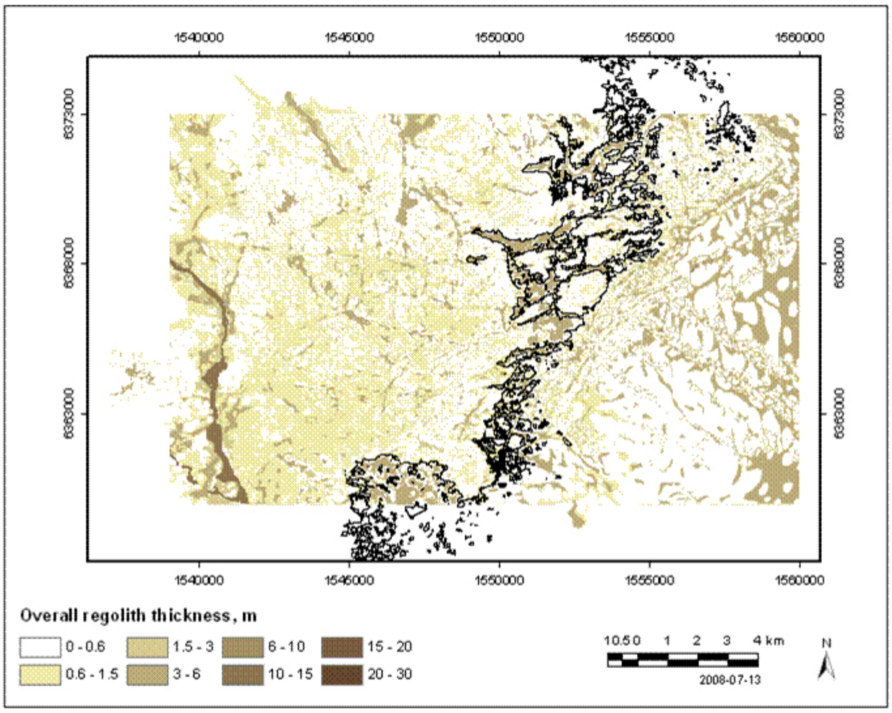


Figure 3-23. *Overall thickness of the regolith in the Laxemar-Simpevarp area, based on data presented and modeled in /Sohlenius and Hedenström 2008/.*

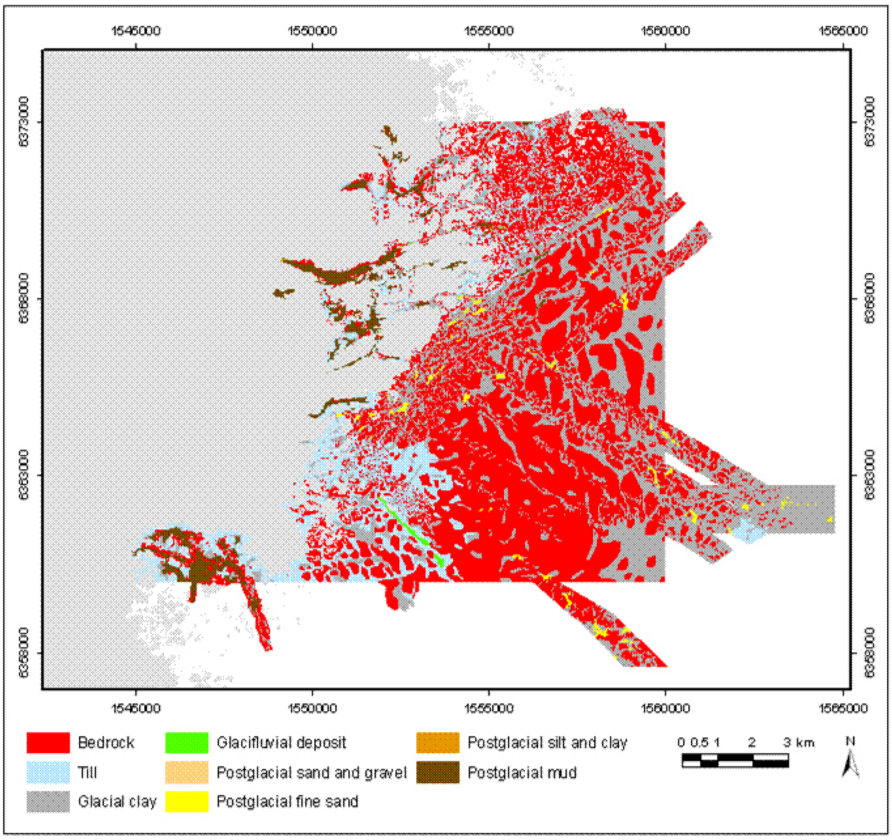


Figure 3-24. *Overview of the genesis and composition of the dominant fraction of the seabed in the Laxemar-Simpevarp area. Stratigraphy and sediment distribution based on data from /Sohlenius and Hedenström 2008/.*

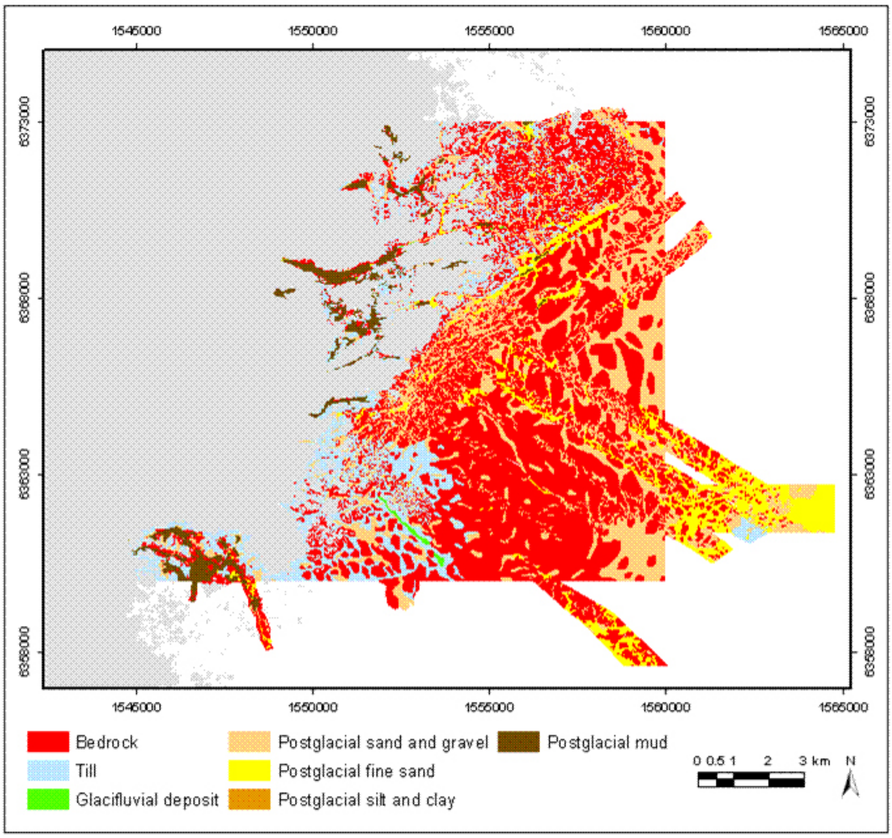


***Figure 3-25.** Overview of the seabed in the Laxemar-Simpevarp regional model area, showing the thin, uppermost layer where it differs from the dominant fraction. Stratigraphy and sediment distribution based on data from /Sohlenius and Hedenström 2008/.*

3.4 Biota in the marine ecosystem

Compared to fully marine environments, the Baltic Sea with its brackish water has a very poor flora and fauna. The Baltic is inhabited by a mix of marine and freshwater species adapted to the brackish conditions. Where salinity levels are low, in the Baltic's northern and eastern waters, fewer marine species can thrive and marine habitats are dominated by freshwater species, especially in estuaries and coastal waters. In southern areas with higher salinity, marine species dominate.

The following section contains a brief description of biotic components of the ecosystems (producers and consumers in the functional groups) at the two sites. The data mainly come from the SKB site investigation programme. In some cases, data from investigations in nearby areas of the Bothnian Sea and the Baltic proper have been used, for comparison and for showing long time series. In Appendix 4, a list of species found in the investigations is presented.

3.4.1 Habitats and functional groups

The marine ecosystems at the sites include three major environments: semi-enclosed bays affected to a varying degree by the freshwater effluence, coastal archipelago with sheltered areas, and Baltic Sea habitat exposed to sea currents and wave action. The following habitats occur in these environments: pelagic, soft bottom and hard bottom habitats. In a traditional sense, pelagic means "open sea" (e.g. /Kaiser et al. 2005/) and is characterized by an absence of contact with bottom or shore /Horne and Goldman 1994/. Here, pelagic habitat refers to the open water, even in small in-shore basins. The organisms represented in the habitats, in both Forsmark and Laxemar-Simpevarp have been divided into functional groups comprising primary producers and consumers, see Table 3-17.

Table 3-15. Statistics for sea level changes at the monitoring station *PFM010039* in Forsmark. Positive values indicate changes above the 10-year mean while negative values indicate changes below this mean value.

	Mean	Median	Std. Dev.	Min	Max	25%-tile	75%-tile	N
Forsmark	0.02	0.01	0.2	–0.6	1.3	–0.12	0.14	43,800

3.4.2 Macrophytes and microphytobenthos

The producers in the benthic habitat, the phytobenthos, consist of large photosynthesizing algae and vascular plants (macrophytes) and microscopic unicellular organisms (microphytes including cyanobacteria). They are limited to the photic zone, which extends from the surface down to a maximum depth of approximately 30 m and in areas with low visibility less than 10 m.

In the photic zone, sediment-associated microalgae (microphytobenthos) can be expected to influence the exchange of carbon and nutrients at the sediment-water interface. Considerable microphytobenthic biomass and primary productivity have been documented at depths of 15–20 m in coastal temperate areas /Sundbäck et al. 1991/.

Forsmark

A number of surveys aimed at gathering information on the vegetation communities have been carried out as a part of SKB's site investigations. In 2004, a total of 59 diving transects were performed and 30 quantitative samples were taken, resulting in coverage (percent sea floor coverage) and biomass data of macrophytes /Borgiel 2005/. Forty-eight video recordings of the sea floor were also made during a marine geological survey /Elhammer and Sandkvist 2005a/ over large parts of Öregrundsgrepen, although these were sparsely distributed. Three diving transects, gathering quantitative and semi-quantitative (macrophyte coverage estimates), were performed in the exposed areas in 1998 /Kautsky et al. 1999/. These data, plus complementary data from other sources, have been used in two analyses producing a benthic vegetation map of the coastal area (Figure 3-26) /Fredriksson 2005b/.

Large parts of the Forsmark marine area are open sea and are delimited by the steep sloping island of Gräsö to the east and the gradual slope of the mainland to the south-west (see map Appendix 1). The area to the east and south of the Forsmark area is best known and is therefore the focus in the present description. Most of the area consists of shallow exposed hard bottoms (boulders or bedrock) interspersed with deeper valleys with soft bottoms (see Section 3.3.2). The photic zone is roughly between the surface and twice the average water transparency[4], and as the average water transparency is not more than 3.4 to 3.6 m in the coastal zone, large areas deeper than 7 m lack vegetation cover. The vegetation in the photic zone is dominated by red algae (e.g. *Polysiphonia nigrescens*) and brown filamentous algae (e.g. *Spacelaria arctica*) and the larger *Fucus vesiculosus* (Figure 3-27). In the sub-littoral zone, green algae such as *Cladophora glomerata* are present as well as the moss Fontinalis dalecarlica. This moss is frequently observed in the Gulf of Bothnia but does not occur in the Baltic Proper /Borgiel 2005, Kautsky et al. 1999, Lindahl et al. 1983/.

Table 3-16. Statistics for sea level changes at the monitoring station *PSM0000371 in Laxemar-Simpevarp*. Positive values indicate changes above the mean while negative values indicate changes below the mean value.

	Mean	Median	Std. Dev.	Min	Max	25%-tile	75%-tile	N
Laxemar-Simpevarp	0.03	0.01	0.2	–0.5	0.7	–0.05	0.2	1,314

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[4] Measured as Secchi depth.

Table 3-17. Functional groups according to this report occurring in the marine ecosystem in Forsmark and Laxemar-Simpevarp.

Functional group	Description/comment	Primary producer/consumer
Macrophytes	Phytobenthos – Large photosynthesizing algae and vascular plants	Primary producer
Microphytobenthos	Phytobenthos – microscopic unicellular photosynthesizing organisms	Primary producer
Phytoplankton	Free living, pelagic, photosynthesizing organisms	Primary producer
Benthic bacteria	Heterotrophic bacteria living on sea floor and in sediment	Consumers
Benthic fauna	Macroscopic heterotrophic organisms living in (infauna) or on (epifauna) the sediment	Consumers
Zooplankton	Macroscopic free living, pelagic, heterotrophic organisms	Consumers
Bacterioplankton	Free living, pelagic, heterotrophic bacteria	Consumers
Fish		Consumers
Birds		Consumers
Mammals	Here seals	Consumers

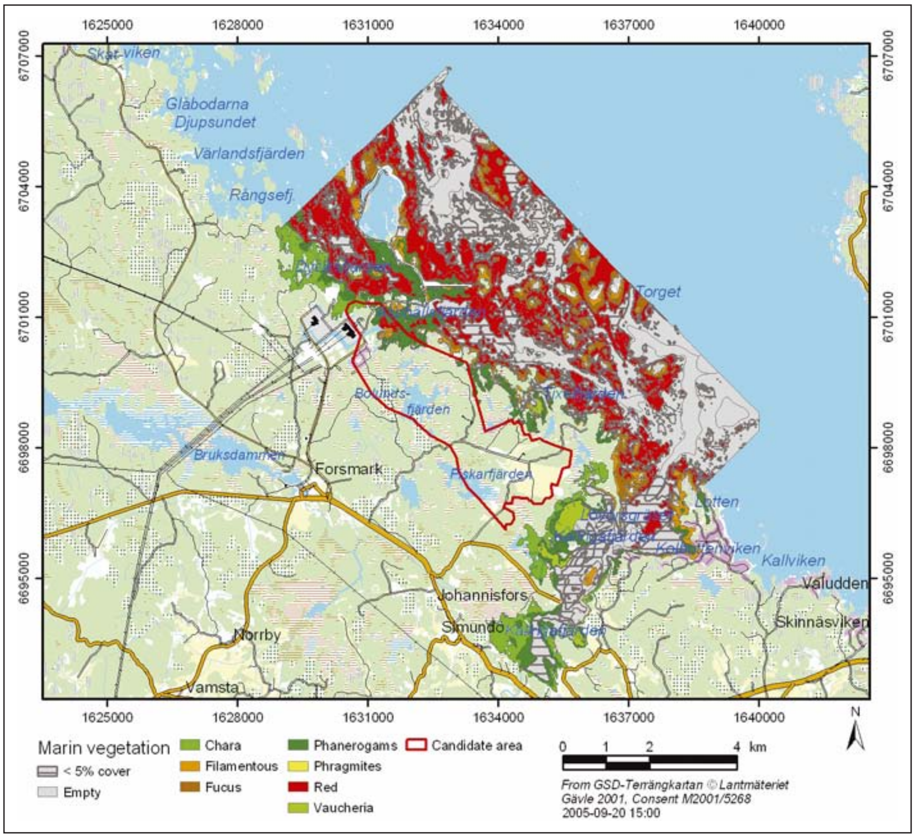


Figure 3-26. *Vegetation communities in Forsmark presented by /Fredriksson 2004/.*

***Figure 3-27.** Fucus vesiculosus and brown filamentous algae on bedrock at 1 m depth at the island of Marträd, located 6 km east of the Forsmark power plant.*

A few bays are more or less secluded from wave exposure and host soft bottom communities, e.g. Kallrigafjärden in the south and Asphällsfjärden by the Forsmark power plant. In these areas, soft bottom dwelling phanerogams (e.g. *Potamogeton pectinatus*, see Figure 3-28) and *Charophyceae* (e.g. *Chara tomentosa*) dominate the macrophytes in the shallow areas. In deeper areas in Tixelfjärden and Kallrigafjärden, the *Xanthophyceae* alga *Vaucheria dichotoma* is found in high densities. The water transparency is lower here than in the exposed areas (only 1.1–1.5 m) in Kallriga and Tixelfjärden, so areas below 2 m are vegetation-free or have only low densities of vegetation /Borgiel 2005, Kautsky et al. 1999/.

In the photic zone, the seabed is to a large extent also covered by a layer of microalgae, mainly diatoms. Biomass estimates and primary production for microphytobenthos in Forsmark have been reported by /Snoeijs 1986/. Biomass values ranged between 12–17 gC m^{-2} and primary production between 25–46 gC m^{-2} $year^{-1}$ at three sites outside the Biotest basin in Forsmark.

In the inner parts of Kallrigafjärden, large belts of emergent macrophytes (mainly reed, *Phragmites australis*) delimit the sea from land. These belts forms a boundary between land and sea and are further described in the wetland section in /Löfgren 2008/.

Benthic primary production and respiration were measured in a study in May, July and August 2005 /Borgiel et al. 2006/ at four sites (n=5 at each site) on four different macrophyte communities: red algae, *Vaucheria sp. Chara sp.* and vascular plants (*Zanichellia sp.*), see Appendix 1. The measurements were made using oxygen meters recording oxygen concentration every 15 min during a period of 24 h. Changes in oxygen concentration were used to calculate primary production during the light period and respiration during the dark period. The results showed high respiration and negative net primary production for the communities in several of the measurements. *Vaucheria sp.* and *Chara sp*. show negative net primary production (NPP) early in the season and positive NPP later on, while the opposite pattern seems to be valid for Red algae, see Table 3-18.

Figure 3-28. Potamogeton pectinatus on a soft bottom at a depth of approximately 2 m in Asphällsfjärden.

Laxemar-Simpevarp

Several studies gathering information about the vegetation communities have been carried out in Laxemar-Simpevarp as a part of SKB's site investigations. In 2002 a general survey of 1,274 independent sites was performed including recordings of macrophytes species and coverage (percent coverage of sea floor), 20 diving transects and 57 quantitative samples. In a marine geological study, 40 video recordings of the sea floor and qualitative grab samples were taken the same year /Elhammer and Sandkvist 2005b, Tobiasson 2003/. As part of a monitoring programme, three sites within the area are being monitored every year by the Regional monitoring program /KVF 2007/.

Table 3-18. Average Biomass, Respiration (R) and Net Primary Production (NPP), measured in five replicates at four sites in the Forsmark area.

	Period	Biomass (mg dw m^{-2})	Biomass (mg C m^{-2})	R (mg O_2 m^{-2} h^{-1})	NPP (mg O_2 m^{-2} h^{-1})
Chara sp.	May	2.4	0.3	77	–20
PFM006016	July	44	6.0	133	–1.5
	August	31	4.1	99	12
Vaucheria sp.	May	294	115	105	–21
PFM006017	July	580	227	26	5.9
	August	493	193	27	11
Vascular plants	May	0		29	–0.55
PFM006018	July	–		–	–
	August	–		–	–
Red algae	May	116	41	80	6.3
PFM006019	July	91	32	83	–8.6
	August	–		–	–

The data from the survey, plus complementary data from other sources, have been used in two analyses showing the benthic vegetation as a map in the coastal area /Fredriksson and Tobiasson 2003, Carlén et al. 2007/ (Figure 3-30). The vegetation map was drawn by hand (also using sea charts and a marine geology map), and the accuracy is dependent on the density of the observations – generally higher in the inner bays and coastal areas and lower in the offshore area. The modelled grids /Carlén et al. 2007/ were made using spatial modelling (GRASP) and several spatially varying datasets such as average annual temperature, wave exposure etc.

From the general survey, nine different vegetation communities were defined based on dominant species or higher taxa (Figure 3-30). The red algae community covered the largest area, followed by the *Potamogeton pectinatus* community, *Chara sp* and *Fucus vesiculosus.* The vegetation communities consist of sub-areas of different species composition and degree of coverage. Species diversity, composition and methods are presented in more detail in /Fredriksson and Tobiasson 2003/.

The benthic area in Laxemar-Simpevarp can be divided into three areas with more or less distinct characteristics with regard to structuring factors such as wave exposure, light penetration and substrate type. These areas are: secluded bays (e.g. Borholmsfjärden and Granholmsfjärden), shallow exposed archipelago (in the south-east area) and deep exposed areas (the coast and water mass outside Simpevarp, Ävrö and Upplångö). The bays are characterized by low visibility (yearly average of 2–3 m) and low wave exposure, while the archipelago and the outer exposed areas have an average annual visibility of 4 to 7 and 12 m, respectively.

The inner soft bottom parts of the archipelago north of Laxemar-Simpevarp (around the island of Äspö) are dominated by *Chara sp*. West of Ävrö, a large area is covered by *Xanthophyceae* generally *Vaucheria dichotoma*. On corresponding bottoms in the southern area, the vegetation is dominated by vascular plant communities, mostly *P. pectinatus* and *Zostera marina*. The sheltered inner coastal waters, particularly south of Laxemar-Simpevarp, are dominated by *P. pectinatus* (Figure 3-28*)*.

Further out towards more exposed areas *P. pectinatus* and *Z. marina* occur together in a patchy distribution. On hard substrates, in shallow areas, the vegetation is dominated by *Fucus vesiculosus* (Figure 3-31), and in deeper areas red algae cover the hard substrates (Figure 3-32) /Fredriksson and Tobiasson 2003/. Low abundances of *Fucus sp.* are recorded to a depth of approximately 10 m and red algae down to approximately 30 m /Tobiasson 2003/.

Primary production and respiration were measured in nine of the identified macrophyte communities (see Appendix 2) /Wijnbladh and Plantman 2006/. Net primary production in July ranged between 17–95 mgC m^{-2} h^{-1} during the daytime and respiration ranged between 5–80 mgC m^{-2} h^{-1}. At three sites, primary production and respiration were studied during a period of one year, and the estimated annual net primary production was found to be lower than in a previously published model based on literature data /Wijnbladh and Plantman 2006/. Biomass, respiration and NPP are presented for three of the sites in Table 3-19, and one of the *Vaucheria sp.* sites where NPP measurements were performed (Figure 3-33).

***Figure 3-29.** Measurements of benthic primary production and respiration in a red algae community in Laxemar-Simpevarp /Borgiel et al. 2006/. Photo: M. Borgiel.*

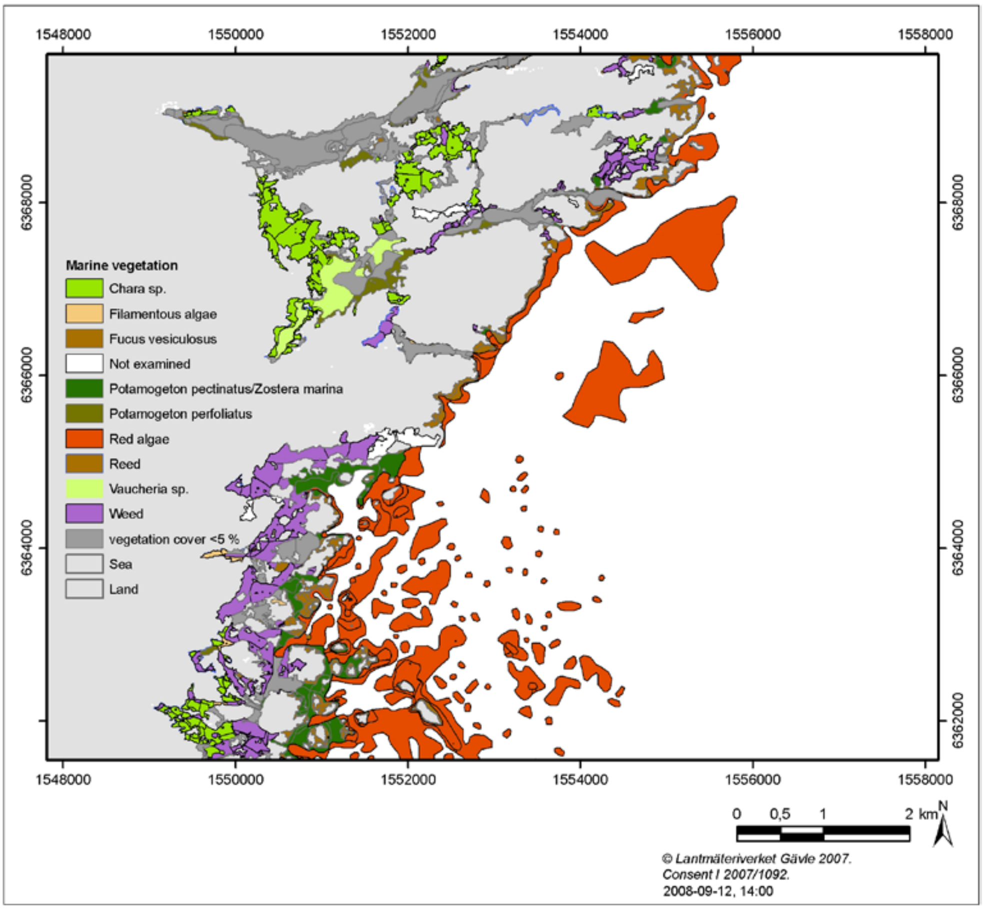


Figure 3-30. *Marine vegetation communities in Laxemar-Simpevarp presented by /Fredriksson and Tobiasson 2003/.*

Figure 3-31. *Fucus vesiculosus habitat in the Laxemar-Simpevarp marine basin.*

Figure 3-32. *Red algae on hard bottom substrate in the Laxemar-Simpevarp marine basin.*

Figure 3-33. *A Vaucheria sp. site in the Laxemar-Simpevarp area, where benthic primary production and respiration were measured.*

Table 3-19. Average Biomass, and annual Respiration (R) and Net Primary Production (NPP) in the three out of nine sites in the Laxemar-Simpevarp area.

	Period	Biomass (mg DW m^{-2})	Biomass (mg C m^{-2})	R (mg O_2 m^{-2} year^{-1})	NPP (g C_2 m^{-2} year^{-1})
Potamogeton pectinatus PSM007093	Jan, Apr, May, July, Aug	2.5	0.8	–96	28
Mixed PSM007094	‘’	27	8.3	–168	16
Chara sp. PSM007095	‘’	63	8.5	–131	21

3.4.3 Phytoplankton

Phytoplankton species composition and biomass varies throughout the year. Generally in the Baltic, the spring bloom as well as the autumn maxima is dominated by diatoms. After the spring bloom of diatoms, dinoflagellates and other smaller flagellates become more abunadant to be followed by maximum densities of cyanobacteria and zooplankton.

The basis for phytoplankton succession is the nutrients, temperature variation and light. The spring bloom of phytoplankton begins after ice break-up and the intensity reflects the size of the nutrient reserves. The spring bloom species, diatoms and dinoflagellates, consume most of the phosphorus and nitrogen accumulated in the water during previous winter. In the open sea, spring bloom is often nitrogen limited, while in the near-shore coastal zone the limiting nutrients are more often phosphorus and silica.

After spring bloom, primary production in the water column decreases and the concentrations of phytoplankton are low during summer due to lower nutrient supplies and grazing by zooplankton. Large blooms of cyanobacteria often occur later in the summer in warm and calm weather. However, the recent situation with excessive cyanobacterial blooms in the Baltic Proper thriving off an excess of phosphorus may, have diminished the importance of both the major spring bloom and the minor fall bloom and their associated sedimentation, especially in the less phosphorus-rich Bothnian Sea /Larsson et al. 2006/.

Sampling and analyses of species abundance and biomass of phytoplankton were performed during SKB's site investigations in 2003 and 2004 in Forsmark and Laxemar-Simpevarp /Huononen and Borgiel 2005, Sundberg et al. 2004/. Chlorophyll sampling (a relative measure of phytoplankton biomass in the water) was performed regularly at the sites along with measurement of hydrology parameters in the site investigation programme between 2002 and 2006 /Nilsson and Borgiel 2007, Ericsson and Engdahl 2007/.

Forsmark

The average biomass value for phytoplankton in Öregrundsgrepen between June 1972 and May 1973 was 0.5 gC m^{-2} /Eriksson et al. 1977/.

In Öregrundsgrepen 1977–1978, the spring bloom of phytoplankton was dominated by diatoms and dinoflagellates. The vernal maximum culminated in late April–early May. Maximum values per 24 hours of phytoplankton biomass, chlorophyll and primary production were about 50 g ww m^{-2}, 100 mg chl a m^{-2} and 600 mgC m^{-2}, respectively. Annual phytoplankton production was estimated to be 59 gC m^{-2} (1977). At that time this rate of primary production was about half of the production rate in the northern Baltic Proper, but 5–6 times higher than production in the Gulf of Bothnia /Lindahl and Wallström 1980/.

In a more sheltered bay of Öregrundsgrepen, Asphällsfjärden (PFM00062), which was studied in 2003–2004, the diatoms dominated only during the late winter growth period, while the autotrophic red tide ciliate *Mesodinium rubrum* dominated the spring maximum as well as the late fall decline and the winter minimum. The mean carbon biomass for phytoplankton during 2003–2004 was 14 mgC m^{-3} at the station PFM00062 /Huononen and Borgiel 2005/.

Monthly means for the period 2002–2006 of chlorophyll, nutrients and light penetration in Tixelfjärden at Forsmark are shown in Figure 3-34. Chlorophyll values from Forsmark are considered quite low compared with data from Swedish Environmental Quality Criteria (EQC), which during 1995 to 2003 varied between 5.4– 8.0 ugL^{-1} in the southern Bothnian Sea /Larsson et al. 2006/.

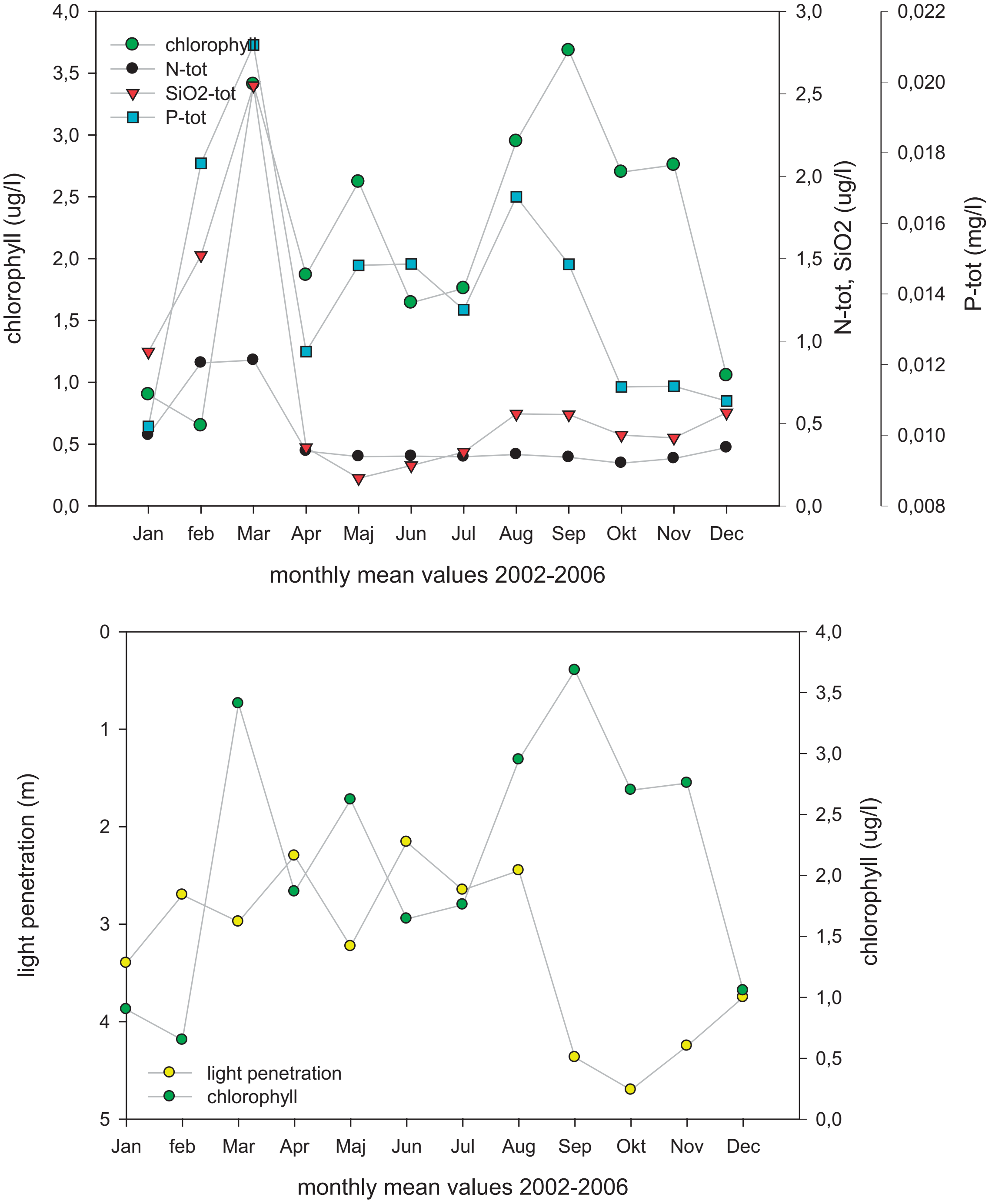


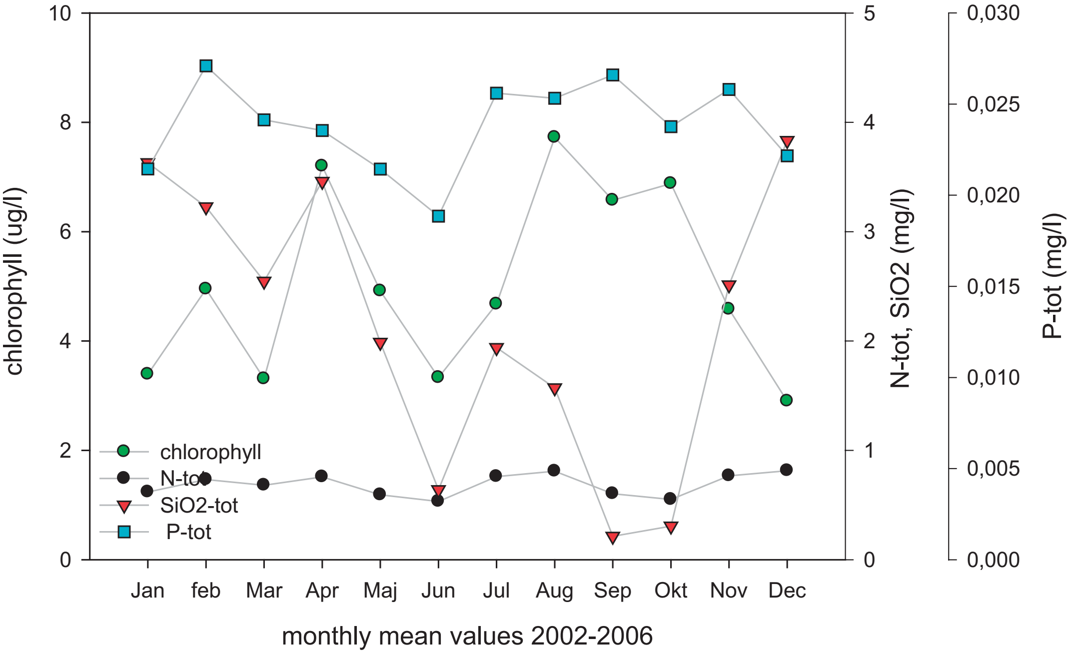
Figure 3-34. *Monthly mean value of chlorophyll (µg/l) compared with P-tot (mg/l), N-tot and SiO_2 (µg/l) (upper graph) and light penetration (m) (bottom graph) in Tixelfjärden (PFM000063) in Forsmark for the period 2002–2006. Data from site investigations by SKB /Huononen and Borgiel 2006/.*

Laxemar-Simpevarp

The phytoplankton communities at the three investigated sites in Laxemar-Simpevarp were dominated by diatoms during the spring bloom while, Dinophytes (Dinoflagellates) and cyanobacteria were the most abundant groups in July /Sundberg et al. 2004/.

The phytoplankton biomass varied between 0.03–1.2 mg ww L^{-1} and the mean value was 0.3 mg ww L^{-1}, equivalent to 60 g C m^{-3} (assuming 20% carbon content) calculated from /Sundberg et al. 2004/.

Monthly means of chlorophyll, nutrients and light penetration during the period 2002–2006 in Borholmsfjärden (PSM002062) in Laxemar-Simpevarp are shown in Figure 3-35. In comparison to the EQC, the concentrations of chlorophyll during this period were high /Naturvårdsverket 1999/.



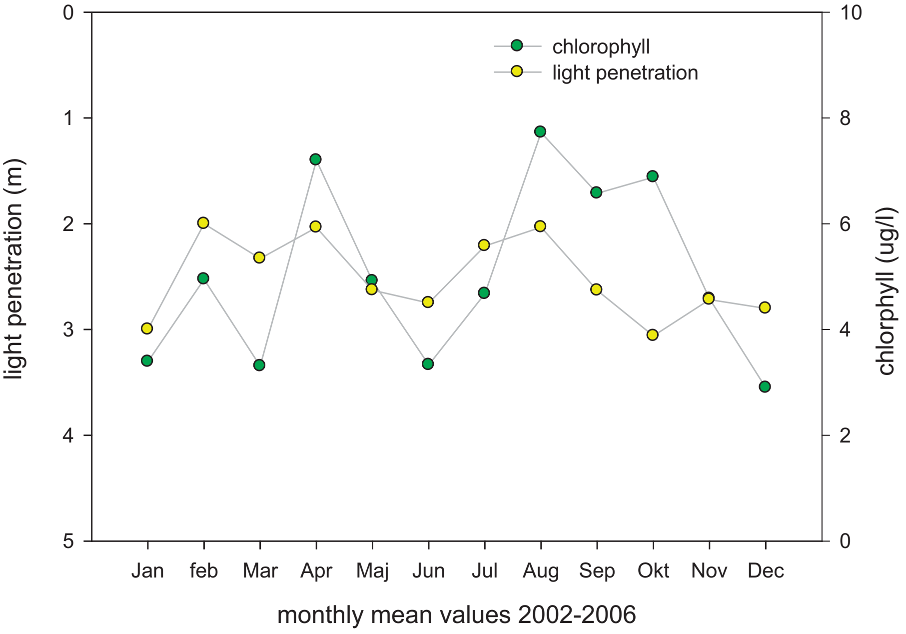


Figure 3-35. *Monthly mean value of chlorophyll (µg/l) compared with inorganic P (mg/l), inorganic N and SiO_2 (mg/l) (upper graph) and light penetration (m) (bottom graph) in Borholmsfjärden (PSM002064) in Laxemar-Simpevarp for the period 2002–2007. Data from site investigations by SKB /Ericsson and Engdahl 2007/.*

3.4.4 Benthic bacteria

Benthic (heterotrophic) bacteria are found in all benthic habitats, both on the sea floor and in the sediment. Benthic cyanobacteria, or blue-green algae, are photosynthesising organisms and therefore included in the section discussing microphytes, see Section 3.4.2.

Abundance and biomass of benthic bacteria were surveyed in a study in the summer of 2006 in Laxemar-Simpevarp and Forsmark /Andersson et al. 2006/, see Table 3-20. Sediment cores were sampled with a boat, or by hand by SCUBA divers. The top 5 cm were collected from the samples, and bacteria larger than 0.22 µm were counted using an epifluorescence microscope. The number of cells were between 3.03 and 7.29×10^9 cells/ml in Laxemar-Simpevarp and between 1.15 and 4.28×10^9 cells/ml at two sites in Forsmark. Biomass data were calculated for an average of 5 cm sediment depth.

Abundance of benthic bacteria was studied by /Jørgensen and Revsbech 1989/ at ten sites between Kattegat and the Baltic and results ranged from 0.025 to 1×10^9 at depths of between 14 and 200 m. In the Baltic Sea, /Mohammadi et al. 1993/ found benthic bacteria biomasses in the summer of 1.06 gC m^{-2} (SD 0.44), recalculated for 5 cm sediment depth, in deep sea (> 100 m depth) sediment. In the investigation of bacterial biomass performed by the SKB, the abundance was generally higher than in the other studies performed at greater depths /Andersson et al. 2006/.

3.4.5 Benthic fauna

Benthic fauna, bottom fauna or sometimes benthos refers to the macroscopic animals that live in (infauna) or on (epifauna) the bottom substrate. Here, benthic fauna refers to all macro- and meiofauna in this habitat, including fauna living on vegetation, except benthic fish, which are treated separately.

The biomass and abundance of benthic fauna are dependent on factors such as type and characteristics of substrate, salinity, oxygen, and temperature. Due to the importance of substrate they are often classified as soft bottom and hard bottom living. This division is also practical for sampling reasons and hence used widely, including in the studies referred to below.

In the Baltic and Bothnian Seas, the species and abundances of benthic fauna are clearly dependent on salinity: marine species diversity decreases northwards along the salinity gradient, and fresh-water species dominate in the northern Bothnian Sea and the Bothnian Bay /Sjöberg 1997/. Water with a salinity of 5 to 6 psu (e.g. Forsmark) is considered to harbour the fewest species.

Table 3-20. Abundance and biomass of benthic bacteria found in studies in Forsmark and Laxemar-Simpevarp, summer of 2006.

	Mean	Median	Std. Dev.	Min	Max	N
Forsmark						
cells/ml	2.7×10^9	2.9×10^9	1.4×10^9	1.3×10^9	4.3×10^9	5
gC m^{-2}	3.5	4.6	1.8	1.4	5.1	5
Laxemar-Simpevarp						
cells/ml	4.8×10^9	4.6×10^9	1.4×10^9	3.0×10^9	7.3×10^9	8
gC m^{-2}	6.5	5.5	3.0	3.4	12.2	8

Forsmark

Several studies on benthic biomass have been performed in the Forsmark area /Borgiel 2005, Sandström et al. 2002, Odelström et al. 2001, Wallström and Persson 1997, (Swedish Board of Fisheries) Adill et al. 2006/. Data from the various investigations are presented in Table 3-21.

The environmental surveys performed in the Forsmark area by the Swedish Board of Fisheries (SBF) also include benthic fauna. The development of benthic fauna in the Forsmark area has been monitored since the end of the 1970s. An increase in benthic biomass and species diversity has been seen since the start of the monitoring (Figure 3-36). The increase in total biomass can also be seen elsewhere in the Baltic, probably due to the increased nutrient load. In soft bottoms (at 16 m depth) the biomass has varied from slightly above 50 g ww m^{-2} to around 270 g ww m^{-2}. The biomass at the soft bottom sampling sites has been dominated by the Baltic mussel (*Macoma baltica*), and in deeper areas another abundant species has been *Monoporeia affinis,* Figure 3-37. Since 1997 when *Marenzellaria viridis* showed up for the first time in Forsmark, it has become more and more important in terms of biomass. In 2004 *M. viridis* represented 27% of the total biomass at some stations /Adill et al. 2005/.

The benthic fauna in the county of Uppsala was investigated at 10 sites in 2000 /Odelström et al. 2001/. At 9 of the 10 sites 5–7 taxa were found, while at one site in the Östhammarsfjärden only 2 taxa were found. The abundance of individuals per m^{-2} varied between 16 (Southern Östhammarsfjärden) and 4,431 (Kallrigafjärden). The biomass varied between < 1 and 190 gm^{-2}. The detrivore *M. baltica* was found at 8 of 10 sites, where it completely dominated the biomass. The biomass of the mussels varied between 5 and 189 g m^{-2}, Table 3-21.

/Borgiel 2005/ studied benthic macrophyte communities and vegetation-associated bottom fauna as well as soft bottom macrofauna in SKB's site investigation programme. The total biomass of the vegetation-associated fauna ranged from 6 to 60 g d w m^{-2} and was dominated by detrivores, especially the snail *Hydrobia sp.* and the mussel *M. baltica*.

The soft bottom community (benthos) was less abundant in terms of biomass; its mean biomass was 8.8 and 11 g dw m^{-2}, in the two investigated bays respectively. In the soft bottom community, the same species dominated the benthic fauna as in the vegetation-associated bottom fauna communities, i.e. detrivores like *Hydrobia sp* and *M. baltica*. In /Sandman et al. 2008/ mean biomasses for hard bottom substrates in the Forsmark area (Grasö) are 15.5 g dw m^{-2}, see Table 3-21.

The reported values from all investigations are of the same order of magnitude, ranging from 0.6 gC m^{-2} to 28 gC m^{-2}, with the highest values reported for vegetation-associated soft bottom fauna.

Table 3-21. Abundance, biomass and number taxa of benthic fauna from various investigations performed in the Forsmark area.

	Mean	Min.	Max.
/Odelström et al. 2001/	*Soft bottom fauna (County of Uppsala) (n=10)*		
Abundance (ind m^{-2})	1,614	16	4,431
Biomass (d w g m^{-2})*	14	0	39
Biomass (g C m^{-2})*	4	0	12
Number of taxa	6	2	7
/Borgiel 2005/	*Vegetation associated soft bottom fauna (Forsmark) (n=30)*		
Abundance (ind m^{-2})			
Biomass (d w g m^{-2})	28	2	93
Biomass (g C m^{-2})*	8.3	0.6	28
Number of taxa	9	2	19
/Borgiel 2005/	*Soft bottom fauna (Forsmark) (Tixelfjärden (Kallrigafjärden) n=20)*		
Abundance (ind m^{-2})	2,276 (3,178)		
Biomass (d w g m^{-2})	8.8 (11)	6.4	44
Biomass (g C m^{-2})*	2.6 (3.3)	1.9	13
Number of taxa	5.6 (6.2)	2	9
/Sandström et al. 2002/	*Hard bottom fauna (Forsmark)*		
Abundance (ind m^{-2})			
Biomass (d w g m^{-2})	16		
Biomass (g C m^{-2})*	5		
Number of taxa			
/Adill et al. 2006/	*Soft bottom fauna (16 m/41 m depth) (Forsmark 1973–2006)*		
Abundance (ind m^{-2})			
Biomass (d w g m^{-2})*		~ 11	~ 55
Biomass (g C m^{-2})*		~ 3.3	~ 17
Number of taxa		4	7

* Calculated from g ww according to /Kautsky 1995/.

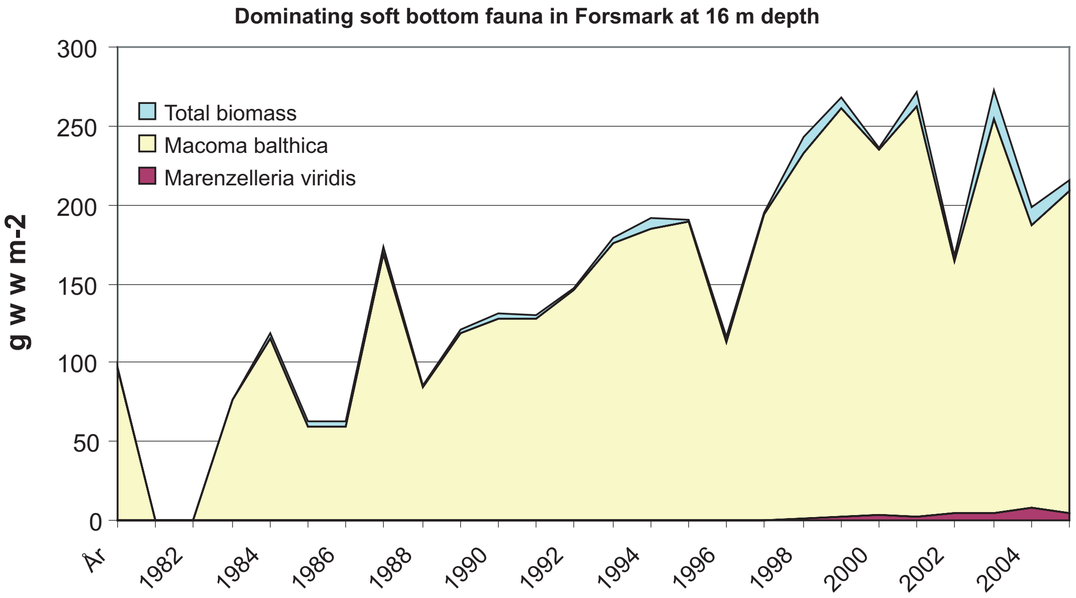


Figure 3-36. *Benthic soft bottom fauna at one sampling station in the Forsmark area at a depth of 16 m during the period 1981–2006 (data from the /Adill et al. 2006/). Note that the benthic fauna was not sampled in 1982 and this does not indicated abscence of benthic fauna.*

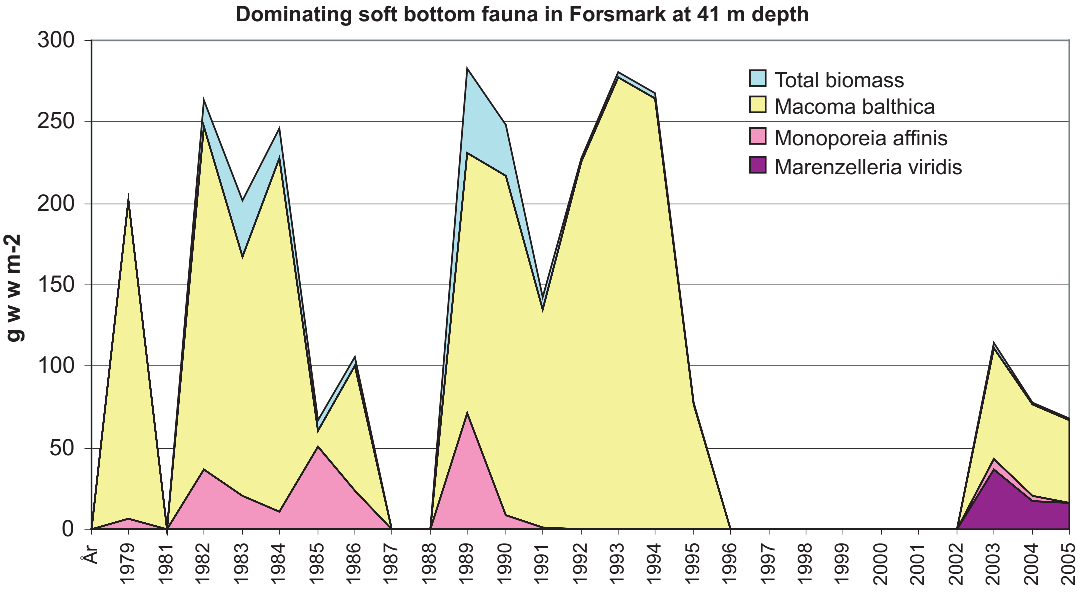


Figure 3-37. *Benthic soft bottom fauna at one sampling station in the Forsmark area at a depth of 41 m during the period 1979–2006 (data from the /Adill et al. 2006/). Note that some years have not been sampled and this does not indicate an absence of benthic fauna.*

Laxemar-Simpevarp

Several studies on benthic biomass have been performed in the Laxemar-Simpevarp area /Ericsson and Engdahl 2004c, Fredriksson 2004, 2005a, Andersson et al. 2005, Kustvattenkommittén i Kalmar län (KVF) 2007/. Data from the various investigations are presented in Table 3-22.

Systematic investigations of the benthic fauna in the county of Kalmar have been performed by the University of Kalmar since the 1960s. Long term trends in the benthic fauna show a slow but significant increase in biomass and species diversity. The biomass decreased slightly for a few years in the beginning of the 21st century, only to increase again in 2005. Species diversity has increased from a mean of 6 species to around 10 in 2000 /KVF 2007/.

Soft bottom macrofauna in the Laxemar-Simpevarp area has been monitored since the early sixties by the Swedish Board of Fisheries. Three species dominate the benthic fauna in the area: *Mytilus edulis* and *M. baltica,* and in deeper areas also *Monoporeia affinis*. The number of species found has increased since the beginning of the monitoring from 4 to around 14, and the biomass has varied between 75 g ww m^{-2} and 170 g ww m^{-2}. Biomass was less than normal in the deeper stations in the early 1990s, and an oxygen deficit was observed during some of the years. Abundance declined in the deeper stations in the area in the late 1980s due to a sharp decrease in the abundance of the small crustacean *M. affinis*. This species had not recovered completely by the end of the investigated period. A long term increase in abundance was observed in the shallow stations, mostly due to a favourable trend for the mussels *M. edulis* and *M. baltica* /Andersson et al. 2005/.

Benthic fauna was studied within the site investigation programme in Laxemar-Simpevarp by /Fredriksson 2004, 2005a/.

In soft bottoms, the filter feeding bivalve *M. baltica* clearly made the largest contribution to the total biomass in all areas. The most frequent taxa in the samples from the archipelago north of Simpevarp were *Chironomidae* and *M. baltica*. *Chironomidae* was also the most prominent contributor to the total abundance and made *Insecta* the largest taxonomic group in terms of abundance. The most frequent taxa in the archipelago south of Simpevarp were *Chironomidae* and *Hydrobia sp.* which were present in all of the samples from the area /Fredriksson 2004/.

Table 3-22. Abundance, biomass and number of Bentic fauna of taxa from various investigations /KVF 2003, SBF 2005, Fredriksson 2004, 2005a/ performed in the Laxemar-Simpevarp area.

	Mean	Min.	Max.
/KVF 2003/	*Soft bottom fauna (County of Kalmar, n=62)*		
Abundance (ind m^{-2})	1,501	33	11,273
Biomass (d w g m^{-2})*	12	0.4	58
Biomass (g C m^{-2})*	4	0.1	17
Number of taxa	11	5	24
/SBF 2005/	*Soft bottom fauna (Laxemar-Simpevarp)*		
Abundance (ind m^{-2})			
Biomass (d w g m^{-2})		15	35
Biomass (g C m^{-2})*		5	11
Number of taxa		4	14
/Fredriksson 2004/	*Soft bottom fauna (Laxemar-Simpevarp, n=45)*		
Abundance (ind m^{-2})	2,440	150	12,000
Biomass (d w g m^{-2})	13	0.1	83
Biomass (g C m^{-2})*	4	0.03	25
Number of taxa	8	3	18
/Fredriksson 2005a/	*Hard bottom fauna (Laxemar-Simpevarp)*		
Abundance (ind m^{-2})			72,643
Biomass (d w g m^{-2})		76	1,520
Biomass (g C m^{-2})*		9	140
Number of taxa			

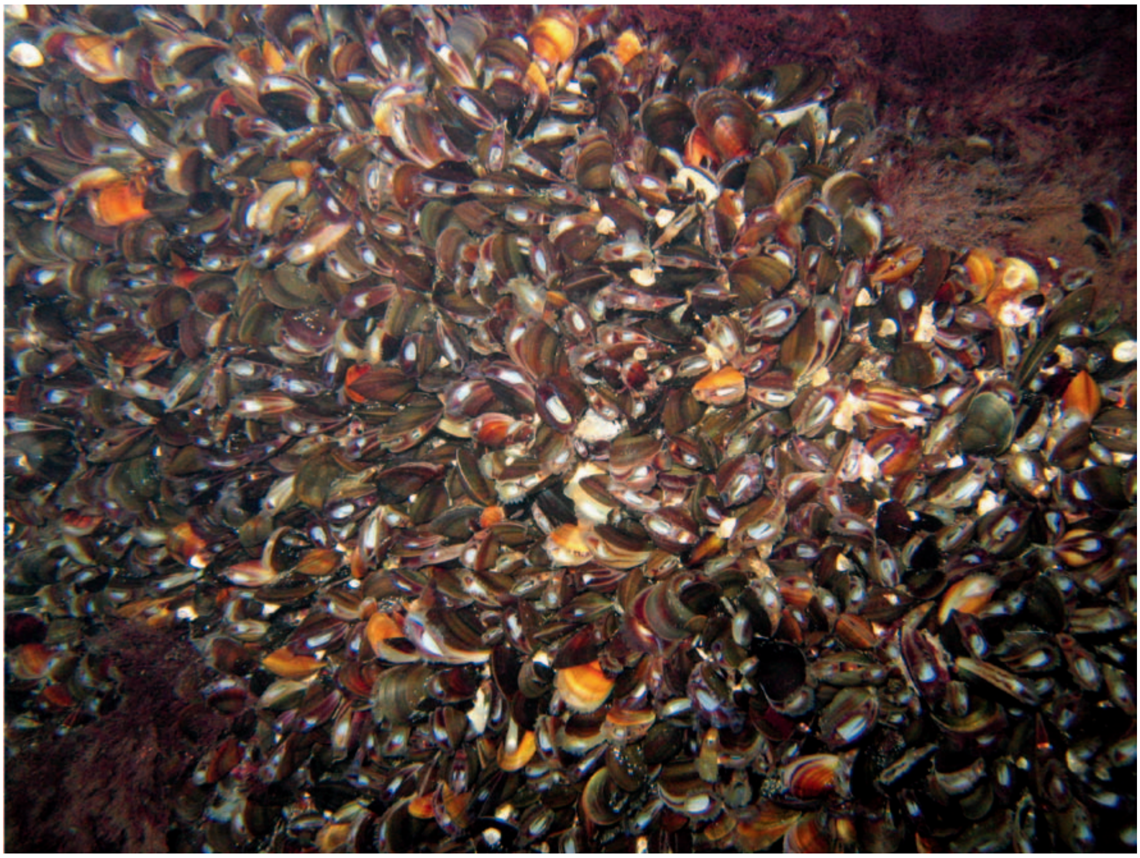


***Figure 3-38.** Blue mussels (Mytilus edulis) on a bottom in Laxemar-Simpevarp.*

The sessile macrofauna, attached to hard substrates (hard bottom fauna), is completely dominated by *M. edulis* (Figure 3-38) in terms of both biomass and abundance. Usually, hard bottom substrate changed into a soft substrate at a water depth of between ten and thirteen metres at the visited locations. The total estimated biomass of *M. edulis* in the whole area studied was approximately 4,500 metric tons, or 96% of the total sessile epifaunal biomass /Fredriksson 2005a/.

The soft bottom fauna investigated in SKB's site investigations was well in accordance with other reported biomass estimates, see Table 3-22.

3.4.6 Zooplankton

The most common zooplankton taxa in the Baltic are the small crustaceans, copepods and cladocerans, but rotifers, ciliates and larvae from other organisms (e.g. the blue mussel *Mytilus edulis*) are also present. During and after the spring bloom of phytoplankton, the zooplankton biomass increases in the pelagic zone. The zooplankton maximum generally occurs in July–August in the Baltic and is dominated by copepods, which comprise 80% of the zooplankton biomass /Lindahl et al. 1983/. The species composition of zooplankton is closely linked to changes in salinity, where nerictic copepod species are favoured by higher salinity while the opposite is true for freshwater groups /Vourinen et al. 1998/.

The most abundant copepod species in both Forsmark and Laxemar-Simpevarp was *Acartia bifilosa*, while the cladoceran *Bosmina coregoni* occasionally occurred abundantly /Karås 1992/. /Karås 1992/ recorded the number of individuals in the cooling water intake and outlet at the nuclear power plants (Laxemar-Simpevarp 1975 and 1976, Forsmark 1984 and 1986). The number of zooplankton in the inlet water reached a maximum in July in Forsmark and in August in Laxemar-Simpevarp.

Forsmark

Several studies of zooplankton have been performed in Öregrundsgrepen /Eriksson 1973, Eriksson et al. 1977, Lindahl et al. 1983, Olsonen 2007/, and in site investigations performed by SKB /Huononen and Borgiel 2005/.

In the summer of 1970 (86 hauls by /Eriksson 1973/), the zooplankton biomass and species diversity maximum occurred in August, with the highest densities in the inner parts of Öregrundsgrepen. Zooplankton abundances were also higher than in adjacent Baltic areas, especially in August. The zooplankton carbon biomasses reported in these studies show a wide range of variation from 0.366 gC m^{-2} (Öregrundsgrepen 1972–1973, 2–3 hauls per month year-round) /Eriksson 1973/ to 1.8 gC m^{-2} (Åland sea) /Lindahl et al. 1983/. The Finnish Institute of Marine Research /Olsonen 2007/ reported zooplankton biomasses in the Baltic Sea outside Forsmark in the late summer 2007. The biomass of the most abundant crustacean zooplankton taxa was around 2.7 gC m^{-2}, dominated by the copepod *Acartia sp*.

In the biweekly site investigations performed during 2003–2004, copepods dominated the zooplankton fauna and the biomass maximum occurred in October. The zooplankton carbon biomass in Asphällsfjärden Bay varied between 0.6 and 9.4 mgC m^{-3} (mean 4.5 mgC m^{-3}) /Huononen and Borgiel 2005/ at a sample depth of 4 m, which seems low in comparison with the older investigations. However, the values are hard to compare due to different units (per m^{-2} and m^{-3}, respectively).

Laxemar-Simpevarp

Biomass values for zooplankton in the Nordic parts of the Baltic Proper in the late summer 2007, reported by the Finnish Institute of Marine Research /Olsonen 2007/, ranged between 4 and 6 gC m^{-2}. To the authors' knowledge, no studies reporting zooplankton biomasses in Laxemar-Simpevarp have been available for comparison with site investigation data reported by /Sundberg et al. 2004/. There have been studies carried out concerning the zooplankton fauna in Laxemar-Simpevarp, however, the studies have focused on species composition and not zooplankton biomass.

The zooplankton communities at the investigated sites in the Laxemar-Simpevarp archipelago, consisted mainly of macro zooplankton, dominated in the winter and spring by copepods but showed a more diverse composition in the summer with cladocerans, rotifers and larvae of some benthic macro invertebrates. The highest biomasses were found in July. The biomass varied between 0.01 and 0.4 mg d w L^{-1} with a mean of 0.05 mg d w L^{-1} /Sundberg et al. 2004/, corresponding to 40 mg w w L^{-1}, in turn corresponding to 2 gC/m^{-3} (assuming 5% of the wet weight to be carbon), which is of the same order of magnitude as reported by /Olsonen 2007/, but not completely comparable due to a difference in units (gC m^{-2} and gC m^{-3}).

3.4.7 Bacterioplankton

Bacterioplankton are bacteria free living in the pelagic habitat, here consisting of all heterotrophic bacteria living in the water column. Cyanobacteria, or blue-green algae are photosynthesising organism and therefore included in Phytoplankton, see Section 3.4.2.

Abundance and biomass of bacterioplankton were studied in summer 2006 in Laxemar-Simpevarp and Forsmark /Andersson et al. 2006/, see Table 3-23. Surface water samples (0–2 m) were collected and all bacterioplankton larger than 0.22 μm were counted with an epifluorescence microscope. The biomass was within the range found in the summer in the Gulf of Finland in the Baltic Sea (11–36 mgC m^{-3} /Kuparinen 1987/) and abundances were similar to those reported as averages for a year in other temperate areas, e.g. 1×10^9 L^{-1} in the North Sea 1.1×10 L^{-1} in Massachusetts Bay /Toolan 2001/.

3.4.8 Fish

The Baltic fish fauna is often referred to as cold- or warm-water species, due to the optimal temperatures for the various species. Warm water species usually include species with a freshwater origin, such as perch (*Perca fluviatilis*), roach (*Rutilus rutilus*) and white bream (*Blicca bjoerkna*), but also carp (*Cuprinidae*), pike (*Esox lucius*) and eel (*Anguilla anguilla*). Warm-water species have a temperature optimum around 20°C and are generally stationary in the coastal zone. Cold-water fish include species such as cod (*Gadus morhua*), sprat (*Sprattus sprattus*), herring (*Clupea harengus*), bull routs (*Myoxocephalus scorpius*) and eelpout (*Zoarces viviparous*). They have a preference for cold water and generally avoid water with temperatures above 10–15°C. They generally spend most of their life in the open sea.

The Baltic fish fauna is a mixture of freshwater and marine species, where the freshwater species inhabit coastal and northern areas and marine species dominate offshore and in southern areas. Since the beginning of the 1990s, recruitment of pike and perch has decreased dramatically in the whole Baltic, in some places by as much as 80–90% /Bernes and Naylor 2005/.

The most abundant species in the Baltic are sprat, herring and cod; these species represent 80–90% of the total annual catch in the Baltic /Mackenzie et al. 1996/ and about 80% of the total fish biomass /Hjerne and Hansson 2002/. In recent years the cod population shows a weak increase in relation to the former years when the population decreased dramatically in the entire Baltic Sea. Still however, today the cod represents much less of the total catch and fish biomass than in the earlier studies. The Baltic herring population has also declined steadily since the early 1980s, but there seems to have been some recovery since the beginning of 2000 /Bernes and Naylor 2005/.

Herring and sprat are the dominant zooplanktivores. Herring migrate to coastal areas for spawning on bottom substrates, but they spend most of their life cycle in the open sea. Sprats spend their entire life in the open sea and spawn pelagically, as do cod. About half of the cod diet consists of benthos /Hjernae and Hansson 2002/. The decline of cod in the entire Baltic Sea since the early 1980s has affected the whole ecosystem since cod is an important top predator. The sprat population has benefited from the cod decline and is now the dominant pelagic fish species in the Baltic. The growing sprat population might also be the explanation for the decreasing recruitment of perch and pike, since sprat feed on zooplankton, which is the main food source for pike and perch larvae /Bernes and Naylor 2005/.

The estimated biomass of pelagic fish populations for two years from the southern Baltic was 0.5 g m^{-2} (std. dev. 0.5), corresponding to 0.2 gC m^{-2} /Thiel 1996/.

Table 3-23. Biomass (mgC m^{-3}) and abundance of bacterioplankton (cells L^{-1}) in Forsmark and Laxemar-Simpevarp in summer 2006.

	Mean	Median	Std. Dev.	Min	Max	25%-tile	75%-tile	N
Forsmark								
Biomass (mgC m^{-3})	24	22	7.2	15.	37	20	28	9
Cells L^{-1}	1.8×10^6	1.8×10^6	5.5×10^6	1.2×10^6	2.8×10^6	1.3×10^6	2.2×10^6	9
Laxemar-Simpevarp								
Biomass (mgC m^{-3})	25	25	2.4	22	27	24	26	3
Cells L^{-1}	1.3×10^6	1.3×10^6	1.6×10^6	1.2×10^6	1.5×10^6	1.3×10^6	1.4×10^6	3

Forsmark

A number of investigations regarding fish populations, abundance and biomass have been conducted in the Forsmark area /Adill et al. 2005, Lindahl et al. 1983/ and within SKB's site investigations /Heibo and Karås 2005, Axenrot and Hansson 2004/.

Biological monitoring of the fish population in the Forsmark area has been performed by the Swedish Board of Fisheries since the 1980s. Due to sampling technique and depth, it has focused mainly on the population of warm-water species in shallow waters. Perch is the dominant species in the Forsmark area. In 2006, perch accounted for 75% of the species caught /Adill et al. 2005/, Figure 3-39.

Biomass estimates were made in shallow areas of the nearby Gräsö archipelago in the 1980s. The biomass maximum was estimated to be between 10 and 15 g m^{-2}, with a mean value for the whole area of 1–5 g m^{-2} (0.5–2.5 gC m^{-2}) /Lindahl et al. 1983/.

The estimates of fish biomass made in SKB's site investigations /Heibo and Karås 2005, Axenrot and Hansson 2004/ are of the same order of magnitude as in previous investigations.

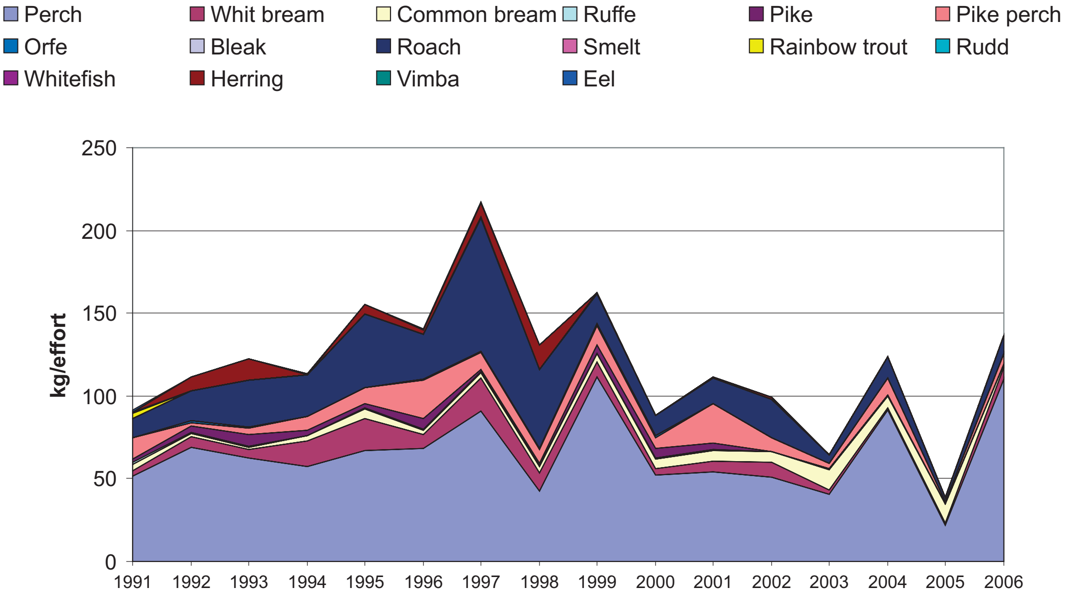


Figure 3-39. *The different species caught during test fishing for monitoring of the fish population in the Forsmark area. Data from the /Adill et al. 2006/.*

Data were compiled by the Swedish Board of Fisheries concerning the coastal fish community in Forsmark and estimates of fish biomasses in the area were reported /Heibo and Karås 2005/. The fish biomass varied between 60 and 70 kg ha^{-1}/ (3–3.5 gC m^{-2}). Herring, stickleback, goby and sprat were the dominant fish species.

Fish abundances, biomass, densities and species composition were investigated in the outer parts of the archipelago in Forsmark and compared with two reference areas /Axenrot and Hansson 2004/. Herring dominated the fish fauna. The biomasses were twice as high in Forsmark as in the reference area of Gudinge (north of Forsmark). In the other reference area, Öregrund, fish abundances were eight times higher than in Forsmark, although densities were about the same. The calculated fish biomasses in Forsmark, Gudinge and Öregrund in May were 0.003, 0.001 and 0.009 kg m^{-2}, respectively, and in August/September 0.004, 0.002 and 0.003 kg m^{-2}, respectively (0.5–5 gC m^{-2}).

Laxemar-Simpevarp

A number of investigations regarding fish populations, abundance and biomass have been conducted in the Laxemar-Simpevarp area /Andersson et al. 2005, KVF 2007/ and within SKB's site investigations /Enderlein 2005, Adill and Andersson 2006/.

Biological monitoring has been performed in the recipient monitoring programme for the nuclear power plant (OKG) in Laxemar-Simpevarp since 1962 by the Swedish Board of Fisheries. Perch, roach and white bream have consistently dominated the catches in the monitoring of warm-water species. A total of 25 species have been caught during the time period in the area. The total test-fishing catch, exhibits a major increase since the beginning of the period /Andersson et al. 2005/.

Investigations of the cold-water species in the outer archipelago began in 1970. A total of 31 species were found, and 90% of the species in the catch consisted of herring. Other species caught were cod, roach, eelpout and bull rout. Herring abundance increased rapidly in the 1980s, and a peak in the early 1990s was followed by a negative trend. Abundance of cod increased dramatically in the 1970s. In the late 1980s catches fell to very low levels, which prevailed during the rest of the period studied. The trend occurred in the eastern Baltic stock, although the decline near the Swedish coast was greater /Andersson et al. 2005/.

Environmental monitoring in the county of Kalmar includes investigation of the fish populations. Perch, roach and vimba are the main species caught during the marine fish survey in the county of Kalmar /KVF 2007/.

In SKB's site investigations, pelagic fish (dominated by cold-water species) in offshore areas were investigated on three occasions in the summer of 2004 in the Laxemar-Simpevarp area. The estimated biomass on these three occasions was 50, 21 and 57 kg ha^{-1}, respectively (2.5, 1 and 1.3 gC m^{-2}). The most numerous species was sprat, followed by herring, stickleback and dab /Enderlein 2005/.

The coastal fish population (dominated by warm-water species) in Borholmsfjärden (PSM002062) was investigated within SKB's site investigation programme in 2005. The study resulted in estimates of total fish biomass. The total fish biomass (not including eel) was estimated to be 79 kg ha^{-1} and 69 kg ha^{-1}, (3.4–3.9 gC m^{-2}) in the spring and summer respectively. The estimated eel biomass was 1.8 kg ha^{-1} (0.09 gC m^{-2}). The contribution of piscivorous fish, mainly perch and pike, was 58% in the spring and 74% in the late summer. Adult bream and tench were common and dominated the cyprinid biomass /Adill and Andersson 2006/.

3.4.9 Birds

A detailed description of the various bird species in the Baltic region was provided by /Birdlife International 2000/. Some 340 species are found regularly in the region. Many of them are water fowl living in the Baltic Sea. Others, such as waders, live in the coastal area or surrounding wetland. Since the Baltic habitat is available to both marine and freshwater birds, the Baltic bird fauna is species rich compared to other marine environments.

Most of the bird species migrate between winter grounds and nesting grounds in the spring and summer. Thus, most birds leave the Baltic to winter further south. However, large numbers of long-tailed duck overwinter in the southern Baltic, as do tufted duck, mute swan, Canada goose and herring gull.

The eider duck is the most numerous of all waterfowl in the Baltic. It is very widespread, being absent only from the inner parts of the Gulf of Bothnia and the Gulf of Finland. Its main food is blue mussel. However, during recent years the eider duck population in the Baltic Sea has decreased substantially.

In the Western Gotland Basin, deep basins (areas deeper than 50 m) are the most common bird habitat. Outside the breeding season, gulls and auks dominate these areas.

In the transitional zone between the coastal zone and the deep water basins, the sub-littoral, the bird fauna is dominated by pelagic feeders such as divers and auks, during the non-breeding season. Densities of divers and sea ducks can increase dramatically in cold winters.

The littoral zone is highly diverse as a habitat and it is important for a large number of non-breeding waterfowl. However, the distribution of wintering waterfowl in the near-coastal zone, as well as around islands, is typically dispersed, and with the exception of Steller's eider the near-coastal areas do not support the main concentrations of any waterfowl in the Baltic Sea during normal winters.

The most important habitat for a number of animals including waterfowl are the offshore banks. They are shallower than 25 m but separated from the shore by deeper water (sub-littoral zone). Piscivorous birds such as the black guillemot have their main concentrations on the shores of the Baltic Proper. In addition, the shores of the Baltic Proper support large numbers of long-tailed duck.

Important concentrations of a wide range of shallow-water species are found in the lagoons during the non-breeding season. These species are benthivores, herbivores such as mute swan and carnivores such as scaup, as well as piscivores such as smew.

In the site investigations at Forsmark and Laxemar-Simpevarp, the bird fauna has been investigated and monitored on a yearly basis since 2002, with the aim to monitor the possible effects of the site investigations on bird numbers and breeding results.

Forsmark

Among the 169 coastal and marine important bird areas (IBAs) identified in the Baltic Sea, one IBA is situated near Forsmark in the Gräsö archipelago east of Gräsö Island (60°20'N 18°30'E). Survey from 1995 show that there were 2,000–3,000 cormorants (*Phalacrocorax carbo*), 20–28 white-tailed eagle (*Haliaeetus albicilla*), 75–85 Caspian tern (*Sterna caspia)* and 90–100 common tern (*Sterna hirundo*) /Birdlife International 2000/ in the area.

The Forsmark subarea also contains high densities of both common and rarer species /Green 2005, 2006a, 2006b/. Of eleven monitored species listed in the Swedish Red List and in the Birds Directive, three piscivores forage or breed in the marine environment: osprey, white-tailed eagle and black-throated diver.

Laxemar-Simpevarp

Two IBAs are situated in the Western Gotland Basin, in the vicinity of Laxemar-Simpevarp (Oskarshamn 57°15’N, 16°30’E, Skäggenäs-Mönsterås 56°54’N, 16°28’E) /Birdlife International 2000/.

Between 340 and 15,135 tufted ducks (*Aythya fuligula*) were observed during the period 1987–1999 in Oskarshamn /Birdlife International 2000/. During the same time period, between 0 and 19,165 tufted ducks (*Aythya fuligula*), between 0 and 450 smews (*Mergus albellus*) and between 0 and 4,885 goosanders (*Mergus merganser*) were observed in Skäggenäs-Mönsterås /Birdlife International 2000/.

3.4.10 Mammals

Three species of seal live in the Baltic: the grey seal (*Halichoerus grypus*), the ringed seal (*Pusa hispida*) and the harbour seal (*Phoca vitulina*). The grey seal is the largest and the ringed seal is the smallest species. Small populations of the Grey seal occur in Forsmark and Laxemar-Simpevarp.

The ringed seal is mainly found in the Bothnian Sea, the Gulf of Bothnia, the Gulf of Finland and the Gulf of Riga but is seldom found in the southern parts of the Baltic. The grey seal lives in the archipelagos along the Baltic coast. During the ice-free period of the year the seals are found on shallow rocks in the archipelago. The harbour seal inhabits only the southernmost part of the Baltic.

In 2005, a total of 18,300 grey seals inhabited the Baltic Sea, of which 6,600 were in Sweden. During the period 1990–2005 the Swedish grey seal population has shown a 7.9% increase in numbers /Karlsson and Helander 2005/.

3.5 Chemical composition of marine biota

The chemical composition of various marine biota in the marine ecosystems in Forsmark and Laxemar-Simpevarp was analyzed in SKB’s site investigation programme by /Kumblad and Bradshaw 2008/ and /Engdahl et al. 2006/ respectively. Samples from functional groups except bacteria, birds and mammals in the marine ecosystems were analyzed, a total of 33 samples in Forsmark and 24 in Laxemar-Simpevarp (Tables 3-24 and 3-25). Some radioisotopes were also analysed but is presented elsewhere /Roos et al. 2007/.

The chemical composition of marine biota is affected by biological processes such as uptake and excretion, respiration, photosynthesis and predation and reflects to a great extent the chemical composition of the environment (seawater or sediment), the trophic level and the type of organisms. The principal chemical constituents that make up the soft tissues of all organisms are oxygen, hydrogen, carbon, nitrogen and phosphorus (oxygen and hydrogen have not been analyzed in this study). Depending on the organism and the habitat, various organisms utilize additional elements to varying degrees. For example, organisms that form hard parts utilize elements such as calcium and silicon to a greater extent than others.

The biotic samples from the two marine ecosystems of Forsmark and Laxemar-Simpevarp were analyzed for 49 and 63 elements, respectively. The elements were selected in order to cover as many as possible of the elements which may occur as isotopes in the spent nuclear fuel or are important from a ecological point of view. The compiled data for all analyzed elements are presented in Appendix 5. Concentrations of elements from the various chemical groups – C, N, P (non-metals), I (halogens) Si (metalloids), Ca (alkaline earth metals), Zn (metals), Ho (lanthanides) and Th (actinides) – are presented in Figures 3-40 and 3-41 according to functional group. For many of the trace elements (and sometimes for other elements as well), the results of the analyses are below the detection limit. In these cases, a value half of the detection limit was used in the calculations of mean concentrations (estimated mean).

Table 3-24. Number of samples of different biota in the marine ecosystem in Forsmark (PSM000063).

Type of sample/Name	Number of samples
Plankton	
Phytoplankton	3
Zooplankton	1
Microphytobenthic flora	
Benthic microalgae	2
Benthic flora	
Fucus vesiculosus (macrophyte)	3
Pilayella littoralis (macrophyte)	3
Potamogeton pectinatus (macrophyte)	3
Benthic herbivores	
Theodoxus fluviatilis	2
Idotea spp.	2
Benthic filter feeders	
Cerastoderma glaucum	2
Macoma baltica	3
Fish	
Rutilus rutilus (planktivore)	3
Gymnocephalus cernuus (benthic omnivore)	3
Osmerus eperlanus (piscivore)	3

Table 3-25. Number of samples of different biota in the marine ecosystem in coastal areas in Laxemar-Simpevarp.

Type of sample/Name	Number of samples
Plankton	–
Microphyobenthos	–
Benthic flora	–
Fucus vesiculosus (macrophyte)	3
Chara sp. (macrophyte)	3
Potamogeton pectinatus (macrophyte)	3
Filamentous green algae (macrophyte)	3
Benthic herbivores	–
Benthic filter feeders	
Mytilus edulis	3
Fish	
Clupea harengus (zooplanktivore)	3
Pleuronectus flesus (Benthic omnivore)	3
Perca fluviatilis (Piscivore)	3

3.5.1 Forsmark

Marine biota were sampled in the spring of 2005 /Kumblad and Bradshaw 2008/. In this study the elemental composition of biota, water and sediment from a shallow bay (PSM000063, see Appendix 1) was analyzed for 49 different elements (Al, As, Ba, Br, C, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Er, Eu, F, Fe, Gd, Hg, Ho, I, K, Li, Lu, Mg, Mn, N, Na, Nd, Ni, P, Pb, Pm, Pr, Ra, Rb, S, Se, Si, Sm, Tb, Th, Ti, Tm, V, Yb, Zn, Zr).

The number of samples of each functional group is shown in Table 3-24. The concentrations of C, N, P, I, Si, Ca, Zn, Ho and Th are presented in Figure 3-40 for each functional group.

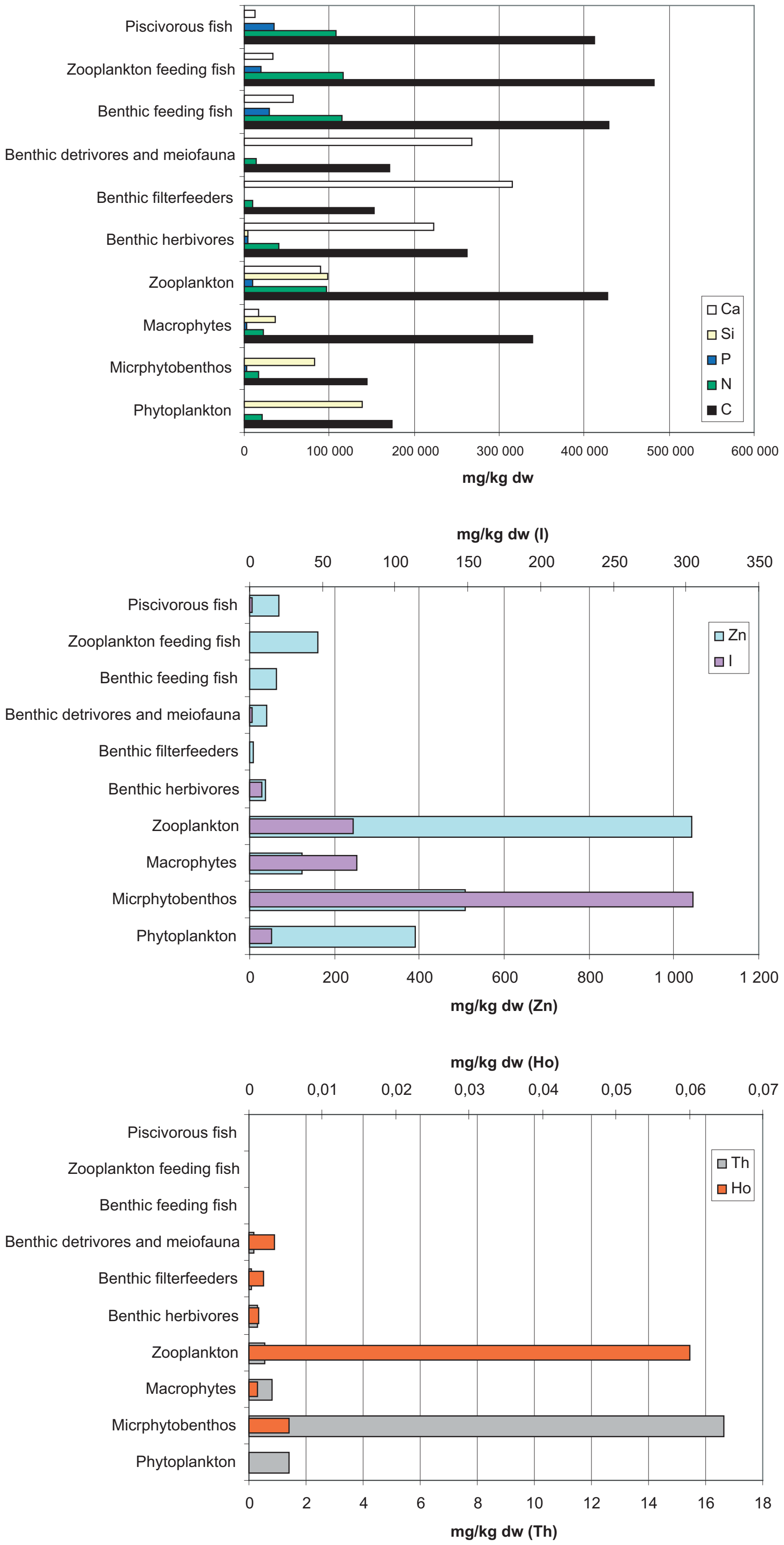


***Figure 3-40.** Concentrations of various elements (C,N,P, Si, Ca (a), Zn, I (b), Ho and Th (c)) in different functional grous in the marine ecosystem in Forsmark 2005 (PFM000063). Note the different scales on the axis**.** Ho and Th concentrations in fish were reported below detection limit and are therefore presented as best estimate, i.e. reported value diveded by two.*

The average carbon concentration in the functional groups varied between 140 gC/kg dw (microphytobenthos) and 480 gC/kg dw (zooplankton feeding fish) and was generally highest in zooplankton and fish. This distribution pattern also applied to N, although in lower concentrations. The P concentrations were highest in fish and were quite evenly distributed among the piscivorous, zooplanktivorous and benthivorous fishes. The largest biotic pool for Si was in producers and in zooplankton. The other functional groups had concentrations several orders of magnitude lower. Ca concentrations were highest in benthic fauna, probably due to a large proportion of organisms with hard parts, such as mussels.

Iodine concentrations were highest in microphytobenthos, followed by macrophytes and zooplankton, with about half the concentration in microphytobenthos. The highest Zn concentrations were found in zooplankton followed by microphytobenthos and phytoplankton. Zn concentrations in the other functional groups were much lower. Ho occurs in very low concentrations in the marine environment. Among the functional groups analyzed, zooplankton organisms had the highest values. Th also occured in low concentrations, but in this case microphytobenthos organisms exhibit the highest concentrations.

3.5.2 Laxemar-Simpevarp

Aquatic biota from marine functional groups were sampled and analyzed in /Engdahl et al. 2006/ for 63 elements (C, N, Ag, Al, As, B, Ba, Be, Br, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Hf, Hg, Ho, I, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Pr, Rb, S, Sb, Sc, Si, Sm, Sn, Sr, Ta, Tb, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn and Zr). The selection of elements was based on the aim to include the major part of elements that might occur as a radionuclide in spent nuclear fuel. Not all functional groups in the marine ecosystem were sampled in Laxemar-Simpevarp. *Chara sp.* is categorized as a macrophyte but is singled out in the presentation since it exhibits a different chemical composition compared to other macrophytes, especially with regard to Ca.

The number of samples from the analyzed functional group is shown in Table 3-25. The concentrations of C, N, P, I, Si, Ca, Zn, Ho and Th are presented in Figure 3-41 for the functional groups that were analyzed in the marine ecosystem in Laxemar-Simpevarp.

The average carbon concentration in the functional groups varied between 253 gC/kg dw (macrophytes) and 530 gC/kg dw (zooplanktivorous fish) and were generally highest in fish. The carbon concentration in *Chara sp*. was of the same order of magnitude as for other macrophytes. Like carbon, N and P concentrations were also highest in the fish groups. The Si concentration in the analyzed groups varied between 142 mg $kgdw^{-1}$ (benthic feeding fish) and 8,033 mg $kgdw^{-1}$ (*Chara sp.*). Other macrophytes also had quite high concentrations of Si, however, when the different Ca concentrations in macrophytes are studied it is evident that Ca does not follow the general trend. The concentration of Ca, in *Chara. sp*. is over 200 times higher than the Ca concentration in fish and 9 times higher than the Ca concentration in filter feeders (without shells). The highest concentration of I, as well as of Ho and Th, was also found in *Chara sp*. Filter feeders had the highest concentrations of Zn.

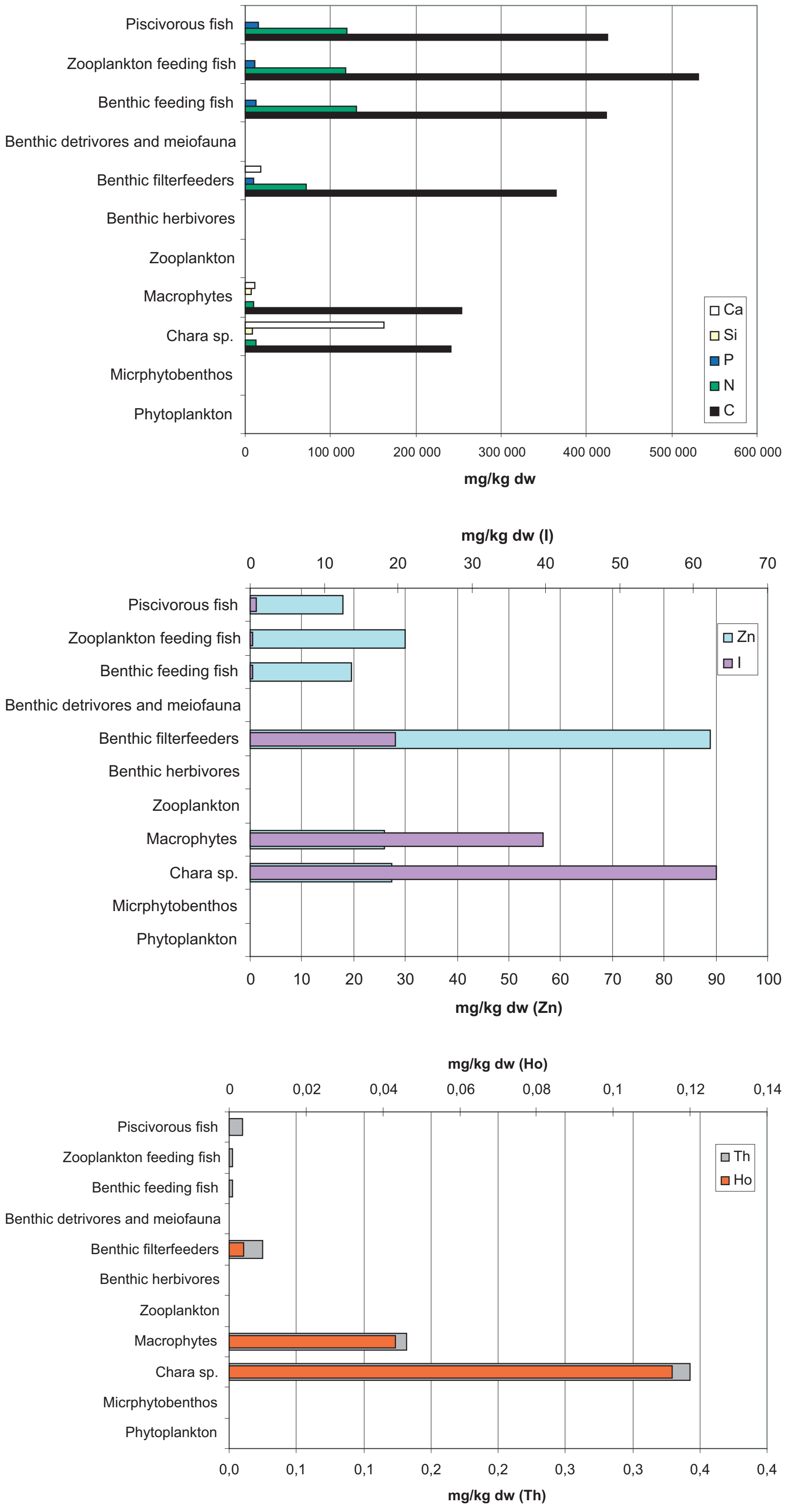


Figure 3-41. *Concentrations of various elements (C, N ,P, Si, Ca (a), Zn, I (b), Ho and Th (c)) in different functional grous in the coastal marine ecosystem in Laxemar-Simpevarp. Note the different scales on the axis and the fact that not all functional groups were analyzed in Laxemar-Simpevarp, in contrast to Forsmark. Ho and Th concentrations in fish were reported below detection limit are therefore presented as best estimates, i.e. reported value divided by two.*

3.6 Human impact

3.6.1 Industry and forestry

Forsmark

Since the area was raised above sea level, land use in the Forsmark area was dominated by the use of the region's iron ore mines. Iron mines occurred at Dannemora since the 16th century and at Ramhäll since the 18th century, until the iron works in Forsmark were shut down in the 1890s. Following the iron era, and mainly due to the general scarcity of rich soils /Miliander et al. 2004a/, the area was sparsely settled until the construction of the nuclear power plant in the 1970s. Industrial emissions related to the iron works were restricted to the dams, lakes and rivers in their vicinity, for example Bruksdammen Lake, the Forsmarksån River and Kallrigafjärden Bay.

/Jonsson et al. 1993, Wulff et al. 1993/ identified the presence of polluting emissions from the pulp bleach industry in open Bothnian Sea sediments. The nearest industrial plants are Stora Cell, Skutskär, situated in Gävlebukten Bay near the mouth of the Dalälven River, and Karlit in Lövstabukten Bay (Figure 3-42). Emissions included mercury and organochlorines, but they have gradually been reduced or eliminated. Direct mercury emissions from Stora Cell and Korsnäsverken (near the city of Gävle) in Gävlebukten ceased in 1977 and 1982, respectively /Persson et al. 1993/.

/Jonsson et al. 1993/ found elevated contaminant concentrations in sediment accumulation bottoms (A-bottoms) within 30–50 km of pulp mills. In view of the similar findings of /Meili et al. 2000/ that archipelagic A-bottoms may well trap contaminants and co-transported organic matter from adjacent regional and offshore areas, and since these contaminants have not been analyzed in Forsmark area sediments, the possibility cannot be ruled out that Forsmark area A-bottoms could also trap contaminants originating from industries on the Bothnian Sea coast further to the north.

Laxemar-Simpevarp

By comparison to Forsmark, the Laxemar-Simpevarp area is a part of and directly influenced by a more versatile industrial province, Småland. Along the northern coast of Kalmar county, this has led to emissions of heavy metals in particular from pulp mills and mining and metallurgical industries /Jansson 2005/.

However, the immediate surroundings of the Laxemar-Simpevarp area in Misterhult parish etc have a history without any major local industrial impact and have traditionally been predominantly occupied with forestry and agriculture /Miliander et al. 2004b/.

3.6.2 Agriculture and nutrient load

Forsmark

Both forestry and agriculture related to the iron mills probably had limited regional effects due to emissions /Miliander et al. 2004a/. Even today, a significant part of the nitrogen and phosphorus entering the coastal zone in Uppland arrives with rivers and streams. Table 3-26 and Figure 3-42 summarize and permit comparison among contributions from the various coastal sources of nitrogen and phosphorus in the Forsmark area.

Nutrient enrichment also emanates from larger-scale urban and industrial sewage and agricultural fertilization, but the local contribution is minor in comparison /Svealands Kustvattenvårdsförbund 2001/. Due to a general counter-clockwise circulation, the south-west Bothnian Sea and the Forsmark area are influenced by the Bothnian Sea coast, but also by the open Bothnian Sea, which in turn is influenced by water from the open Baltic Proper entering via the Åland archipelago /Walve and Larsson 2005/. The Baltic Proper is more eutrophicated than the Bothnian Sea /Andersen et al. 2006/, with high levels of phosphorus. Its primary production is nitrogen-limited, which favours nitrogen fixation and frequent cyanobacterial blooms in the summer /Larsson et al. 2006/.

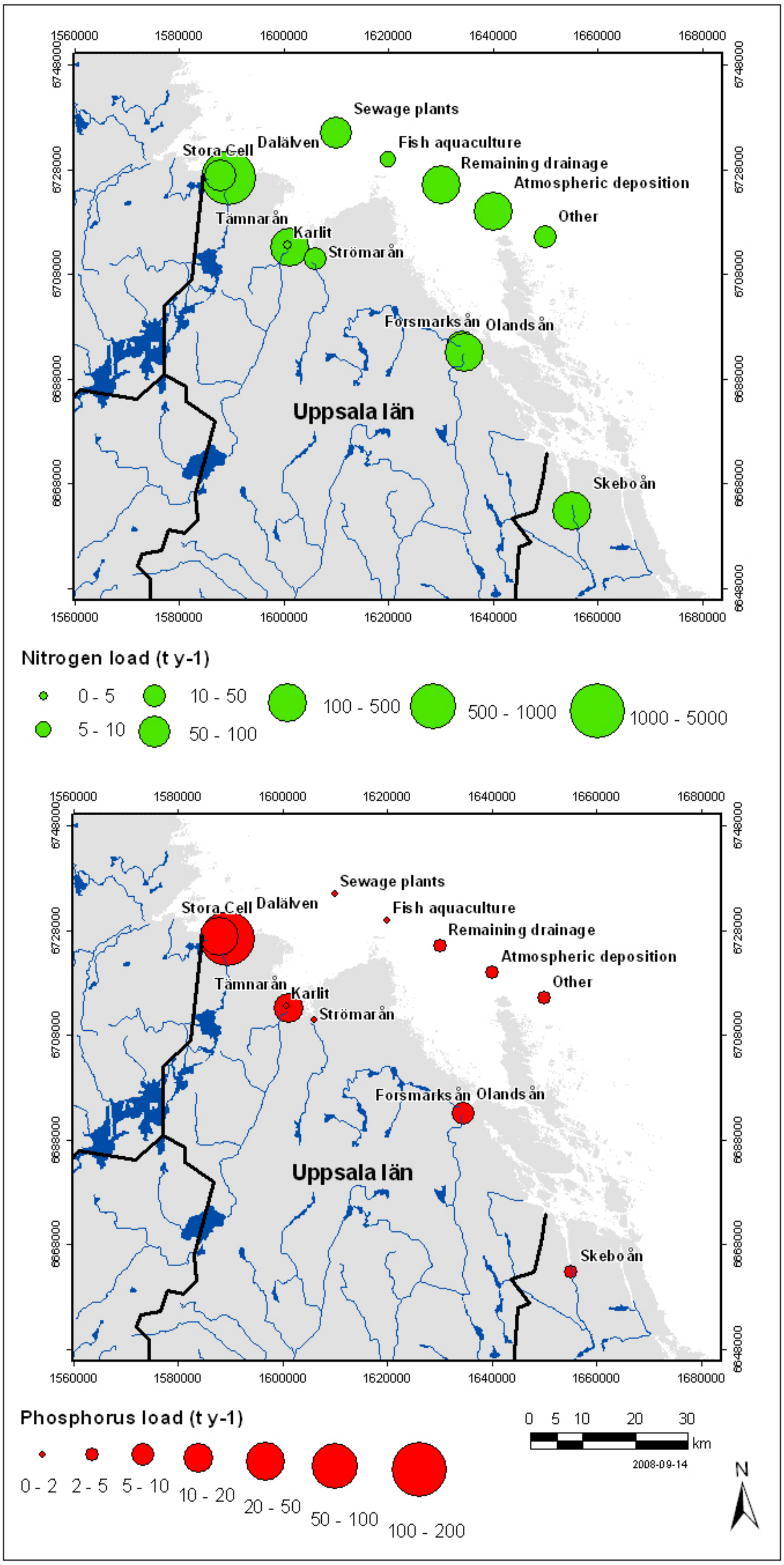


***Figure 3-42.** Annual load of nitrogen and phosphorus to coastal Uppsala county from coastal point sources (mills, rivers and streams) and five additional, diffuse terrestrial and coastal sources (not including the deep-water source).*

Table 3-26. Data on nitrogen and phosphorus emissions from coastal Uppsala county, compiled from /Persson et al. 1993, Wallström 1999/.

	Mean discharge $m^3 s^{-1}$	Nitrogen ton y^{-1}	%	Phosphorous ton y^{-1}	%
Sources					
Mills					
Stora Cell, Skutskär		85	1.3	25	9.9
Karlit, Karlholmsbruk		5	0.1	1.5	0.6
Sewage plants		87	1.4	1.5	0.6
Fish aquaculture		7.5	0.1	1.2	0.5
Rivers and streams					
Dalälven	355	4,550	71.3	180	71.1
Tämnarån	10	420	6.6	12	4.7
Strömarån	1.3	45	0.7	2.0	0.8
Forsmarksån	2.8	95	1.5	2.0	0.8
Olandsån	6.0	245	3.8	9.0	3.6
Skeboån	4.4	110	1.7	5.0	2.0
Remaining near-coastal drainage		228	3.6	4.4	1.7
Atmospheric deposition		456	7.1	5.0	2.0
Other		45	0.7	4.5	1.8
SUM		6,379	100	253	100

As a result, the open Bothnian Sea has shown decreasing moderate decrease in water clarity measured by Secchi depth readings. The water clarity have been reduced by about 3 m (from ~ 10 to 7 m), or 35%, especially during the period 1930–1970 /Laamanen et al. 2004/. Only a few coast-to-offshore nutrient gradients have been studied here, however.

In the coastal zone, /Kautsky et al. 1986/ discovered that the lower depth limit of the *Fucus vesiculosus* belt had been moved several metres closer to the water surface in comparison to Waern's and Pekkari's observations /Waern and Pekkari 1973/, made in the 1960s. Meanwhile, chlorophyll *a* concentrations have increased considerably, which are interpreted as signs of large-scale eutrophication /Larsson et al. 2006/. Increased turbidity may also have caused a shift in Baltic herring spawning grounds /Anéer 1987/.

The overall status /Larsson et al. 2006/ of Öregrundsgrepen has proved better than that of the Östhammar-Singö archipelago immediately to the south. In lieu of local explanations, this fact has been interpreted as a possible effect of more nutrient- and particle-rich bottom water arriving there from Öregrundsgrepen through the narrow Öregrund sound.

Further north along the Bothnian Sea coast, the influence of humic substances from freshwater increases /Jonsson et al. 1993/. This has an effect similar to nutrient enrichment, since bacterioplankton are also able to feed on humic substances /Kuparinen et al. 1996/.

Laxemar-Simpevarp

Table 3-27 and Figure 3-43 summarize and permit comparisons of the contribution of the various sources of nitrogen and phosphorus to the Laxemar-Simpevarp area. Data compiled from /Länsstyrelsen i Kalmar län 2000/.

3.6.3 Shipping and dredging

Exotic species introduced through shipping are probably present in the area's ecosystems. As an example, the benthic polychaete worm *Marenzellaria viridis* has spread north after having established a presence in the Baltic proper /Cederwall et al. 2007/. As yet, the effect this species has on existing Baltic species and ecosystems is uncertain.

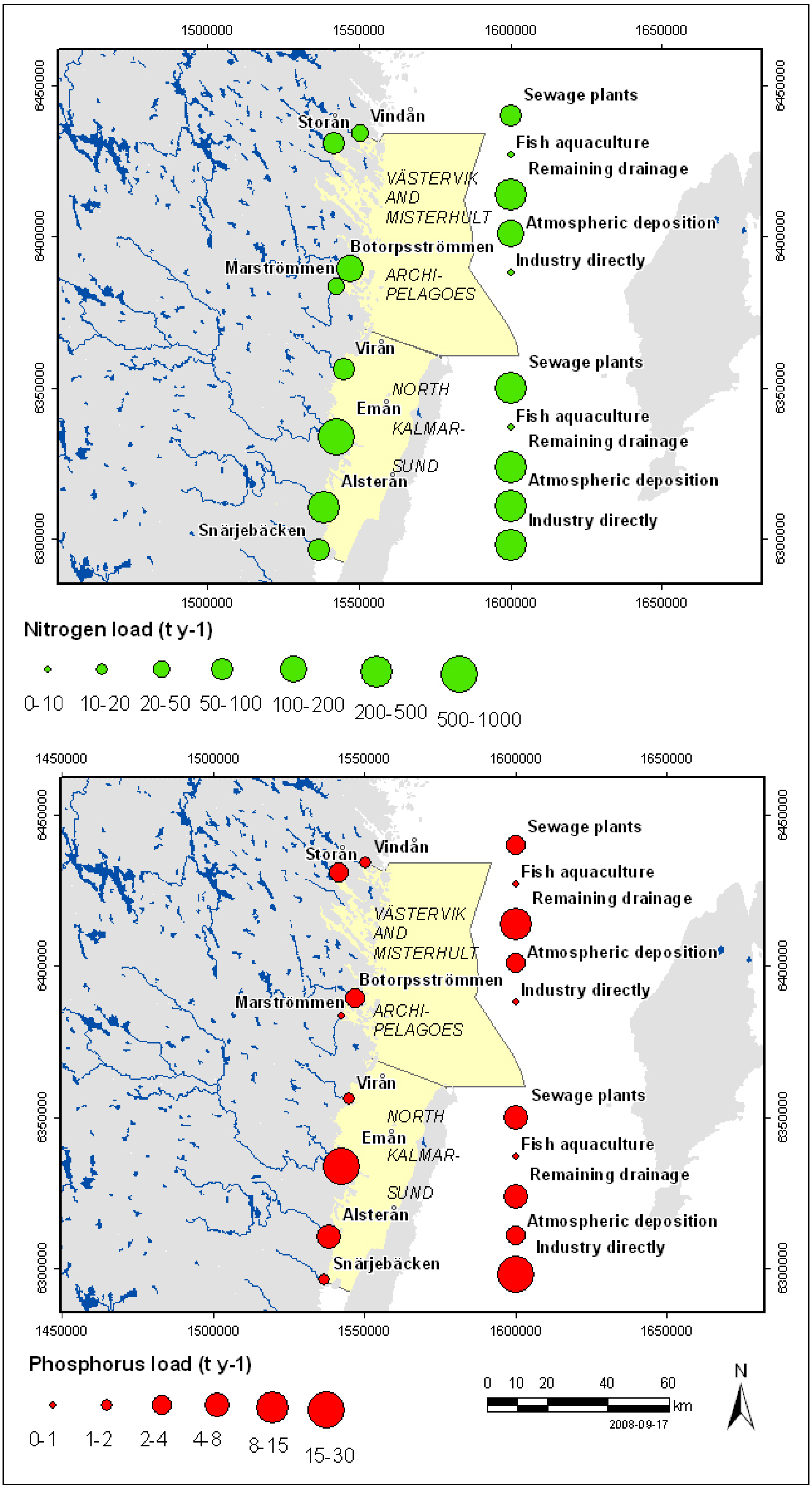


Figure 3-43. Annual load of nitrogen and phosphorus in two coastal areas north of (Västervik and Misterhult archipelagos) and south of (North Kalmarsund) the Laxemar-Simpevarp area, from rivers and streams, and from five additional coastal sources.

Table 3-27. Data on nitrogen and phosphorous emissions to the North Kalmarsund, Västervik and Misterhult archipelagos (see map Figure 3-43). Data compiled from /Länsstyrelsen i Kalmar län 2000/.

	Mean discharge $m^3 s^{-1}$	Nitrogen $t y^{-1}$	%	Phosphorous $t y^{-1}$	%
Sources					
Industry directly		206	7.0	27	30
Sewage plants		379	13	6.5	7.2
Fish aquaculture		8.1	0.3	1.0	1.2
Streams					
Vindån	1.9	45	1.5	1.8	2.0
Storån	2.6	78	2.7	2.7	3.0
Botorpsströmmen	4.9	123	4.2	2.5	2.8
Marströmmen	1.8	43	1.5	1.0	1.1
Virån	2.9	61	2.1	1.2	1.3
Emån	27.6	674	23	15.1	17
Alsterån	9.8	210	7.1	4.1	4.6
Snärjebäcken	1.5	89	3.0	1.1	1.2
Remaining near-coastal drainage		594	20	17	20
Atmospheric deposition		431	15	7.8	8.7
SUM		2,941	100	89	100

Forsmark

Flads and gloes in the Forsmark area are in need of local protective measures. The practice of broadening flad and glo inlets to create sheltered boat jetties, and the use of toxic repellents on boat hulls in those areas, are jeopardizing the sequence of events behind the formation of the unique, clear water *Chara sp.* habitat, related in turn to fish recruitment /Wallström and Persson 1997/.

Laxemar-Simpevarp

Regarding the Laxemar-Simpevarp area, no situation similar to the situation in Forsmark is described in Jansson account of the environmental status of coastal areas in Kalmar County /Jansson 2005/.

3.6.4 Cooling water emissions

The major coastal impact of the nuclear reactors is the warm-water plume created by the release of the heated cooling water. In particular, apparent signs of eutrophication may be due to the combined effect of elevated nutrients and heat dynamics, caused by dampening of the upward nutrient entrainment and by declining bottom-water oxygen concentrations /Larsson et al. 2006/.

Forsmark

The excess temperature of the Forsmark cooling water is about 8°C /Sandström et al. 2002, Ingemansson and Lindahl 2005/. It is discharged into the relatively enclosed Biotest Lake (1 km^2 area and 2.5 m mean depth) at a rate of approximately 135 $m^3 s^{-1}$. An increase to 165–170 $m^3 s^{-1}$ is being planned. From there, the water is released into the open sea.

The size and spread of the cooling-water plume depending on the weather situation has been simulated /Ingemansson and Lindahl 2005/. The coastal area that could be affected by an increase in water temperatures of at least 3–4°C is less than 1 km^2, while the area that could be affected by an increase in temperature of at least 1°C is approximately 30 km^2 (Figure 3-44).

Laxemar-Simpevarp

The heated cooling water from the three units is discharged into the primary recipient, Hamnefjärden. Hamnefjärden is connected to the surrounding coast via a sound (50 m wide and 5 m deep). The discharge rate is around 90–100 $m^3 s^{-1}$, which creates a jet of water in the recipient and thereby effective mixing. The excess temperature of the cooling water is about 10–12°C /Edman and Lindahl 2007/.

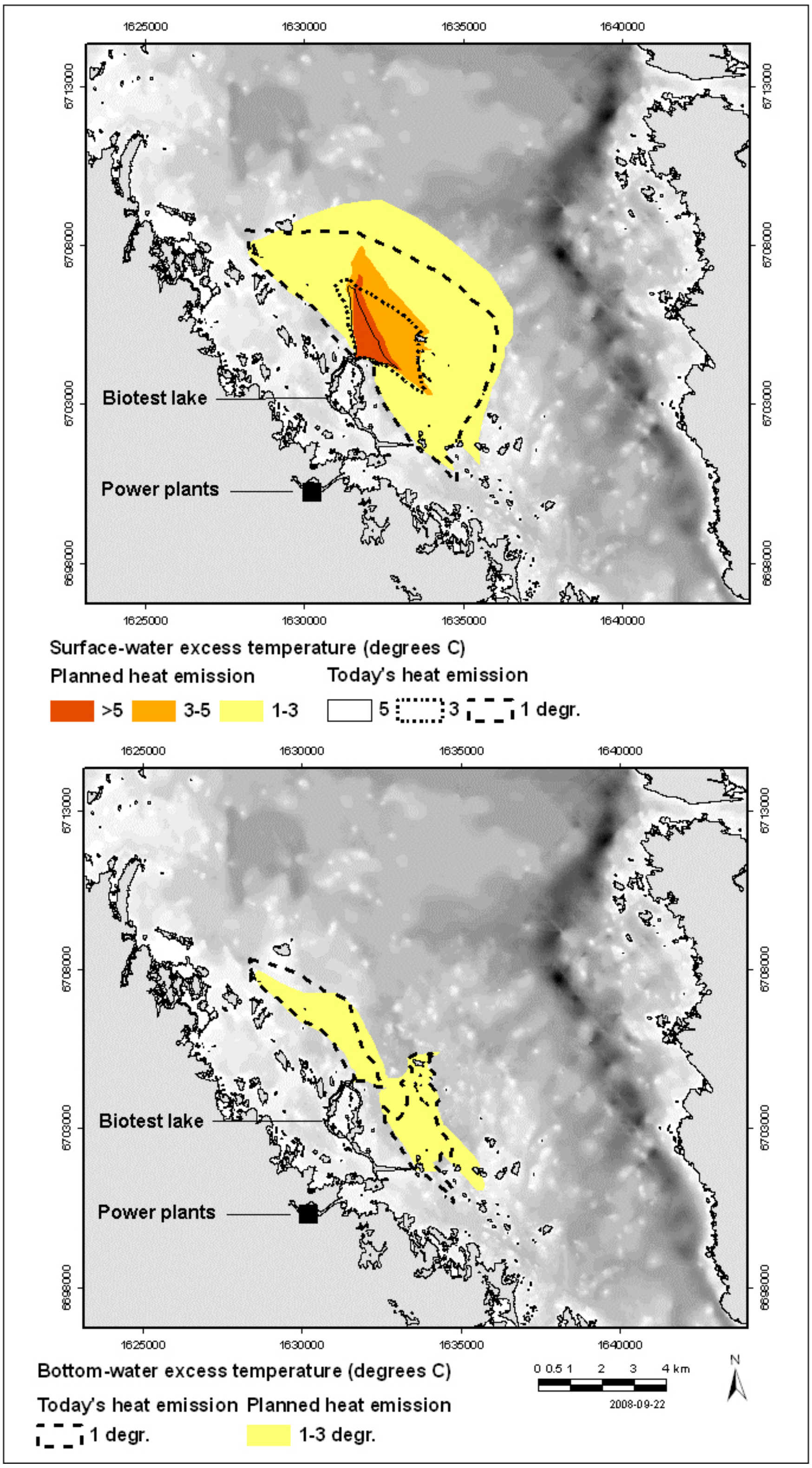


***Figure 3-44.** The area of surface water (above) and bottom water (below) outside Forsmark that could be affected by an increase in temperature of at least 1°C, given current and planned heat emissions (outlines from /Ingemansson and Lindahl 2005/, redrawn).*

The size and spread of the affected coastal area is determined by the climate and weather situation, most importantly the wind direction. The coastal area that could be affected by an increase in temperature of at least 1°C is between 17 and 20 km^2, see Figure 3-45, although under normal weather conditions the affected area is around 6 km^2 /Edman and Lindahl 2007/.

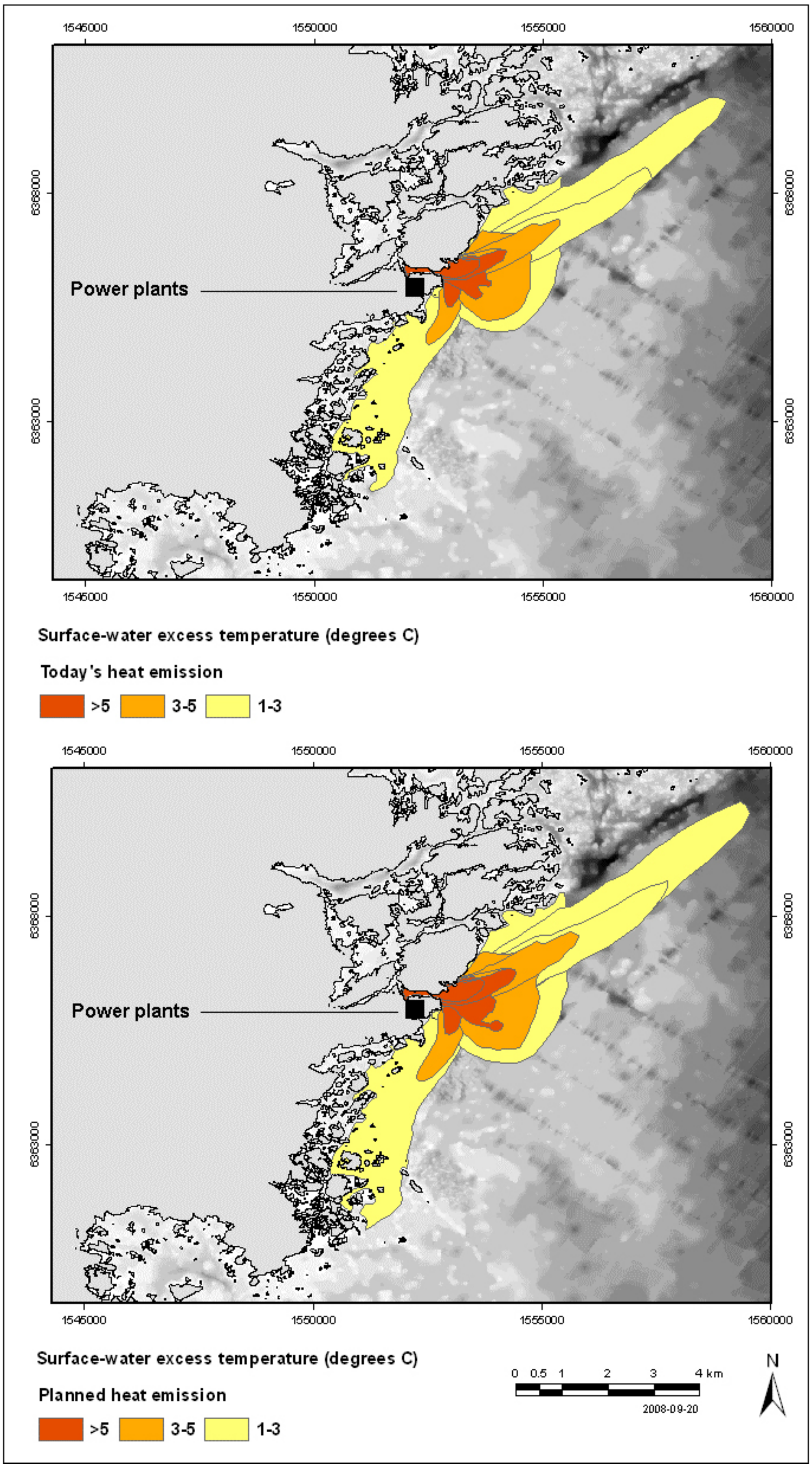


Figure 3-45. *Heat plumes modeled as resulting from four characteristic wind situations in the Laxemar-Simpevarp subarea, showing coastal areas influenced by at least 1°C of increased temperature due to cooling water emissions, from /Karlsson and Lindahl 2003/.*

3.6.5 Fishery

The total commercial fish catch has been stable or increasing in the Bothnian Sea during the period 1994–2002, while in the Baltic Proper it has decreased by 80% during the same period /Ljunggren et al. 2005, Sjöstrand 2007/.

Forsmark

The Forsmark area is more affected by larger-scale fishery than by local exploitation.

The two commercially most important types of fish caught in the Bothnian Sea, Baltic herring and migrating fish, are clearly affected by fishery, the former by overfishing (in particular by-catches due to trawling), the latter by hydropower regulation /Karås 1993/. The introduction of safer fishing gear has ameliorated the effect of trawling on seal and otter mortality, as well as that of bycatches on Baltic herring and migrating fish. The latter type of pressure was also reduced by a tightening of trawling-zone limitations in 2004 /Sjöstrand 2007/.

In a comparison between coastal areas in the Bothnian Sea /HELCOM 2006, Appelberg et al. 2007/, the Forsmark area did not show a status markedly below average on any of five indices as estimated in 2003–2005: Species richness, trophic level of fish communities, total biomass, mean weight per individual, European perch biomass and European eel biomass.

Laxemar-Simpevarp

Kalmar county fishermen are responsible for more commercial fishery than the rest of the Swedish east coast taken together, with fishermen registered in Borgholm and Västervik catching most of the fish. This makes Kalmar county the fifth largest fishing county in Sweden /Miliander et al. 2004b/. This catch is mostly offshore.

Among coastal areas, higher catches are reported in the larger Laxemar-Simpevarp area (EU grid 44G) than in the Västervik-Misterhult archipelago's grid to the north (neighbouring EU grid 44G6). In a comparison between coastal areas in the Baltic Proper conducted in 2003–2005 /HELCOM 2006, Appelberg et al. 2007/, Kvädöfjärden in the Västervik archipelago showed a status markedly below average on the index for European eel biomass, and a status markedly above average for species richness.

Also the estimated catch per area by recreational fishery is relatively small in Misterhult parish, 39.6 kg km^{-2}, compared with both Oskarshamn municipality and Kalmar county where it is 3–4 times greater /Miliander et al. 2004b/.

4 The marine ecosystem – conceptual and quantitative carbon models

The marine ecosystems were conceptualized in marine ecosystem models for quantifying pools and fluxes of matter in the Forsmark and Laxemar-Simpevarp areas. The models were based on grids with a spatial resolution of 20×20 m. The models were built to describe the fluxes of matter within delimited basins between functional groups in the ecosystem, and between the basins and the surrounding environment, the terrestrial ecosystem and the adjacent sea. The system is assumed to be in a steady, non-seasonal, state and all input data are based on annual means.

The models are non-dynamic and there are no feedbacks between processes in the system. The processes of each unit or functional group are driven by independent data on biomass, concentrations, irradiation and temperature measured in the field. The parameters used in the calculations have been interpolated to the 20 m grid by using a number of different methods which are described below (Sections 4.2 and 4.3). Model output is presented for the whole area and for the individual basins, per square metre or per basin. The pools and fluxes of matter have been studied in detail using carbon as a proxy.

To get an overview of the major pools and fluxes and to strengthen the conclusions from the marine ecosystem model, coarse-grained mass balances identifying the major pools and fluxes have been studied for carbon (C), nitrogen (N), iodine (I), uranium (U) and thorium (Th).

The elemental composition of the major pools in the ecosystem was also calculated for 49 elements based on analyses performed in the site investigations done by SKB.

The studied area in Forsmark has been divided in 28 sub-basins (called basins below) based on today's bathymetry and future drainage areas. The studied area in Laxemar-Simpevarp has been divided into 19 sub-basins using the same methodology. The basins are presented in Figures 4-1 and 4-2 for Forsmark and Laxemar-Simpevarp, respectively, together with the digital elevation model for the marine areas.

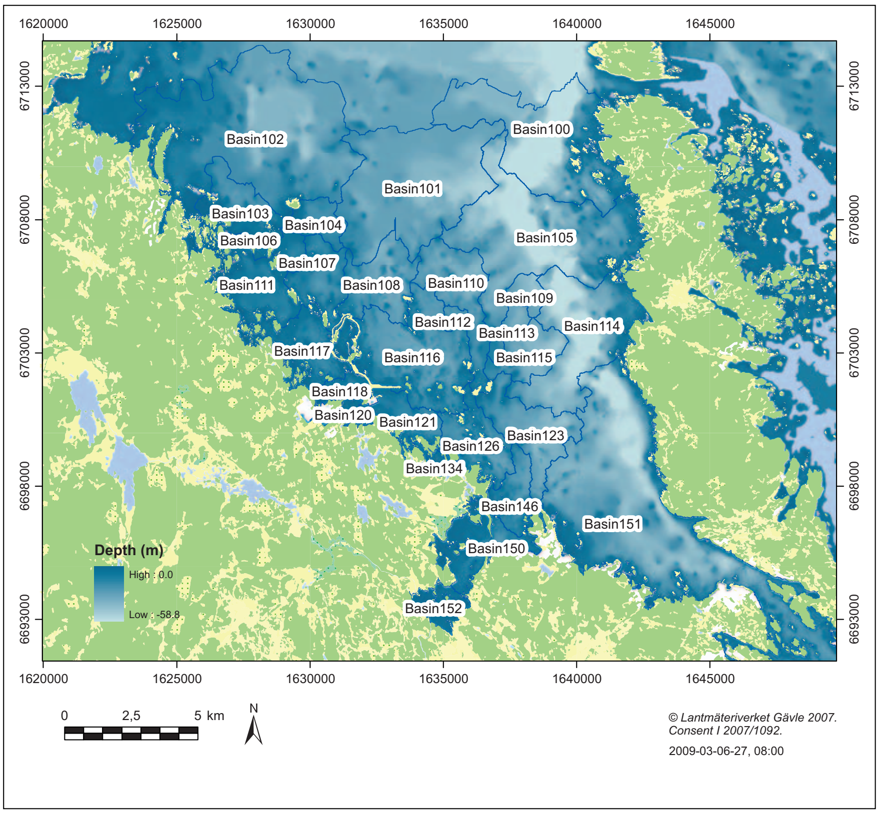


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Figure 4-1. The bathymetry in the Forsmark area and the marine basins.

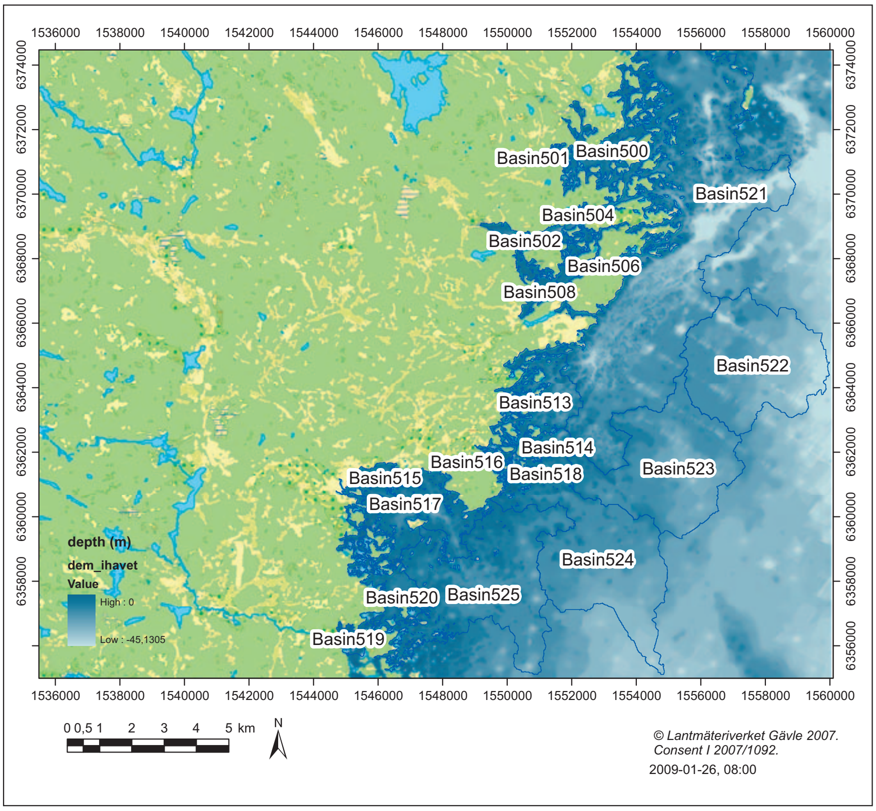

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Figure 4-2. *The bathymetry in the Laxemar-Simpevarp area and the marine basins.*

4.1 Conceptual model

4.1.1 Basin delimitations

Most of the separate basins (Figure 4-1 and 4-2) are not clearly separated today by islands or even clear bathymetric thresholds, but have an open border to several other basins. The delimitation was done to suit the overall aim of the project to assess the long term safety of a deep repository for nuclear waste. Within the period of time assessed, the landscape will change form, partly due to the ongoing shoreline displacement in the area.

The delimitations of the basins are the boundaries to drainage areas of future lakes that are predicted to arise within the coming 18,000 years. Changes in water depths in the sea are calculated using the shore level displacement equations published in /Påsse 1997/. Shore displacement is calculated as glacio-isostatic uplift (U) minus global eustatic sea level rise (E). The detailed method for identification of basin delimitations is described in /Brydsten 2006/. The drainage area is calculated as the sum of upstream watersheds with final discharge in the separate marine basins, excluding the actual area of the marine basin.

Physical characteristics of the basins are presented in Table 4-1, for Forsmark and in Table 4-2 for Laxemar-Simpevarp.

Table 4-1. Area, mean depth, volume, drainage area and average age of water (AvA; see Section 5 of the marine basins in the Forsmark area) of the marine basins in the Forsmark area.

Basin name	Area (km^2)	Mean depth (m)	Volume (×10^6 m^3)	Drainage area (km^2)	AvA (days)
Basin 100	18	19	358	4.5	0.34
Basin 101	22	16	352	0	0.39
Basin 102	34	11	371	31	0.68
Basin 103	5.7	5.5	31	0.6	0.13
Basin 104	2.7	7.7	21	0.05	0.07

Basin name	Area (km²)	Mean depth (m)	Volume (×10⁶ m³)	Drainage area (km²)	AvA (days)
Basin 105	23	18	413	5.1	0.49
Basin 106	1.4	4.5	6.2	0.05	0.14
Basin 107	4.6	7.0	32	0.2	0.22
Basin 108	7.2	11	76	0.4	0.19
Basin 109	1.5	19	29	0	0.04
Basin 110	7.1	12	88	0.1	0.12
Basin 111	6.7	3.3	22	12	0.99
Basin 112	0.70	11	7.6	0	0.02
Basin 113	1.6	13	20	0	0.03
Basin 114	14	19	273	4.9	0.44
Basin 115	4.2	16	68	0	0.12
Basin 116	14	9.5	128	0.6	0.74
Basin 117	5.8	3.7	21	10	1.4
Basin 118	1.5	3.1	4.4	0.55	0.67
Basin 120	0.7	2.5	1.8	9.6	0.33
Basin 121	3.7	5.5	20	10	0.27
Basin 123	7.3	14	99	0.43	0.12
Basin 126	5.4	7.5	41	1.8	0.24
Basin 134	0.59	1.8	1.1	1.4	0.02
Basin 146	3.4	7.7	26	0.42	0.09
Basin 150	5.9	3.6	21	9.8	0.69
Basin 151	42	13	554	50	4.5
Basin 152	2.1	1.4	3.1	1,275	0.52

Table 4-2. Area, mean depth, volume, drainage area and average age of water (AvA; see Section 5 of the marine basins in the Laxemar-Simpevarp area) of the marine basins in the Laxemar-Simpevarp area.

Basin name	Area (km²)	Mean depth (m)	Volume (×10⁶ m³)	Drainage area (km²)	AvA (days)
Basin 500	2.9	12	5.8	13	4.3
Basin 501	0.33	6.9	1.1	1.8	16
Basin 502	1.1	16	5.5	35	24
Basin 504	0.61	12	2.2	1.9	5.9
Basin 506	0.33	11	1.1	0.95	2.8
Basin 508	1.4	3.2	2.4	47	10
Basin 513	4.1	1.9	18	7.1	0.29
Basin 514	0.95	3.6	4.3	0.22	0.31
Basin 515	0.87	4.8	2.9	2.6	6.9
Basin 516	0.48	3.3	0.07	2.7	9.3
Basin 517	6.7	1.7	24	32	1.0
Basin 518	0.76	4.3	2.9	0.14	0.4
Basin 519	0.59	4.5	0.14	139	8.0
Basin 520	2.3	0.10	5.6	12	0.4
Basin 521	38	3.7	426	8.2	0.81
Basin 522	14	3.3	216	0	0.19
Basin 523	14	3.5	161	0.01	0.27
Basin 524	15	2.4	171	0.35	0.14
Basin 525	15	0.22	106	1.2	0.31

4.2 Ecosystem model

The marine ecosystem model is based on a food web that consists of biotic pools (primary producers and consumers), abiotic pools (sediment, particulate and dissolved matter) and fluxes of matter in the ecosystem (primary production, respiration, consumption, sedimentation, advection and runoff). The classification scheme of which groups to use and how to divide the organisms among them is similar to the model structure used by /Kumblad et al. 2003/ but modified somewhat to fit the specific purpose at the sites. The primary producers included in the model are benthic micro- and macrophytes and phytoplankton, and the consumers are bacterioplankton, zooplankton, fish (benthivores, zooplanktivores and piscivores), benthic fauna (herbivores, filter feeders, carnivores and detritivores), benthic bacteria, mammals, birds and humans consuming fish (see Table 3-17 in Section 3.4.1 and Figures 4-3 and 4-4).

The marine environment is commonly divided into benthic and pelagic habitats and the organisms and pools are assumed to be divided between them. In the sections presenting results (Section 6), we have kept these divisions to permit comparison between the two habitats.

The marine ecosystem can further be divided into aphotic and photic zones, soft bottom and hard bottom benthic communities and other divisions. These terms are used in the report for descriptions (in Section 3), but as physical and organism characteristics are often continuous rather than discrete, we have striven to use parameters along a continuum, an example being using light attenuation to estimate primary production rather than using a measure of photic or aphotic area. However, when lack of detailed data has limited this method, distributions and estimates have been made based on discrete variables, e.g. the lower depth limit of primary producers.

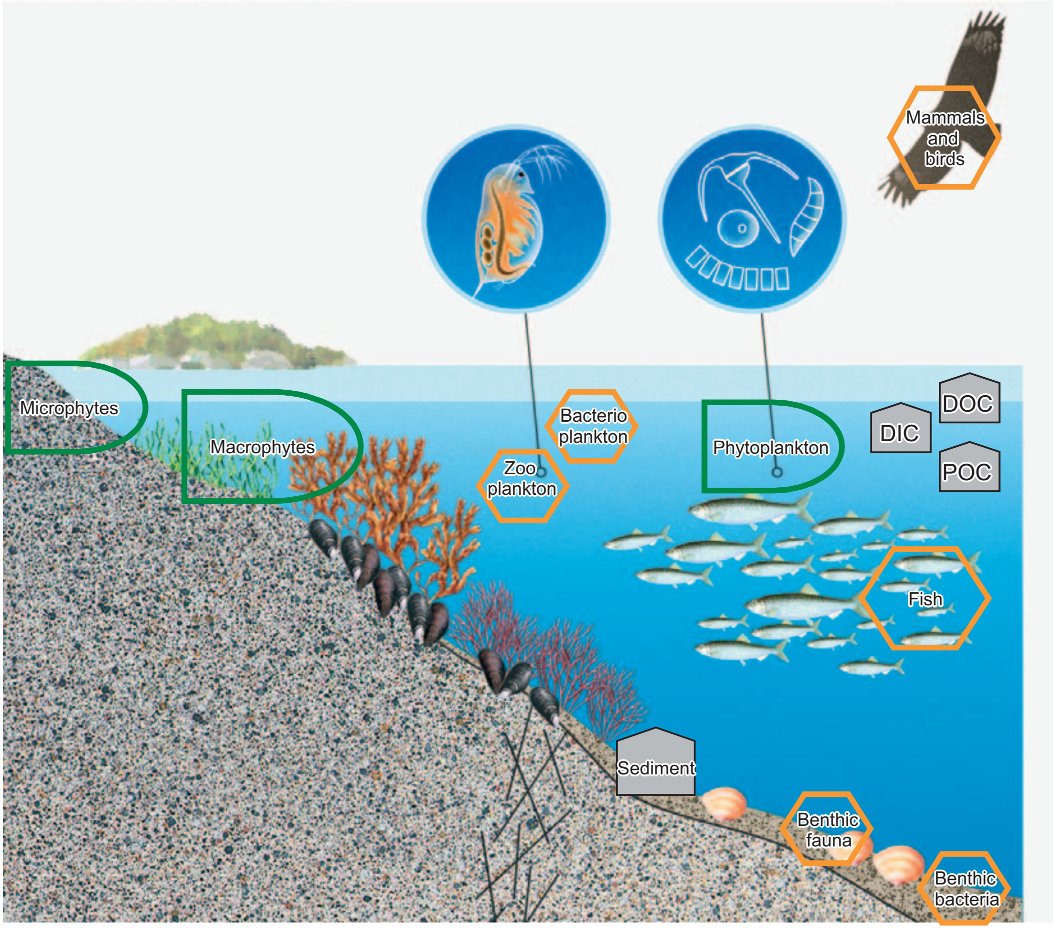


***Figure 4-3.** Illustration of marine ecosystem and food web units – functional groups and abiotic pools. Benthic fauna includes the functional groups benthic filter feeders, benthic herbivores, benthic detrivores and meiofauna, and benthic carnivores. Mammals and birds include seals, humans and birds feeding in the marine habitat.*

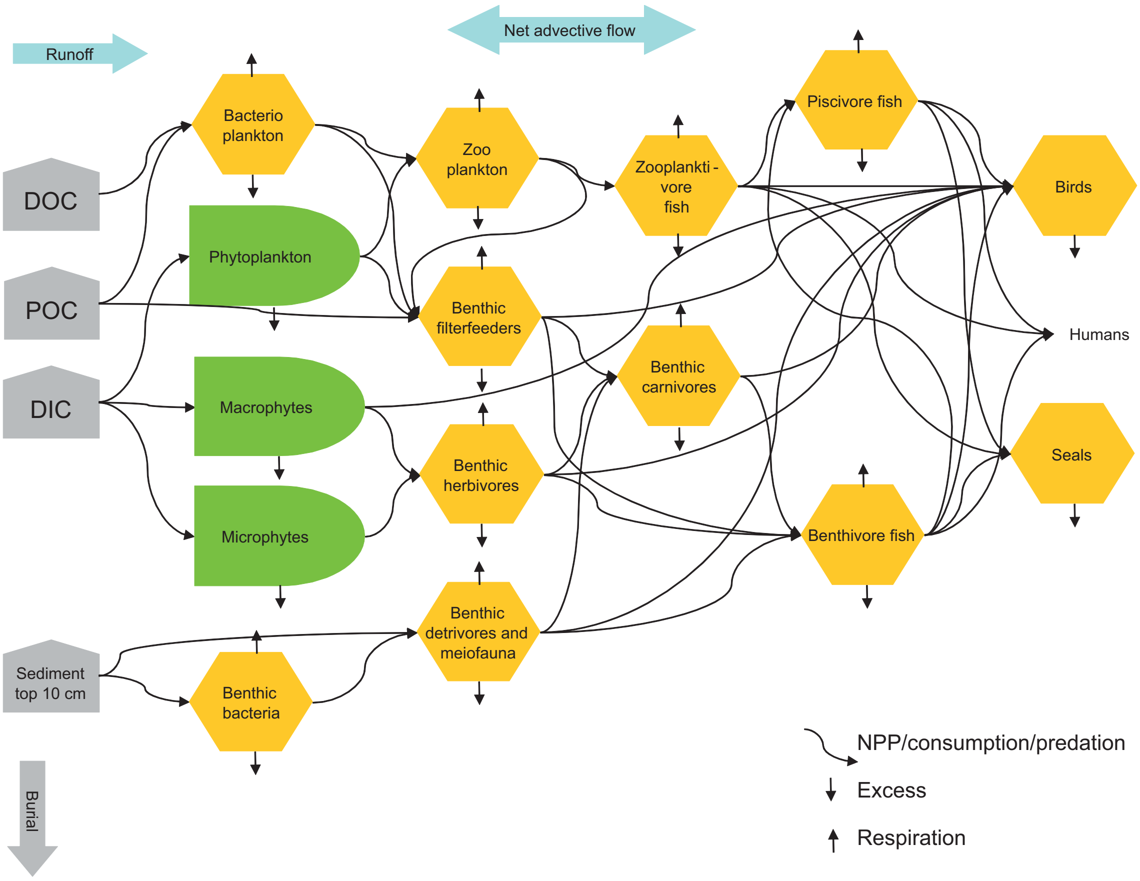


Figure 4-4. *Conceptual illustration of the food web-based marine ecosystem model. Boxes denote pools of matter while arrows denote fluxes: NPP = Net Primary Production, Excess = NPP/consumption minus respiration minus grazing/predation, POC = particulate organic matter, DOC = dissolved organic matter and DIC = dissolved inorganic matter. "Humans" refers to consumption of fish by humans.*

4.2.1 Units of the ecosystem – functional groups

In this section definitions and explanations of the food web, fluxes and terms used in the marine ecosystem model are presented. The parameterization of the various pools and fluxes are presented in Section 4.2 and 4.3.

Primary producers

Primary producers are all autotrophic organisms in the ecosystem. They are divided into:

1. Large benthic algae and plants – macrophytes,
2. Unicellular benthic autotrophs – microphytobenthos,
3. Pelagic primary autotrophs – phytoplankton.

Any epiphytic primary producers are assumed to be included in the estimates of primary production and biomass of the macroalgae. In the inner parts of bays, large belts of emergent macrophytes (e.g. reed, *Phragmites australis*) delimit the sea from land. These belts form a boundary between land and sea and are further described and included in the wetland section in /Löfgren 2008/. Any reed located outside this boundary in the sea is included in the macrophytes.

The primary producers in the food web of the marine ecosystem model constitute biomasses that are spatially distributed in the studied areas. The fluxes associated with the primary producers in the marine ecosystem model are Primary Production (PP), when carbon is fixed in the process of photosynthesis, and autotrophic Respiration (R), or Net Primary Production (NPP, NPP = PP-R) (Figure 4-4).

In the marine ecosystem model, all primary producers are assumed to use dissolved carbon for photosynthesis.

Consumers

Consumers are defined as all heterotrophic organisms in the ecosystem, i.e. herbivores, carnivores and detrivores. In the quantitative marine ecosystem model, these organisms are divided into;

1. Benthic bacteria,
2. Benthic fauna (herbivores, filter feeders, detrivores including meiofauna and carnivores),
3. Zooplankton,
4. Bacterioplankton,
5. Fish (zooplankton feeding, benthic feeding and piscivorous fish),
6. Mammals (seals),
7. Birds and
8. Human (consuming fish).

The consumers in the food web of the marine ecosystem model constitute biomasses that are spatially distributed at the studied areas, except for humans, which are included merely as an outflux of matter due to human consumption (or rather catch) of fish. The fluxes associated with the consumers in the marine ecosystem model are consumption and heterotrophic Respiration (R) (Figure 4-4).

Bacteria play an important role in the remineralization of dead organic material and recirculation of nutrients. Their species composition is not known but is assumed to be insignificant for the budget calculations. Because bacteria on different substrates are assumed to assimilate carbon from different pools and to be eaten at different rates, they have been divided into two groups: bacterioplankton (living in the pelagic) and benthic bacteria (living in and on the sea floor).

The benthic fauna was classified into four groups: (i) benthic filter feeders dominated by molluscs feeding on planktonic organisms and particulate matter; (ii) benthic detrivores feeding on benthic bacteria and benthic organic matter in the sediment; (iii) benthic herbivores feeding on macro- and microphytes, and (iv) benthic carnivores feeding on the other groups (i–iii) of benthic fauna.

Zooplankton is a heterogeneous group with respect to organism size, life cycle and food choice. However, that level of detail has been omitted in this budget, as it was assumed to be of no importance for the carbon budget calculations.

Fish were divided into the functional groups zooplanktivorous fish (feeding on zooplankton), benthivorous fish (feeding on benthic fauna) and piscivorous fish (feeding on fish). See also Section 4.2.8 for classification of species.

Mammals (i.e. seals) and humans feed on fish, birds feed on fish and benthic fauna, and they all thereby contribute to the flux of matter in the marine ecosystem model.

Abiotic pools

The abiotic pools in the marine ecosystem model comprise sediment, particulate matter and dissolved matter.

Sediment was divided into two parts: the bioactive layer, where the upper 0–10 cm (a default modelling value for the bioactive layer in accumulation bottoms in coastal areas in the Baltic /Håkanson et al. 2004/) was assumed to be the active part of the system, while sediment below 10 cm was treated as being outside the system. Pore water was included in the sediment pool and was not regarded as a separate pool in the model.

Particulate matter (POC when containing carbon) is assumed to be evenly distributed in the water column (but have a spatial variation) and it does not include living planktonic organisms.

Dissolved matter can be organic (DOC) or inorganic (DIC). DOC and DIC are assumed to be evenly distributed in the water column.

Food-web matrix

In Figure 4-4 conceptual presentation of the food-web model is found. In Table 4-3 the primary production and consumption relationship between the biotic and abiotic pools in the system are revealed.

For the groups feeding on two or more other groups (all consumers except zooplanktivore fish and benthic bacteria), the proportion of consumption was determined by the availability of biomass. The assumption is that consumers do not discriminate between food sources, but feed on the most abundant source. Due to the spatial variation of biomass, the proportion of consumption was individually calculated for each grid cell.

All primary producers (except emergent macrophytes), i.e. macrophytes, microphytobenthos and phytoplankton, are assumed to assimilate 100% of their carbon demand from the dissolved inorganic carbon pool (DIC).

Benthic bacteria are assumed to assimilate carbon from sediment and bacterioplankton was assumed to assimilate carbon from POC and DOC.

Benthic herbivores are assumed to consume macrophytes and microphytobenthos. Benthic filter feeders are assumed to consume POC, phytoplankton, bacterioplankton and zooplankton. Benthic detritivores are assumed to consume sediment and benthic bacteria. Benthic carnivores are assumed to consume other benthic fauna groups, i.e. benthic herbivores, filter feeders and detritivores.

Zooplankton are assumed to consume phytoplankton and bacterioplankton.

Fish feeding on zooplankton are assumed to consume only zooplankton and not phytoplankton or bacterioplankton, as these groups are assumed to be too small to be ingested. Fish feeding on benthic fauna are assumed to consume benthic fauna (benthic herbivores, filter feeders, detrivores and carnivores). Piscivore fish are assumed to eat only fish.

Birds are assumed to feed on benthic macrophytes, benthic fauna or on fish. Their food choice was dependent on the spatial distribution of the functional groups they feed on. Between the surface and a depth of 5 m, 98% of the birds are benthivores and are therefore assumed to consume benthic organism (macrophytes and benthic fauna). Below 5 m, 48% of the birds are assumed to be benthivores and 52% piscivores.

Table 4-3. Food web matrix, describing the interactions between the biotic components in the ecosystem. The groups represented by the rows use the groups represented by x-marks in the columns as source of matter in primary production (P1–P3) or consumption (C1–C9).

	P1	P2	P3	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	DIC	DOC	POC	Sediment
P1, Macrophytes														x			
P2, Microphytes														x			
P3, Phytoplankton														x			
C1, Benthic bacteria																	x
C2, Benthic herbivores	x	x															
C3, Benthic filter feeders			x						x	x						x	
C4, Benthic detrivores and meiofauna				x													x
C5, Benthic carnivores					x	x	x										
C6, Zooplankton			x							x							
C7, Bacterioplankton															x	x	
C8, Benthivore fish					x	x	x	x									
C9, Zooplanktivore fish									x								
C10, Piscivore fish											x	x					
C11, Bird	x				x	x	x	x			x	x	x				
C12, Seal											x	x	x				
C13, Humans											x	x	x				

Fluxes in the ecosystem

The fluxes in the marine ecosystem model are biotic (net primary production, respiration and consumption) and abiotic (runoff, advective flux, groundwater inflow, burial, diffusion and deposition). Parameterization of the fluxes is described in Section 4.3, except for advective flux which is described in Section 5 of this report.

Net Primary Production (NPP) is Gross Primary Production (GPP) minus Respiration (R) by primary producers and comprises the conversion of inorganic dissolved carbon (DIC) in the water column to organic carbon via photosynthesis. GPP and R of primary producers are not calculated separately in the model but included in NPP.

Respiration (R) comprises heterotrophic cell respiration and is calculated for all consumers, living in the water, i.e. excluding mammals, birds and humans.

Consumption (C) comprises the consumption of other organisms by a functional group and is calculated for all consumers.

Excess (E) is the remainder of the carbon/energy budget comprising primary production (or for consumers consumption) minus predation and respiration. It includes secondary production, excretion and faeces, and mortality. Since the model is assumed to be static in terms of biomass development, all excess is assumed to be an input to the pools, sediment, POC and DOC. The DIC pool is assumed to be in equilibrium with atmospheric carbon.

Advective fluxes comprise flows of water, and matter transported by water, between the different basins. Advective fluxes are calculated by two different models driven by factors such as runoff, atmospheric pressure, wind speed etc and are described in Chapter 5 of this report.

Runoff, or discharge, comprises fluxes of water or other matter transported by water from surrounding watersheds or drainage areas.

Burial is the export from surface sediment (top 10 cm) to deeper sediment (10 cm), considered to be outside the modelled ecosystem. Groundwater inflow comprises net inflow of water from the near-surface hydrological domain /Follin et al. 2007/. Positive net inflow occurs in areas where groundwater discharges into the basins and negative net inflow occurs where there is a net outflow from the basins to the groundwater. Data for this is however not included in the massbalance calculations.

4.2.2 Mass balance

To get an overview of major pools and fluxes within the marine ecosystem, mass balance calculations were performed for carbon (C), nitrogen (N), phosphorus (P), iodine (I), thorium (Th) and uranium (U). The mass balance models for the marine ecosystem comprise pools and major fluxes of matter in the marine ecosystems in Forsmark and Laxemar-Simpevarp. The mass balance calculations include the same pools (biotic and abiotic) as the marine ecosystem model, but the pools are clumped in primary producers and consumers. The major fluxes into and out of the ecosystem (runoff, deposition net advective flow, burial, total net primary production (NPP) and total respiration (R)) are also the same as in the marine ecosystem model (see previous section). No fluxes within the functional groups of the ecosystem are included in the mass balance calculations. NPP was considered for C and for N and P based on estimates calculated from the Redfield ratio. Respiration was included in carbon balances. These processes are not known for other element balances and are therefore not included; see Figure 4-5 and Table 4-22.

Some identified processes may potentially influence the mass balance, but are not included in the mass balance calculations, e.g. gas exchange between water and atmosphere (i.e. evaporation, transpiration and volatilization although diffusion was included for carbon). These processes may be of importance for some elements such as N and I, but for the majority of elements they are probably of minor importance. Migration of organisms, e.g. fish, may be of importance, for example for N, but with regard to the biomass of fish in comparison to other volumes in the ecosystem, this process is probably of minor importance. (Table 4-4).

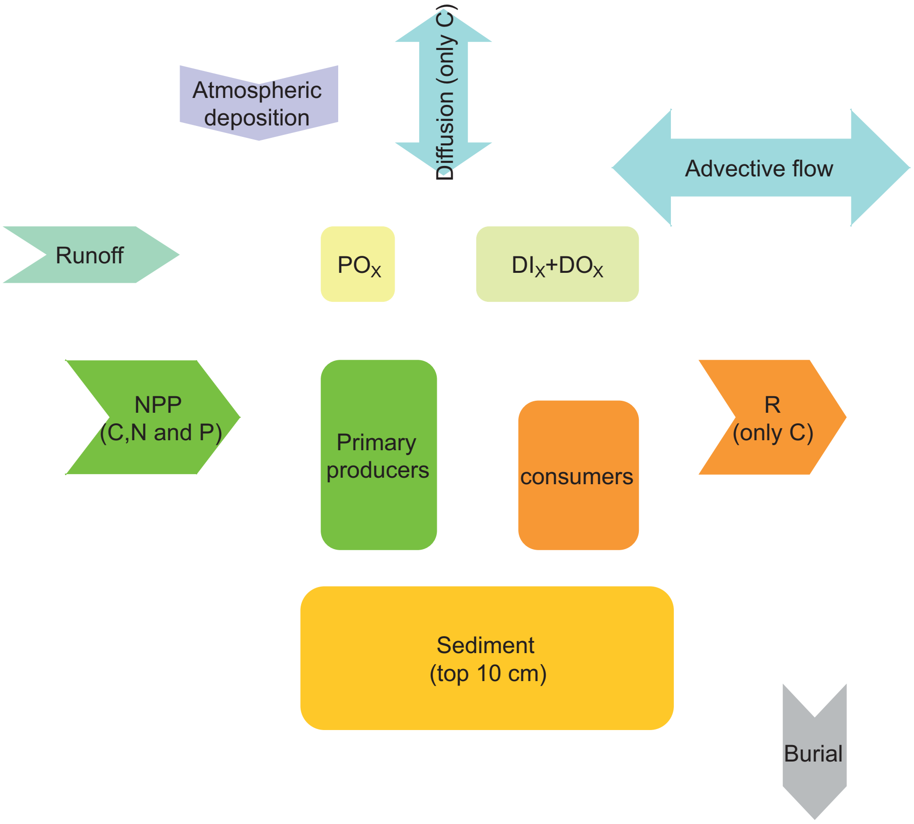


Figure 4-5. *Conceptual model for calculating mass balances for elements showing considered pools and fluxes considered for the elements (C, N, P, I ,Th and U) X in the figure could represent any of these elements. The same structure was used for all elements, except that NPP was only considered for C, N and P and R only for C.*

Table 4-4. Pools and fluxes considered in the mass balance models for C ,N, P, I, TH and U.

Fluxes to the system	**Process**	**Mass balance carbon, remarks**	**Mass balance other elements, remarks**
In through water	Runoff	X	X
In through water	Advective flow	X	X
In from atmosphere	Net Primary Production	X	Not applicable
In from atmosphere	Precipitation, deposition	X	Considered for C, N and P
In from atmosphere	Gas exchange atmosphere/ water	X	Not considered
Diffusive inflow	E.g. migration of organisms	Not considered	Not considered
Fluxes from the system			
Out through water	Advective flow	X	X
Out to atmosphere	Respiration	X	Not applicable
Out to atmosphere	Evaporation/transpiration/ volatilization	Not considered	Not considered
Diffusive outflow	E.g. Migration of organisms	Not considered	Not considered
Accumulation	Burial	X	X
Pools			Considered for most elements
Producers		X	X
Consumers		X	X
Sediment upper (top 10 cm)		X	X
Sediment deep (> 10 cm)		Not considered	Not considered
Particulate		X	X
Dissolved		X	X

4.2.3 Elemental composition

To identify major pools in the functional groups and abiotic pools in marine ecosystems, the elemental compositions of organisms, sediment and water were analyzed within SKB's site investigation programme /Nilsson 2004, Bradshaw and Kumblad 2008, Engdahl et al. 2006, 2008/. In Forsmark and in Laxemar-Simpevarp 49 and 63 elements were analyzed respectively. Results on the elemental compositions of organisms are presented in Section 3.5 and 3.6.

From analyses of carbon (C) and other elements (X) in the various organisms and abiotic samples in the ecosystem, a C:X ratio for each functional group or abiotic pool was derived. These C:X ratios were then used to calculate the mass of each element in the various abiotic and biotic pools.

4.3 Parameterization of biotic properties

4.3.1 Macrophytes

Macrophyte biomasses in both Forsmark (7 communities) and Laxemar-Simpevarp (8 communities) were modelled in detail for separate vegetation communities named after dominant species or taxa found at the sites (Table 4-5). Modelling methods and assumptions is extensively described in /Carlén et al. 2007/. The seventh vegetation community in Forsmark dominated by *Fucus sp*. was not modelled, since the data density was too low. Instead, semi-quantitative cover data from 10 transects was used to generate the biomass distribution for the ecosystem model.

The extent of the modelling area is the same as for the digital elevation models for Forsmark and Laxemar-Simpevarp. Predictors and resulting models are in 20×20 m grids.

Point and transect data from field surveys were used for modelling. Transect data were converted to give one data point for every meter of the transect length. This procedure has proven effective when modelling marine biota /Sandman et al. 2008/.

Modelling for all macrophytes except *Fucus vesiculosus* and emergent macrophytes was done in GRASP (Generalized Regression Analysis and Spatial Predictions), a set of S-PLUS/R functions developed for modelling and analysis of the spatial distribution of species /Lehmann et al. 2002/. GRASP communicates with ArcView, and resulting distribution maps are in ArcView format.

GRASP uses GAM, generalized additive models /Hastie and Tibshirani 1990/, to fit predictor variables independently by means of non-parametric smooth functions. The best model is selected by a stepwise procedure where progressively simpler models are compared with a measure such as Akaike's Information Criterion. Abundance modelling was used here, and the results are presented in the form of grids with estimates of biomass (in this case gC m^{-2}) for each grid cell.

Table 4-5. Vegetation communities/functional groups of macrophytes in Forsmark and Laxemar-Simpevarp.

Vegetation community	Forsmark	Laxemar-Simpevarp
Filamentous brown and green algae (mostly *Pilayella*)	x	x
Chara sp. (mostly *Chara sp*. but also *Najas marina* if present together with *Chara sp.*)	x	x
Phanerogams (*P. pectinatus, P. perfoliatus, Myriophyllom, Caltriche, Zanichellia* if dominant together or alone)	x	x
Potamogeton perfoliatus (if present alone, otherwise under former group)	x	x
Vaucheria sp (if alone or dominant)	x	x
Red algae (if dominant)	x	x
Fucus sp.	x	x
Zostera marina		x

Macrophyte biomass – both sites

Data used in Forsmark in the modelling of macrophytes were mainly collected in August–September 2004 and consist of dive transects, general survey dive transects and point sampling with an Ekman grab sampler /Borgiel 2005/. To get better coverage further out from shore, video survey point data from 2002 were also used also here /Tobiasson 2003/. In all, 7,145 data points were used in modelling, 7,080 of which were created by dividing dive transect data into one-metre segments (Figure 4-6).

The data used in the modelling of macrophytes in Laxemar-Simpevarp were mainly collected in September–November 2002 during dive transects and a general survey using boat, water field glasses and rake /Fredriksson and Tobiasson 2003/. However, to get better coverage further out from shore, video survey point data from 2002 were used /Tobiasson 2003/. In all, 2,965 data points were used in the modelling, 1,632 of which were created by dividing dive transect data into one-metre segments (Figure 4-7).

For each data point in the dataset, the vegetation was assigned to one of the vegetation communities/functional groups depending on the dominant species/family according to percent cover degree /Fredriksson 2005b/. Before modelling, percent cover was converted to grams dry weight per m^2 (g dw m^{-2}) using a specific conversion factor for each community /Fredriksson 2005b/, and then from g dw m^{-2} to gram carbon per m^2 (gC m^{-2}) using species/family-specific conversion factors /Kautsky 1995/ for each of the contributing taxa. The conversion factors are shown in Table 4-6.

The data points assigned to the group *Potamogeton perfoliatus* at both sites were so few that they were modelled together with the phanerogam group. The vegetation communities/functional groups represented in the ecosystem model in Forsmark are, filamentous brown and green algae, *Chara sp*, phanerogams, *Vaucheria sp*. and red algae. The vegetation communities/functional groups represented in the ecosystem model in Laxemar-Simpevarp are filamentous brown and green algae, *Chara sp*, phanerogams, *Vaucheria sp,* red algae, *Fucus sp*. and *Zostera sp*.

The initial modelling was done using data from surveys performed in August and September (in Forsmark), and September–November (in Laxemar-Simpevarp), so the resulting biomass of carbon per square metre was not representative of the annual mean. In /Kiirikki 1996/ the variation in percent cover degree for a number of algae at Tvärminne, Northern Baltic Proper, is shown over a period of three years. This dataset, together with information on algal lifecycles /Tolstoy and Österlund 2003/, was used to estimate the approximate length of the vegetation period for the vegetation groups and to roughly convert the modelled biomasses into yearly means. This process is described for each vegetation group below. Conversion factors are given in Table 4-6.

The maximum cover of most annual species was reached in June–August. However, the annual species considered here are present for most part of the year. The yearly average is therefore calculated as ½ of the modelled maximum. Phanerogams and *Chara sp.* were considered annual groups in this case.

Filamentous brown and green algae are dominated by *Pilayella sp.* at the sites. *Pilayella sp.* has a vegetation period that extends over a larger proportion of the year, approximately from February to August, with a peak around March or April. The yearly average was calculated as twice the modelled biomass from August (in Forsmark) and from September–November (in Laxemar-Simpevarp).

Vaucheria sp. is perennial that is present and growing throughout the year. The yearly average is considered to be the same as the modelled biomass. In Forsmark, *Vaucheria sp*. was only found in Kallrigafjärden (Basin M150 and 152), so the modelled biomass was set to zero in all other areas.

Most red algae in this study were perennials, for example *Ceramium tenuicorne*. In general red algae are present throughout the year but have a biomass maximum during June to August. The yearly average was calculated as half the modelled maximum.

Zostera marina and *Fucus vesiculosus* are perennial species and are present year-round. Their yearly averages are considered to be the same as the modelled biomass.

Predictors determining the vegetation were chosen in order to be easy to parameterise from data och directly measured in the site investigation programme at the sites. Selected predictors in the modelling of macrophytes in Forsmark and Laxemar-Simpevarp were depth, slope, aspect, bottom temperature, pelagic temperature, Secchi depth, wave exposure, light percentage at the bottom and days with solar insulation above 5 MJ. The wave exposure grid was log transformed and this grid was used throughout the modelling.

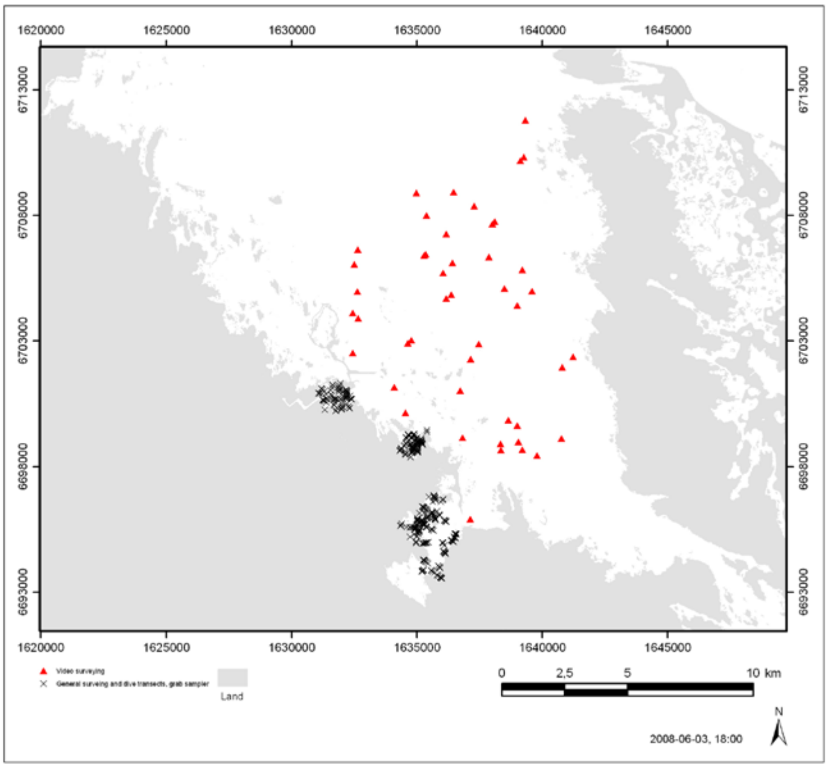


***Figure 4-6.** Field data used in modelling of macrophyte biomass in the Forsmark area.*

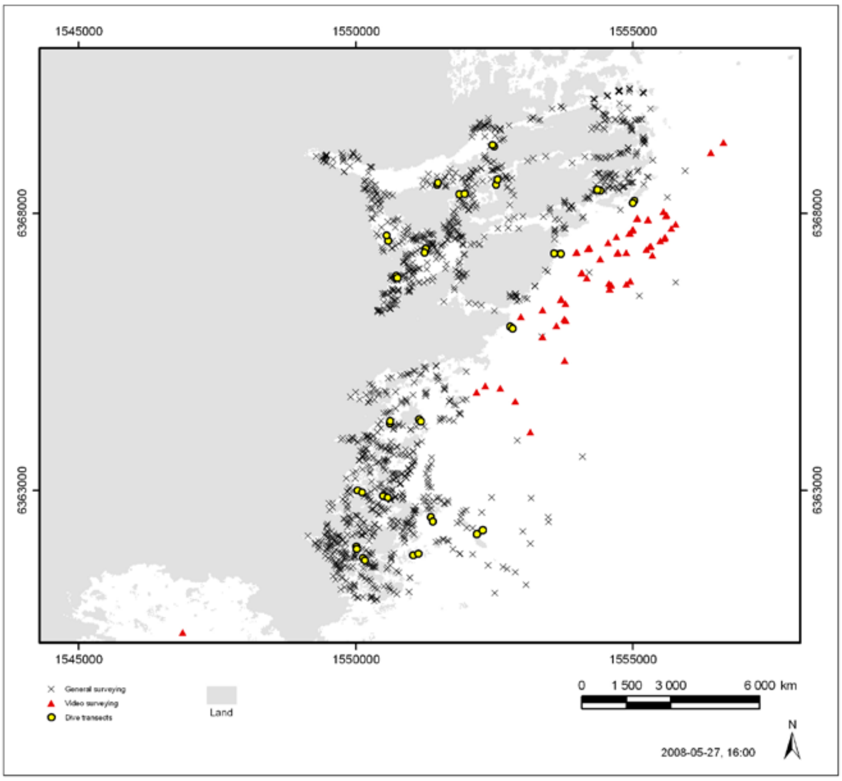


***Figure 4-7.** Field data used in modelling of macrophyte biomass in the Laxemar-Simpevarp area.*

Table 4-6. Conversion factors for the macrophyte species groups present in the Forsmark /Fredriksson 2005b/ and Laxemar-Simpevarp areas /Fredriksson and Tobiasson 2003/. Conversion factor from g dw m^{-2} to gC m^{-2} from /Kautsky 1995/.

	Conversion factor from percent cover to g dw m^{-2}	Conversion factor from g dw/m^2 to gC m^{-2}	Conversion factor to yearly mean
Forsmark			
Filamentous brown and green algae	0.29	~ 0.3	×2
Chara sp.	1.6	~ 0.14	×0.5
Phanerogams	0.59	~ 0.3	×0.5
Vaucheria sp.	4.0	~ 0.4	×1
Red algae	0.74	~ 0.35	×0.5
Laxemar-Simpevarp			
Filamentous brown and green algae	0.5	~ 0.3	×2
Chara sp.	3.5	~ 0.25	×0.5
Phanerogams	1.6	~ 0.35	×0.5
Vaucheria sp.	3.1	~ 0.4	×1
Red algae	1.7	~ 0.35	×2
Fucus sp.	8.8	~ 0.35	×1
Zostera marina	1.7	~ 0.35	×1

Table 4-7. Limitations in depth (m) and wave exposure for the macrophyte species/ Functional groups present in the Forsmark and Laxemar-Simpevarp area.

	Delimitationin depth (m)	Delimitation in log-transformed wave exposure
Forsmark		
Filamentous brown and green algae	20	–
Chara sp.	4	–
Phanerogams	5	–
Vaucheria sp.	7	> 10.15
Red algae	25	–
Laxemar-Simpevarp		
Filamentous brown and green algae	20	–
Chara sp.	4	–
Phanerogams	4	–
Vaucheria sp.	7	> 7.95
Red algae	–	–
Fucus sp.	7	–
Zostera marina	5	< 9.00

Because field data cover was denser in shallow waters than in deep waters, the models could not always distinguish at what depth algae no longer are present and therefore,, biomass below a certain depth was set to zero. The depth limits for the different functional groups were set according to literature /Tolstoy and Österlund 2003, Leinikki et al. 2004, Mossberg et al. 1992/, and are shown in Table 4-7.

Data cover was also less dense in areas of both low and high wave exposure. This is probably the reason that the model for *Vaucheria sp.* failed to capture the fact that this taxon is exclusively found in very sheltered areas. Therefore, a limit was also set for *Vaucheria sp*. in wave exposure. This limit was set by finding the highest log-transformed wave exposure for *Vaucheria sp*. presence and rounding this number up to the nearest five hundred. Above this value *Vaucheria sp.* biomass was set to zero. The same problem was evident for *Zostera marina* (in Laxemar-Simpevarp), where the model did not capture the fact that *Zostera marina* needs at least moderate wave exposure. Disregarding a few outliers, the lower limit was found and rounded down to the nearest five hundred. Below this limit, *Zostera marina* biomass was set to zero.

Fucus vesiculosus biomass in Forsmark

Data density for *Fucus vesiculosus* was lower and not enough for GRASP modelling in Forsmark. Semi-quantitative cover (%) data on *F. vesiculosus* are found in 10 transects in the Forsmark area from four studies /Borgiel 2004a, 2005, Kautsky et al. 1999, Wallström et al. 2000/, six of which were used in this study. Four of the transects are located in Asphällsfjärden, and as these are affected by the intake channel for the nuclear power plants, the environmental conditions are assumed to be atypical with regard to abiotic factors (e.g. water transparency) determining the distribution of macroalgae. Depth, substrate and wave exposure (or correlated characteristics) are among the structuring factors for *F. vesiculosus* e.g. /Isæus 2004, Kautsky et al. 1986/ and depth determines the maximum depth distribution. These factors were used to find probable habitats for *F. vesiculosus*.

Observed cover (%) of *F. vesiculosus* was plotted against depth and wave exposure index presented in /Carlén et al. 2007/. *F. vesiculosus* was found in areas with a wave exposure index (SWM) between 100,000 and 300,000 and a depth between 0 and 7 m. The distribution, increasing from the surface and decreasing at depths deeper than 4 to 6 m, is similar to that found by /Kautsky et al. 1986/. A curve was fitted to data on cover (C) of *F. vesiculosus* at depth intervals (D) 0–1 m, 1–2 m etc. (Figure 4-8) according to:

$$C = (1.33 \cdot D^2) - 11.14D$$

Further, *F. vesiculosus* was assumed to be present on hard substrates and distributed according to the structuring factors of depth, substrate and wave exposure. The relationship between cover and dry weight /Fredriksson and Tobiasson 2003/ and between dry weight and carbon /Engdahl et al. 2006/ was used to calculate the biomass of *F. vesiculosus* (gC m^{-2}) in Forsmark.

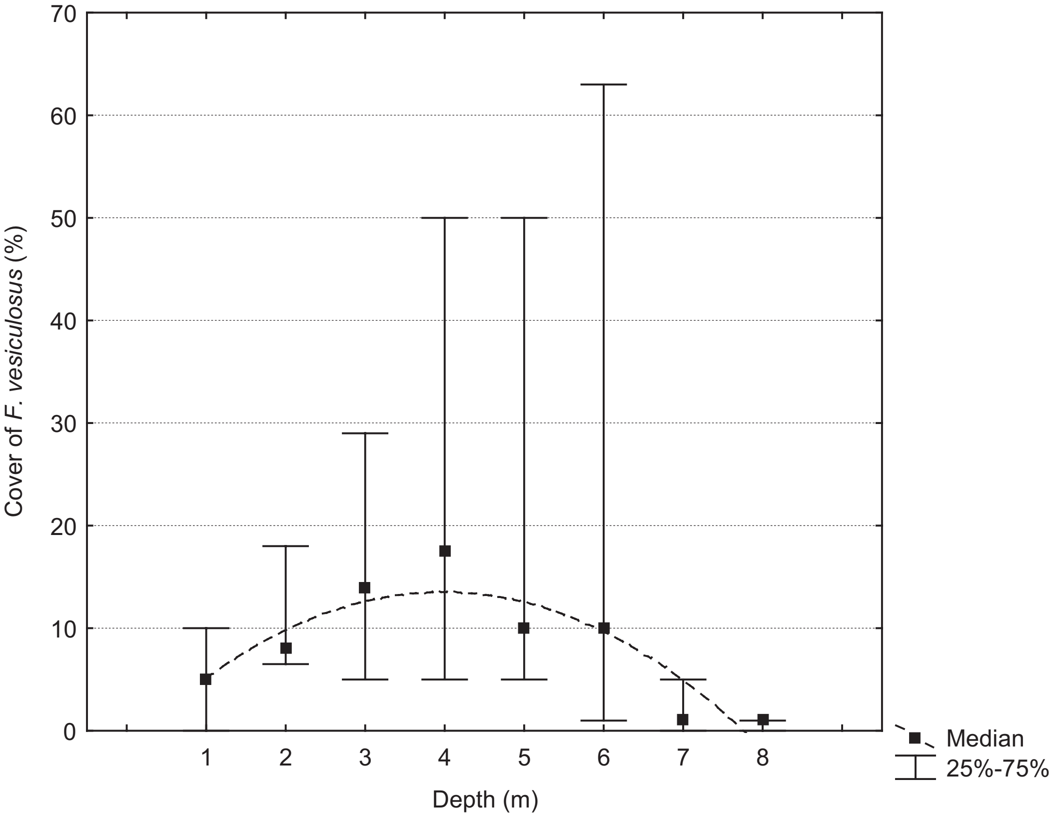


Figure 4-8. *Median cover, 25 and 75% percentiles, of F. vesiculosus at different depth intervals (1; 0–1, 2; 1–2 etc) in Forsmark.*

Emergent macrophytes – both sites

Emergent macrophytes are present in the shore zone in the shallow, secluded bays in the coastal area. They are present in shallow water or in wet terrestrial areas. As the upper delimitation of the marine ecosystem is the mean seawater level in the elevation model, most emergent macrophytes are not included. However as these plants (mainly reed, *Phragmites australis*) have relatively high primary production, it is likely that they contribute to some extent to the organic matter transport to the marine system and excluding them would probably underestimate the input of carbon to the system. For this reason, all emergent macrophytes within an area submerged by water at the 95th percentile of positive deviation (0.50 m) from average mean sea level are included as a source of organic matter for the marine system.

Occurrences of emergent macrophytes were obtained from satellite interpretations of vegetation communities by /Boresjö Bronge and Wester 2003/ as "Open wetland, reed-dominated" .

Primary production of macrophytes – both sites

Several studies of *in situ* measured primary production were performed to obtain productivity figures for the seven different vegetation communities, see Table 4-8. For most vegetation communities, net primary production (NPP) was related to daily irradiation. In some cases the relationship was weak, but as no correlations with other parameters were found either, these figures were used.

Generally, if productivity in the references was given in other units than gC, the measure was converted using conversions between gC and g dw found in /Engdahl et al. 2006/ or /Kautsky 1995/ and productivity ($gC^{-1}\ h^{-1}$) was converted to daily figures ($gC^{-1}\ d^{-1}$) using average hours of irradiation data from the reported date of experiment in the references. Daily irradiation ($MJ\ m^{-2}\ d^{-1}$) was calculated from depth (D) and daily irradiation at the surface ($I_{surface}$) and average light attenuation in Laxemar-Simpevarp /Lindborg 2006, Section 4.3.3/ according to:

$$\sum I_{surface} \cdot e^{-0.79 \cdot D}$$

If not given in the reference, daily irradiation was estimated from average Forsmark or Laxemar-Simpevarp datasets, depending on latitude in the Baltic area.

When NPP was not reported separately, it was calculated from measured GPP using a relationship for GP:R of 10:1 found by /Binzer et al. 2006/ from 134 studies of phytoelements, primary production and respiration.

Below is a description of the production of separate vegetation communities and how they are correlated to irradiation. "N" in the section below refers to number of separate measurements or measuring period and does not include sub samples.

Table 4-8. Primary production conversion factors for the different vegetation communities, where I is average irradiation (MJ PAR d^{-1}). Note the different units.

Vegetation community	Factor	Unit	Original data references
Filamentous	20.91	$mgC\ gC^{-1}\ l^{-1}\ day^{-1}$	/Paalme and Kukk 2003, Guterstam et al. 1978, Wallentinus 1978/
Chara sp.	10.61	$mgC\ gC^{-1}\ l^{-1}\ day^{-1}$	/Torn et al. 2006, Karlsson and Andersson 2006, Borgiel et al. 2006, Wijnbladh and Plantman 2006/
Phanerogams	19.41	$mgC\ gC^{-1}\ l^{-1}$	/Wijnbladh and Plantman 2006/
Vaucheria sp.	67	$gC\ m^{-2}\ year^{-1}$ when $B > 25\ gC\ m^{-2}$	/Borgiel et al. 2006/
Red algae	10.40	$mgC\ m^{-2}\ l^{-1}\ day^{-1}$	/Paalme and Kukk 2003, Wallentinus 1978, Borgiel et al. 2006/
Fucus vesiculosus	3.30	$mgC\ gC^{-1}\ l^{-1}\ day^{-1}$	/Guterstam et al. 1978, Guterstam 1979, Lindblad et al. 1984, Paalme and Kukk 2003/
Zostera	2.37	$mgC\ gC^{-1}\ l^{-1}$	/Wijnbladh and Plantman 2006/

Three studies of daily NPP for *Pilayella littoralis* (n=5) *Cladophora glomerata* (n=5) and *Enteromorpha intestinalis* (n=2) /Paalme and Kukk 2003, Guterstam et al. 1978, Wallentinus 1978/ were used to calculate factors for NPP of filamentous brown and green algae (see also Table 4-8). Primary production was, albeit weakly, correlated to irradiation ($r^2 = 0.22$). The weak relationship is probably due to the different species having varying life strategies.

Factors for calculating NPP of the *Chara sp.* communities in four studies of daily NPP for *Chara tomentosa* (n=4) /Torn et al. 2006/ and *Chara* sp. (n=15) /Karlsson and Andersson 2006, Borgiel et al. 2006, Wijnbladh and Plantman 2006/ were correlated to daily irradiation (Table 4-8). NPP was positively correlated to irradiation ($r^2 = 0.45$), Figure 4-9.

NPP in phanerogam communities was measured by /Wijnbladh and Plantman 2006/ in communities dominated by *P. pectinatus* during 2005 and 2006 (Figure 4-10 and Table 4-8). In July and October there was a strong correlation between biomass and NPP, while in August the correlation was weaker.

Values for *Vaucheria sp*. communities were obtained from NPP measurements performed in the Baltic within the SKB Site Investigation programme at Forsmark (n=10 sites) /Borgiel et al. 2006/. The study was performed at two occasions, and therefore no reliable correlation to irradiation was obtained. Instead, monthly NPP was estimated for the site (biomass: 152 gC m^{-2}) and annual production was estimated using interpolation in relation to average monthly irradiation. Annual NPP was calculated to be 67 gC m^{-2} and assumed to be an average valid for all areas with a biomass equal to or exceeding 25 gC m^{-2} (Table 4-8).

For red algae communities, data from three studies of daily NPP for *Furcellaria lumbricalis* (n=4 sites) /Paalme and Kukk 2003, Wallentinus 1978/ and *Phyllophora truncate* (n=1) /Wallentinus 1978/ and red algae community (n=1) /Borgiel et al. 2006/ displayed no correlation to daily. Red algae have a wide depth range, therefore the studies cited represent several depths. It is likely that algae present at larger depths are better adapted to poor light conditions, and thus it is not surprising to find a lack of P-I relationship for this diverse group. For production calculation, average daily NPP was assumed to be present at all light conditions. Factors for calculating NPP of filamentous algae are found in Table 4-8.

Daily *in situ* measured NPP from four studies of *F. vesiculosus* (n=72) /Guterstam et al. 1978, Guterstam 1979, Lindblad et al. 1984, Paalme and Kukk 2003/ were correlated to daily irradiation. NPP was positively correlated to irradiation ($r^2 = 0.57$), see Figure 4-11 and Table 4-8.

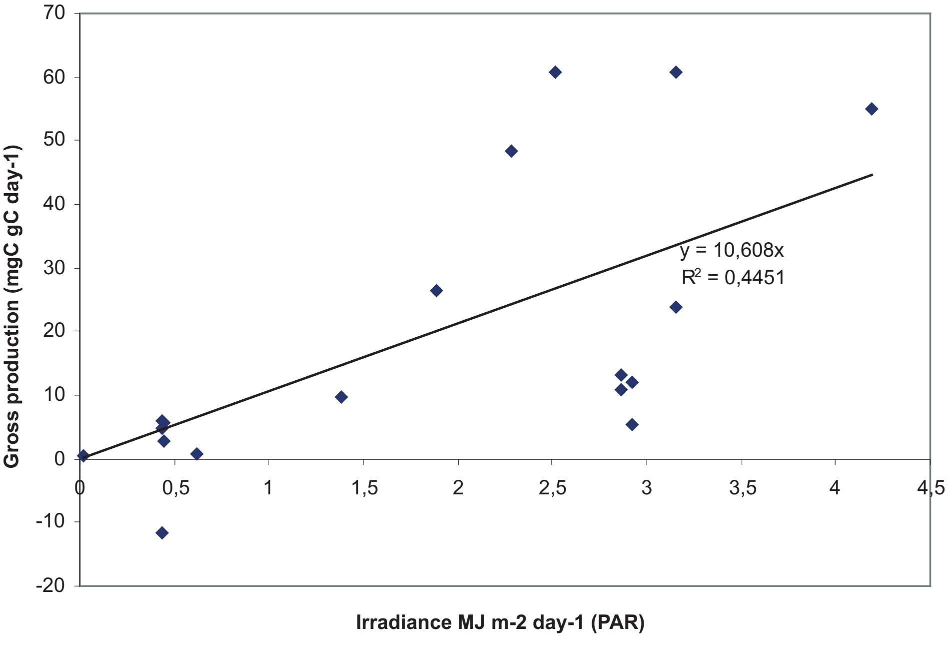


Figure 4-9. *Gross primary production of Chara sp. (mgC gC^{-1} day^{-1}) and daily in situ irradiation (MJ PAR m^{-2} day^{-1}) from four different studies.*

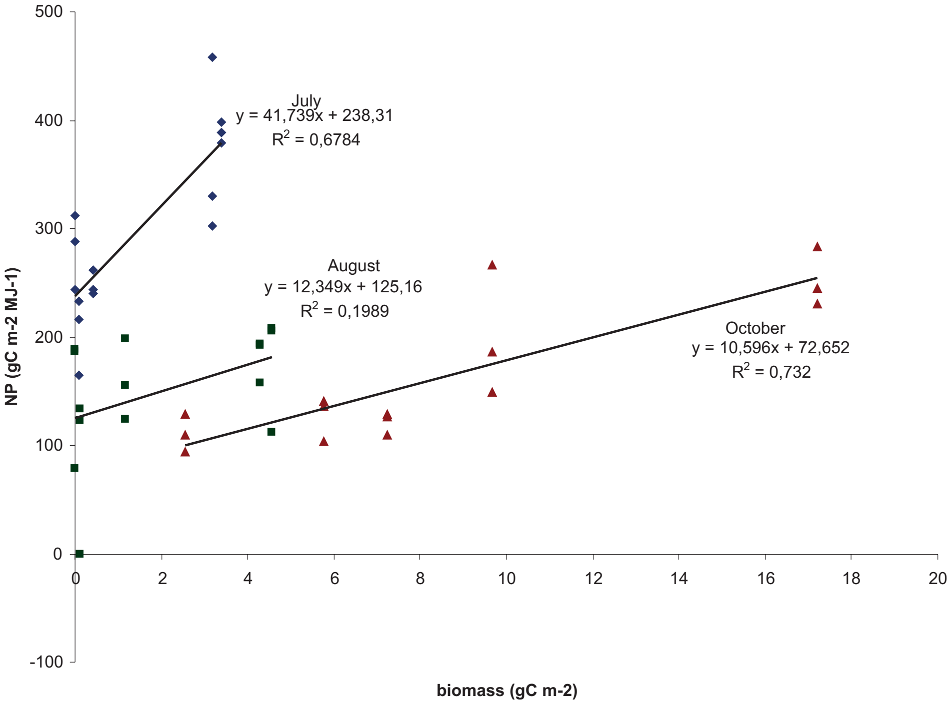


Figure 4-10. *Net primary production of Potamogeton pectinatus. (mgC m–2 MJ^{-1}) and biomass (gC m^{-2}) at different periods from the study by /Wijnbladh and Plantman 2006/.*

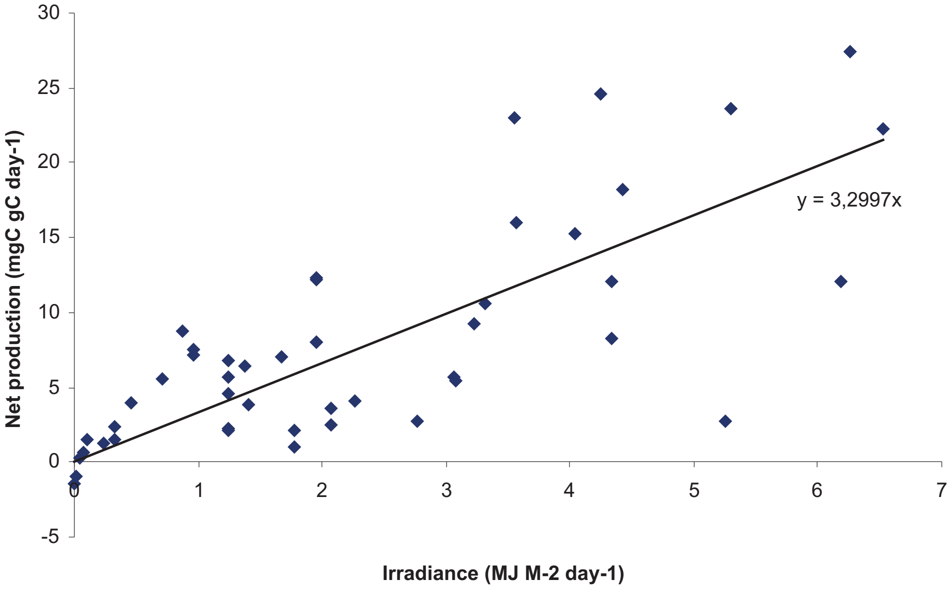


Figure 4-11. *Net primary production of Fucus vesiculosus (mgC gC^{-1} d^{-1}) and daily in situ irradiation (MJ PAR m^{-2} d^{-1}) from four studies. (r^2 = 0.57).*

For *Z. marina* data from measurements performed by /Wijnbladh and Plantman 2006/ during 2005 and 2006 were used (Figure 4-12).

Incorporation by nitrogen (N) and phosphorus (P) during photosynthesis were estimated according to the Redfield ratio, C:N:P = 106:16:1. The Redfield ratio is the molecular ratio of carbon, nitrogen and phosphorus in phytoplankton /Redfield 1934/. This was applied to the production of the functional groups of all primary producers and was done to give an indication of the amount of N and P in the NPP flux, and thus not intended to be valid for the actual amount of N and P which is incorporated during photosynthesis.

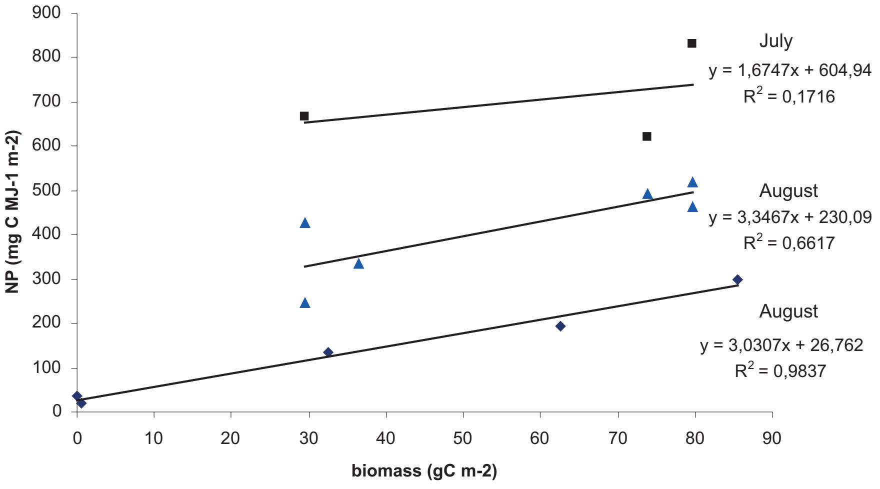


Figure 4-12. *Net primary production of Zostera marina (mgC m^{-2} MJ^{-1}) and biomass (gC m^{-2}) at different periods from the study by /Wijnbladh and Plantman 2006/.*

4.3.2 Microphytes – both sites

Biomasses of microphytobenthos were measured *in situ* by /Snoeijs 1986/ and were assumed to be evenly distributed in the photic zone. Biomasses at Forsmark and Laxemar-Simpevarp were estimated from GP/B quotas (k = 12.9) from /Snoeijs 1986/, which are similar to average GP/B quotas (12.1) for other reported biomass and production measurements.

Microphytobenthos primary production was estimated by /Borgiel et al. 2006/ (Forsmark) and /Wijnbladh and Plantman 2006/ (Laxemar-Simpevarp). NPP was assumed to be dependent on *in situ* irradiation and potential substrate. All substrates were assumed to be possible substrates except dense (> 50% cover) vegetation communities. Vegetation is a possible and in some cases a plausible substrate for microphytobenthos but is assumed to be included in macrophyte primary production and hence excluded as a separate item.

$D \cdot I \cdot LA \cdot x$

Where D is depth (m), I is measured irradiation over water (MJ m^{-2}), LA is light attenuation (%) (se Section 4.3.4) and x is a constant (x = 24.57) obtained from a relationship found between light and measured Net Primary Production on eight occasions (including five samples on each occasion) in the Simpevarp area /Wijnbladh and Plantman 2006/, see Figure 4-13.

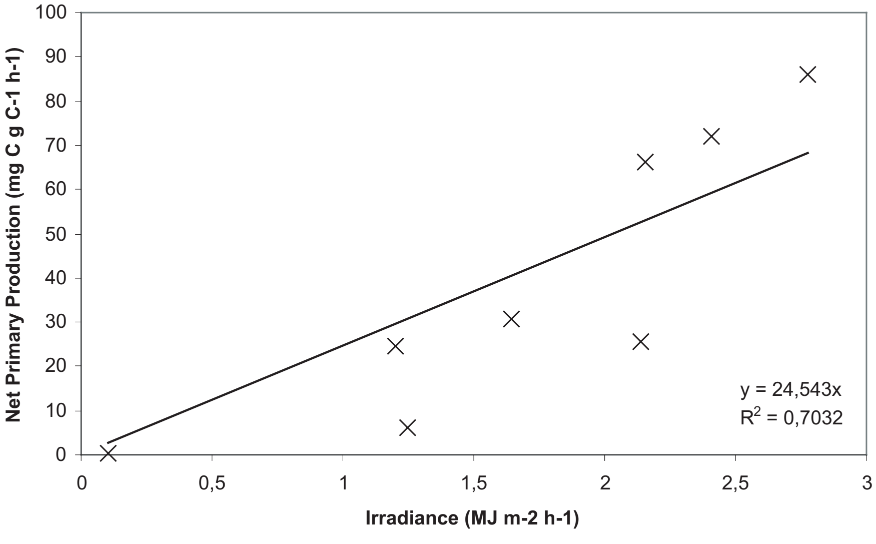


Figure 4-13. *Net primary production by microphytobenthos (mgC gC^{-1} h^{-1}) and daily in situ irradiation (MJ PAR m^{-2} h^{-1}) from one study. (r^2 = 0.70).*

4.3.3 Phytoplankton – both sites

Three factors were accounted for in modelling of phytoplankton biomass and production: (1) deep-water nutrients, (2) coastal nutrients and (3) specific stratified estuarine situations.

Firstly, the summary of available phytoplankton measurements at the study sites suggests an overall correlation between phytoplankton abundance and availability of higher concentrations of nutrients (notably phosphorus) below the upper thermocline or halocline. A lower mean phytoplankton biomass concentration is seen, for example, in the shallower Asphällsfjärden compared with the central Öregrundsgrepen, which is more directly in contact with water below the spring thermocline. An overall rough fit between observations and morphology was obtained when the phytoplankton biomass (in gC m^{-3}, on a yearly basis) based on this contribution was modelled as

$= 0.5/p = 0.025$ for $d > p$

$= 0.5/p - 0.03\ (1 - \exp((0.0002/s) \times (d - p))$ for $b < d < p$

$= 0$ for $d < b$

where d is water depth, p is the depth of the thermocline (= 20 m), s is the overall coastal slope (1/500 in Forsmark and 1/400 in Laxemar-Simpevarp, see Section 3.3.1) and b sets a depth limit for deepwater influence at $b = ((\ln (1-((0.5/p)/0.03)))/(0.0002/s)) + p$.

The deepwater nutrient contribution to the mean phytoplankton biomass was thus described as reaching a maximum where the depth > 20, then exponentially decreasing towards zero at a depth dependent on the overall slope.

Secondly, lower wave incidence and associated mixing in sheltered areas play a vital role for triggering the onset and intensity of the spring bloom /Eilola 1998/. The Simplified Wave Model exposure index (SWM) /Isæus 2004/ was therefore used to describe an additional diffuse contribution to phytoplankton biomass from coastal runoff, thus calculated (in gC m^{-3}) as

$\frac{6 - \log \mathrm{SWM}}{150}$ in Forsmark, and

$\frac{6 - \log \mathrm{SWM}}{75}$ in the less oligotrophic Laxemar-Simpevarp area.

Thirdly, an estuarine contribution was assumed in the two cases with marked river-nutrient enriched estuarine stratification, namely in Kallrigafjärden (Forsmark area) and the innermost part of Borholmsfjärden (Laxemar-Simpevarp area), and derived as in Table 4-9.

In the spatial analysis, both areas were divided into two sub-areas along the estuarine gradient, plus a third outer transition zone off Kallrigafjärden. In the innermost sub-areas, the estuarine contribution to phytoplankton biomass (in gC m^{-3}) was modelled as

$0.17 - (0.0000175 \times SWM)$ in Kallrigafjärden, and

$0.07 - (0.0000133 \times SWM)$ in Borholmsfjärden

and in the outer subareas as $(0.02 \times d2) + 0.01$ in both areas, where $d2 = 2$ where water depth $d > 2$, and $d2 = d$ where $d < 2$.

The three contributions were added to yield the total phytoplankton biomass in gC m^{-3}. Areal biomass (gC m^{-2}) was then obtained by multiplying by the water depth d (where $d < 20$) or 20 (where $d > 20$).

Annual average phytoplankton production (in gC m^{-2} y^{-1}) was obtained by multiplying areal biomass by an overall production/biomass (P/B) ratio set at 101 and 98 y^{-1} in Forsmark and Laxemar-Simpevarp, respectively, based on annual average of ratios listed by /Harvey et al. 2003/, in turn based on /Sandberg et al. 2000/, based on /Elmgren 1984/ and /Wulff and Ulanowicz 1989/.

Table 4-9. Derivation of the estuarine contribution to primary production and biomass from runoff in Kallrigafjärden Bay (Forsmark subarea) and Borholmsfjärden Bay (Laxemar-Simpevarp subarea).

Quantity	Kallrigafjärden Bay		Borholmsfjärden Bay		Units
	Innermost part	Entire bay	Innermost part	South basin	
Freshwater inflow, q	8.8 [1]	8.8 [1]	0.19 [2]	0.19 [2]	m^3 s^{-1}
Ambient freshwater PO_4-P conc. P	0.15 [3]	0.15 [3]	0.26 [4]	0.26 [4]	uM P
Recipient area, a	2.2 [5]	7.6 [6]	0.18	0.93	km^2
Surface layer thickness, h	1.6 [5]	1.9 [6]	3.0	4.0	m
Volume above pycnocline, v = ha	0.0035	0.014	0.00053	0.0037	km^3
Recipient flushing time, t = v/q	4.6	19	32	225	d
Phytoplankton rate of PO_4-P removal,[7] V	0.18	0.18	0.27	0.27	d^{-1}
PO_4-P removal during flushing, p = P(1–(1–V)^t)	0.087	0.14	0.26	0.26	uM P
Carbon equivalence[8], p/t	8.8	3.5	3.7	0.53	gC m^{-3} y^{-1}
Fluvial-based primary prod. p/th	14	6.6	11	2.1	gC m^{-2} y^{-1}
Production/Biomass ratio[9], r	70	70	70	70	y^{-1}
Fluvial-based biomass per area, p/thr	0.20	0.094	0.16	0.030	gC m^{-2}
Fluvial-based biomass per volume, p/tr	0.13	0.051	0.053	0.0076	gC m^{-3}

[1] /Persson et al. 1993/.

[2] Product of catchment size (sum of catchments 9 and 10) and the regional relationship discharge: catchment size (from Emån) /Goffeng 1977/.

[3] Mean PO_4-P concentration in 1972–2006 in Forsmarksån Johannisfors 4.5 µg L^{-1} /IMA 2007/.

[4] Mean PO_4-P concentration at PSM002085 and PSM002087 /Tröjbom and Söderbäck 2006a, b/.

[5] Data for recipient Kallriga I in /Håkanson et al. 1984/.

[6] Data for recipient Kallriga II in /Håkanson et al. 1984/.

[7] Estimated using Michaelis-Menten uptake kinetics ($V = V_mP/(K_s+P)$) with a maximum specific PO_4-P uptake V_m at 0.8 d^{-1} /Lessin et al. 2007/ and a half saturation constant for PO_4-P, K_s at 0.5 µM /Fisher et al. 1988/.

[8] Using Redfield molar ratio C:P = 106:1.

[9] For new production /Harvey et al. 2003/.

4.3.4 Benthic bacteria – both sites

Benthic bacteria biomass in the top 5 cm of sediment was measured by /Andersson et al. 2006/ in marine basins in Forsmark and in Laxemar-Simpevarp. The mean biomasses from these investigations were used in the calculations.

Bacterial biomass samples from shallow (less than 20 m depth) less exposed (n=4) soft bottoms in Forsmark were found to correlate ($r^2 = 0.99$) to the Simplified Wave Model exposure index (*SWM*) /Isæus 2004/. The correlation was used to generate the spatial distribution of bacteria on the site, with the *SWM* grid.

In Laxemar-Simpevarp the correlation was weaker, and therefore the mean bacterial biomass (6.53 gC m^{-2}, n=8) was used for all the less exposed (*SWM* < 20,000, representing coastal marine areas) soft bottoms on the site to model the spatial distribution of benthic bacteria.

For soft bottoms representing offshore areas where the *SWM* index exceeds 20,000, the average found by /Mohammadi et al. 1993/ in the Bothnian Bay, 2.13 gC m^{-2}, was used for both Forsmark and Laxemar-Simpevarp.

Studies of bacterial density in sediment by /Jørgensen and Revsbech 1989/ in Öresund were used to model the depth distribution of bacteria in the soft bottoms. /Jørgensen and Revsbech 1989/ found decreasing density with sediment depth. Their study shows that 20.5% of the bacteria in 10 cm of sediment were found below 5 cm and 79.5% above 5 cm, and calculations of the data generated a factor (1.26) for modelling of the depth distribution of the total bacterial biomass in the top 10 cm of the soft bottom sediment.

The bacterial biomass in Forsmark on shallow less exposed soft bottom sediment was modelled according to:

$Biomass = [13.938 - (2.325 \cdot \mathrm{Log}SWM)] \cdot 1.26$

The bacterial biomass in Forsmark and Laxemar-Simpevarp offshore on deeper soft bottom sediment was modelled according to:

$Biomass = [2.13 \cdot SWM > 20{,}000] \cdot 1.26$

where SWM is the wave exposure index.

The bacterial biomass in Laxemar-Simpevarp on shallow less exposed soft bottom sediment was modelled according to:

$Biomass = [6.53 \cdot SWM < 20{,}000] \cdot 1.26$

where SWM is the wave exposure index.

Hard bottom substrate was assumed to have one tenth of the average bacterial biomass calculated for soft bottoms according to:

$Biomass = [2.13 \cdot SWM > 20{,}000] \cdot 1.26 \cdot 0.1$

for deeper more exposed offshore hard bottoms at both sites, and according to:

$Biomass = [13.938 - (2.325 \cdot \mathrm{Log}SWM)] \cdot 1.26 \cdot 0.1$

for shallower areas in Forsmark and according to:

$Biomass = [6.53 \cdot SWM < 20{,}000] \cdot 1.26 \cdot 0.1$

for less exposed areas in Laxemar-Simpevarp.

Respiration (R) was calculated using the grids for annual average temperature and biomass (see above) together with specific values (for each functional group) describing specific respiration in relation to biomass. The specific respiration figures were given in gC gC^{-1} d^{-1} and had to be summarized to gC gC^{-1} d^{-1} $year^{-1}$ before calculation, since the grids for temperature and biomass are annual mean values.

Consumption was calculated with a C/R-factor (2) for benthic bacteria from /Kumblad et al. 2003/.

4.3.5 Benthic fauna – both sites

Benthic fauna was diveded into four functional groups: carnivores, detrivores, filter feeders and herbivores. Species were grouped into each of these groups using classifications in /Kautsky 1995/. Biomass was calculated for these groups from average values obtained from four studies in the area /Borgiel 2005, Kautsky et al. 1999, Odelström et al. 2001/ including unpublished monitoring data (1993 or 1997 to 2006) from the National Board of Fisheries, parts of which are reported in annual reports, e.g. /Mo 2003, 2004, Sandström et al. 2002/. Data from three sample sites south of the area (Gräsö area) were used to compensate for the lack of data from deep soft-bottom communities /Lindahl et al. 1983/.

Benthic detritivores also include meiofauna, an organism group that has not been studied in the areas. Data from studies in the northern Baltic Proper, the Askö area, southeast of Stockholm, were therefore used in the calculations /Ankar and Elmgren 1978/.

The functional group benthic omnivores (represented by crustaceans such as *Gammarus sp.* and *Idothea* sp.) was divided into benthic carnivores and benthic herbivores (50% in each).

Distribution of benthic fauna biomass data was done depending on vegetation community or substrate type according to the diagram in Figure 4-14. Substrate type was classified as described in Section 4.3.7 and vegetation type as defined earlier in this section.

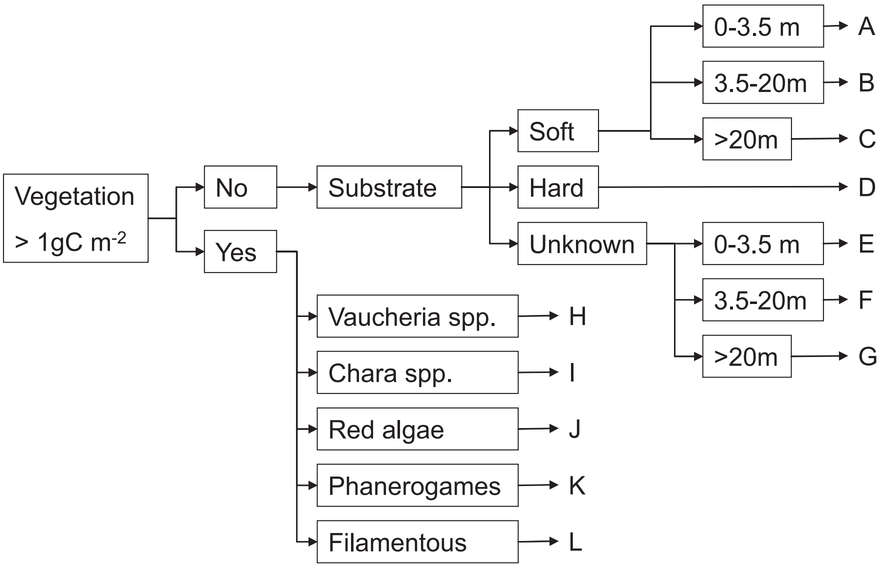


Figure 4-14. Classification of vegetation community or substrate type used to distribute benthic biomass.

Biomasses for each of the four functional benthic fauna groups were assigned average values from the compiled dataset according to bottom class A–L (see Table 4-10). In areas with vegetation > 1 gC m^{-2}, the biomass of the benthic fauna was calculated as follows:

$$Biomass = \left(\frac{B_H}{\sum_H^L B} \right) \cdot F_H + \left(\frac{B_I}{\sum_H^L B} \right) \cdot F_I + \left(\frac{B_J}{\sum_H^L B} \right) \cdot F_J + \left(\frac{B_K}{\sum_H^L B} \right) \cdot F_K + \left(\frac{B_L}{\sum_H^L B} \right) \cdot F_L$$

where B_X is the vegetation biomass in each cell and F_X is the benthic fauna biomass for vegetation community X. The values of F for the vegetation communities and other substrate types A to L are found in Table 4-10.

This method was repeated for the four functional groups in Forsmark and for three of the functional groups in Laxemar-Simpevarp (Table 4-10).

Table 4-10. Benthic fauna biomass (gC m^{-2}) in bottom class A–L (see Figure 4-14).

	Carnivores	Detrivores	Filter feeders	Herbivores	Sample size (incl. sub samples)
A	0.06	4.19	0.02	0.25	5 (17, 2,724)[1]
B	0.66	2.04	0.41	0	5 (17, 2,724)[1]
C	0.68	2.88	0	0	2
D	0.23	1.93	0.83	0.95	(13)
E	0.12	3.93	0.95	0.99	Av[2]
F	0.37	2.65	1.03	0	Av[2]
G	0.57	3.00	0.94	0	Av[2]
H	0.17	4.39	0.55	0.27	2 (6)
I	0.18	11.32	0.49	2.23	1 (3)
J	0.26	3.29	3.34	2.91	20 (44)
K	0.15	9.21	0.50	0.89	3 (7)
L	0.06	6.58	1.52	1.64	8 (29)

1. Five sites, in all 17 subsamples and 2,726 samples during the period 1980–2005.
2. *Av* is Average for occurrence of soft and hard substrate in the area.

Hard bottom fauna in Laxemar-Simpevarp were investigated specifically in /Tobiasson 2003, Fredriksson and Tobiasson 2003, Fredriksson 2005a/. Based on data from the investigations, covering degree of *M. edulis* was correlated to depth, and a relationship between cover degree, biomass and total share of biomass by the various functional groups was also found. These relationships were used to calculate the spatial distribution of hard bottom fauna in Laxemar-Simpevarp, according to:

$\text{Biomass} = B \cdot F_L$

Respiration was calculated using the grids for annual average temperature and biomass (see above) together with specific values (for each functional group) describing specific respiration in relation to biomass. The specific respiration figures were given in gC gC^{-1} d^{-1} and had to be summarized to gC gC^{-1} d^{-1} $year^{-1}$ before calculation, since the grids for temperature and biomass are annual mean values. Consumption was calculated with a C/R-factor (3) for benthic fauna from /Kumblad et al. 2003/.

4.3.6 Zooplankton – both sites

For the model to roughly describe measured mean concentrations of zooplankton (biomass per volume in gC m^{-3}) /Eriksson et al. 1977, Huononen and Borgiel 2005/, this value was set at 1/3 of the volume for phytoplankton. As with phytoplankton, areal biomass (gC m^{-2}) was obtained by multiplying the obtained value by the water depth d (where $d < 20$ m) or 20 (where $d > 20$ m).

To estimate zooplankton consumption and respiration (in gC m^{-2} y^{-1}) Q/B (consumption/biomass), ratios of 222 and 307 y^{-1} were used for the Forsmark area and the Laxemar-Simpevarp area, respectively, and R/B (respiration/biomass) ratios of 90 and 126 y^{-1}, respectively, based on measurements /Sandberg et al. 2000, Harvey et al. 2003/.

4.3.7 Bacterioplankton

Bacterioplankton biomass shows much less spatial and temporal variability than phytoplankton biomass. It was measured by /Andersson et al. 2006/ and a mean concentration in the surface water (above the thermocline) can be modelled uniformly at 0.025 gC m^{-3} in both Forsmark and Laxemar-Simpevarp, which is similar to the spring values reported by /Kuparinen et al. 1996/. They also reported low bacterioplankton growth in the deeper pelagic, so the areal biomass (in gC m^{-2}) was expressed as $0.025 \times d$ (water depth) for $d < 20$ m and 0.025×20 for $d > 20$ m.

Forsmark

For mapping yearly bacterioplankton consumption and respiration (in gC m^{-2} y^{-1}), consumption/biomass (Q/B) and respiration/biomass (R/B) ratios of 257 and 114 y^{-1}, respectively, for the Bothnian Sea were used /Sandberg et al. 2000, Harvey et al. 2003/. Thus, consumption was set equal to biomass×257 y^{-1} and respiration to biomass×114 y^{-1}. The difference, biomass×143 y^{-1}, represents bacterioplankton production.

Laxemar-Simpevarp

Similarly, in Laxemar-Simpevarp, Q/B and R/B ratios for the Baltic Proper of 248 and 105 y^{-1}, respectively, were used, based on measurements /Sandberg et al. 2000, Harvey et al. 2003/. Thus, consumption was set to equal biomass×248 and respiration to biomass×105 (in gC m^{-2} y^{-1}). The difference represents the same level of bacterioplankton production as that used for Forsmark, biomass×143 y^{-1}.

4.3.8 Fish

The fish species at both sites were divided into three functional groups: zooplanktivorous (zooplankton-feeding) fish, benthivorous (benthic-feeding) fish and piscivorous (fish-feeding) fish, according to /Lindborg 2006/. Divisions were made in the dataset from /Heibo and Karås 2005/, (Table 4-11).

Table 4-11. Fish divided into three functional groups; zooplanctivorous, benhtivorous and piscivorous (piscivorous) feeders.

Functional group	Zooplanktivorous	Benthivorous	Piscivorous
Species	Sik (Baltic whitefish), Löja, (Bleak), Strömming (Baltic herring), Skarpsill (Sprat), Nors (Smelt)	Björkna (Silver Bream), Braxen (Bream), Gers (Ruffe), Mört (Roach), Sarv (Rudd), Vimma (Vimba), Hornsimpa (Fourhorned sculpin), Sutare (Tench), Tånglake (Viviparous blenny), Stensimpa (Bullhead)	Id (Ide), Abborre (Eurasian Perch) Gädda (Northern Pike), Gös (European pike-perch), Lake (Burbot)

Forsmark

The method for modelling of fish in Forsmark is extensively described in /Carlén et al. 2007/. Modelling was done in GRASP (Generalized Regression Analysis and Spatial Predictions), a set of S-PLUS/R functions developed for modelling and analysis of the spatial distribution of species /Lehmann et al. 2002/. GRASP communicates with ArcView, and resulting distribution maps are in ArcView format.

GRASP uses GAM, generalized additive models /Hastie and Tibshirani 1990/ to fit predictor variables independently by means of non-parametric smooth functions. The best model is selected by a stepwise procedure where progressively simpler models are compared with a measure such as Akaike's Information Criterion. Abundance modelling was used here, which gives results in the form of grids with abundance estimates (in this case gC m^{-2}) for each grid cell.

Three sets of data were used to spatially model fish biomass in the investigated area: two studies on pelagic fish populations from August to September 2004 using Coastal survey nets and Nordic nets (data from the /Swedish Board of Fisheries, Abrahamsson and Karås 2005, Heibo and Karås 2005/), and one study on demersal fish from August to September 2006 using hydroacoustics and trawling (Sture Hansson, pers. comm.). In all, 309 data points were used in modelling.

Estimates of fish biomass per hectare were calculated by multiplying biomass per net and night of fishing by the constant 17. This conversion factor is used for Nordic nets of the size 82.35 square metres. Coastal nets were further multiplied by 0.7843 to compensate for the smaller size of these nets. These conversion factors are highly uncertain but were used in the absence of other available methods /Heibo and Karås 2005/.

The values were converted from wet weight to dry weight using conversion factors from /Engdahl et al. 2006/, and then to gC using species-specific conversion factors from /Kautsky 1995/. Conversion factors are shown in Table 4-12.

Modelling was done using data from surveys carried out during August and September. However, there is no detailed knowledge about the yearly variation of fish stocks, and therefore no correction to achieve a yearly mean has been attempted.

Available predictors in the modelling of fish biomass in the Forsmark area were depth, slope, aspect, bottom temperature, pelagic temperature, Secchi depth, wave exposure (SWM, log-transformed), light percentage at the bottom and days above 5 MJ, all described in Section 4.3. Macrophyte grids from the modelling above were also used as predictor layers /Carlén et al. 2007/.

Table 4-12. Conversion factors for fish species groups in the Forsmark area.

	Conversion factor from ww m^{-2} to g dw m^{-2}	Conversion factor from g dw m^{-2} to gC m^{-2} (for exact numbers for each species see /Kautsky 1995/)
Zooplanktivorous	0.209	~ 0.5
Benthivorous	0.209	~ 0.5
Piscivorous	0.209	~ 0.5

Food preference of perch has a great impact on the proportions of functional groups of the fish, a special effort was made to estimate this in Forsmark. In Figure 3-1 in /Heibo and Karås 2005/ food preference is presented for each size group. Planktivory is dominant in sizes up to 7 cm, larger fish are benthivorous up to 15 cm and to a small extent piscivorous. Half of the food of fish larger than 25 cm is other fish. Based on fish catches in Forsmark in 2004 and a weight-size ratio /Heibo and Karås 2005, Figures 3-1, 4-4/, it was estimated that less than 1% of the perch biomass was planktivorous, 85% was benthivorous and 15% was piscivorous. Of the modelled "piscivorous" fish, perch constituted approximately 77%. Therefore, to obtain a more reliable estimate of the biomass of true piscivores, the modelled piscivores were recalculated according to:

$$\mathrm{P} = \left(P_m \cdot 0.23\right) + P_m \cdot 0.77 \cdot 0.15$$

where P is the piscivorous fish biomass and P_m is the originally modelled biomass.

The difference between the originally modelled and the recalculated piscivorous fish biomass was added to the benthivorous group.

Laxemar-Simpevarp

The detailed spatial resolution of fish data was not available in Laxemar-Simpevarp, so another method was used.

Different methods for inshore and offshore areas were used. Offshore area was defined on the basis of wave exposure: a clear gradient is found at $SWM > 20{,}000$, where inshore areas are separated from offshore areas. Data from Hydroacoustics and trawling /Enderlein 2005/ were used for offshore areas and data from a thorough programme including several separate methods was used for modelling fish one basin in the inshore area /Adill and Andersson 2006/. Both studies presented fish density.

To estimate piscivorous fish, the proportion between zooplankton-feeding fish and piscivorous fish found in catches by the Swedish Board of Fisheries (*Sw: Fiskeriverket*) between zooplankton feeding fish and piscivorous fish was used. The biomass of benthivorous fish was estimated in the same way for inshore and offshore areas. Fish densities for different vegetation and bottom types were estimated by /Jansson et al. 1985/ by diving and counting *in situ* in an archipelago south of Stockholm (Askö area). These figures were set in proportion to those found by modelling of the various vegetation communities (see earlier in this section) as follows:

$$Biomass = \left(\frac{B_A}{\sum_{VI}^{A} B}\right) \cdot F_A + \left(\frac{B_V}{\sum_{VI}^{A} B}\right) \cdot F_V + \left(\frac{B_I}{\sum_{VI}^{A} B}\right) \cdot F_I + \left(\frac{B_{II}}{\sum_{VI}^{A} B}\right) \cdot F_{II} + \left(\frac{B_{III}}{\sum_{VI}^{A} B}\right) \cdot F_{III} \left(\frac{B_{VI}}{\sum_{VI}^{A} B}\right) \cdot F_{VI}$$

where B_X is the vegetation biomass in each cell and F_X is the fish biomass for each vegetation or bottom type X. The values of F for the vegetation communities are shown in Table 4-13.

Table 4-13. Fish biomasses for various vegetation communities in Laxemar-Simpevarp.

Code	Bottom type (this study)	Vegetation type /Jansson et al. 1985/	Biomass (gC m^{-2})
A	Chara spp.	Average	0.418
V	Zostera spp.	Potamogeton-Ruppia	0.11
V	Phanerogams	Potamogeton-Ruppia	0.11
I	Filamentous	Annual belt	0.1
II	Fucus spp.	Fucus belt	0.43
III	Red algae	Red-algal belt	0.21
VI	Vaucheria spp.	Deep soft bottoms	0.6

As the fish associated with bottom type was assumed to be benthivorous (all of the dominant species were benthic feeding species in /Jansson et al. 1985/), piscivorous and zooplanktivorous fish in inshore areas were calculated from the proportions of these groups found in the beach seine catches in the study by /Adill and Andersson 2006/. The ratio of benthivorous to piscivorous fish was found to be 1:0.3 and zooplankton-feeding to benthic-feeding 1:0.29.

No trends of biomass in realtion to physical variables were found for the few individual samples from the hydroacoustic lines sampling, so an average for offshore areas was used to estimate pelagic fish. The average (0.424 gC m^{-2}) was derived from /Enderlein 2005/ representing zooplanktivorous species (mainly sprat and herring) that were evenly distributed in the offshore areas. Piscivorous fishes were calculated using the proportions of these groups found in reported catches from pelagic waters outside Simpevarp /Swedish Board of Fisheries unpubl./. The ratio of zooplankton-feeding fish to piscivorous fish was found to be 1:0.04.

4.3.9 Birds and mammals

Birds biomass and consumption – both sites

The biomass of each bird species was calculated as body weight × the number of adults per breeding territory × the number of breeding territories in the area, as compiled by /Appendix 4 in Löfgren (ed) 2010/. This fresh-weight biomass (in kg) was multiplied by the factor 511 kJ per 100 g wet weight /Fineli 2007/, then divided by the conversion factor 45.806 kJ per gC /Humphreys 1979/ and the area of the foraging environment (in Forsmark, 20 km^2 for 0–5 m water depth and 83 km^2 for 0–20 m; in Laxemar-Simpevarp, 21 km^2 for 0–5 m water depth and 89 km^2 for 0–20 m), thus:

$$B = \frac{FW \cdot 511}{A \cdot 45.806 \cdot 10^5}$$

where *B* is Biomass in gC m^{-2}, *FW* is biomass in g fresh weight, *A* is area in $m^{2.}$

Bird consumption was estimated via field metabolic rates (*FMR*), where *FMR* is represented by the exponential relationship.

FMR (in kJd^{-1}) = body weight (in g)×a^b .

with the values for the constants a and b depending on bird metabolism category as listed in Table 4-14.

The *FMR* values (kJd^{-1}) were multiplied by the breeding period in days to yield the *FMR* in kJy^{-1}.

The total *FMR* in kJy^{-1} was divided by 45.806 kJ per gC /Humphreys 1979/, then further divided by the relevant area to obtain bird consumption in gC m^{-2} y^{-1} for each bird group and habitat (0–5 m and 5–20 m water depth, respectively).

Table 4-14. Power relation constants a and b for each bird-metabolism category /Nagy et al. 1999/.

	a	b
Carnivores and obligate herbivores	10.5	0.681
Order Charadriiformes	8.13	0.77
Order Pelicaniformes (Great cormorant only)	4.54	0.844
Remaining omnivores except eider	9.36	0.628
Eider + remaining piscivores and insectivores	14.25	0.659

Forsmark

Areal biomass and consumption was calculated using data /Green 2005, 2006a, b, Löfgren 2008/ for 44 species of birds breeding in or near the marine environment of the Forsmark area, and foraging in its shallow-water zone (0–5 m depth, with areal extent 20 km^2). Eight of these species were also spatially allocated to the 5–20 m depth zone (areal extent 63 km^2).

The resulting aquatic environment bird biomass was 0.0257 gC m^{-2} for the shallow zone ($d < 5$ m) and 0.00118 gC m^{-2} for the deeper zone (5 m $< d <$ 20 m).

The *FMR*-derived bird consumption was 4.07 gC m^{-2} y^{-1} for the shallow zone ($d < 5$ m) and 0.171 gC m^{-2} y^{-1} for the deeper zone (5 m $< d <$ 20 m).

Laxemar-Simpevarp

Areal biomass and consumption was calculated using data /Löfgren 2008/ on the 39 species of bird breeding in or near the marine environment of the Laxemar-Simpevarp area, and foraging in its shallow-water zone, 0–5 m depth, with areal extent 21 km^2. Nine of these species were spatially allocated also to the 5–20 m depth zone with areal extent 68 km^2.

The biomass was 0.0216 gC m^{-2} for the shallow zone ($d < 5$ m) and 0.000183 gC m^{-2} for the deeper zone (5 m $< d <$ 20 m).

The *FMR*-derived bird consumption was 3.11 gC m^{-2} y^{-1} for the shallow zone ($d < 5$ m) and 0.0170 gC m^{-2} y^{-1} for the deeper zone (5 m $< d <$ 20 m).

Seal biomass and consumption – both sites

Grey seal (Halichoerus grypus) is the dominant species of seal in the area. A second species, ringed seal (Phoca hispida), is present but much less abundant /Karlsson 2003/.

Based on a photo ID survey undertaken at all major seal haul-outs in the northern Baltic Proper and the Gulf of Bothnia, the number of seals along 200 km of the SW Bothnian Sea coastline was estimated at 4,940 /Hiby et al. 2007/. Furthermore, the seals are very mobile, capable of moving several 100 km or feeding for prolonged periods fairly close to the haul-out sites /Karlsson 2003/. Since the grey seal also dives to depths up to 100 m with a mean depth of 25 m /Sjöberg 1999/, its foraging biomass and consumption were allocated uniformly across a 20 km wide coastal zone along the 200 km coast, including Öregrundsgrepen, suggesting a foraging seal density of approximately 1.2 seals km^{-2}, with a mean seal body weight of 100 kg (O. Hjerne, pers. comm.), a seal caloric value of 535 kJ hg^{-1} /USDA 2006; Alaska native ringed seal/ and a conversion factor of 45.806 kJ/gC /Humphreys 1979/ this corresponds to an areal seal biomass of 0.0144 gC m^{-2}.

Studies of seal diet composition based on digestive tract content indicate that the fraction of herring, increasing with the decline of the cod population, today constitutes 73%and 48% of the weight of the seal diet in the Bothnian Sea and Baltic Proper, respectively /Lundström et al. 2007/. Based on diet, the total consumption of herring biomass in the Northern Baltic proper was 6,600 ton per 5,700 seals (O. Hjerne, pers. comm*.),* /Bergström et al. 2006/. Comprising 73% of the diet in that geographical area, this would correspond to a total fish consumption of 1.6 tons y^{-1} or 4.4 kg d^{-1}. Using a herring caloric value at 491 kJ hg^{-1} /Fineli 2007/, the corresponding carbon consumption is 170 kg C y^{-1}, or, with the above areal seal density, 0.21 gC m^{-2} y^{-1}.

An alternative estimate of consumption is offered by the compilation of field metabolic rates, *FMR*, for mammals suggesting $FMR = 4.82\ M_b^{0.734}$ /Nagy 2005/ where M_b is the body weight in g and *FMR* is expressed in kJ d^{-1}. When applied to a 100 kg seal, this relationship yields a field metabolic rate of 22,545 kJ d^{-1}, equivalent to 0.22 gC m^{-2} y^{-1} in the above area.

While in good agreement, the former of the two estimates is judged to be a less accurate estimate of the actual consumption per individual in the SW Bothnian Sea, as compared to the Baltic Proper. The figure applied, 0.22 gC m^{-2} y^{-1}, is therefore mainly an *FMR*-based estimate for the Forsmark area.

The corresponding figure chosen for the Laxemar-Simpevarp area /Hiby et al. 2007; south of geographical area A/ was 780 seals over a 100×20 km coastal stretch (seal density 0.39 km^{-2}), equivalent to an areal carbon biomass of 0.0046 gC m^{-2}. The diet-based consumption estimate is then 2.4 t y^{-1} or 6.6 kg d^{-1} with an equivalent carbon consumption of 260 kg C y^{-1} or 0.10 gC m^{-2} y^{-1} and an *FMR*-based estimate of 0.070 gC m^{-2} y^{-1}. As the Laxemar-Simpevarp area is situated to the south of area A along a gradient with declining grey seal abundance, the lower of two estimates, 0.070 gC m^{-2} y^{-1}, was applied.

4.3.10 Human fish consumption – both sites

Catch statistics reported in kg ww year^{-1} in a 1×1 minute rectangle (1.694 km^{-2} in Forsmark, 1.835 km^{-2} in Laxemar-Simpevarp) were kindly provided by Swedish Board of Fisheries (Håkan Westerberg, pers. comm.).

Of the eight fish species caught as a result of commercial and recreational fishery in the southern Bothnian Sea /Ask and Westerberg 2006/ – perch, pike, pike-perch, salmon, common whitefish, herring, eel and sea trout – the detailed statistics suggest eel and salmon are not caught in Öregrundsgrepen. Furthermore, one position in the centre (at 60°25’N: 18°20’E) shows exceptionally high values. It was assumed that this position represents the entire central Öregrundsgrepen. The position was therefore removed and its value divided between and added to the rest of the non-zero values in the area (20 other positions between 60°20’ and 60°30’N) in proportion to these values.

Using conversion factors of 490 kJ/hgww^{-1} (www.fineli.fi) and 45.8 kJ/gC /Humphreys 1979/, the total catch in gC m^{-2} y^{-1} is then distributed as in Figures 4-15 and 4-16.

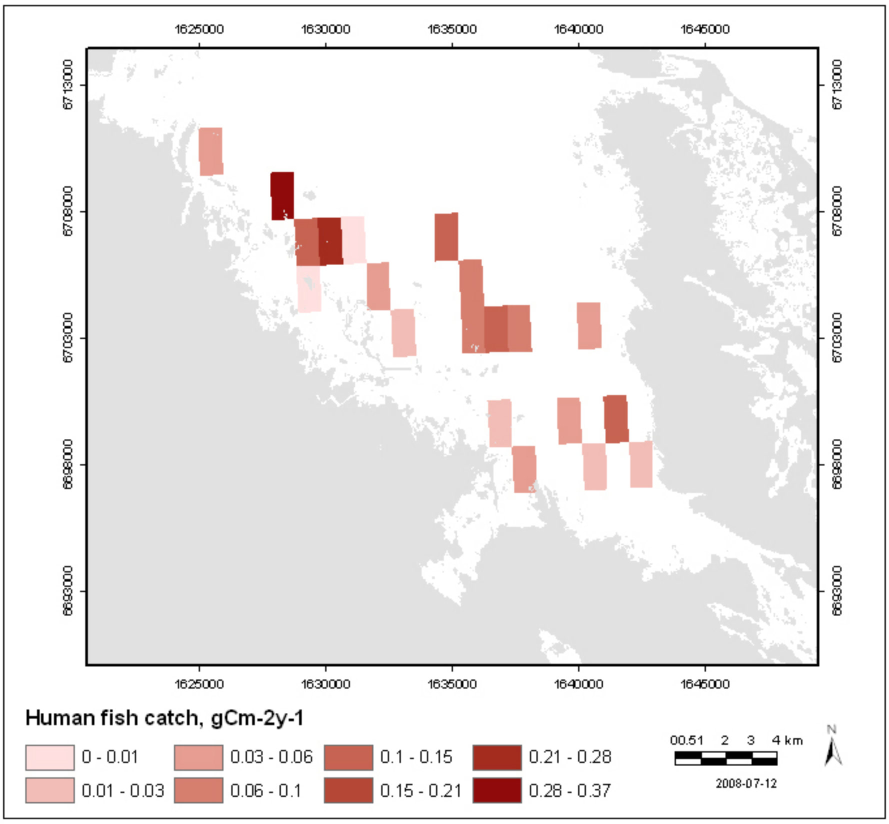


***Figure 4-15.** The distribution of fish catch by humans in the Forsmark area (in gC m^{-2} y^{-1}); sum of perch, pike, pike-perch, common whitefish, herring and sea trout as reported to the Swedish Board of Fisheries (Håkan Westerberg, pers. comm.) and slightly modified with regard to one position. Areas in white have no reported catch of the species.*

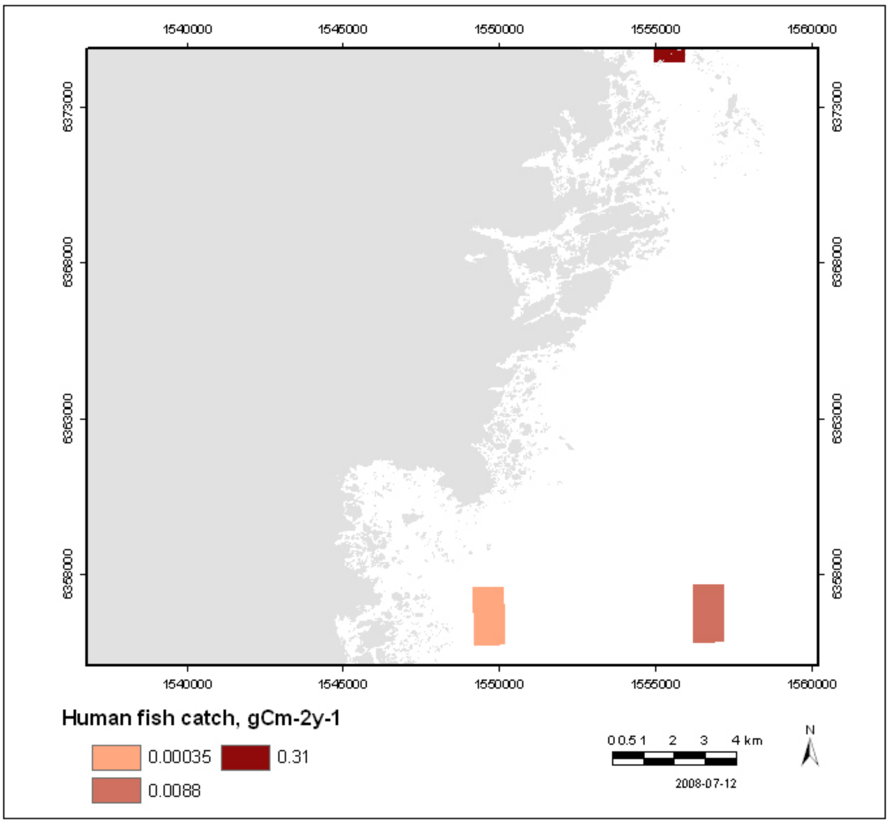


Figure 4-16. *The distribution of fish catch by humans (in gC* $m^{-2}\,y^{-1}$*); sum of perch, pike, pike-perch, common whitefish, herring and sea trout as reported to the Swedish Board of Fisheries (Håkan Westerberg, pers. comm.) in the Laxemar-Simpevarp area. Areas in white have no reported catch of the species.*

4.3.11 Respiration and consumption

Respiration was calculated from biomass and average annual temperature. Respiration of organisms that reside in the pelagic was calculated using the pelagic temperature grid, and for benthic-living organisms, the benthic temperature grid. Calculations of the temperature in the pelagic and benthos are presented in Section 4.3.

Respiration was calculated using established conversion factors (from T, degree days to respiration) on specific respiration ($gC \times gC^{-1} \times day^{-1}$) normalized for 20ºC /Kautsky 1995/ using the relationship:

$$Degreedays = \frac{T \cdot 365}{20}$$

where T was the annual mean of temperature.

Consumption was estimated from respiration using reported conversion factors from earlier modelling in the Forsmark area, and human consumption from fishery catch, see Table 4-15.

Table 4-15. Consumption/respiration ratio used to calculate consumption from respiration.

Functional group	C/R factor
Zooplankton, benthic fauna,	3 /Kumblad et al. 2003/
Bacterioplankton, benthic bacteria	2 /Kumblad et al. 2003/
Fish	1.73 /Kumblad et al. 2006/
Humans	Consumption calculated from fishery catch.

4.4 Parameterization of abiotic properties

4.4.1 Particulate and dissolved matter – Forsmark

Concentrations of particulate organic carbon (POC) were found to be higher at sheltered stations in the Forsmark area and lower in exposed areas. POC concentration was found to be related (weakly, $r^2 = 0.43$) to wave exposure index (SWM). SWM is the Simplified Wave Model exposure index according to /Isæus 2004/.

POC concentration was multiplied by the DEM (Digital Elevation Model) to obtain an area-dependent POC density grid. The site PFM000062 was excluded as it is likely not to be representative of the ambient wave exposure (as the cooling water is located nearby).

Mean concentrations of DOC (surface and bottom water) was found to be related to POC ($r^2 = 0.77$; $POC = 1.8783e^{2.2109x}$, where x = DOC). Figures on DOC concentration were multiplied by the POC grid to obtain an area-dependent density grid.

Mean concentrations of DIC (surface and bottom water) were found to be related to modelled temperature ($R^2 = 0.67$; $DIC = 5.2533x–25.924$), where x=T). DIC concentrations were multiplied by the DEM to obtain an area-dependent DIC density grid. The site PFM000062 was excluded as it is likely not to be representative of the ambient wave exposure (as the cooling water is located nearby).

4.4.2 Particulate and dissolved matter – Laxemar-Simpevarp

In Laxemar-Simpevarp there was no relationship between the wave exposure index (SWM) and the measured concentrations of POC, DOC and DIC. Mean values of the parameters at sampling sites representative of coastal marine areas were therefore used together with the SWM grid and the DEM to calculate the spatial distribution of POC, DOC and DIC. Coastal marine areas were defined by SWM-index < 20,000.

For offshore basins, mean values of POC, DOC and DIC in the most offshore sampling site were used together with the SWM grid and the DEM. Offshore areas were defined by SWM index > 20,000.

4.4.3 Irradiation – both sites

The same method was used for Forsmark and Laxemar-Simpevarp.

To calculate the percentage of global irradiation (T) reaching the bottom, a script in ArcView was used, where the depth is Z and the light penetration depth is s. N and M are constants corresponding to $I_{surface}$ and κ mentioned in the text and Z is the depth:

$$T = N \times e^{(M \times Z/s)}$$

In addition to a digital elevation model, the script requires a grid of the penetration depth and the light attenuation coefficients as input values. The derivation of these grids and coefficients is detailed below.

Global irradiation was assumed to consist of 45% photosynthetic active irradiation (PAR), and therefore this figure was used to convert figures of global irradiation to PAR. PAR was needed for correlations to primary production.

Light penetration depth (s) – both sites

Measurements of the penetration depth in the marine environment were available from seven sampling sites in the Forsmark area (PFM000062–65, 82–84) and from five sites in the Laxemar-Simpevarp area (PSM002060–64) for the years 2002 to 2006. These measurements were used to calculate penetration depth grids for Forsmark and Laxemar-Simpevarp.

As a first step these data were compiled into monthly mean values. Some of the stations were monitored more frequently than others, so the monthly averages are based on a varying number of observations.

For the Forsmark sites there is a concentration of curves around two levels of penetration depth: 3–4 m and about 1.5 m. The curves with values around 4 m all represent stations located in the more open waters in the north (stations 62, 63 and 82) while the curves around 1.5 m penetration depth represent stations located further to the south in the more closed bay of Kallrigafjärden (stations 64, 65, and 84).

In the Laxemar-Simpevarp case we see the corresponding distinction between open-water stations and closed-bay stations, but with a more gradual increase towards greater penetration depths. By far the greatest penetration depths are found at station PSM002060.

The monthly values for each station were subsequently averaged to obtain yearly mean values as given in Tables 4-16 and 4-17. Note that Forsmark stations 82–84 were omitted at this stage due to their poor data coverage in time.

The yearly mean point values were converted into a grid by creating a regression between the point values and a parameter for which a grid was available.

Two parameters which could logically affect the penetration depth were tested: station depth (digital elevation model, DEM) and wave exposure. All stations for which penetration depth data were available (both in Forsmark and Laxemar-Simpevarp) were included. The penetration depth was more strongly correlated with wave exposure than with depth, $R^2 = 0.825$ (SWM-index) in comparison with $R^2 = 0.5608$ (DEM), so the equation of this regression line was used to create the light penetration depth (L_p) grids for Forsmark and Laxemar-Simpevarp based on the wave exposure grid for each site, according to

$$L_p = 1.975\ \mathrm{LN}(SWM) - 13.686$$

Table 4-16. Forsmark light penetration depth (m). Yearly mean values for 2002–2006 and standard deviation.

Station	Pen. Depth (m)	Std. Dev. (m)
PFM000062	3.73	0.3
PFM000063	3.53	0.8
PFM000064	1.49	0.2
PFM000065	1.13	0.2

Table 4-17. Laxemar-Simpevarp light penetration depth (m). Yearly mean values for 2002–2006 and standard deviation.

Station	Pen. Depth (m)	Std. Dev. (m)
PSM002060	12.49	2.7
PSM002061	7.72	0.9
PSM002062	2.20	0.4
PSM002063	5.03	0.6
PSM002064	3.58	0.6

Light attenuation coefficients – both sites

A mean value of the light attenuation coefficient was calculated based on Photosynthetic Active Radiation (PAR) data, measured at the Forsmark sea stations PFM000062–65 during 2003 and 2004.

The PAR data were first normalized to the surface (maximum) value of each measured profile and then expressed as a function of depth by exponential trend curves according to the function

$I = I_{surface} \cdot e^{-\kappa D}$,

where I is the normalized PAR at a given depth D (m), $I_{surface}$ is the PAR at the surface (normalized), and κ is the attenuation coefficient (m^{-1}). The PAR profiles and trend curves for each sample site are shown in Figure 4-17. The coefficients associated with each trend curve are summarized in Table 4-18.

The similar values of $I_{surface}$ at all stations indicate similar atmospheric conditions and reflectivity of the water during the PAR measurements. However, the fairly broad variation in κ reflects the different types of environment at the different stations.

In the ArcView script, $I_{surface}$ is the same as the constant N, and κ is equivalent to –M/s so that the constant M in the script is the same as $-\kappa \cdot s$.

The ArcView script asks for two values of N and M. However, our knowledge concerning the difference between the two values for each constant in these specific areas is limited, so for the subsequent modelling the overall mean values had to be used: $N(I_{surface}) = 0.77$ and $M(-\kappa \cdot s) = -1.88$.

Incoming light to bottom

The penetration depth grid and the light attenuation coefficient were then used with the ArcView script to calculate grids of percent of global irradiation reaching the bottom.

The number of days with more than 5 MJ m^{-2} reaching the bottom was derived by combining the global irradiation as measured at station PFM010700 in Forsmark with the respective grids of percent of global irradiation that reach the bottom, presented in the section above.

The half-hourly observations of incoming global irradiation were first integrated to daily values for the period between 1 July 2003 and 30 June 2006 in Forsmark, and between 1 January 2004 and 31 December 2006 at Laxemar-Simpevarp. All three years were then merged into one average curve, as shown in Figure 4-18.

By multiplying these average curves by a factor between 0 and 1 (i.e. 0–100%), number of days was plotted against incoming light to the bottom for which the incoming irradiation was greater than 5 MJ m^{-2}. A simple linear curve was fitted and used to extrapolate a light day grid. The results presenting days per year with incoming irradiation greater than 5 MJ are shown in Figures 4-19 and 4-20.

Table 4-18. The normalized surface PAR value $I_{surface}$ and light attenuation coefficient κ (m^{-1}) for the Forsmark stations PFM000062–65.

Station	$I_{surface}$	κ (m^{-1})
PFM000062	0.797	0.565
PFM000063	0.805	0.683
PFM000064	0.765	1.043
PFM000065	0.701	1.316
Mean value	**0.77**	**0.90**

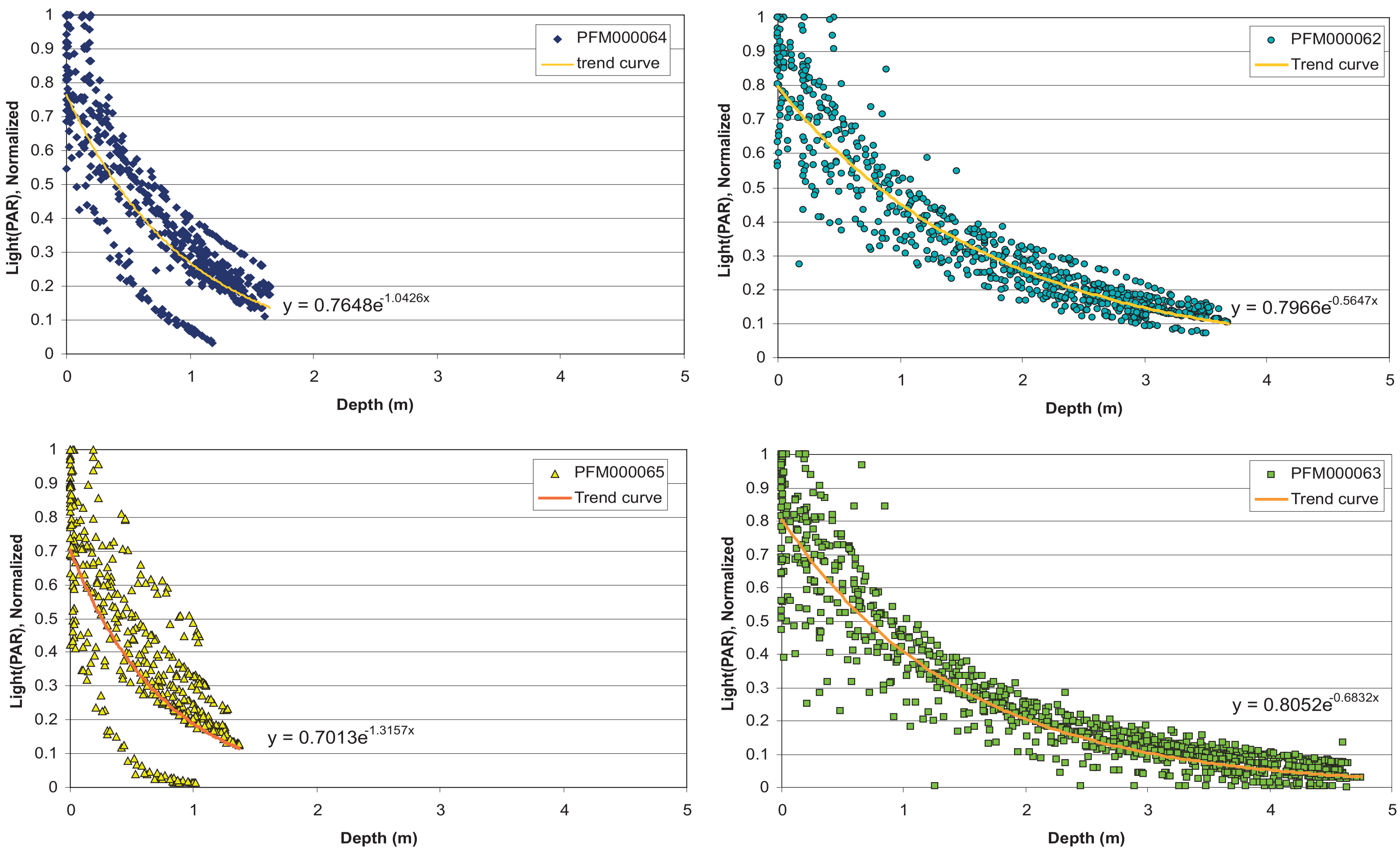


Figure 4-17. *Forsmark incoming radiation (PAR). Exponential trend curves superimposed on observations made during 2003–2004.*

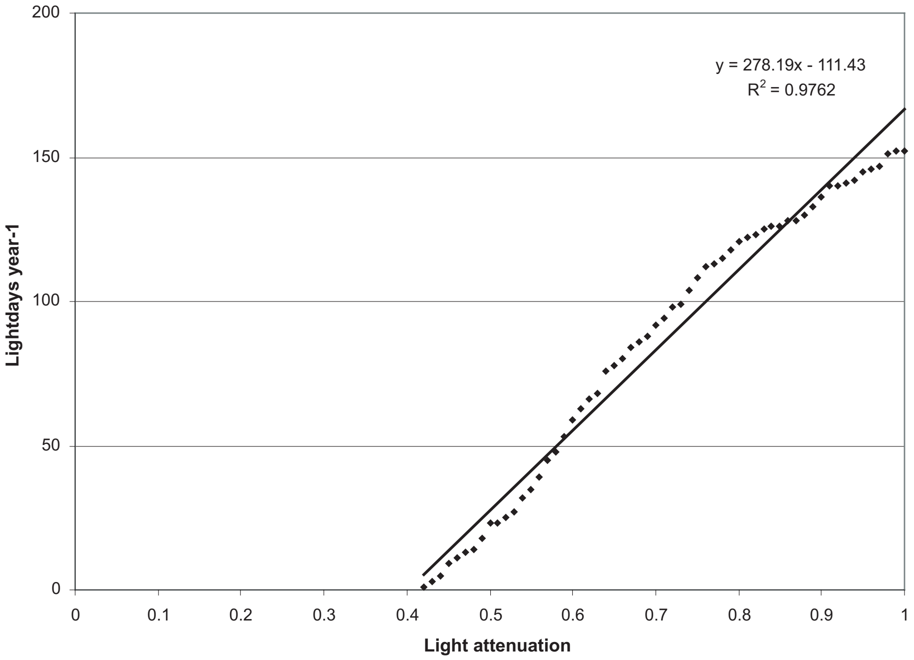


Figure 4-18. *Light days per year in areas with light attenuation between 0 to 1.*

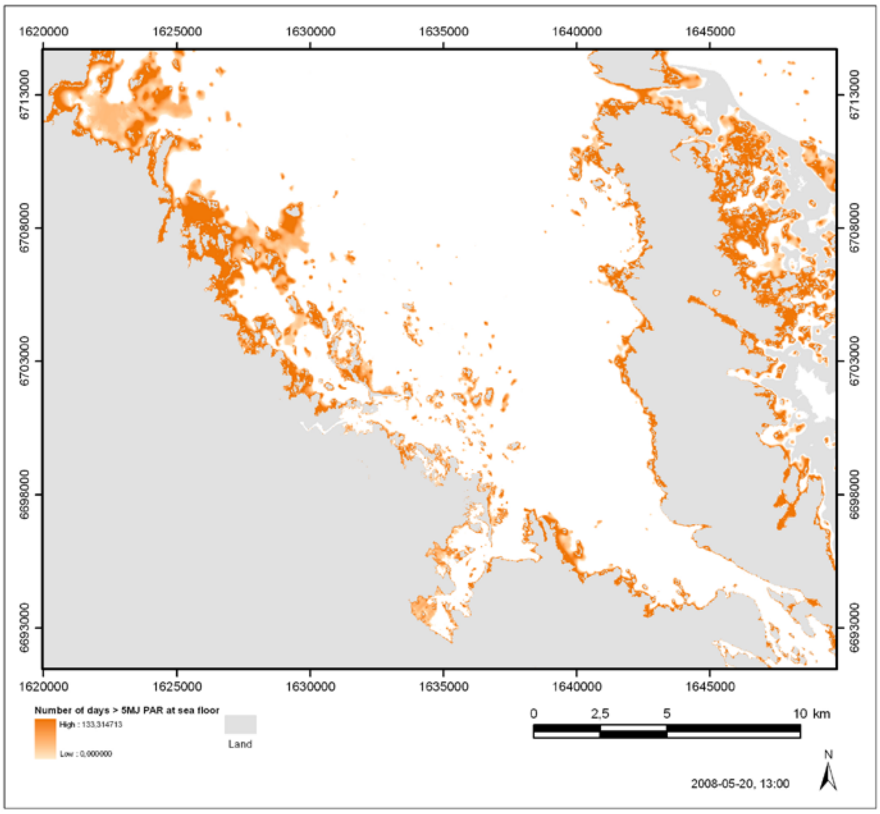


Figure 4-19. *Number of days per year on which irradiation exceeds 5 MJ (PAR) at the bottom in the Forsmark area.*

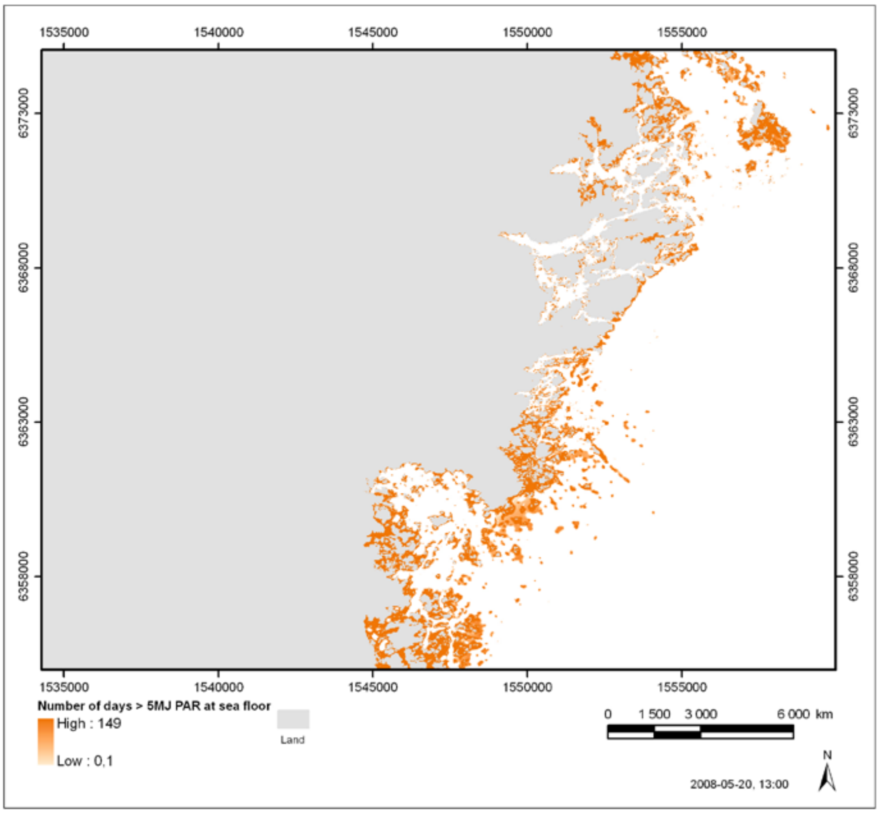


***Figure 4-20.** Number of days per year on which irradiation exceeds 5 MJ (PAR) at the bottom in the Laxemar-Simpevarp area.*

4.4.4 Temperature – both sites

Water temperature at both sites was generated in the modelling of advective flows in the 3D oceanographic modelling, see Section 5 in this report. The mean temperature used here was generated by average temperatures saved every second week (n=25) in the modelling year. Mean pelagic temperature was calculated from data from all 3D grid cells and benthic temperature only from data from cells in contact with the sea floor.

Average annual temperature varied between 5.0 and 7.7°C in different areas in both bottom water and the pelagic water in the Forsmark area (Figure 4-21).

Average annual temperature varied between 6.1 and 8.8°C in different areas in bottom water and between 6.5 and 9.0°C in the pelagic water in the Laxemar-Simpevarp area (Figure 4-22).

4.4.5 Atmospheric deposition – both sites

Data for mean elemental concentration in precipitation /Tröjbom and Söderbäck 2006a, b, Karlsson et al. 2003, Pihl Karlsson et al. 2008, Tyler and Olssson 2006/ along with data on precipitation amounts at the sites /Wern and Jones 2007, Werner et al. 2008/ were used to calculated the annual mean deposition of C, N, P and some other elements (see Table 4-19) in Forsmark and Laxemar-Simpevarp. Nitrogen in precipitation has not been measured in the site investigations performed by SKB, so data from the national monitoring performed by IVL /Pihl Karlsson et al. 2003, 2008/ were used (Table 4-19).

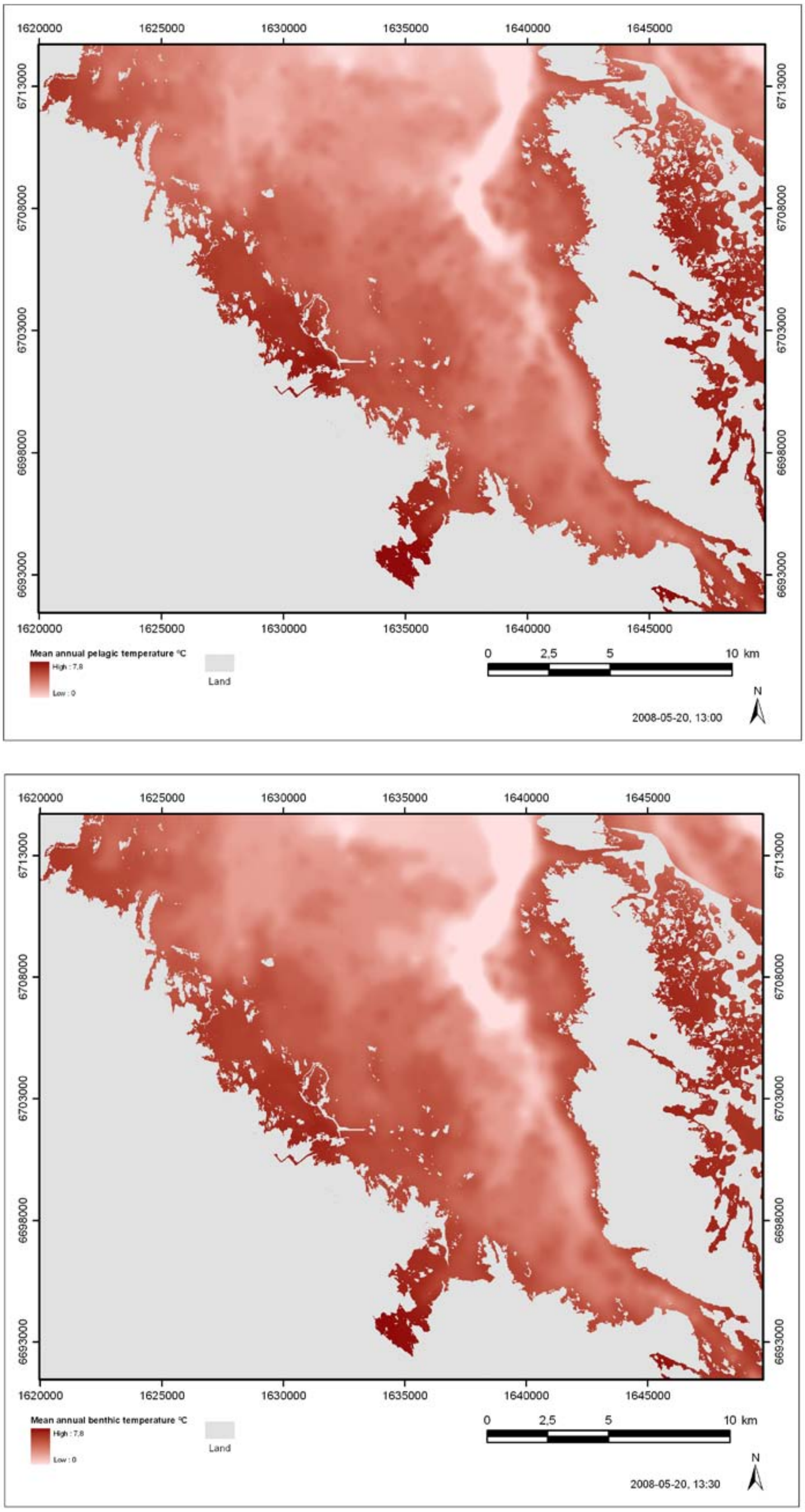


Figure 4-21. *Average annual pelagic (above) and benthic (below) temperature in Forsmark used for predictions of respiration.*

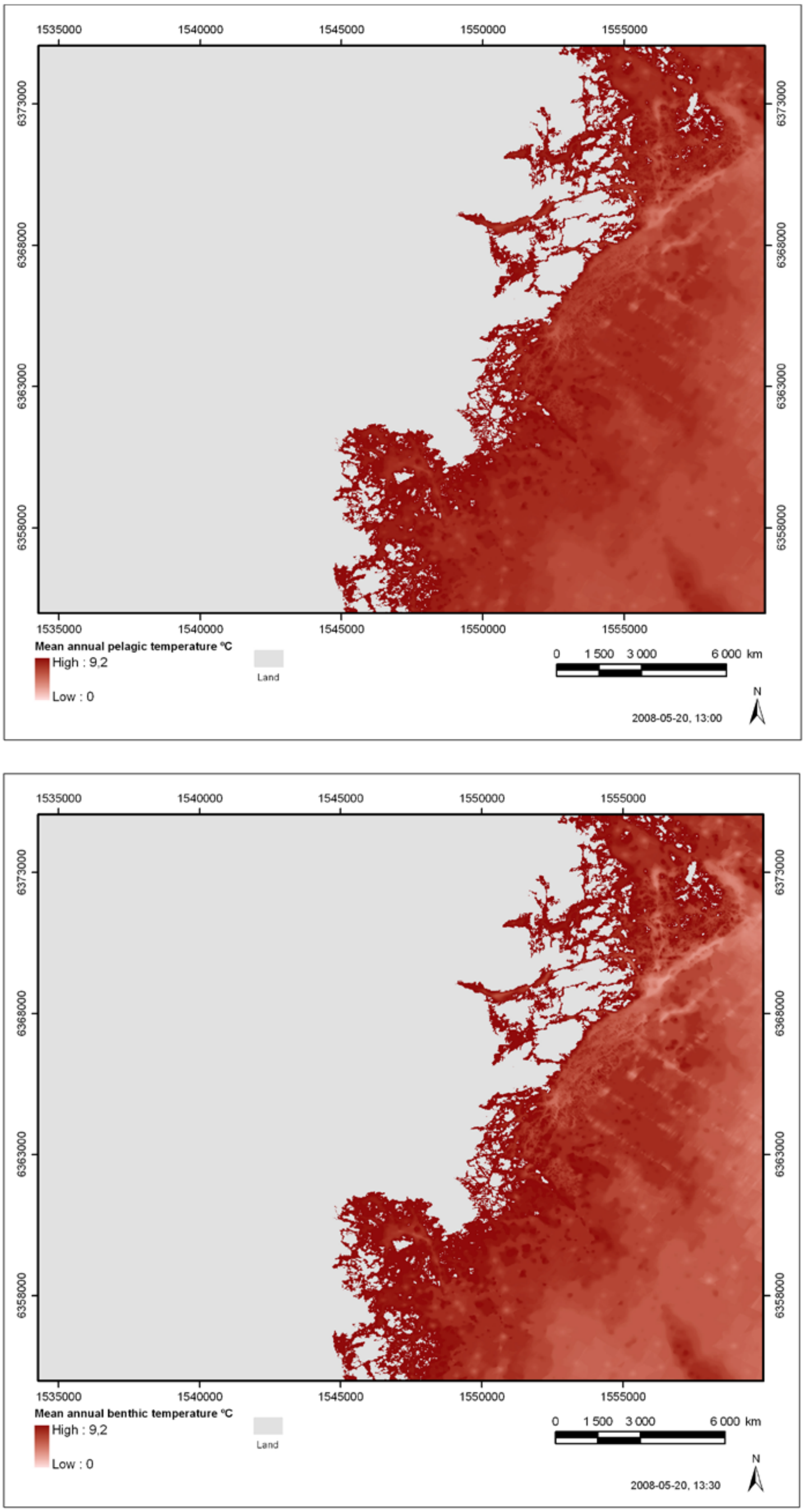


Figure 4-22. *Average annual pelagic (left) and benthic (right) temperature in Laxemar-Simpevarp used for predictions of respiration.*

Table 4-19. Calculated atmospheric deposition (g m^{-2}) via precipitation in Forsmark and Laxemar-Simpevarp.

Forsmark (g m^{-2})		Reference
1.3	Carbon (C)	/Tröjbom and Söderbäck 2006a/
0.36	Nitrogen (N)	/Pihl Karlsson et al. 2003/ (IVL)
0.012	Phosphorus (P)	/Tröjbom and Söderbäck 2006a/
2	Uranium (U) **(**ug m–^{2}**)**	/Tyler and Olsson 2006/
5	Thorium (Th) **(**ug m–^{2}**)**	/Tyler and Olsson 2006/
0.00028	Iodine (I)	Sicada, October 2007, site investigation
0.00002	Aluminium (al)	/Tröjbom and Söderbäck 2006a/
0.0014	Bromide (Br)	Sicada, October 2007, site investigation
0.17	Calcium (Ca)	/Tröjbom and Söderbäck 2006a/
0.51	Chloride (Cl)	/Tröjbom and Söderbäck 2006a/
0.018	Iron (Fe)	/Tröjbom and Söderbäck 2006a/
0.046	Magnesium (Mg)	/Tröjbom and Söderbäck 2006a/
0.098	Potassium (K)	/Tröjbom and Söderbäck 2006a/
0.0084	Silicon (Si)	/Tröjbom and Söderbäck 2006a/
0.30	Sodium (Na)	/Tröjbom and Söderbäck 2006a/
0.28	Sulfur (S)	/Tröjbom and Söderbäck 2006a/
0.013	Manganese (Mn)	/Tröjbom and Söderbäck 2006a/
0.0047	Strontium (Sr)	/Tröjbom and Söderbäck 2006a/
Laxemar-Simpevarp (g m^{-2})		
1.9	Carbon (C)	/Pihl Karlsson et al. 2008/ (Rockneby Kalmar län medel 2000–2007) (IVL)
0.64	Nitrogen (N)	/Pihl Karlsson et al. 2008/ (Rockneby Kalmar län medel 2000–2007) (IVL)
0.027	Phosphorus (P)	/Knape 2001/
2	Uranium (U) **(**ug m–^{2}**)**	/Tyler and Olsson 2006/
5	Thorium (Th) **(**ug m–^{2}**)**	/Tyler and Olsson 2006/
0.0003	Iodine (I)	Site investigation Forsmark
0.00002	Aluminium (al)	Site investigation Forsmark
0.08	Bromide (Br)	Sicada, October 2007, site investigation
0.42	Calcium (Ca)	Sicada, October 2007, site investigation
0.74	Chloride (Cl)	Sicada, October 2007, site investigation
0.038	Iron (Fe)	Sicada, October 2007, site investigation
0.13	Magnesium (Mg)	Sicada, October 2007, site investigation
0.36	Potassium (K)	Sicada, October 2007, site investigation
0.033	Silicon (Si)	Sicada, October 2007, site investigation
1.03	Sodium (Na)	Sicada, October 2007, site investigation
0.34	Sulfur (S)	Sicada, October 2007, site investigation
0.014	Manganese (Mn)	Sicada, October 2007, site investigation
0.0051	Strontium (Sr)	Sicada, October 2007, site investigation

4.4.6 Runoff – both sites

Water runoff from land and concentrations of carbon and other elements in runoff have been measured in several sampling stations in running waters representing a number of catchment areas in the Forsmark area during the period 2002 to 2007, see /Nilsson et al. 2003, Nilsson and Borgiel 2004, 2005, 2007/ and in the Laxemar-Simpevarp area /Ericsson and Engdahl 2004a, b, 2007, 2008/. Data from these years were compiled and analyzed by /Tröjbom et al. 2007/, who calculated specific runoff of water and Ca, Cl, HCO_3, K, Mg, Na, N, P, Si, SO_4, Sr and TOC (total organic carbon). Runoff was presented individually for sub-catchments where sampling stations were present and average runoff for the entire drainage area.

In the present report, specific runoff is used where possible and average runoff for catchment areas without sampling stations. To illustrate the various size of runoff in the different basins and for the different elements, runoff per basin is illustrated in, Figures 4-23 and 4-24. Catchment areas for all basins are presented in Table 4-1, and runoff in figures for the specific basins and elements is presented in Table 4-20.

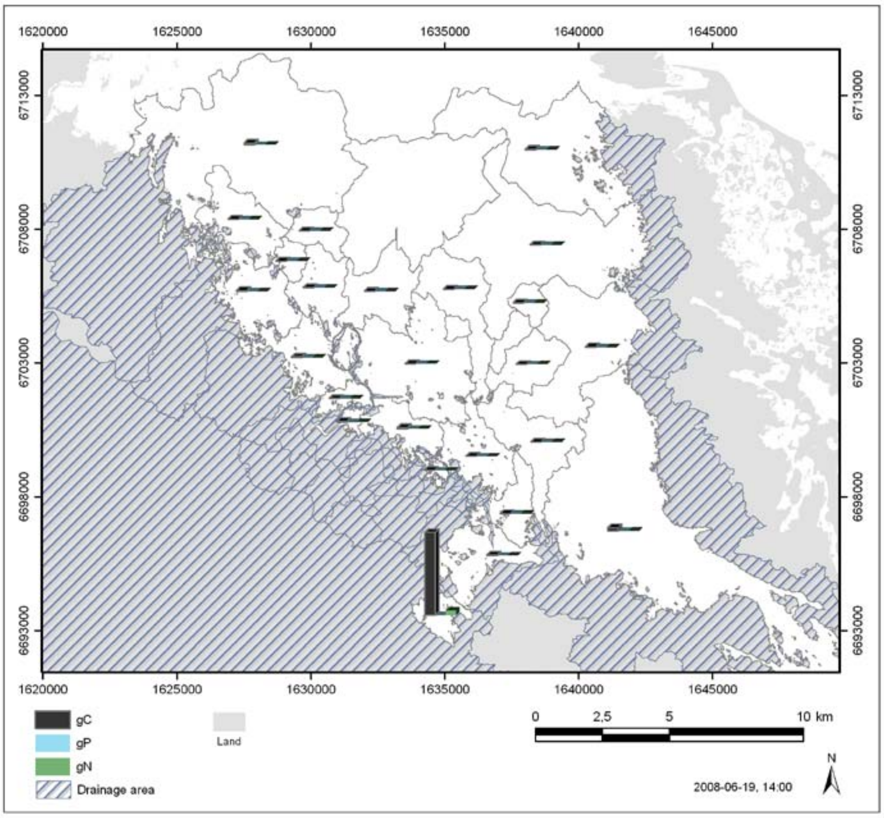


Figure 4-23. *The marine basins, associated catchment areas and runoff (measured as tonnes of C, N and P year^{-1}) in Forsmark.*

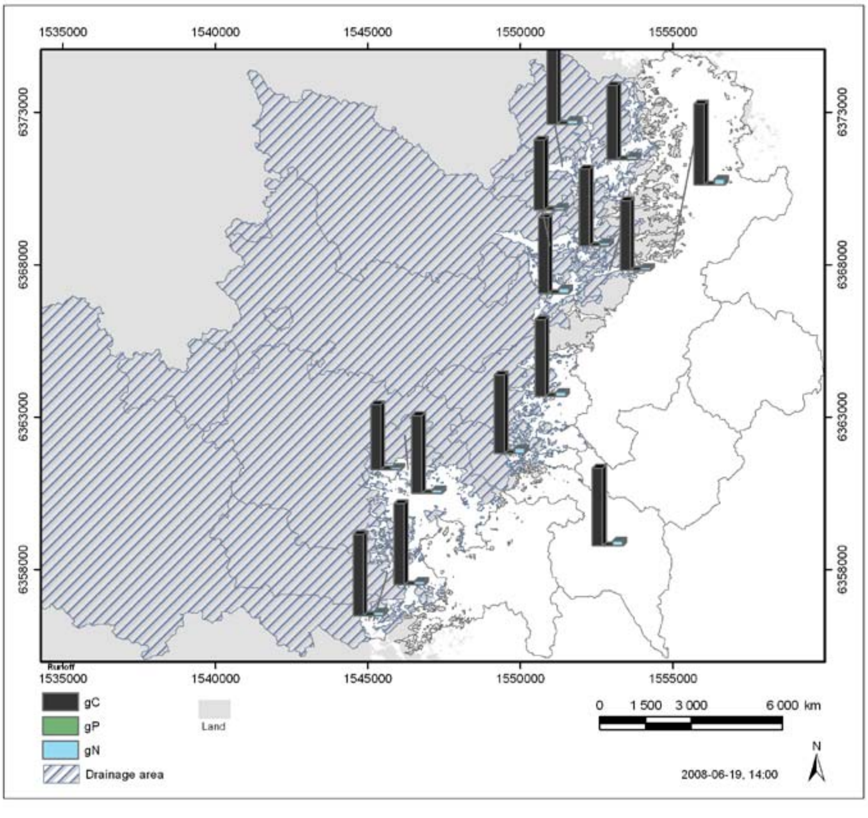


Figure 4-24. *The marine basins, associated catchment areas and runoff (measured as tonnes of C, N and P year^{-1}) in Laxemar-Simpevarp.*

Table 4-20. Average yearly runoff to the marine basins in Forsmark and Laxemar-Simpevarp for C, N and P.

Forsmark	Carbon (C) tonnes year^{-1}	Nitrogen (N)	Phosphorus (P) kg year^{-1}
Basin 102	82	10	101
Basin 100	12	3.4	14
Basin 101			
Basin 105	13	4.2	16
Basin 103	1.7	0.9	2.0
Basin 104	0.1	0.4	0.2
Basin 108	1.1	1.1	1.3
Basin 106	0.1	0.2	0.1
Basin 111	32	2.8	39
Basin 107	0.6	0.7	0.7
Basin 110	0.3	1.1	0.3
Basin 114	13	2.9	16
Basin 109			
Basin 116	1.3	2.1	0.6
Basin 113			
Basin 117	27.5	2	34
Basin 112			
Basin 115	0.01	0.6	0.02
Basin 151	131	14	161
Basin 118	1.5	0.3	1.8
Basin 123	1.2	1.2	1.4
Basin 152	3,384	192	4,149
Basin 150	30	2.3	56
Basin 146	1.0	0.6	0.3
Basin 126	4.4	1.1	3.9
Basin 134	6.1	0.3	5.1
Basin 121	55	2.1	41
Basin 120	33	1.6	23
Laxemar-Simpevarp			
Basin 524	0.6	0.02	0.5
Basin 525			
Basin 522			
Basin 523			
Basin 521	5.5	0.24	5.6
Basin 501	0.1	0.003	0.09
Basin 500	0.1	0.003	0.09
Basin 504	8.2	0.37	9
Basin 502	162	10	295
Basin 506	4.4	0.21	6
Basin 508	213	14	391
Basin 513	34	2.1	57
Basin 514			
Basin 516	12.8	0.72	20
Basin 518			
Basin 515	53	3.5	99
Basin 517	104	7.6	220
Basin 520	0.1	0.003	0.09
Basin 519	0.6	0.04	1.0

4.4.7 Groundwater fluxes – both sites

Average annual vertical flows (recharge and discharge) at the sea floor surface were computed using CONNECTFLOW software and are presented for some basins in Forsmark in Figure 4-25. Modelling techniques were presented in /Follin et al. 2007/. Groundwater inflow was assumed to equal vertical flow. As the model only covers a few basins, groundwater flow was only presented where more than 50% of the basins areas were modelled. The results indicate a net discharge in most basins.

For Laxemar-Simpevarp the modelling results were not ready in time for the printing of this report.

4.4.8 Advective flux – both sites

Flux of water was one of the outputs computed in the oceanographic model (see Section 5 in this report). Fluxes were presented both as gross fluxes to and from all basins and as net fluxes. To calculate potential transport of carbon and other elements we used concentrations in the basin multiplied by gross outflux and concentrations in the adjacent basins multiplied by gross influx.

These calculations were possible for dissolved and particulate carbon for all basins where concentrations were estimated in a grid. For all other elements, annual mean concentrations from the individual water sampling sites (see Section 3.1) were used to represent the respective basins (Table 4-2). Due to a lack of data, most basins were not represented by a sampling site, and an average rate for all sites was used.

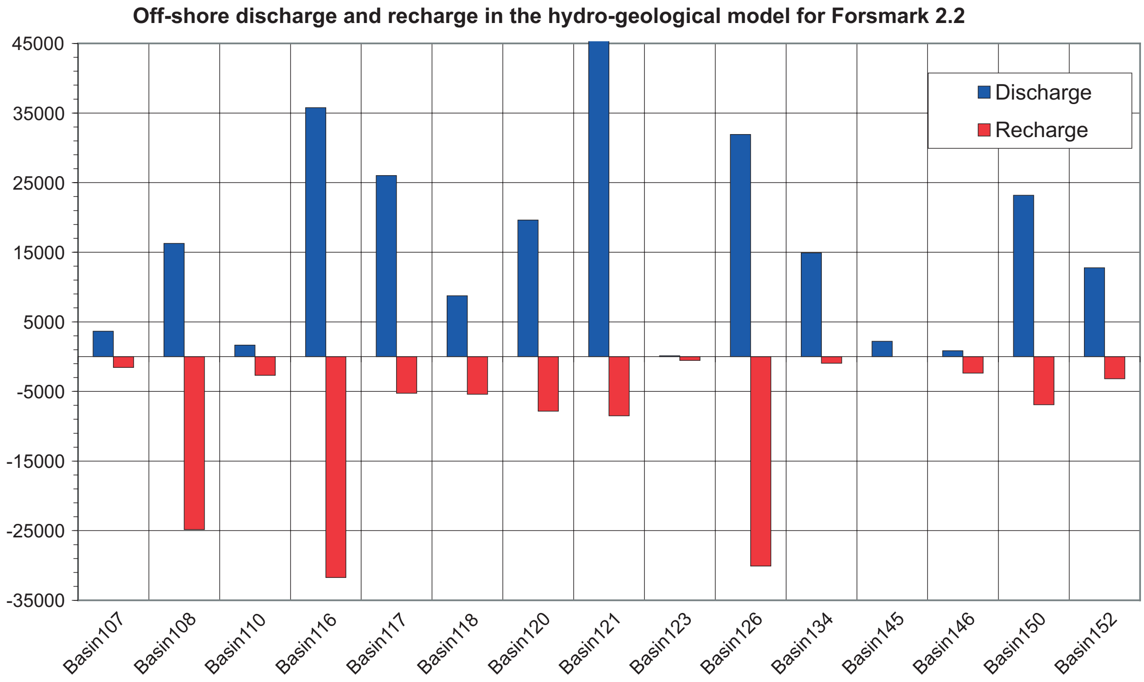


Figure 4-25. *Groundwater flow in marine basins in Forsmark computed using CONNECTFLOW software. From /Follin et al. 2007/.*

4.4.9 Regolith

Organic carbon concentration in sediment – both sites

The following analysis of sediment organic carbon concentrations (0–10 cm) is based on cores taken in the Forsmark area, and core-based maps for this area. In the Laxemar-Simpevarp area, only parameters for the top 0–10 cm of sediment were used.

Bulk sediment organic carbon densities were calculated from measured TOC concentrations and wet sediment bulk density (in ww gm^{-3}). The latter was calculated using /Håkanson and Jansson 1983/:

$$\rho_{bulk} = \frac{100\rho_s}{100 + (W + IG\,(1 - (\frac{W}{100}))(\rho_s - \rho_w)}$$

where W is water content (%), IG is loss-on-ignition (% dry weight), and ρ_s and ρ_w are the densities of minerogenic solids in the sediment (2.6 g cm^{-3}) /Håkanson and Jansson 1983/ and of the pore water (in Forsmark, 1.005 g cm^{-3}), respectively. Where IG measurements were lacking, loss-on-ignition was assumed to be 2×TOC, i.e. twice the content of total organic carbon in % dry weight /Jonsson 1992/.

The bulk sediment organic carbon density ρ_C (gC m^{-3}) was then derived from:

$$\rho_C = \rho_{bulk}\frac{100 - W}{100}TOC$$

Data on sediment water and organic carbon content are available from the geological and lagoonal surveys (map in Figure 3-24, Chapter 3.3.2), including from /Wallström and Persson 1997/, and partly from deeper cores from lakes in the area /Hedenström 2003, Hedenström and Risberg 2004/. They are summarized in Figure 4-26.

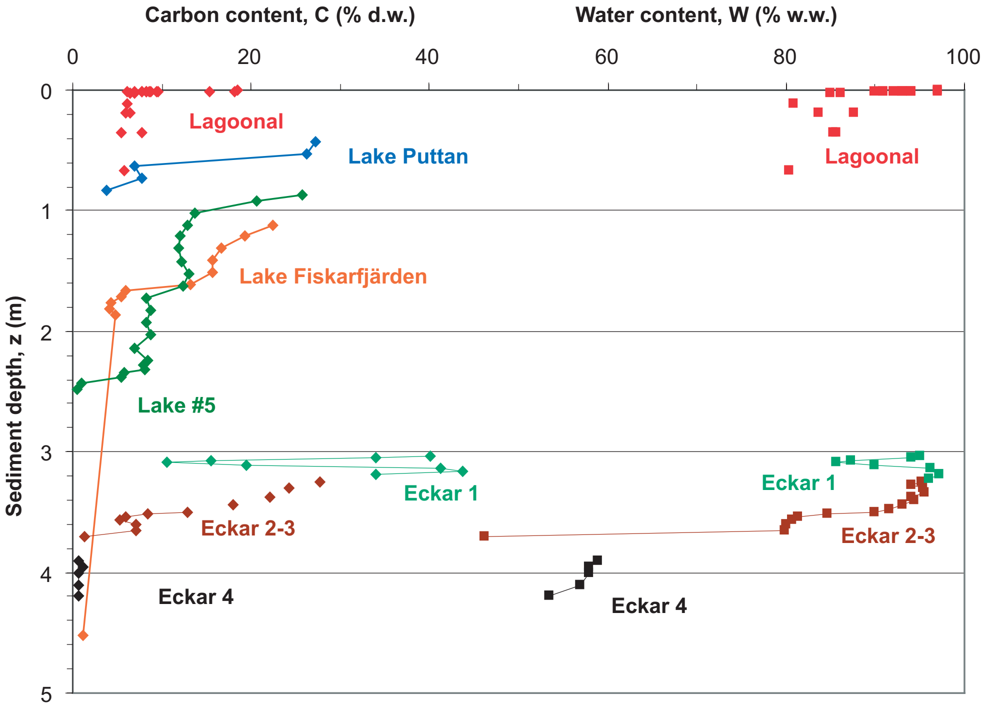


Figure 4-26. *Total organic carbon and water content as a function of sediment core depth, from lagoonal sampling /Wallström and Persson 1997, Sternbeck et al. 2006/, from the recently isolated gloe lakes Lake Puttan, Lake Fiskarfjärden and Lake #5 /Hedenström 2004/, and from Lake Eckarsfjärden, stages Eckar 1–4 /Hedenström and Risberg 2003/.*

The lake cores illustrate the sequence from glacial and postglacial marine over lagoonal to lacustrine environments, which are fully represented from Lake Fiskarfjärden, Lake #5 and Lake Eckarfjärden (the latter divided into stages Eckar 1–4; for location of lakes see Section 3.3.2, Figure 3-16). The total organic carbon content of postglacial marine deposits generally stays within a limited range of around 4–10% dw (lower part of Eckar 2 and upper part of Eckar 3). The much higher C concentrations are lacustrine and peat deposits (Eckar 1), while lower concentrations are from glacial or early postglacial deposition (e.g. Eckar 4).

For lagoonal data from the upper 68 cm (Figure 4-27) of core and grab samples /Wallström and Persson 1997, Sternbeck et al. 2006/ the following depth integral can be derived:

$$\rho_C = 13{,}896\, z^{\,0.1714} \qquad \text{for } z < 0.68$$

and $$\rho_C = 13{,}000 \qquad \text{for } z > 0.68$$

where z is sediment depth in m, Thus, ρ_C is set constant with depth for marine postglacial deposits in cores, based on the deeper marine lake-deposit data /Hedenström and Risberg 2003, Hedenström 2004/, except in the uppermost unconsolidated part. By means integration, these relationships permit carbon content in core samples to be estimated as a function of stratigraphy, their primitive functions being:

$$\int \rho_C dz = \frac{z^{1.1714}}{1.1714}$$

for $z < 0.68$

and

$$\int \rho_C dz = 13000z$$

for $z > 0.68$

and the ρ_C integral from z to 0 in cores:

$$\int_0^z \rho_C dz = \frac{13896 \cdot z^{1.1714}}{1.1714}$$

when $z < 0.68$

and

$$\int_0^z \rho_C dz = 7551 + 13000\,(z - 0.68)$$

when $z > 0.68$

which was used to calculate the depth-integrated organic carbon content for available core stratigraphies (Figures 4-28 and 4-29). Glacial and early postglacial accumulations were then not depth-integrated, but set to 0 and 4,000 gC m^{-3}, respectively.

An additional set of W (watercontent) and IG (loss on ignition) data from Kattegat /Floderus and Håkanson 1985/ was used for estimating surficial ρ_C over wider areas, offering a rare wider range of characteristic carbon densities from coarser bottoms of erosion and transport. Figure 4-30 shows how such surficial sediments form a U-shaped ρ_C/W relationship from low to high water content, while the consolidated lake core deposits (Eckar 1–4, shown in green, brown and black) deviate from this pattern with the exception of the marine facies Eckar 2–3 (brown). Thus, once again, unlike the deep lacustrine (green) and early postglacial deposits (black), buried marine deposits show a similarity with recent marine ones.

As indicated in Figure 4-30, the bulk organic carbon content in surficial sediments may be reasonably well approximated ($R^2 = 0.54$) from water content using the polynomial:

$$\rho_{Csurf.} = 729\, W - 5.64\, W^2 - 12{,}676$$

used as in Table 4-21 for classifying organic carbon densities for the top 10 cm of surficial sediment.

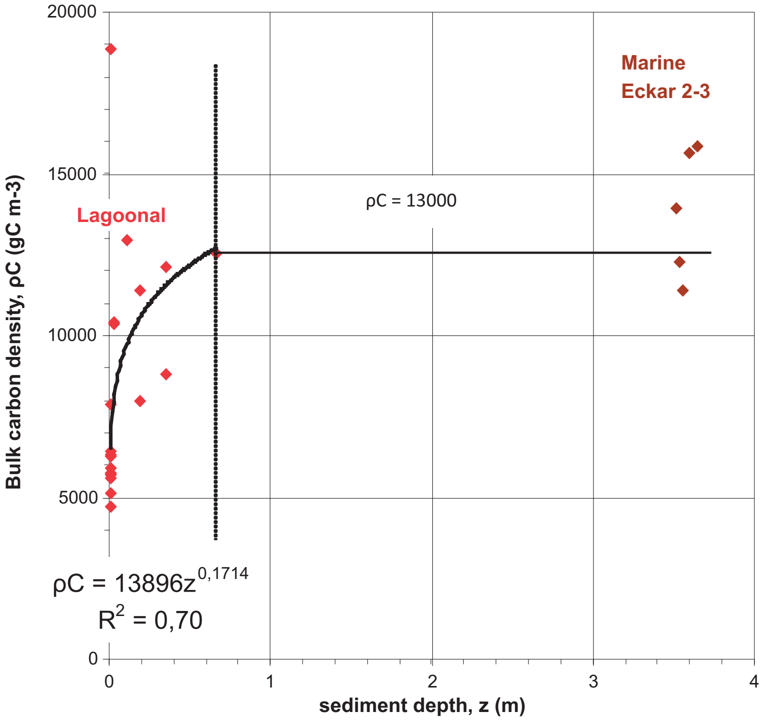


Figure 4-27. The relationships used for depth integration of carbon content.

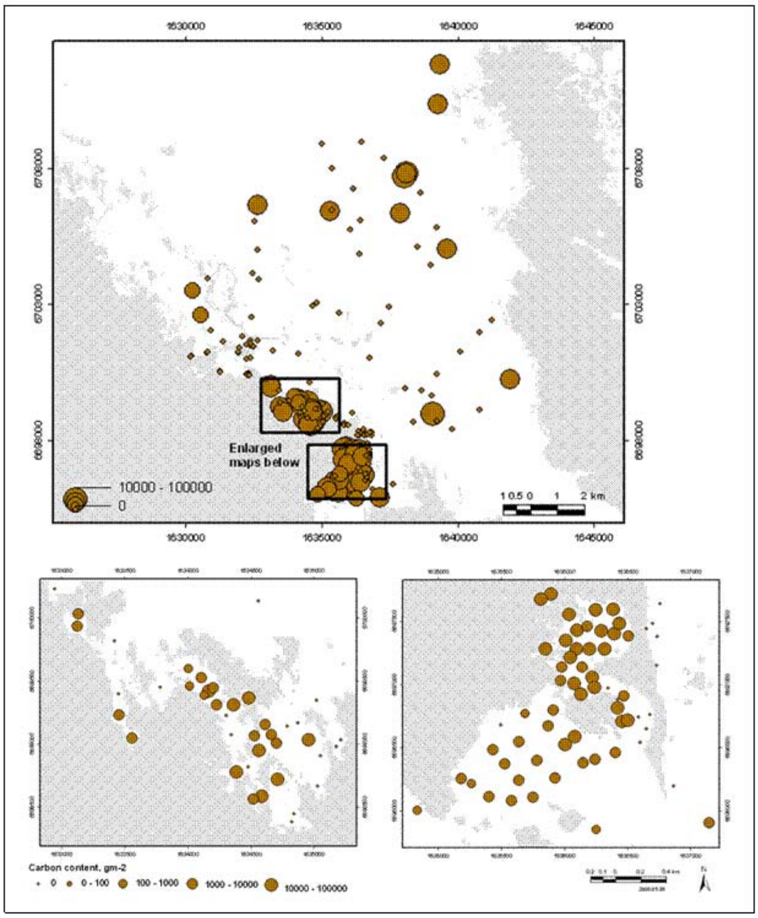


Figure 4-28. *The total carbon content (gC m^{-2}) of subrecent parts of cored samples in Forsmark. The maximum sediment depth of such a deposit is 4.32 m, while the mean is 0.74 m and the median 0.53 m.*

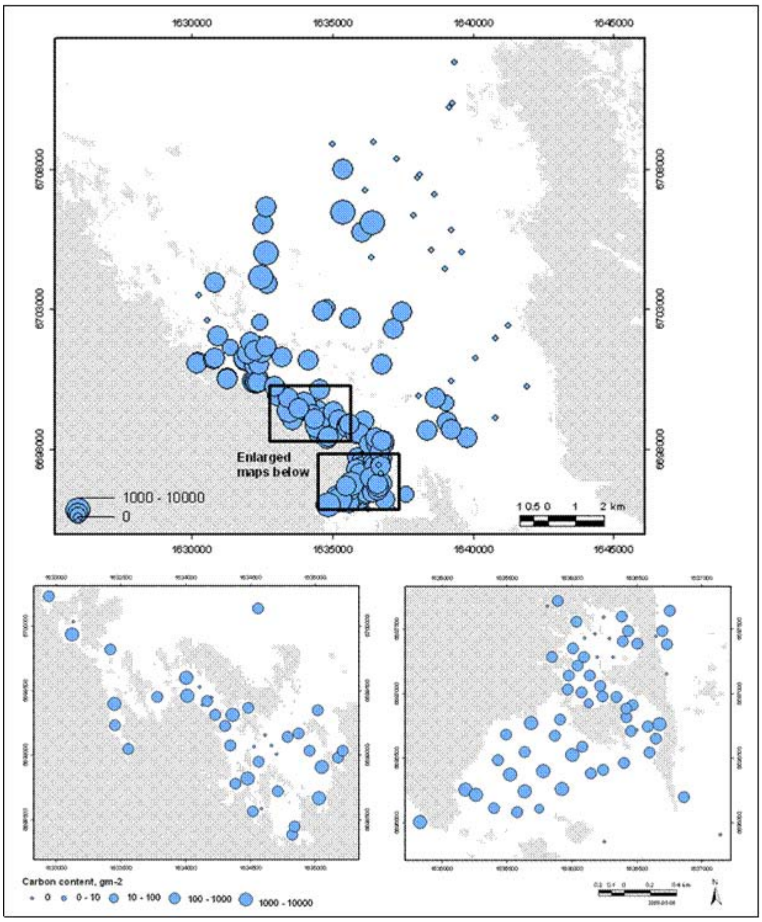


Figure 4-29. *The total organic carbon content (gC m*$^{-2}$*) of deeper glacial and early postglacial parts of cored samples, not including subrecent carbon in Forsmark.*

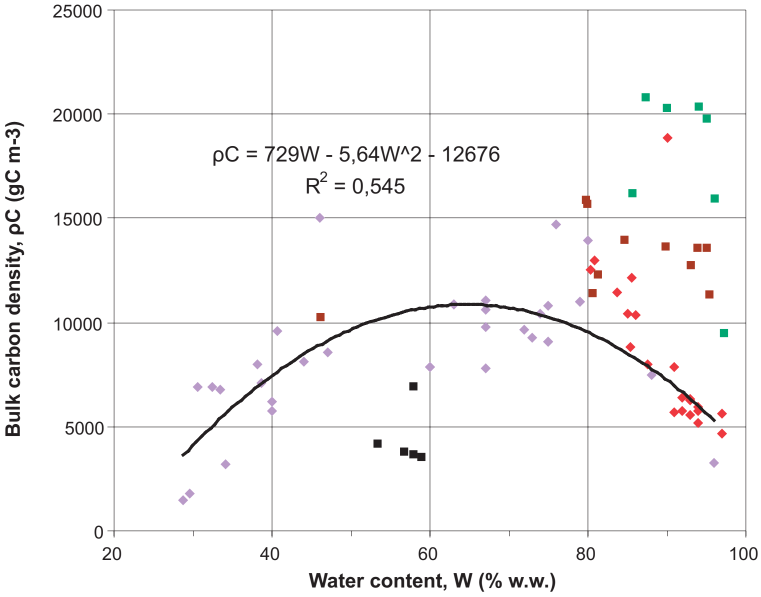


Figure 4-30. *Bulk organic carbon density as a function of water content in surficial sediments from bottoms of erosion and transport (purple) /Floderus and Håkanson 1985/. Also shown are data from surficial and near-surficial lagoonal sediments in the Forsmark area (red) /Wallström and Persson 1997, Sternbeck et al. 2006/ and from Lake Eckarfjärden /Hedenström and Risberg 2003/, stages Eckar 1 (green), 2–3 (brown) and 4 (black). The polynomial is a best-fit curve derived from the (purple) erosion- and transport-bottom samples only.*

As can be expected, the value for clay-gyttja is near the ρ_C depth-integral as derived above from lagoonal samples (Figure 4-27) from $z = 0.1$ m to 0, which is 800 gC m^{-2}.

The resulting maps of carbon concentrations in the top 10 cm of sediment, thus based on the spatial distribution and classification used in the marine geological and soil survey (Chapter 3.3.2) are shown in Figures 4-31 and 4-32.

Top-10-cm organic carbon, a depth characteristic of the bioactive layer in the Baltic /Håkanson et al. 2004/ and elsewhere /Boudreau et al. 1998/ was used in the budget calculations as the source of carbon for detritivores and benthic bacteria. Areas not covered by the marine geological investigations were then filled with data according to water depth, with average carbon content calculated for depth intervals 0–5 m, 5–20 m and > 20 m and distributed evenly according to these depth intervals.

Carbon burial (gC m^{-2} y^{-1})

Marine sediment and organic carbon burial (not including the reed zone) was assumed to take place beneath two main types of accumulation bottoms (A-bottoms): shallow lagoonal (in the Forsmark area only) and deeper focusing-related A-bottoms.

Lagoonal burial – Forsmark

Areas mapped as covered by the periphytic yellow-green algae *Vaucheria* sp. were identified as representing burial of lagoonal-water algal mat deposits /Bergström 2001/. Such lagoonal burial takes place *in situ* below algal mats in the mostly shallow *flad* and *gloe* environments as described by /Munsterhjelm 2005/. Lagoonal burial was then set at 25 gC m^{-2} y^{-1} in the *Vaucheria* zone, or 3/8ths of the *Vaucheria* production, and at 30 gC m^{-2} y^{-1} in lagoonal areas without *Vaucheria* but still mapped as clay-gyttja /Sternbeck et al. 2006/.

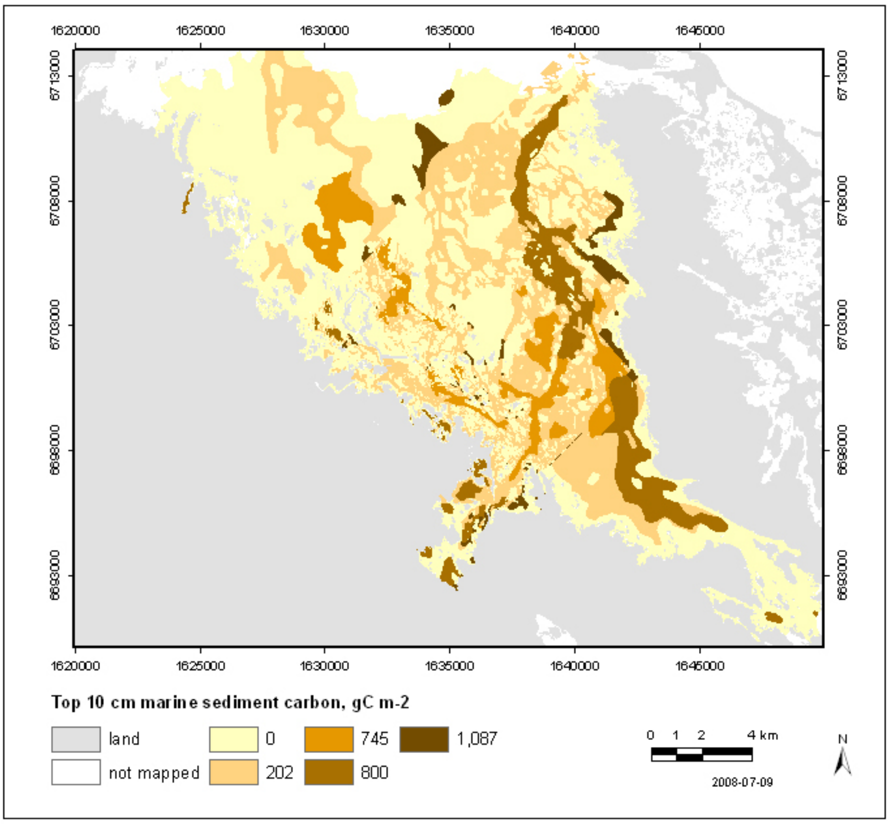


Figure 4-31. *The distribution of bulk total organic carbon content (gC m*$^{-2}$*) in the uppermost 10 cm of the sediment in Forsmark, based on classifications from the geological survey and relationships between sediment water content and organic carbon content.*

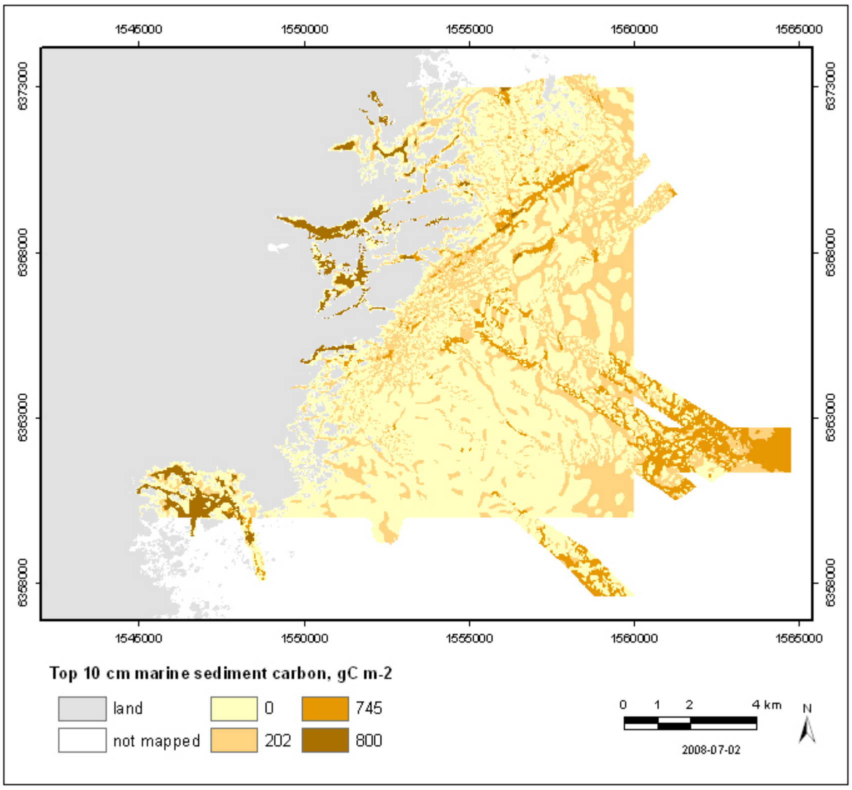


Figure 4-32. *The distribution of bulk total organic carbon content (gC m*$^{-2}$*) in the uppermost 10 cm of the sediment in Laxemar-Simpevarp, based on classifications from the geological survey and relationships between sediment water content and carbon content.*

Focusing-related burial

Focusing-related burial is the result of fine sediment transport along bottoms of erosion and transport towards topographical depressions, the process known as focusing. Water carrying the resuspended load passes over an A-bottom with bottom shear stress conditions insufficient for resuspension. Transported loads therefore accumulate and get buried following deposition.

A fraction of organic carbon and nutrients exported from the pelagic foodweb can be buried in A-bottoms. This fraction increases with the load received. Minerogenic particles also contribute to the load and in particular to burial efficiency. Jonsson's analyses of regional laminated deposits /Jonsson 1992/, formed under anoxic conditions in the Baltic proper and Stockholm archipelago, suggest that the bulk of Baltic Sea laminae are made up of the more inorganic material being resuspended and focused during storm events. Bioturbation and early diagenesis are then not efficient enough regenerative processes to fully control the concentration of organic matter regardless of its minerogenic content. Therefore, element concentrations will co-vary with minerogenic burial, and carbon burial rates in the Baltic Sea /Jonsson et al. 2000/, constituting the downward flux from the base of the mixed surficial zone of fine sediments, will be mainly controlled by sediment accumulation rates.

Total organic carbon burial was estimated as proportional to the ρ_C integral (see Section 4.3.6) for buried non-sealed deposits (in gC m^{-2}):

$$\int_0^z \rho_C dz = \frac{13896 \cdot z^{1.1714}}{1.1714}$$

when $z < 0.68$

and

$$\int_0^z \rho_C dz = 7551 + 4000\,(z - 0.68)$$

when $z > 0.68$

The relationship between burial and this ρ_C integral was then estimated empirically by comparing recent focusing-related carbon burial rates –30 gC $m^{-2} y^{-1}$ in the centre of focusing-related A-bottoms /Sternbeck et al. 2006/ – with ρ_C integrals derived using the above expressions on mapped mud deposit thicknesses. The resulting burial:ρ_C ratio is 0.006 y^{-1}. Thus, burial rate (in gC $m^{-2} y^{-1}$) could be mapped as a function of mud deposit thickness (in m).

Forsmark

Recent focusing-related burial in the Forsmark area took place in areas where bottoms were geologically mapped as fines, postglacial clay and/or gyttja, in the Gräsö trough. To represent the thickness of such deposits, horizontal straight-line distances from the outer edge of the deposit inward, SLD, were calculated, and total sediment thickness, z (in m, to be used in the expression above) was calculated as

$$z = 0.3\times((\log10\ ([SLD])) - 1)$$

which yields a logarithmic expression describing a depth distribution between the deposit center and the deposit edge, serving as depocentre morphology model. Thus, given an association of organic carbon burial with accumulation rate, burial was set in proportion to the thickness of the postglacial-fines deposit, using the ratio 0.006 y^{-1} resulting in a mean about 30 gC m^{-2} y^{-1} in the Forsmark area /Jonsson et al. 2000, Sternbeck et al. 2006/.

Figure 4-33 maps both lagoonal and focusing-related organic carbon burial in the Forsmark area.

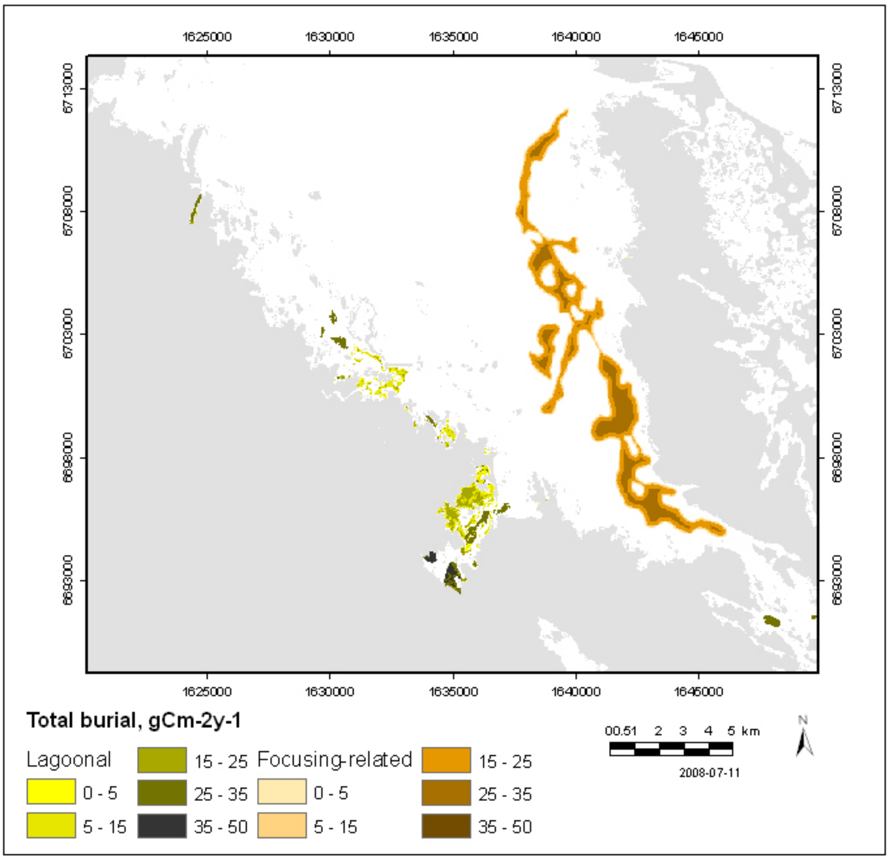


***Figure 4-33.** The distribution of lagoonal and focusing-related organic carbon burial rates (gC m^{-2} y^{-1}) in the Forsmark subarea.*

Laxemar-Simpevarp

No distinction between lagoonal and focusing-related burial was made in Laxemar-Simpevarp. Instead, thicknesses of postglacial-fines deposits could be obtained directly from the soil depth model /Nyman et al. 2008/ in the areas where mapping /Sohlenius and Hedenström 2008/ classified the bulk of the bottom as consisting of clay-gyttja.

A realistic recent focusing-related carbon burial rate (in gC m^{-2} y^{-1}) was again estimated as being proportional to the ρ_C integral derived above using the ratio 0.006 y^{-1}, which given the thicker deposits, and in accordance with the higher rates observed /Sternbeck et al. 2006/ resulted in moderately higher rates in comparison with the Forsmark area.

Figure 4-34 maps total organic carbon burial in the Laxemar-Simpevarp area.

Focusing factors

For an assessment of the burial capacity of the overall marine ecosystem, the "focusing factor" presented and used by /Jonsson et al. 2000/ offers efficient parameterization of focusing as it affects burial. It uses a basin's ratio between total seabed area and A-bottom area, the focusing factor, in order to relate A-bottom deposition and burial to biogenic processes and transport in the pelagic system. The gross deposition rates on e.g. Erstafjärden A-bottoms and many similar bottoms, is 1,000–5,000 g dw m^{-2} y^{-1}. Deposition per pelagic system area decreases with the focusing factor, which in that case ranged between 1.8 and 4.2, the higher figures being from basins where A-bottom areas were comparatively smaller.

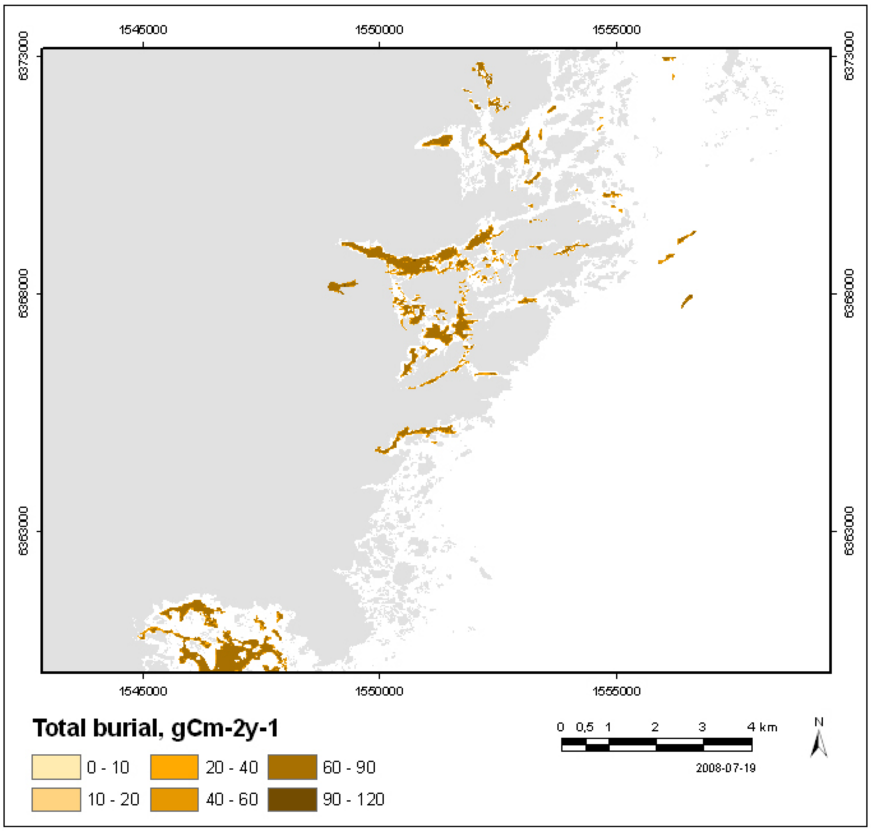


Figure 4-34. *The distribution of organic carbon burial rates (gC m^{-2} y^{-1}) in the Laxemar-Simpevarp subarea.*

Forsmark

As seen in Figure 4-35, the ratio total: A-bottoms area ratio in the Forsmark subarea basins is close to the above low range (1.8–4.2) only in the five basins most dominated by lagoonal *Vaucheria*-type burial: basins 118, 120 (innermost Forsmarksfjärden and Asphällsfjärden), 134 (Tixelfjärden), 150 and 152 (the two Kallrigafjärden basins). In basins with focusing-related burial the focusing factor reaches only as low as ~ 8 in two of the basins in the Gräsö trough.

The latter figure would imply that focusing-related burial at approximately 30 gC $m^{-2} y^{-1}$ represents a sink relative to the pelagic ecosystem locally in the order of 3–4 gC $m^{-2} y^{-1}$ which is within previously published estimates of the carbon burial sink in the wider Baltic Sea, ranging between 1.5 and 9 gC $m^{-2} y^{-1}$ as summarized by /Eilola 1998/. The focusing factor of the entire larger-scale Öregrundsgrepen may be as high as 75, however. So while element burial is significant locally, the latter figure is equivalent to no more than ~ 0.5 gC $m^{-2} y^{-1}$ at the pelagic-system level. In other words, sediments in the Forsmark area itself carry only this more limited capacity for local, larger-scale sediment sequestration of the organic carbon and nutrients assimilated via primary production.

Laxemar-Simpevarp

The Laxemar-Simpevarp coast presents a widely different focusing regime, with significant burial in the inner bays, compared with very little burial along the open exposed coast (see Chapter 6).

4.4.10 Substrate classification, soft and hard bottoms – both sites

To permit estimates of the distribution of benthic organisms, the marine geological map was classified into soft and hard bottoms. All sediment and substrate types were classified as soft, except the following: gravel, moraine/till and bedrock. All other size categories of sediment, i.e. sand to gyttja, were classified as soft based on the assumption that these substrates support burying and digging benthic fauna and provide a suitable habitat for rooted plants (at least in the photic zone). Differences in data availability led to a difference between Forsmark and Laxemar-Simpevarp which is described below.

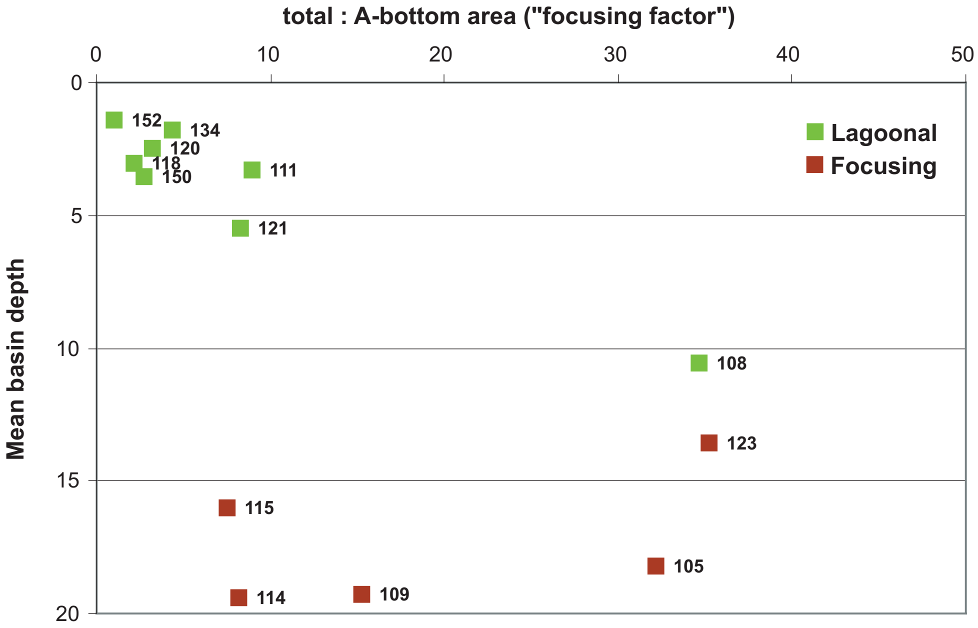


***Figure 4-35.** The relationship between mean basin depth (m) and the ratio total : A-bottom area, i.e. the "focusing factor" (FF) /Jonsson et al. 2000/, or equivalent total: A-bottom ratio in the case of lagoonal burial, in 13 basins in the Forsmark area with area-wise significant burial (FF < 50). The colour indicates the basin's dominant mode of burial. The otherwise deeper basin 108 includes the Vaucheria-dominated (shallow lagoonal) test lake.*

Where the marine area was covered by the Quaternary deposit map /Sohlenius and Hedenström 2008/, this map was used. In the Forsmark area, a regional map (1:500,000) of Quaternary deposits was used for areas outside (Hedenström A 2007, pers. comm.). The estimated distribution of soft and hard bottoms is presented in Figures 4-36 and 4-37.

It was furthermore observed in the Laxemar-Simpevarp area that within the mapped area, the proportions of soft bottom increased with depth. The proportions were estimated for depth categories, and the threshold between dominance of soft bottom over hard bottom in the offshore areas was found to be between 9.5 and 10 m depth. Therefore, all seafloor outside the mapped area below 10 m depth was designated as soft bottom and above 10 m depth as hard bottom.

The percentages of soft bottoms in all sub-basins fully covered by sediment mapping or substrate estimation are listed in Table 4-22.

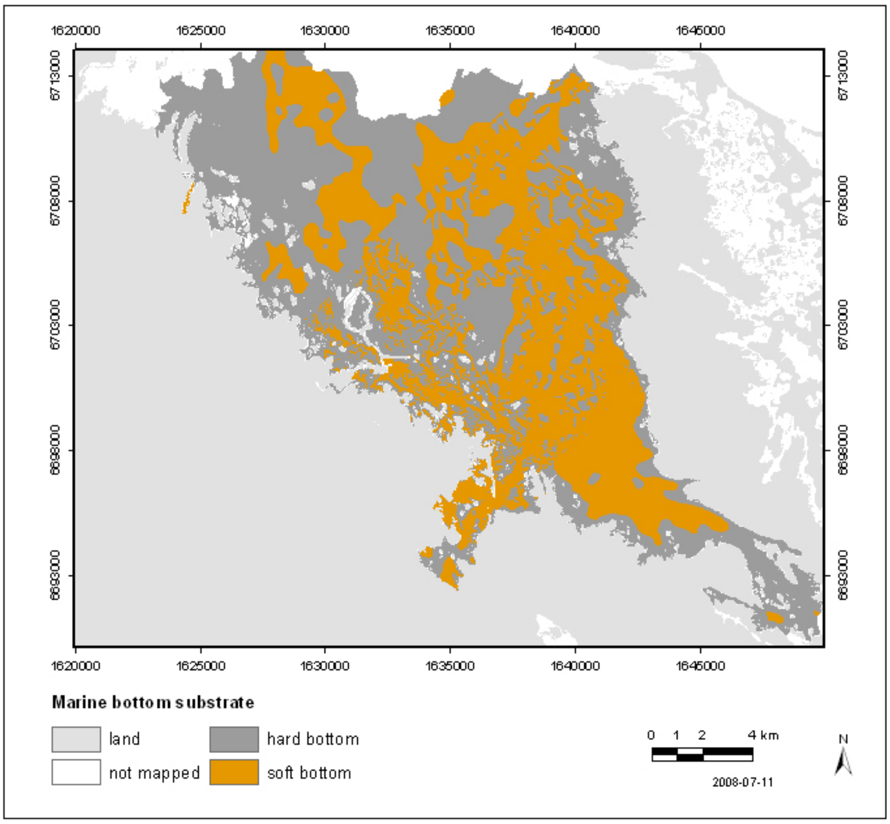


***Figure 4-36.** Distribution of hard and soft bottoms in the Forsmark area.*

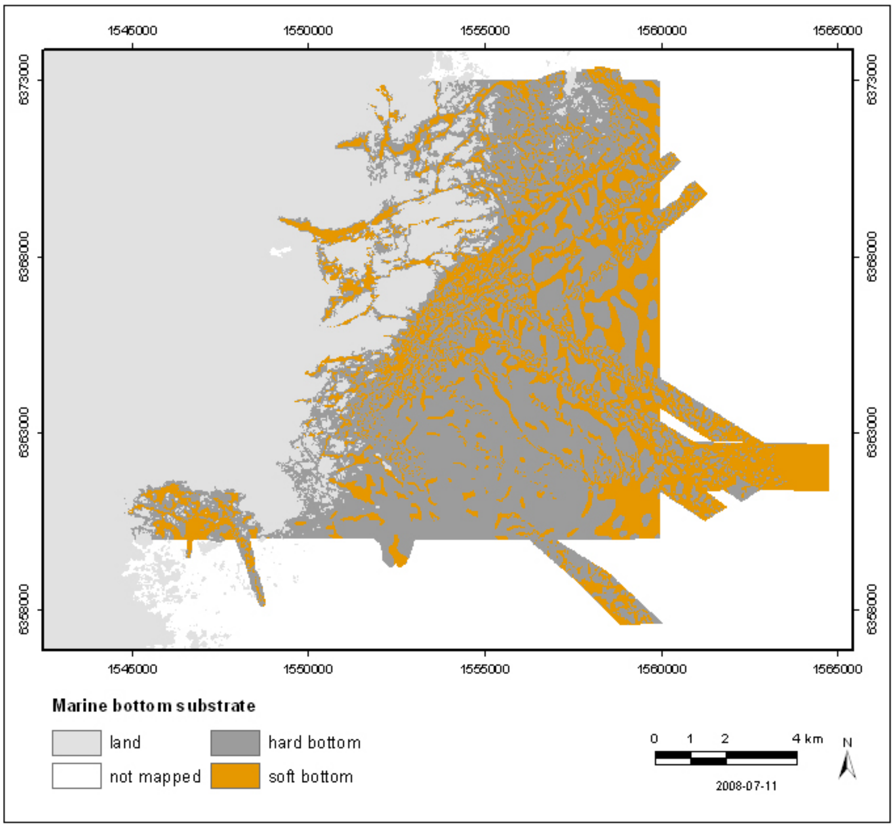


Figure 4-37. *Distribution of hard and soft bottoms in the Laxemar-Simpevarp area.*

Table 4-21. Derivation of top 10 cm organic carbon concentrations.

		Surface ρC		
	W	Mean	Per volume	W
	%ww		gC m^{-3}	%ww
Gyttja	95–100	97.5	4,770	477
Clay gyttja	80–95	87.5	7,915	791
Postglacial clay	50–80	65	10,866	1,087
Coarse silt/fine sand	30–50	40	7,450	745
Sand	20–30	25	2,017	202
Sand/gravel, gravel	0–20	10	0	0

Table 4-22. The percentage of soft-bottoms in all sub-basins fully covered by sediment mapping or substrate estimation.

	Basin Area, m^2	Percent Soft-bottoms		Basin Area, m^2	Percent Soft-bottoms
Forsmark					
Basin 100	18,333,600	31.2	**Forsmark (continued)**		
Basin 101	21,796,800	43.2	Basin 123	72,63,600	73.4
Basin 102	33,822,000	24.9	Basin 126	5,402,800	51.2
Basin 103	5,616,400	0.0	Basin 134	576,400	57.3
Basin 104	2,699,200	70.5	Basin 137	3,600	0.0
Basin 105	22,646,000	54.2	Basin 145	75,600	0.0
Basin 106	1,382,400	37.1	Basin 146	3,358,000	55.5
Basin 107	4,495,600	38.9	Basin 150	5,745,200	71.5
Basin 108	6,924,400	31.5	Basin 151	41,230,000	55.6
Basin 109	1,521,200	65.2	Basin 152	2,084,800	36.0
Basin 110	7,067,600	37.4	**Laxemar-Simpevarp**		
Basin 111	6,575,200	24.6	Basin 501	338,400	44.1
Basin 112	696,800	41.7	Basin 502	1,122,000	62.9
Basin 113	1,596,800	36.4	Basin 504	607,200	40.3
Basin 114	14,058,400	74.1	Basin 506	340,400	47.0
Basin 115	4,211,200	61.1	Basin 508	1,382,000	50.7
Basin 116	13,382,800	37.6	Basin 513	4,044,800	21.7
Basin 117	5,590,400	15.5	Basin 514	956,000	23.6
Basin 118	1,347,200	23.9	Basin 515	869,600	44.9
Basin 120	666,000	28.3	Basin 516	471,200	0.0
Basin 121	3,615,600	61.3	Basin 518	758,800	30.1

4.5 Parameterization – mass balance, both sites

Estimates of abiotic and biotic pools and fluxes were used in the mass balances according to the parameterization presented above.

The functional groups in the biotic pools were added in primary producers (macro-, microphytes and phytoplankton) and consumers (benthic bacteria, benthic fauna, zooplankton, bacterioplankton, fish, birds and seal).

No fluxes or processes within the ecosystem were included only fluxes to and from the ecosystem: atmospheric deposition, runoff, advective flow, burial and total net primary production (NPP). NPP was included for C, N and P according to the presentation in Section 4.2.1.

4.6 Parameterization – elemental composition

Elemental composition analyses were performed in Forsmark and Laxemar-Simpevarp for various abiotic pools and functional groups, see Table 4-23 (see also Section 3.5 of this report). From these data, C:X ratios (where X represents the different elements) were derived for the various pools. Since not all organisms, abiotic pools or elements were analyzed at both sites, data for one pool or element at one site were sometimes used for the other site. Organisms from one functional group were sometimes used for another functional group when data were lacking. The C:X ratios used for each abiotic and biotic pool and element are presented in Appendix 6. For some of the elements (mainly trace elements), the results of the analyses were below the detection limit. In these cases, a value half of the detection limit was used (estimated mean) in the calculations. These elements are marked in the table in the Appendix 6.

Table 4-23. Analyzed abiotic pools and functional groups in Forsmark and Laxemar-Simpevarp. n=, denotes number of studies/replicates.

Pool/functional group	Analyzed in Forsmark	Analyzed in Laxemar-Simpevarp	Reference for Forsmark	Reference for Laxemar-Simpevarp	Comment
Particulate matter in water	n=3	(POC) from SKB's site investigations	/Kumblad and Bradshaw 2008/	/Ericsson and Engdahl 2004a, b, 2007, 2008, Engdahl et al. 2006/	Data on particulate organic carbon (POC) from 2003–2007 in marine water samples were used together with the C:X ratio found in Forsmark.
Dissolved matter in water	n=3	(DIC) from SKB's site investigations	/Kumblad and Bradshaw 2008/	/Ericsson and Engdahl 2004a, b, 2007, 2008, Engdahl et al. 2006/	Data from SKB's database Sicada (dissolved inorganic carbon, DIC) from 2003–2007 were used.
Sediment	n=2	n=2	/Engdahl et al. 2008, Sterneck 2006/	/Nilsson 2004, Engdahl et al. 2008/	N and P concentrations from /Sternbeck 2006/.
Macrophytes	n=9	n=12	/Kumblad and Bradshaw 2008/	/Engdahl et al. 2006/	
Microphytes	n=2	–	/Kumblad and Bradshaw 2008/		Data for Forsmark were used in Laxemar-Simpevarp.
Phytoplankton	n=3	–	/Kumblad and Bradshaw 2008/		Data for Forsmark were used in Laxemar-Simpevarp.
Benthic bacteria	–	–		/Bertilsson et al. 2003, Heldal et al. 2003/	Literature data for concentrations of C, N, P and S were used.
Benthic fauna – herbivores	n=4	–	/Kumblad and Bradshaw 2008/		Data for Forsmark were used in Laxemar-Simpevarp.
Benthic fauna – detrivores	n=2	–	/Kumblad and Bradshaw 2008/		Data for Macoma baltica were used, could also be classified as a filter feeder.
Benthic fauna – filter feeders	n=3	n=3	/Kumblad and Bradshaw 2008/	/Engdahl et al. 2006/	In Forsmark Cerastoderma glaucum, in Laxemar-Simpevarp Mytilus edulis.
Benthic fauna – carnivores	–	–	/Kumblad and Bradshaw 2008/		Data for idothea in Forsmark were used, based on most likely to be similar as to benthic carnivores.
Zooplankton	n=1	–	/Kumblad and Bradshaw 2008/		Data for Forsmark were used in Laxemar-Simpevarp.
Bacterioplankton	–	–		/Vrede et al. 2002 Heldal et al. 2003/	C:N and C:P was taken from averages from cultures from exponential growth, C-, N- and P-limited growth studied by /Vrede et al. 2002/.Sulphur content in cyanobacteria was studied by /Heldal et al. 2003/ and the average molar ratio for six strains was used (C:S = 216).
Fish – benthivorous	n=3	n=3	/Kumblad and Bradshaw 2008/	/Engdahl et al. 2006/	
Fish – zooplanktivorous	n=3	n=3	/Kumblad and Bradshaw 2008/	/Engdahl et al. 2006/	
Fish – piscivorous	n=3	n=3	/Kumblad and Bradshaw 2008/	/Engdahl et al. 2006/	
Birds	–	–			No data.
Mammals	–	–			No data.

4.7 Confidence and uncertainties

4.7.1 Biota

Primary production

Primary production calculations are in this report dependant on annual average biomass (gC m^{-2}) and irradiation (MJ PAR d^{-1}, or days > 5 MJ PAR y^{-1}).

A comparison was made with the Photosynthesis – Irradiation (P-E) relationship proposed by /Binzer et al. 2006/. This study showed a hyperbolic relationship between photsythesis and Irradiation according to:

$$GP = GP_{\max}\left[\frac{\alpha I}{GP_{\max} + \alpha I}\right] \qquad \text{(Equation 4-1)}$$

where α is photosynthetic efficiency (mol photons^{-1}) and I is irradiation (µmol photons m^{-2} s^{-1}) and GP_{max} is maximum Gross Production (GP) (µmol O_2 m^{-2} s^{-1}). From 190 studies they calculated the average: $\alpha = 0.036$ and $GP_{max} = 14.2$. This equation was used to compare the calculations described in Section 4.2, and so two years of irradiation ($I_{surface}$) measures (average every half hour) and spatial variation of light attenuation (LA) was used to integrate a two year average of annual primary production for the Forsmark area according to:

$$\frac{1}{2}\sum_{March2004}^{March2006} 14.2\left[\frac{0.036 \cdot I_{surface} \cdot LA}{14.2 + \left(0.036 \cdot I_{surface} \cdot LA\right)}\right] \qquad \text{(Equation 4-2)}$$

GP (mol O_2 m^{-2} s^{-1}) was recalculated to NP gC m^{-2} y^{-1} to enable comparison using conversions factors. Calculations were performed in Matlab (Mathworks R 2007a) and ArcMap (9.1). As the equation does not take biomass into account although is valid for macrophyte communities, a lower level of biomass was set to 1 gC m^{-2}.

The resulting average annual NP (Table 4-24, Figure 4-38) was similar to the calculations, the maximum NP was lower, 728 gC m^{-2} year^{-1} in the calculations according to /Binzer et al. 2006/ compared to a the NP predicted in this report; 948 gC m^{-2} y^{-1} macrophyte community production or 1,014 gC m^{-2} y^{-1} (including microphytes). Following the heterogeneous biomass distribution the average was lower in this study than in calculations according to Binzer: Average benthic NP was approximately half of predicted benthic primary production, 76 compared to 158 gC m^{-2} y^{-1}. However, the reported mean values for α and GP_{max} has a range of approximately one order of magnitude (0.007–0.076 and 3.15– 25.2) and so the difference between our calculations and Equation 4-2 is well within the range reported in /Binzer et al. 2006/.

The estimates of primary production are based on biomass and irradiation and have been compared with an independent model (Equation 4-1). The quality of the biomass dataset is discussed earlier in this section and the method is evaluated for the Laxemar-Simpevarp area in /Wijnbladh and Plantman 2006/. Light measurements and light penetration are compiled from a large dataset from an investigation with high temporal density /Borgiel 2005/. Data from 11 independent *in situ* primary production studies were compiled in this report to calculate annual NP in the area. These calculations fit well in the range of reported NPs /Binzer et al. 2006/ and also take spatial variation of biomass into account.

Table 4-24. Benthic maximum and average Net Production (gC m^{-2} y^{-1}) and standard deviation (SD) in this study and elswhere reported.

Study	Maximum	Average	SD[1]
Calc. according to /Binzer et al. 2006/	728	158	229
This study[2]	1,013 (948)	76 (53)	162 (148)

1. SD for calculations in this study is standard deviation from the grid dataset.
2. Benthic NP and (only macrophytes NP).

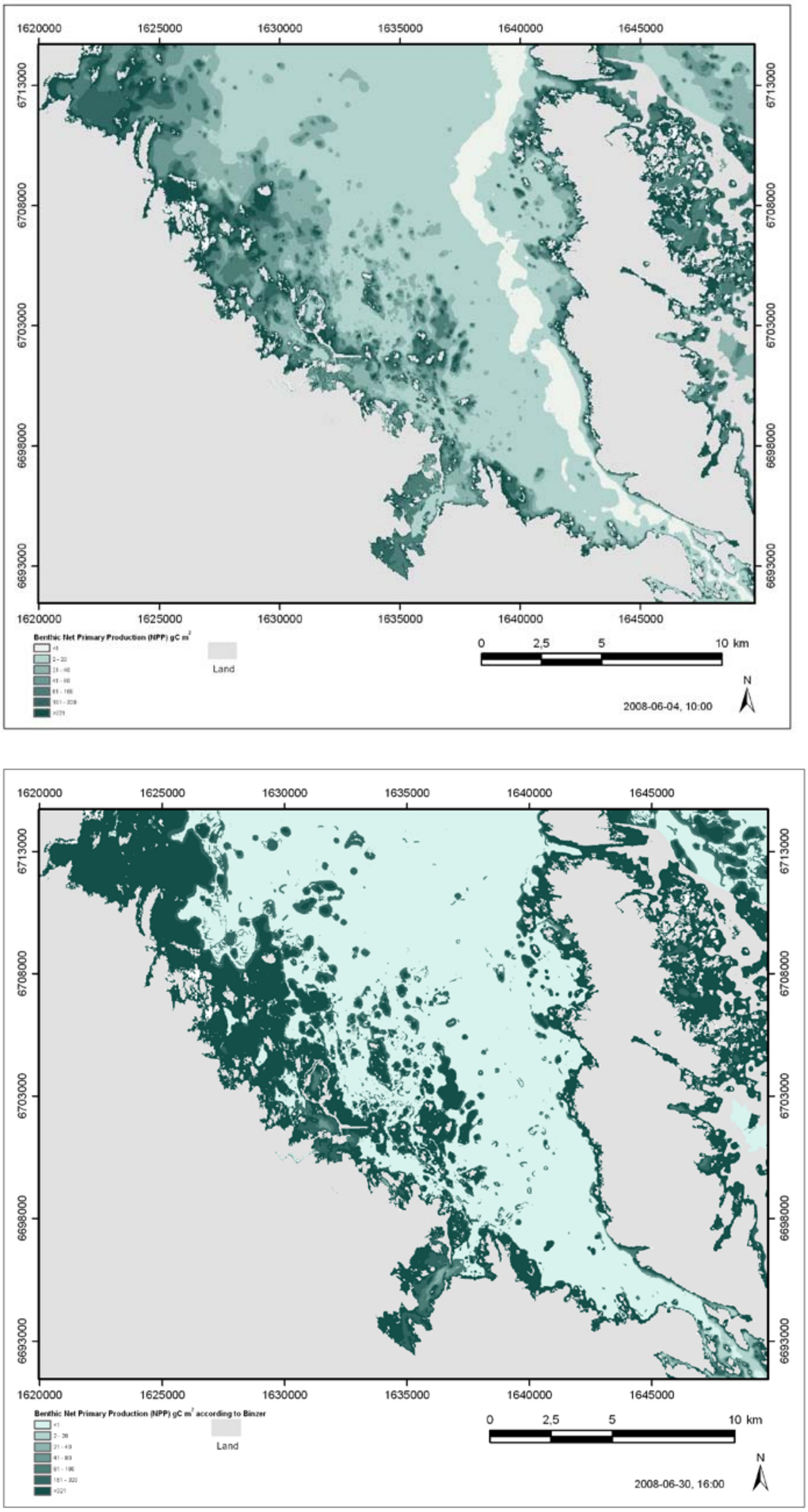


Figure 4-38. *Benthic primary production calculated according to Section 4.2 in this report (above) and according to /Binzer et al. 2006/ (below) in Forsmark.*

Fish biomass

Total (i.e. really including all fishes in the area) biomass or density data on fish biomass are scarce. Most often biomass is reported as an index or at the best CPUE (catch per unit effort) or number of individuals e.g. /Axenrot and Hansson 2004, Horbowy 2003, Hansson and Rudstam 1995/. A few studies have attempted to estimate actual biomass data, however. In this study we have used site specific surveys in GRASP models to estimate biomass (in Forsmark /data from the Swedish Board of Fisheries, /Abrahamsson and Karås 2005, Heibo and Karås 2005/) and site specific data and literature data to estimate and distribute biomass spatially in Laxemar-Simpevarp /Jansson 2005, Enderlein 2005/.

In Laxemar-Simpevarp, one extensive study has been made in one of the basins (basin 508) using several methods to calculate biomass /Adill and Andersson 2006/. Only the proportions of the three functional groups of the catch found in this study were used to estimate total fish biomass. The biomass found in this study can therefore be used to validate calculations described in Section 4.2.1.

The estimated total fish biomass was calculated (see Section 4.2.1 in this report) to be 0.79 (SD = 0.24) g C m^{-2}, varying between 0.42 and 0.85 g C m^{-2} for the other inner basins.

The biomass estimates in /Adill and Andersson 2006/ varied between 81.2 and 71 kg ww ha^{-1} for May and September respectively, equivalent to 0.812 and 0.71 g C m^{-2}, with an average of 76.1 kg ww ha^{-1}.

The deviation between biomass in the model (0.79, calculated from literature data) and biomass observed in field (0.76) is therefore only 4% which must be considered surprisingly small but definitely acceptable.

4.7.2 Regolith

Substrate

Substrate from the geological mapping was used to classify bottom substrate as hard or soft. This is a simplification of real conditions as hard substrate, e.g. bedrock, often contains patches of soft substrate within its area. Further, classifications in the deeper outer parts are subject to error due to the fact that classifications do not concern top sediment. Less than 50 cm sediment has been ignored in the classification in these areas (Hedenström A 2007, pers. comm.).

5 Oceanographic model

5.1 Water exchange

The Baltic coastal waters serve as an intermediary link whereby waterborne material released from the geosphere may eventually be transported via advective and diffusive processes to the world oceans (Figure 5-1). The primary connection with the geosphere may be direct via leakage through the sea floor of the coastal zone or via water runoff (discharged diffusely by groundwater flows, or discretely by localized watersheds such as streams or rivers) which enters the surface layers of the coastal zone. The coastal waters also comprise aquatic ecosystems in which inflowing material can be transformed via food chains. For aquatic ecosystems the rate of water exchange is an indisputable basic parameter that sets the externally forced pace of material turnover. The overall objective was to quantify the water exchange of the coastal area in the vicinity of the planned repositories in such terms that projection into the distant future is made possible. Various water circulation models driven by reasonably simplified but adequate forcing are employed for this purpose, and the large amounts of oceanographic data generated over the cycle of a typical year are condensed into a conceptual form that can serve as a basis for communication with other concerned disciplines. The year 1988 was chosen as the most representative year for the Forsmark coastal area /Larsson-McCann et al. 2002a/, while 1981 was recommended for the Laxemar area /Larsson-McCann et al. 2002b/.

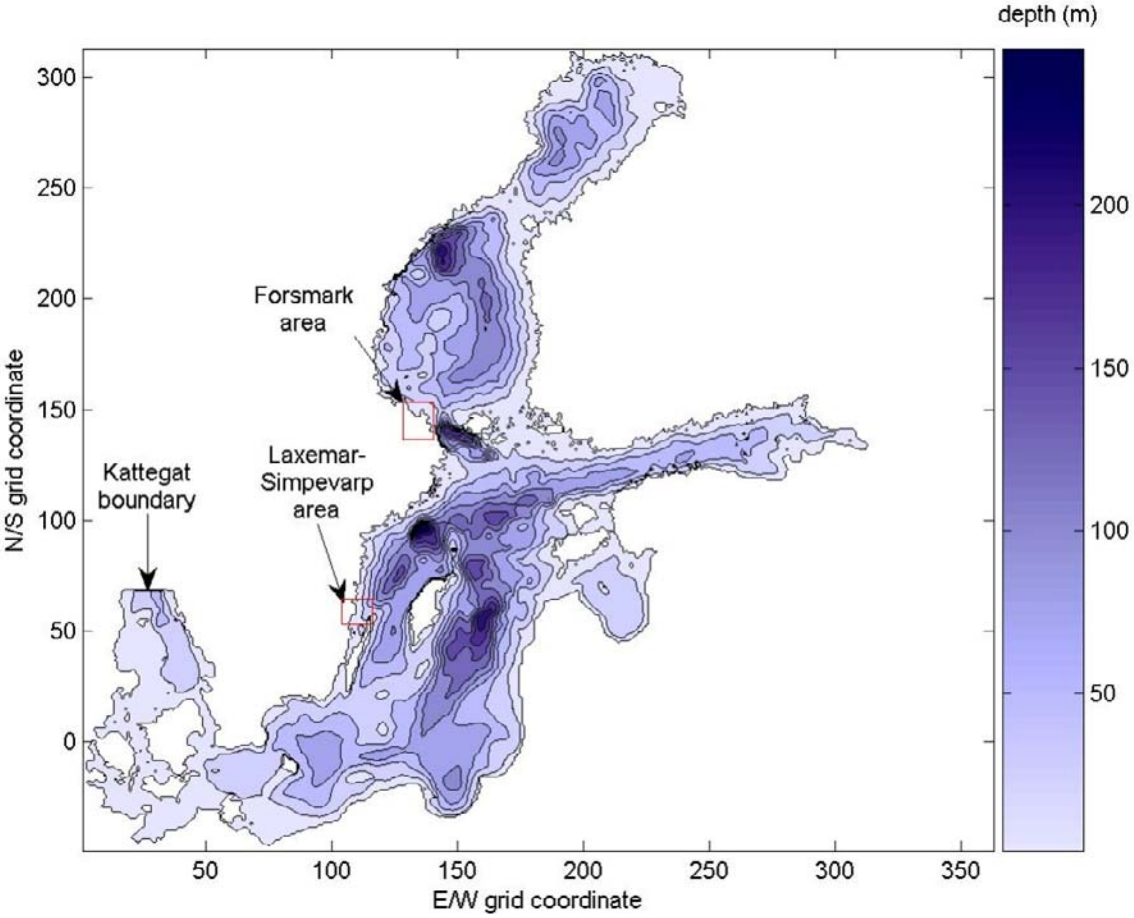


Figure 5-1. *The Baltic model grid displaying the Warnemünde bathymetric data. The approximate locations of the Forsmark and the Laxemar model domains are indicated, as is the boundary of the Kattegat model with Skagerrak.*

In describing the water exchange processes of the coastal zone, those of the deeper open coast and those of the normally shallower and possibly land-locked waters near the mainland should be distinguished. In the open coastal zone, the water circulation is mainly determined by barotropic (sea level-related) surface waves or baroclinic (density difference-related) internal waves. The local wind exerts shear friction on the surface that induces vertical mixing leading to deepening of the surface layer /Stigebrandt 1985/. Horizontal surface currents are also set in motion. Large-scale events such as up- and down-welling generated by Ekman dynamics in adjacent coastal areas normally affect the circulation in a particular section of the coast to a greater extent /Engqvist and Andrejev 1999/. Such events manifest themselves by entering into a particular coastal section through its boundaries. This external influence may be imposed on the interior of the model domains as appropriately varying sea level and density profiles along the boundaries.

5.2 Methodology

To obtain quantitative time-based estimates of particle turnover in general reservoirs, /Bolin and Rodhe 1973/ formulated a strict foundation in statistical terms. One of these well-defined concepts was independently adapted to water circulation models by introducing its volume-specific counterpart /England 1995, Engqvist 1996/. The naming of this concept has been somewhat variable and vague in subsequent years. A clarifying nomenclature fully compatible with the volume-specific concepts has recently been suggested by /Delhez et al. 2004/ and has been adopted. Looking at a particular water parcel present in a reservoir at a given moment and following it individually while measuring the time it takes until it leaves yields its residence time. The ensemble average over all parcels present at a given instant in the specified reservoir gives the *average residence* (*AvR*) time. Analogously, backtracking the same parcel chronologically in reverse until the point in time it entered the reservoir gives the 'age' of that water parcel, and the average age over the water parcel ensemble gives the ***average age*** or *AvA*. The sum of *AvA* and *AvR* gives the ***average transit time*** or *ATR* time, which is sometimes referred to as the (hydraulic) turnover time, since these were proven equal for stationary distribution cases by /Bolin and Rodhe 1973/. *AvA* thus denotes the length of time a particular water parcel of originally exogeneous water (or parts thereof) has on the average spent within a defined connected body of water. This could be discharged freshwater and/or water entering from any other connecting water body with a boundary across which water is exchanged. The relationship between two of those measures and the comparative advantages and disadvantages of other compacting methods to describe water exchange in a transdisciplinary communicative manner are discussed in /Engqvist et al. 2006/.

What is regarded as interior and exogeneous water must thus be specified. Once this has been determined, then the development of *AvA* for the entire defined volume partitioned into subbasins can readily be computed, each of these possibly further subdivided into vertical layers. Each subbasin can then be treated as surrounded by exogeneous water, and this case will be referred to as ***individually*** computed *AvA* values with regard to a particular subbasin. Alternatively, a number of neighbouring subbasins are treated as conjoined, which case is called ***collective*** *AvA* since the subbasins have a delimiting boundary with the exogeneous water in common that may or may not coincide with the borders of any of the individual subbasins.

Given information on the mixing time scales in relation to the advective time scales, it is possible to use the *AvA* concept to obtain an overview estimate of the water exchange over long term periods, typically one year, by computing its average, maximum and minimum values. These values, together with an estimate of the variance, e.g. the standard deviation (S.D.), can be computed from instantaneous *AvA* values. These *AvA* snapshots should be sampled over a shorter time period than the timescales set by the temporal variation of the imposed forcing. The advantage is that diffusive processes are included, all sources of exogeneous water can be accounted for simultaneously and no post-processing is needed /Döös and Engqvist 2008/.

The *AvA* concept must, however, be used with due caution when the associated flows are to be inferred from it, in particular if the *AvA* values reach parity with the designated one-year cycle time scale that is derived from ecological modelling considerations. The highest *a priori* likelihood for this eventuality to occur concerns the decisively landlocked areas, which will therefore consistently be modelled separately. When water exchange estimates are used in integrated ecological models, the fluxes are computed directly from the actual model without recourse to the *AvA* measure.

5.3 Description of models

A common trait of the Forsmark and the Laxemar-Simpevarp coastal areas is that the coastal waters close to a possible nuclide leakage point near the mainland coast are delimited by a land barrier to the east (Gräsö and Öland respectively) forming a funnel-like primary receiving offshore area with its wide end to the north and the narrow end southwards. The horizontal resolution of the corresponding grids of the respective areas are presented in Figures 5-2 (Forsmark) and 5-3 (Laxemar), both with a grid side length of 0.1' (nautical mile). In addition to a coarser morphometric horizontal scale, the Laxemar area also displays a more rugged coastline with considerably more semi-enclosed, landlocked basins.

The bottom along the Laxemar coast gradually slopes in the offshore direction; there are few topographic features that naturally indicate a well-defined delimitation line. The model areas of both Forsmark and Laxemar-Simpevarp are further partitioned into a number of non-overlapping subbasins (SBs) based on the consideration of present underwater structures that, due to future land uplift, will potentially accentuate the confinement of the water movements to a progressively shallower bathymetry until lakes are eventually formed. These areas are shown in Figures 5-4 and 5-5. The location of some of these SBs also coincides with anticipated leakage points connecting to the geosphere. The water exchange of a particular SB is broken down into the yearly volume fluxes across its boundary interfaces with other SBs or the Baltic. These consist typically of flows going in opposite directions, separated in time or in space, both horizontally and vertically. These are accounted for by the sign convention that a positive flow goes from a basin with a higher order number to one with a lower. The sum of these flows (with sign) gives the net flow. The sum of the annually averaged net fluxes along the boundary of each SB should thus be close to zero, within the allowance of an equivalent flow producing the volume of a differing sea level at the beginning and the end of the year-long period.

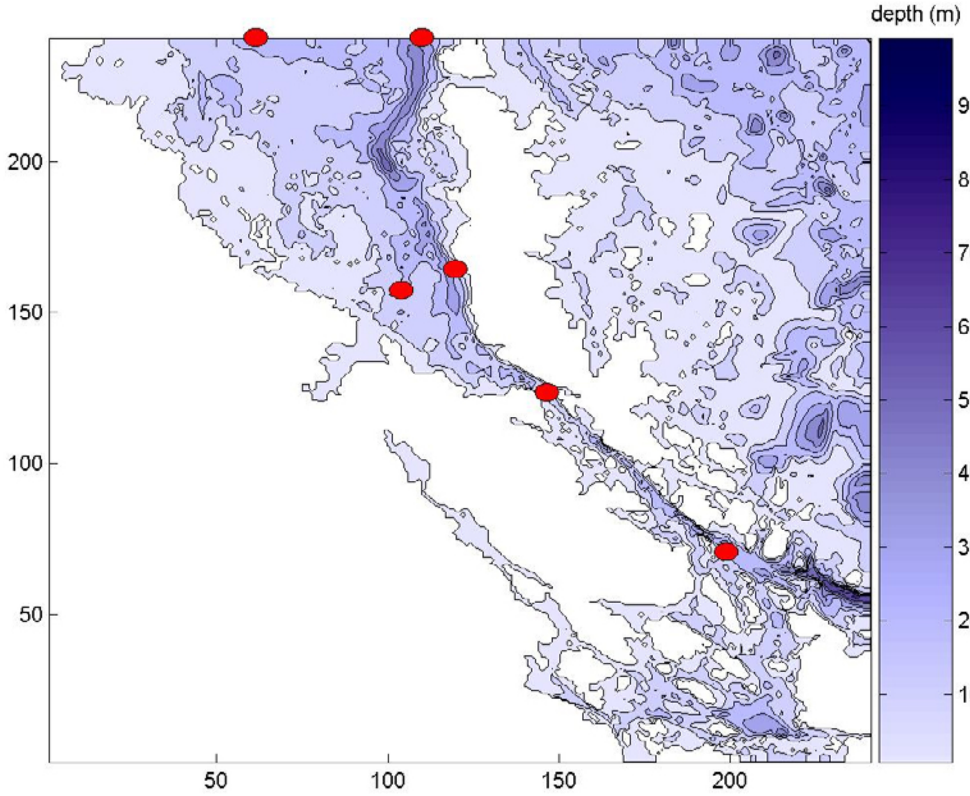


Figure 5-2. The chosen model domain of the Forsmark area with some of the grid cells manipulated manually. In particular, the narrow channels that connect the fjord branches with the southern basins have been made sufficiently wide in a few sections to permit through-flow. The six red spots mark the sites of deployed oceanographic instruments during the validation year 2004.

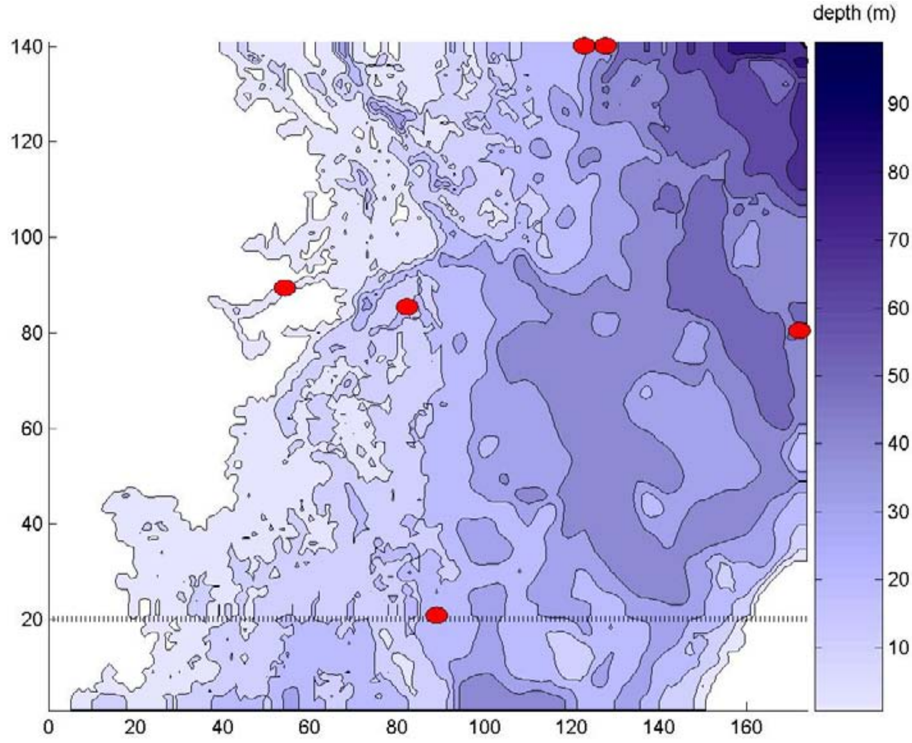


__Figure 5-3.__ The Laxemar-Simpevarp model area. A bit of the island of Öland can be seen in the southeast corner. The broken black line delineates the original grid prior to its extension southward. The sites of the six measurement stations where oceanographic instruments were deployed for the 2004 validation programme are indicated as red spots.

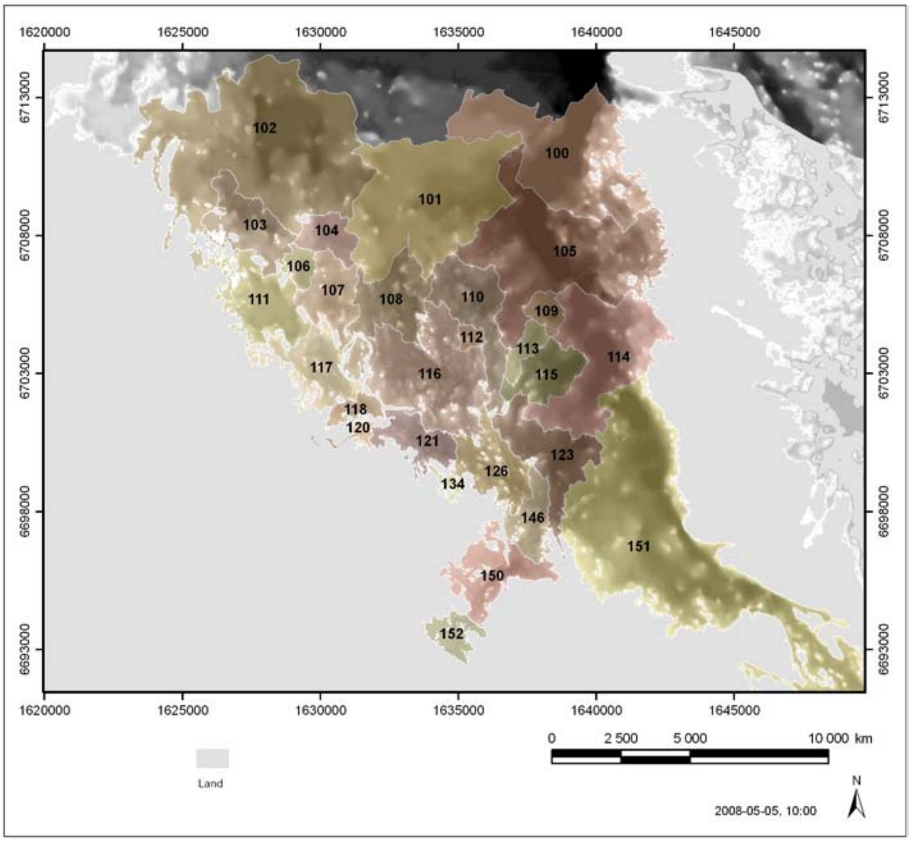


__Figure 5-4.__ The partitioning of the Forsmark coastal area into subbasins (SBs) with labelling of the major basins.

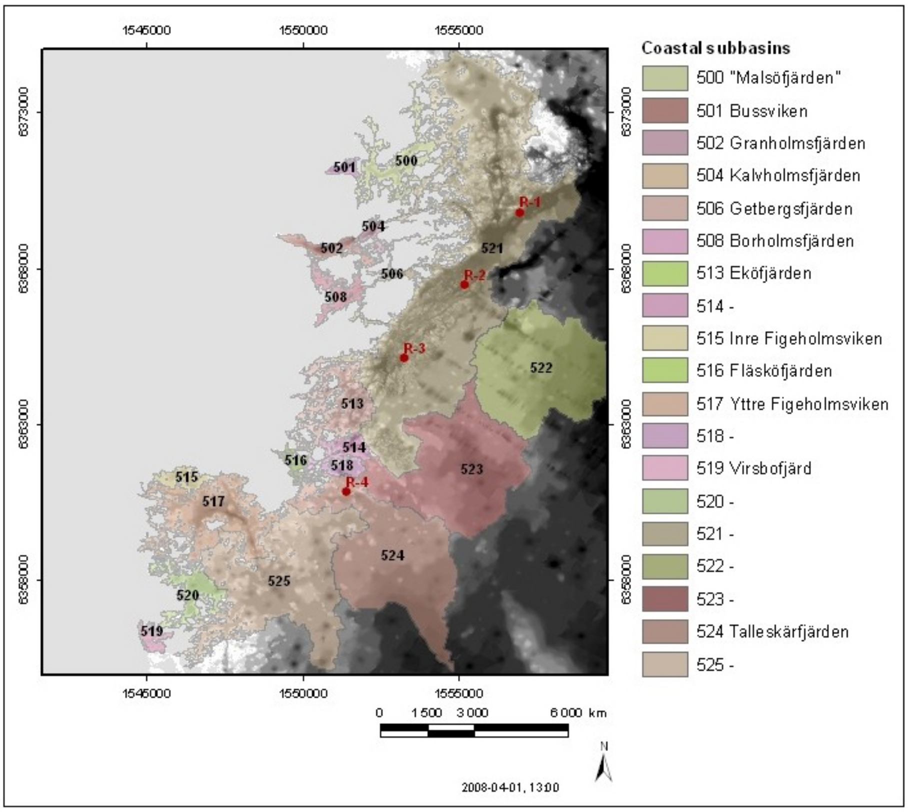


*Figure 5-5. The partitioning of the Laxemar coastal area into subbasins (SBs) together with their numbering and naming when trivial names exist. The red spots denote the locations along the coast for which the forcing (salinity, temperature and sea level) of the **CDB** model has been computed by the **L3D** model. These profiles are used for the modelling of the interior basins, see Figure 5-6.*

Concerning both the Forsmark and the Laxemar-Simpevarp areas, two versions of the same generic 3D model have been employed: one for the entire Baltic Sea circulation and the other for a local section of the near-shore coastal area. These models are nested so that the Baltic oceanographic properties (currents, salinity, and temperature fluctuations) along the border are propagated into the local models. In order to account for the forcing data unequivocally, the Baltic model will be referred to as **B3D** and the two local models as **F3D** and **L3D**. In the Laxemar-Simpevarp area there is an additional model that resolves the coastal embayments that are not deemed appropriate for 3D-modelling. This semi-enclosed area is modelled with hydraulically **c**oupled **d**iscrete **b**asins which will be referred to as the **CDB** model.

The baroclinic 3D model, AS3D, /Andrejev and Sokolov 1990/ has been set up for the entire Baltic and the two offshore areas and run for a specified time period comprising a one-year cycle. Since sufficient oceanographic measured data are not available along the border of the two offshore areas, these are provided by the **B3D** model /Engqvist and Andrejev 1999/. The large-scale Baltic model is thus interfaced to the local models along a geometrically simple delineation line where the grids coincide. All three 3D models comprise 40 vertical levels with monotonically increasing layer thickness towards the bottom. A comprehensive description of the numerical scheme has been given in /Sokolov et al. 1997/ and a succinct summary of the main numerical features can be found in /Engqvist and Andrejev 2003/.

For the more shallow landlocked basins of the Laxemar area adequate resolution of narrow straits may demand a more sophisticated (non-hydrostatic) 3D model approach. In this case a more attractive method is, however, to parameterize the strait exchange /Stigebrandt 1990/ and use CDB models to resolve the area /Engqvist 1997/. This method limits the temporal scale that is possible to resolve, since the basins must be considered horizontally well-mixed. The straits interconnecting such a partition into discrete subbasins may have various geometrical characteristics: lengths and depths and the existence/absence of a sill which will influence the exchange /Engqvist and Stenström

2004/. Straits connected to basins that receive discharged freshwater consequently often display a pronounced estuarine circulation mode. Even with an established estuarine circulation flow regime, the varying density stratification in the offshore waters is often the dominant cause of ventilation of coastal basins /Engqvist and Omstedt 1992/. The choice of appropriate models to simulate the water exchange depends on both the hypsography and how separate model areas are connected.

Due to the existence of narrow internal straits within the primary partitioning, however, an additional split of three of these SBs into a pair of directly connected basins is recommended based on oceanographic considerations. Altogether, this analysis thus involves 19 SBs, ten of which are located along the open coast and will be referred to as *outer* SBs while the other group will be called *inner* SBs, see Figure 5-6.

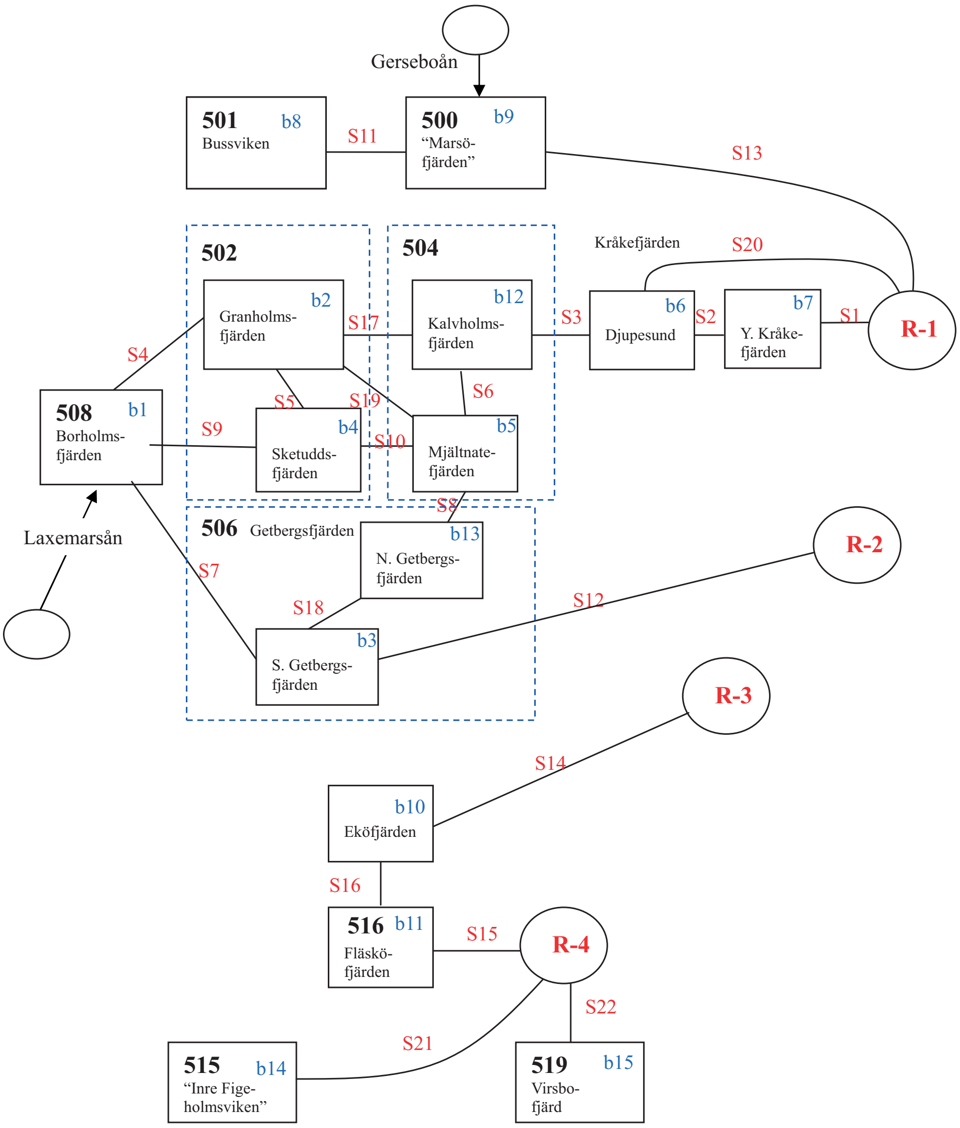


Figure 5-6. *Basin and strait configuration for the computation of AvA times for the semi-enclosed basins of the Laxemar-Simpevarp area. The basins denoted with bold capital ID labels (e.g.* ***508****, Borholmsfjärden) refer to the SKB partitioning and are chosen with regard to their topographic features /Brydsten and Strömgren 2005/. Three of these basins also possess narrow internal passages that constrain water exchange, warranting a further subdivision based on oceanographic considerations; this is indicated by the blue broken lines. The lower-case basin blue ID labels (e.g. b10, Eköfjärden) in the upper right corner are the systematic consecutive labelling used in the model computations. The corresponding labels of the straits are given in red letters. The connections with the coastal basins are labelled R-1 to R-4, Figure 3-5. The sea level, together with the salinity and temperature profiles at these locations, has been computed with the Laxemar coast fine-resolution 3D model.*

5.4 Input data

The input data come from many disparate sources with the common denominator that they are judged to represent the available source with the highest degree of adequacy.

Kattegat boundary data needed for the Baltic model are the sea level, salinity and temperature of the Kattegat model boundary. These sea level data are gauged both on the Swedish side (Göteborg) and on the Danish side (Fredrikshavn). The difference between those levels is an important model parameter and provides the geostrophically adjusted flow. The absolute vertical position of these gauges is not possible to reconstruct reliably from available data; instead the long term average has been used to obtain this information. The salinity and temperature profiles are mainly determined by North Sea dynamics and display a repeating pattern from year to year /Gustafsson, 2000/; these averages have been used.

Bottom bathymetric data for the **B3D** model come from the Warnemünde Oceanographic Institute (http://www.io-warnemuende.de/research/en_iowtopo.html) covering the entire Baltic Sea from 9°00’ to 15°10’ East and from 53°30’ to 56°30’ North. The resolution is 2 (spherical) minutes with respect to latitude, and about 4 minutes with respect to longitude. This corresponds to a grid with a side length of approximately 1 nautical mile. For the **F3D** and the **L3D** models, the grid has been computed from a DEM based on national digitized charts and supplemented by shoreline information from economical maps, resolving the shoreline better. The grid was specified in spherical coordinates WGS84 (SWEREF 99 long lat ellh) with the constraint that to be considered as a wet grid cell, at least 50% of the covered area should consist of water. This necessitates some manual adjustments of channels connecting interior embayments.

The gridding has been performed by the National Land Survey of Sweden. The hypsographic data (area as a function of depth for the discrete basins and width as a function of depth for the straits) of the **CDB** model have been extracted from the 10 m resolution DEM /Brydsten and Strömgren 2005/ using GIS methods, supplemented by field assays performed in August 2005.

Ice formation and melting data pertaining to the **F3D** model stem from systematic data compiled by SMHI and the Swedish Maritime Administration, Figure 5-7a. This is not applicable for the **L3D** model since ice formation rarely occurs. The **B3D** model computes the formation and melting of the ice cover by means of a simple but straightforward mechanism. These data needed as forcing to the CDB model are mainly based on Sicada data but also in a few instances on local observations made by the Swedish Board of Fisheries.

Atmospheric forcing data pertain to all the involved models. The meteorological forcing data of the 3D models comprise wind velocity, at standard 10 m, air pressure, and air temperature sampled every third hour. The primary data used, known as the Mueller data set, has a horizontal resolution of (1°×1°) and consists of synoptic geostrophic wind that needs to be discounted to the standard 10 m level. In addition to the required variables it also includes data pertaining to humidity, cloudiness, precipitation and insolation. These data sets have been used in earlier modelling studies /Engqvist and Andrejev 1999, 2000/ and are made available by the Oceanographic Institute, Göteborg University. SMHI announced that this data set was to be discontinued after 2001. To make up for this loss, so-called Mesan data were offered as a substitute. The wind speed in 1981 for the centre of the Laxemar area is depicted together with a wind rose in Figure 5-7b.

The geographical coverage of both these grids spans the entire Baltic, Figure 5-8. For projected estimates of distant future coastal water exchange, more refined and explicit atmospheric thermal forcing (e.g. humidity, insolation and nebulosity) cannot be assumed to be readily available.

Initialization data for the local models have been produced by tentatively starting from climate average salinity and temperature profiles and then running the model for the month that precedes the starting date a number of times. Reiterated runs of the model are then performed with resulting salinity and temperature states at the end of month as initial data until the boundary properties have to a sufficient degree permeated into the central parts of model area through the boundaries. For the Baltic model, however, all consecutive intervening years have been run.

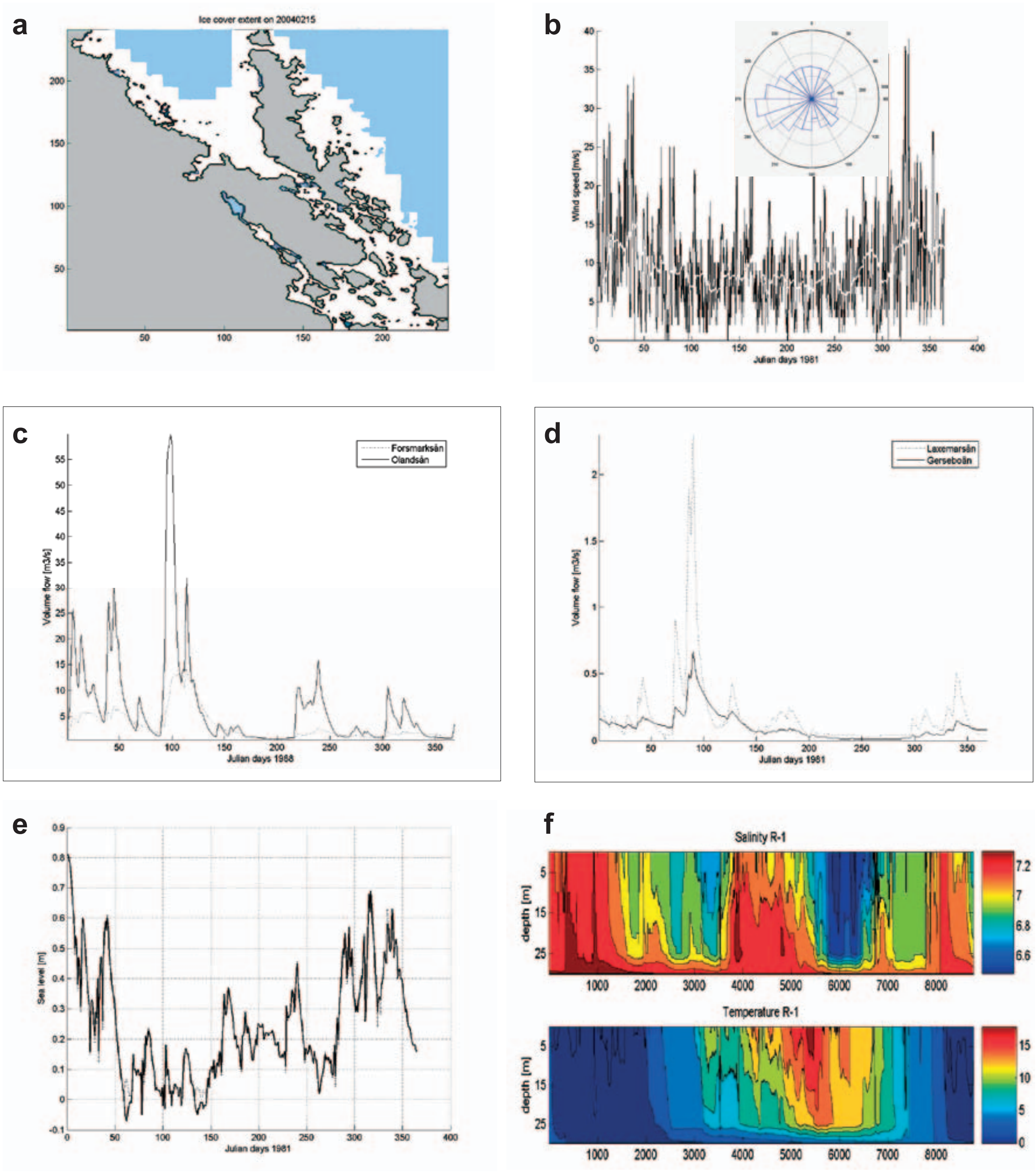


Figure 5-7a. Example of ice statistics concerning the Forsmark area with ice cover in white and land in gray, as presented by the Finnish Institute of Marine Research. ***7b*** *Wind forcing with 3-h resolution as measured at Ölands Norra Udde 1981 near the eastern border of the Laxemar grid. A running average of approximately 3 weeks is shown as a white broken line. A wind rose, showing that the predominant wind direction is from the WSW, is inset at the top.* ***7c*** *Water discharge of the two major streams Forsmarksån and Olandsån 1988.* ***7d*** *Discharge of the two major streams Laxemarån and Gerseboån 1981. Only Laxemarån discharges into the discrete basin model area.* ***7e*** *Sea level forcing of the coastal stations R-1(solid) and R-4 (broken). Only in a few periods (e.g. around day 60 and day 130) is there a noticeable difference between these curves. The computed sea levels of R-2 and R-3 fall within these limits.* ***7f*** *Computed salinity and temperature profiles during the type-year 1981 at a location corresponding to the location R-1 in Figure 4. The incidences of up- and downwelling occasions are clearly seen, as is the stabilizing thermal stratification during the summer period. The other three boundary stations R-2 through R-4 display similar profile dynamics with small variations.*

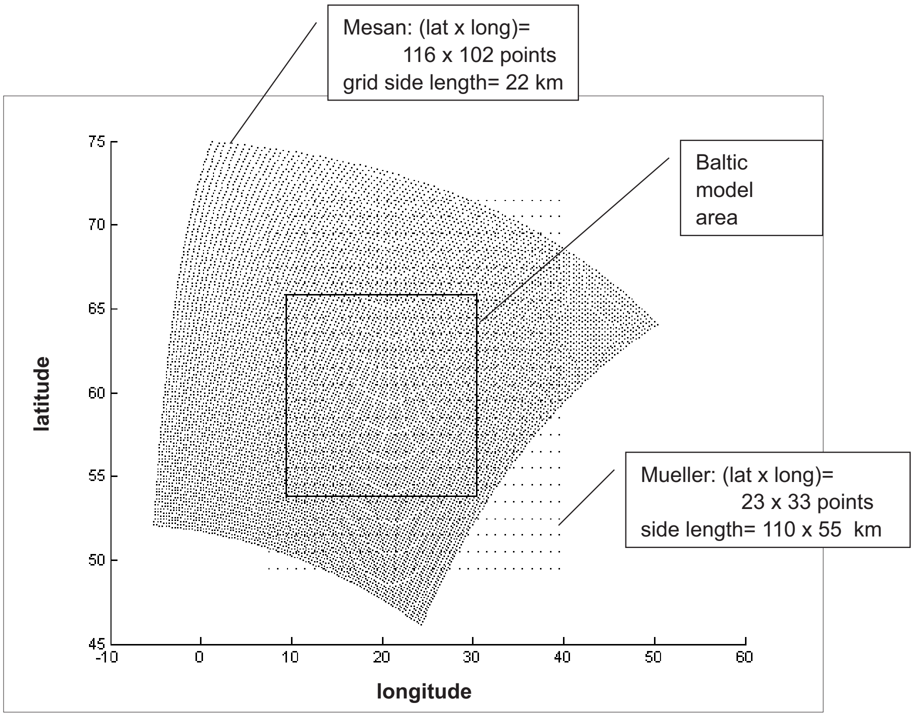


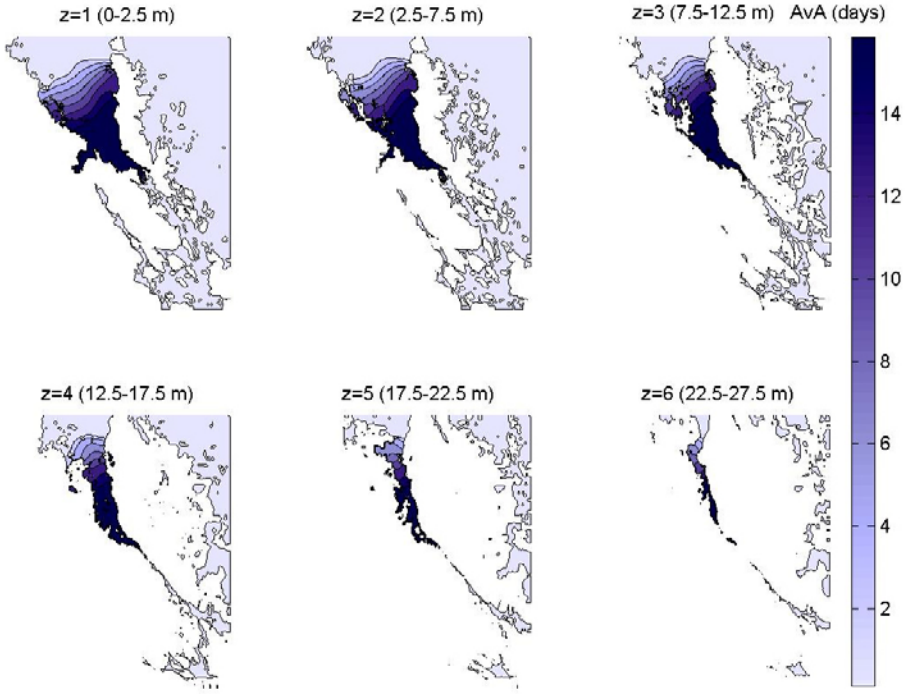
Figure 5-8. *Illustration of the transformation relationship between the two mutually rotated coordinate systems for the Mueller and the Mesan data sets. Both these data sets cover the Baltic model area domain completely.*

Freshwater discharge data for the **B3D** model are based for the type-years (1981 for Laxemar and 1988 for Forsmark) on 10-year averages of runoff data comprising the watershed of the entire Baltic, subdivided into 29 major river discharge locations, all with monthly resolution. For the recent year simulations involving the validation years 2004 and early 2005, the fresh-water discharge data were computed from HBV model data /Graham 1999/ with monthly resolution made available by Phil Graham of the Swedish Meteorological and Hydrological Institute (SMHI). The computation has been able to redistribute in proportion the estimated discharge of the HBV model's 15 areas into the 29 discharge points of the **B3D** model. For the **F3D** and **L3D** models the local freshwater discharge has been directly based on HBV model estimates obtained from the Sicada data base with weekly temporal resolution, Figures 5-7c and 5-7d.

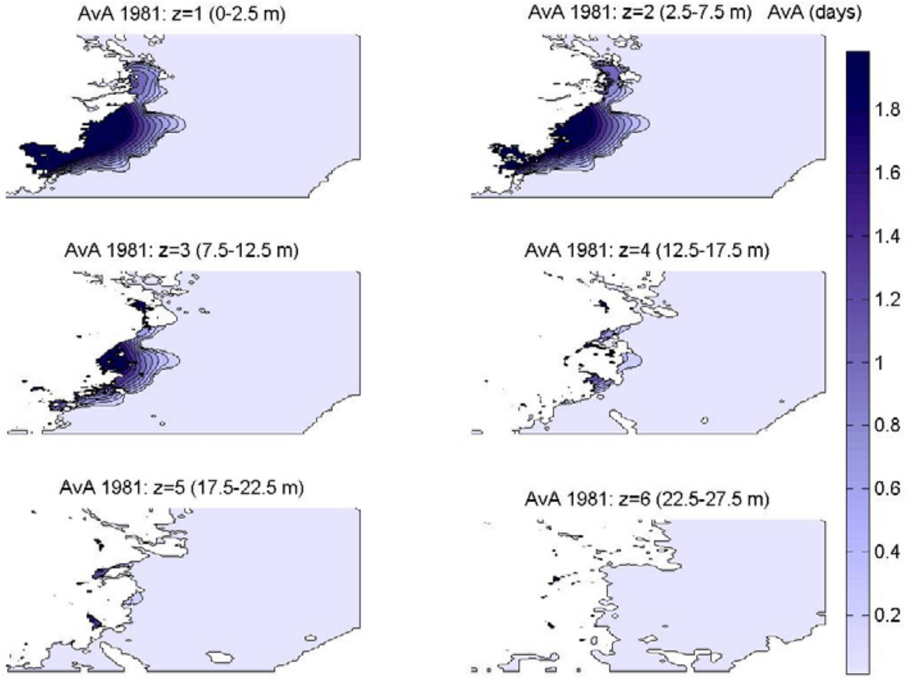
Sea level and density fluctuations at the peripheral boundaries of the respective model areas (i.e. the external border to other adjacent water bodies) concern the **B3D** model derived from (SMHI) sea level measurements at Göteborg harbour and the Danish Meteorological Institute's (DMI) corresponding records from Fredrikshavn. The sea level forcing of the **F3D** and **L3D** models is provided by the Baltic model and the corresponding forcing of the **CDB** model is in turn computed by means of the **L3D** model, Figures 5-7e and 5-7f. These data have hourly temporal resolution in common.

5.5 Results

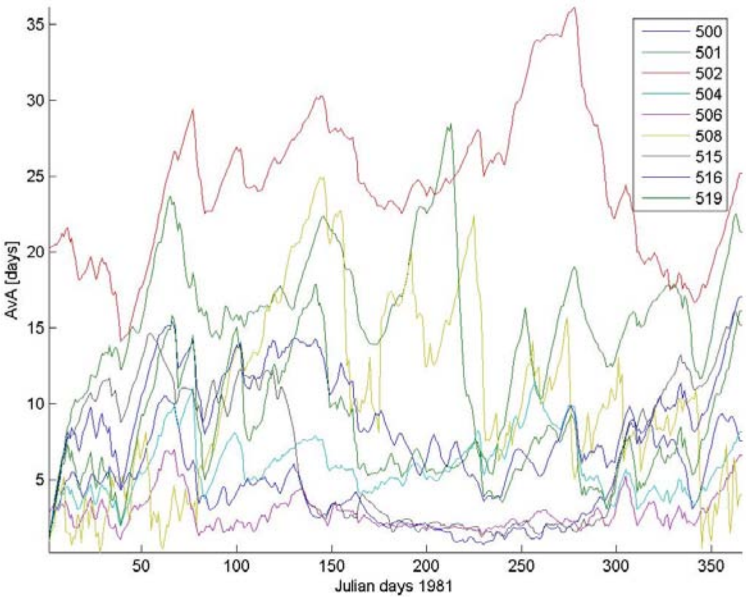
Employed 3D models have the capacity to generate a massive output of data. For the purpose of effective communication of results concerning the water exchange across transdisciplinary boundaries, these data are condensed into the preferred *AvA* measure. The yearly averages of these values are graphically presented with regard to their depth variation in Figures 5-9 through 5-11 for the **F3D**, **L3D** and **CDB** models and as yearly basin volume averages in Table 5-1 for the **F3D** model and Table 5-2 for the combined **L3D** and **CDB** models**.** All these AvA times are an order of magnitude smaller than the one-year cycle over which they are averaged. The intra-annual variations seem to be greater than the short-term inter-annual variations.



Figures 5-9. *AvA times calculated as a yearly average for the type-year 1988 considering the union of all SBs* ***collectively*** *ventilated relative to the adjacent sea. Exogeneous water enters from outside the boundaries of this union, and as the discharge of the two streams, Figures 5-4 to 5-7c. The calculation was based on bi-monthly samples of the AvA times for the different strata down to a depth of 27.5 m. Even for the innermost part of the major coastal subbasin (Öregrundsgrepen) the average AvA times are less than one year.*



Figures 5-10. *AvA times calculated as a yearly average for the type-year 1981 considering all the offshore SBs conjoined to a union as to obtain an appreciation of the general water renewal of this coastal section. Exogenous water is thus considered entering from the adjacent sea and also as discharge from the two streams, Figures 5-4-7d. The calculation is based on bi-monthly samples of the AvA times for the different strata down to a depth (27.5 m). Even for the innermost of the offshore SBs the average AvA times are less than one year and about one order of magnitude smaller than for the corresponding union of the SBs of the Forsmark area.*



Figures 5-11. *Calculations of the* ***individual*** *basin AvA times in 1981 for the inner Laxemar-Simpevarp SBs with each of the adjacent basins counted as exogenous water. These volume-averaged data form the basis of the statistics presented in Table 5-2. The spin-up time is about one month.*

Table 5-1. Individual AvA time [days] estimates for the 28 SBs of the Forsmark area in Figure 5-4 which means that these data are computed with all water outside an individual SB considered as exogeneous.

Basin	Min [days]	Mean S.D. [days]	Mean [days]	Mean S.D. [days]	Max [days]
100	0.045	0.253	0.345	0.437	1.718
101	0.063	0.289	0.391	0.492	1.626
102	0.038	0.47	0.676	0.883	1.004
103	0.031	0.104	0.127	0.151	0.161
104	0.015	0.054	0.067	0.08	0.411
105	0.062	0.343	0.487	0.631	4.261
106	0.026	0.083	0.137	0.192	0.86
107	0.031	0.132	0.217	0.302	1.535
108	0.051	0.141	0.189	0.238	1.001
109	0.013	0.022	0.045	0.068	1.882
110	0.024	0.086	0.124	0.162	1.545
111	0.308	0.619	0.994	1.369	2.843
112	0.008	0.02	0.023	0.026	0.044
113	0.01	0.021	0.031	0.041	0.854
114	0.07	0.301	0.444	0.587	4.063
115	0.025	0.078	0.119	0.16	2.261
116	0.114	0.489	0.74	0.991	1.347
117	0.551	0.576	1.411	2.245	4.227
118	0.276	0.309	0.666	1.022	1.703
120	0.087	0.293	0.329	0.366	0.439
121	0.083	0.219	0.27	0.322	0.354
123	0.029	0.091	0.125	0.158	1.721
126	0.033	0.167	0.245	0.322	0.395
134	0.016	0.022	0.024	0.027	0.039
146	0.025	0.073	0.091	0.108	0.696
150	0.392	0.612	0.686	0.761	0.884
151	1.059	3.281	4.52	5.759	6.897
152	0.188	0.419	0.524	0.628	0.763

Table 5-2 Individual basin AvA time estimates for the 19 SBs in the Laxemar-Simpevarp area, in the form of vertically integrated volume averages. The inner subbasins are computed with the CDB model, while for the offshore SBs these volume averages are calculated directly from L3D model results, which have a temporal resolution of one hour.

	min	mean S.D.	mean	mean+S.D.	max	model type
500	0.73	1.77	4.26	6.75	10.5	CDB
501	0.94	11.2	15.8	20.4	28.5	CDB
502	14.1	19.6	24.4	29.1	36.2	CDB
504	0.82	3.90	5.88	7.86	11.4	CDB
506	1.08	1.62	2.78	3.93	6.99	CDB
508	0.20	4.14	10.3	16.4	25.0	CDB
513	0.09	0.24	0.29	0.35	0.43	3D
514	0.03	0.04	0.31	0.57	1.78	3D
515	0.95	2.28	6.86	11.4	16.0	CDB
516	0.88	6.07	9.25	12.4	17.1	CDB
517	0.29	0.67	1.03	1.38	2.13	3D
518	0.02	0.05	0.40	0.75	1.10	3D
519	0.80	4.41	7.98	11.6	17.9	CDB
520	0.19	0.34	0.40	0.46	0.52	3D
521	0.24	0.57	0.81	1.04	1.53	3D
522	0.04	0.13	0.19	0.26	0.35	3D
523	0.03	0.15	0.27	0.38	0.62	3D
524	0.01	0.08	0.14	0.19	0.25	3D
525	0.08	0.22	0.31	0.40	0.56	3D

When the model results are needed for the water exchange of the associated ecological (integrated) models, however, the flow rates are explicitly computed with an hourly temporal resolution, which can subsequently be averaged into the chosen resolved timescale of the these models. The intra-annual variations may then be represented by an S.D. measure. Since the results are given with regard to the subbasins into which the whole model area has been subdivided, a direct comparison between these areas will to some degree also reflect various sizes, Tables 5-3 and 5-4.

Table 5-3. Average flow (m^3/s) between basins of the Forsmark area. The positive flows go in the direction indicated by 'from' → 'to' and the negative flows in the opposite direction. The sum of these fluxes (with sign) renders the net flow with the sign giving its direction. These estimates have been passed on to the ecological (integrated) model.

Basin ID from	to	Pos. flow [m^3/s]	Neg. flow [m^3/s]	Net flow [m^3/s]
Basin102	The Baltic	2,188.5	–3,006.5	–818.0
Basin100	The Baltic	6,101.0	–4,640.6	1,460.4
Basin101	The Baltic	556.0	–1,268.9	–712.9
Basin101	Basin102	691.4	–1,183.7	–492.2
Basin101	Basin100	1,099.0	–1,112.7	–13.7
Basin103	Basin102	816.0	–918.1	–102.1
Basin104	Basin102	118.2	–346.7	–228.5
Basin104	Basin101	294.7	–173.0	121.7
Basin104	Basin103	13.3	–47.9	–34.6
Basin105	Basin100	2,940.9	–1,469.5	1,471.4
Basin105	Basin101	1,611.2	–2,405.1	–793.9
Basin107	Basin101	8.3	–23.3	–15.0
Basin107	Basin104	130.3	–252.2	–121.9
Basin110	Basin101	139.5	–359.3	–219.8
Basin110	Basin105	1,334.8	–1,081.4	253.4
Basin108	Basin101	715.4	–1,030.4	–315.1

Basin ID from	to	Pos. flow [m³/s]	Neg. flow [m³/s]	Net flow [m³/s]
Basin108	Basin107	187.2	–414.9	–227.7
Basin108	Basin110	297.2	–100.1	197.1
Basin112	Basin110	177.9	–184.9	–7.0
Basin116	Basin110	694.8	–517.0	177.8
Basin116	Basin108	360.9	–707.6	–346.6
Basin116	Basin112	230.4	–237.5	–7.1
Basin117	Basin107	31.3	–21.0	10.3
Basin117	Basin108	2.2	–2.2	0.0
Basin118	Basin117	7.2	–7.0	0.2
Basin121	Basin116	106.5	–175.2	–68.7
Basin121	Basin120	0.8	–0.8	0.0
Basin123	Basin110	21.8	–40.0	–18.2
Basin134	Basin121	0.03	–0.03	0.00
Basin126	Basin110	15.4	–15.7	–0.3
Basin126	Basin116	81.8	–190.9	–109.1
Basin126	Basin121	79.3	–148.6	–69.3
Basin126	Basin123	239.8	–180.9	58.9
Basin146	Basin123	474.7	–342.8	131.9
Basin146	Basin126	167.3	–287.8	–120.6
Basin151	The Baltic	169.9	–55.7	114.2
Basin151	Basin123	959.3	–1,199.3	–239.9
Basin150	Basin146	103.4	–92.6	10.8
Basin152	Basin150	12.8	–2.7	10.1
Basin106	Basin103	39.6	–86.4	–46.7
Basin106	Basin104	50.5	–70.4	–19.9
Basin106	Basin107	162.7	–94.2	68.5
Basin109	Basin105	617.2	–549.2	68.0
Basin111	Basin103	24.9	–46.4	–21.5
Basin111	Basin107	34.0	–22.7	11.4
Basin111	Basin117	24.9	–15.6	9.3
Basin111	Basin106	23.1	–21.5	1.6
Basin113	Basin105	183.4	–467.8	–284.4
Basin113	Basin110	75.6	–289.9	–214.2
Basin113	Basin109	321.9	–230.9	91.0
Basin115	Basin110	51.9	–154.3	–102.5
Basin115	Basin123	229.7	–154.9	74.7
Basin115	Basin109	46.0	–35.9	10.0
Basin115	Basin113	393.8	–801.6	–407.8
Basin114	Basin105	1,435.5	–798.2	637.3
Basin114	Basin123	697.5	–742.2	–44.8
Basin114	Basin151	1,055.4	–1,186.6	–131.1
Basin114	Basin109	504.1	–537.4	–33.3
Basin114	Basin115	1,198.2	–1,624.3	–426.1

Table 5-4 Yearly average volume flow (m^3/s) between the subbasins of the Laxemar area. A positive flow goes consistently from an SB with a higher ID number to one with a lower such number. The sum of these fluxes (with sign) renders the net flow with the sign giving its direction. Estimates to two decimals pertain to the DB model. Flow estimates have been passed on to be used in the ecological (integrated) model.

From basin	To basin	Pos. flow [m^3/s]	Neg. flow [m^3/s]	Net. flow [m^3/s]
501	500	0.88	–0.88	0.00
504	502	2.20	–2.19	0.01
506	504	0.18	–0.20	–0.02
508	506	1.27	–1.09	0.18
508	502	0.66	–0.66	0.00
514	513	64.5	–57.1	7.37
517	515	13.3	–13.3	–0.02
517	515	9.39	–9.39	0.00
518	514	112	–87.2	24.3
518	516	81.0	–81.0	0.00
520	517	2.17	–1.31	0.86
520	519	0.39	–0.39	0.00
521	500	3.59	–3.76	–0.16
521	504	2.53	–2.49	0.04
521	506	4.10	–4.30	–0.20
521	513	202	–210	–7.43
521	514	55.9	–75.5	–19.6
521	500	24.4	–24.5	–0.10
521	504	2.37	–2.35	0.02
521	506	4.02	–4.23	–0.21
522	521	900	–961	–61.0
523	514	44.3	–41.8	2.58
523	518	40.6	–59.0	–18.4
523	521	1,855	–1,820	34.9
523	522	1,145	–1,001	143
524	518	150	–107	42.8
524	523	1,478	–1,122	356
525	517	167.2	–168.2	–0.98
525	520	32.6	–31.8	0.83
525	524	1,569	–1,277	292
Baltic	521	4,085	–4,087	–2.34
Baltic	522	6,387	–6,591	–204
Baltic	523	3,144	–3,337	–194
Baltic	524	11,959	–11,852	106
Baltic	525	4,175	–3,883	291

5.6 Confidence and uncertanties

5.6.1 Sensitivity analysis

Sensitivity analysis with regard to variations of the forcing has been performed for the **F3D** model /Engqvist and Andrejev 2000/. The greatest sensitivity occurred when the wind speed was reduced by 10% in both the **F3D** and the **B3D** models, which resulted in a 9% increase of the *AvA* measure. The two sensitive forcing parameters for the **CDB** model were additional precipitation and higher frequencies of sea level forcing. The former affects all basins and enhances the estuarine circulation, while the latter increases the net water exchange, above all in the comparatively shallow inner basins. Artificially decreasing the hypsographic surface areas of the basins proportionally has a much greater impact on the *AvA* times than increasing them.

5.6.2 Validation analysis

The most pertinent studies of the uncertainties are the two validation programmes that were launched in order to collect oceanographic data and compare them with corresponding model data. This work has been concluded for the Forsmark area /Engqvist and Andrejev 2008/ but is still going on for the Laxemar-Simpevarp area. Thus only the findings for the first investigated **F3D** model area can be related. Preliminary analysis makes it highly likely that the findings concerning the **L3D** area give improved correlation coefficients on comparison of measured and simulated data.

The major shortcoming of this modelling approach is the inability of the B3D model to maintain the salinity concentration gradients over the extended modelling period, in the case in question consisting of 16 consecutive months /Engqvist and Andrejev 2008/. At least this applies to the transition zone between the Gulf of Bothnia and the Baltic Proper offshore of the Forsmark coastal area. As for the prospect of using these models for estimates projected into the distant future, this does not constitute an unsolvable difficulty since the density structure of the Baltic will, for such projections, probably only be available in general terms that are suitable for data assimilation /Westman et al. 1999/ so that the mean stratification can be upheld. With its present horizontal resolution, the Baltic model does not resolve all the relevant oceanographic features offshore of the Forsmark area. The nested coupling between the **B3D** and **F3D** models yields an acceptably good correlation of salinity between measured and simulated data of an inner station near the centre of the **F3D** area. These arguments seem to permit the conclusion that both the model approach and the design of the validation scheme may be continued to be invested with confidence.

When the Mueller and the Mesan wind data for the same year, 2004, are compared for corresponding closest points in space and time for the entire set of the Mueller grid /Engqvist and Andrejev 2008/, an overall correlation coefficient of typically 50% results. Limiting the analysis to include only one wind station location in the **F3D** domain greatly improves the correlation coefficients, revealing that the Mueller data are systematically higher and closer to the logged wind speed than the Mesan data, Figure 5-12a. The corresponding comparison of a wind station in the immediate vicinity of the **L3D** area yields no such systematic deviation, but an improved correlation for the Mesan data set. Together with the sensitivity analysis of the wind forcing of the **F3D** model, this suggests that it is important to estimate this forcing factor as correctly as possible when the models are used to estimate the circulation of a distant future state of the Baltic Sea.

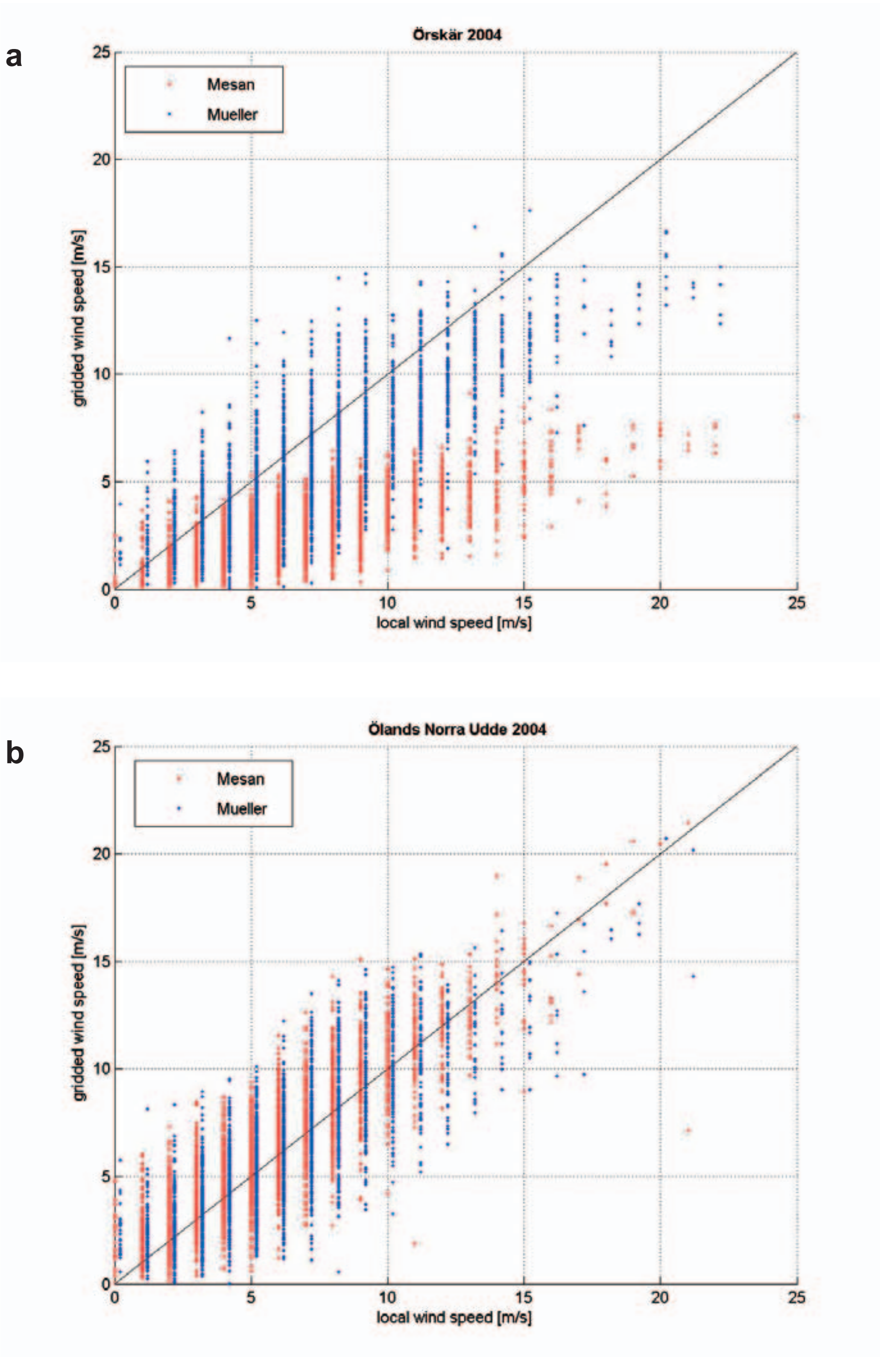


Figure 5-12 a and b. *(a, left panel) Comparison of wind speed for 2004 measurements at Örskär vs. the Mesan and the Mueller data sets. The Mueller data have been adjusted to match the 10 m level of the Mesan data and yield a considerably better match with the black diagonal line, indicating ideal agreement. The correlation coefficient is also slightly improved: ρ=0.73 compared with 0.71 for the Mesan data(b, right panel) A corresponding scatter diagram for the meteorological station at Ölands Norra Udde gives a correlation coefficient of 0.84 for the Mesan data and 0.77 for the Mueller data. In both panels, the Mueller data set has been graphically shifted to the right in order to prevent the two sets blocking each other.*

6 Marine ecosystem – ecosystem models, mass balances and elemental composition

Marine ecosystem models have been developed for the marine basins in Forsmark and Laxemar-Simpevarp to describe the transfer of energy between functional groups and abiotic pools in the ecosystem. The developed marine ecosystem models are, as far as the available data permits, site specific and spatially distinct between the sites and within the sites. Ecosystems models can be developed for any element. In this case carbon has been used as a proxy for energy transfer. Carbon constitutes the major part of the biomass in ecosystems, and besides reflecting the biomass it also represents the maximum accumulation of any element in biota except water. Mass balances can be useful to develop in connection with ecosystem models to strengthen the conclusions from the ecosystem models and to illustrate large-scale characteristics of pools and fluxes in the ecosystem. Elements and/or groups of elements in the marine environment will accumulate/dissolve to a varying degree in various media/pools and be transferred to a varying degree between media, and to illustrate possible major sources and sinks of elements in the marine area, a general elemental composition of marine abiotic and biotic pools has been described.

The results of the marine ecosystem models for carbon (C), nitrogen (N), phosphorus (P) and mass balances for C, N, P, iodine (I), thorium (Th) and uranium (U) are presented in this chapter, along with the elemental composition (49 elements) of abiotic and biotic pools in the marine basins in Forsmark and Laxemar-Simpevarp. C, N and P have been chosen since they are the most important elements in biota in terms of mass. Moreover carbon may be used to describe the flux of C-14, one of the radioactive elements of interest for the safety assessment. I and the actinides (Th and U) since they are elements which represent a large span of particle affinity (Kd) and they are therefore of importance with regard to the safety analysis as they can be used as representatives of radionuclides with different sorption properties /SKB 2006a/. Data presented in Chapters 3 and 4 of this report have been used as quantitative input to the marine ecosystem model, the mass balances and the presentation of elemental compositions in marine pools.

The results of the marine ecosystem model, describing the spatial distribution of carbon in the whole marine model area and in separate basins (Appendix 7), are presented initially (Sections 6.1.1–6.1.2) for each site (marine basins described in Chapter 4 and shown in Figure 4-1 and 4-2). Mass balances for C, N, P, I, Th and U in the whole marine model area are then presented (Section 6.1.3). This section is followed by a third section describing the elemental composition of the marine pools in Forsmark and Laxemar-Simpevarp (Section 6.1.4). The final section (6.1.5) presents marine ecosystem models for C, N and P and mass balances for C, N, P, I, Th and U for 5 specifically chosen basins at each site. These basins are specifically presented since they fulfil two criteria: (i) they are basins where the density of site-specific in data is high and (ii) they are located where exit points for radionuclides were located in a preliminary safety assessment, see /SKB 2005/. In Appendix 8 the results from the marine ecosystem model calculations for carbon is presented. In Appendix 9 pools and fluxes from massbalance calculations, for carbon, nitrogen, phosphorus, thorium, uranium and iodine are presented.

6.1 Marine ecosystem model – Forsmark

The results of the marine ecosystem modelling of carbon (C) are presented below at a model area scale for the Forsmark model area, i.e. the marine area divided into basins (described in Chapter 4 and displayed in Figure 4-1). The food webs of the marine ecosystem are also presented forcarbon (C), nitrogen (N) and phosphorus (P).

6.1.1 Biomass distribution

Total biomass varies from just over 5 gC m^{-2} to 160 gC m^{-2} in the whole area and is distributed unevenly, focused mainly along the coast and in shallow areas. Mean biomass is 18 gC m^{-2} in the whole area, resulting in an estimated total of 4,400 tonnes of carbon fixed in biota in all basins. The mean biomass in separate basins ranges between 7 and 106 gC m^{-2}. In 14 out of 29 basins the mean biomass is higher than the mean biomass for the whole area. The lowest biomass values are found in the deep areas offshore, with biomasses of 5.5 to 8 gC m^{-2} comprising bacteria and plankton and to some extent benthic fauna.

Biomass in most basins is dominated by macrophytes, 4 to 87% of the biomass in separate basins (the latter figure in basin 152). Macrophytes are especially dominating in basins along the western coastline. In the east, Öregrundsgrepen is steeper and the depths in the basins deeper and therefore not as suitable for macrophytes. Here, the consumer part of the biomass is larger and detrivores dominate the total biomass (5–38% of the biomass in separate basins). Apart from these two macroscopic organism groups, the third and fourth largest biomass in the area belongs to microphytes and benthic bacteria up to 19%, of the biomass in separate basins. Other organisms contribute less than 10% of the total biomass, see Figure 6-1. Basin-specific biomass data in gC m^{-2} are found in Appendix 8. Primary producers (dominated by macrophytes) are the most abundant group in most of the basins, especially in the coastal zone. In offshore basins benthic fauna tend to dominate. Pelagic fauna is the smallest group in all basins.

The annual average biomasses for functional groups in the whole marine area are presented in Figure 6-2. In comparison with biomass data from other studies (described in Section 3), the modelled average biomass values for the whole area are somewhat lower, probably due to the fact that the modelled values are interpolations over the whole area with various abiotic characteristics such as suitability of substrate etc while other studies have focused on specific habitats. However, the biomass ranges are in the same size order as others reported.

The biomass is dominated by benthic organisms. The benthic component of the total biomass is shown in Figure 6-3. Altogether, 70–100% (average 91%) of the biomass in all basins consists of benthic organisms.

As Figure 6-1 indicates, the biomass decreases with depth and distance from land. This is clearly illustrated in Figure 6-4, where the mean depth of the basins is plotted against the mean annual biomass in each basin.

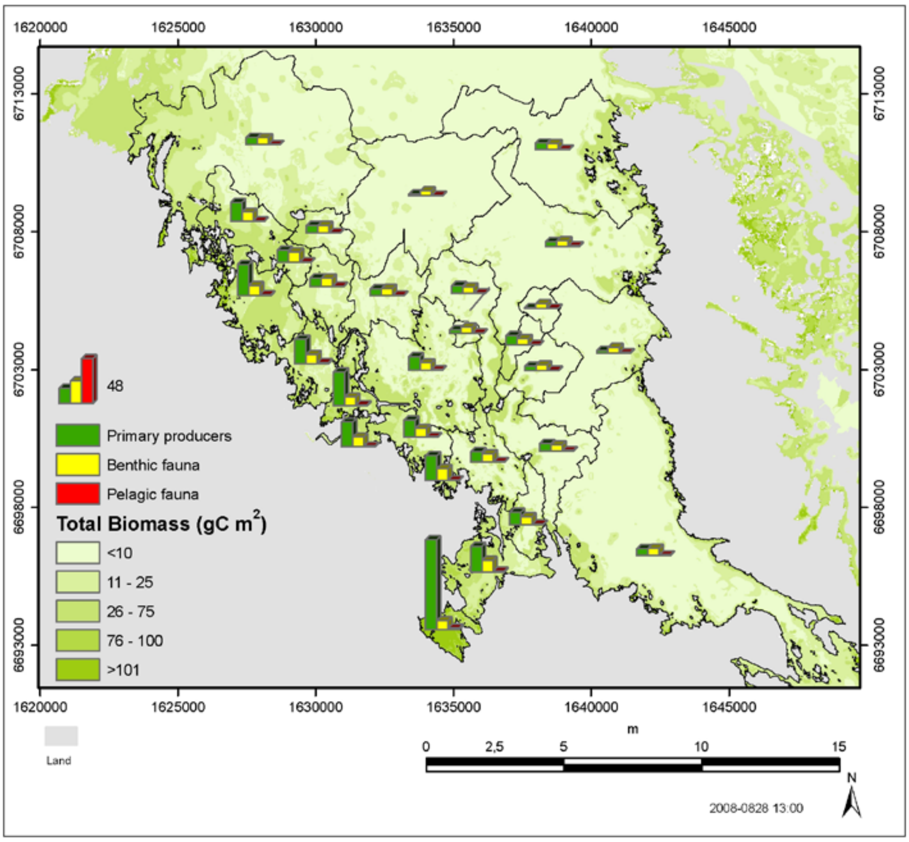


***Figure 6-1.** Proportional biomass distribution of the functional groups in the various basins: primary producers, benthic fauna and pelagic fauna, and total biomass (shaded in background) (g C m^{-2}) for all basins in the Forsmark area. For biomasses in figures per basin, see Appendix 8.*

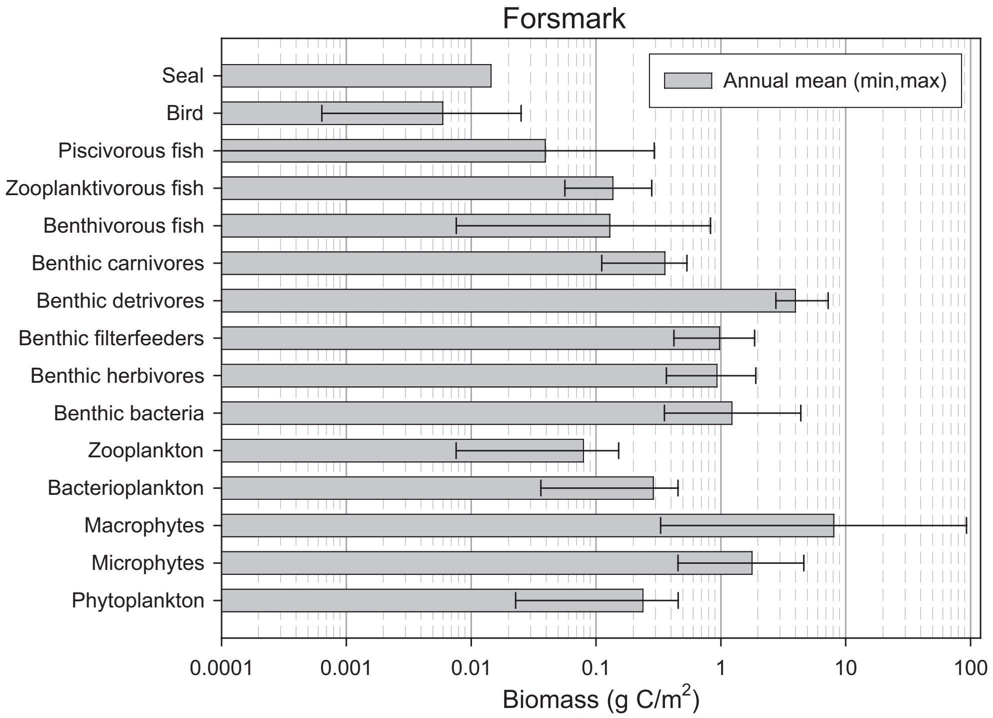


***Figure 6-2.** Annual average biomass (gC m^{-2}) for functional groups of marine biota in the whole marine model area in Forsmark (average for all basins in Forsmark).*

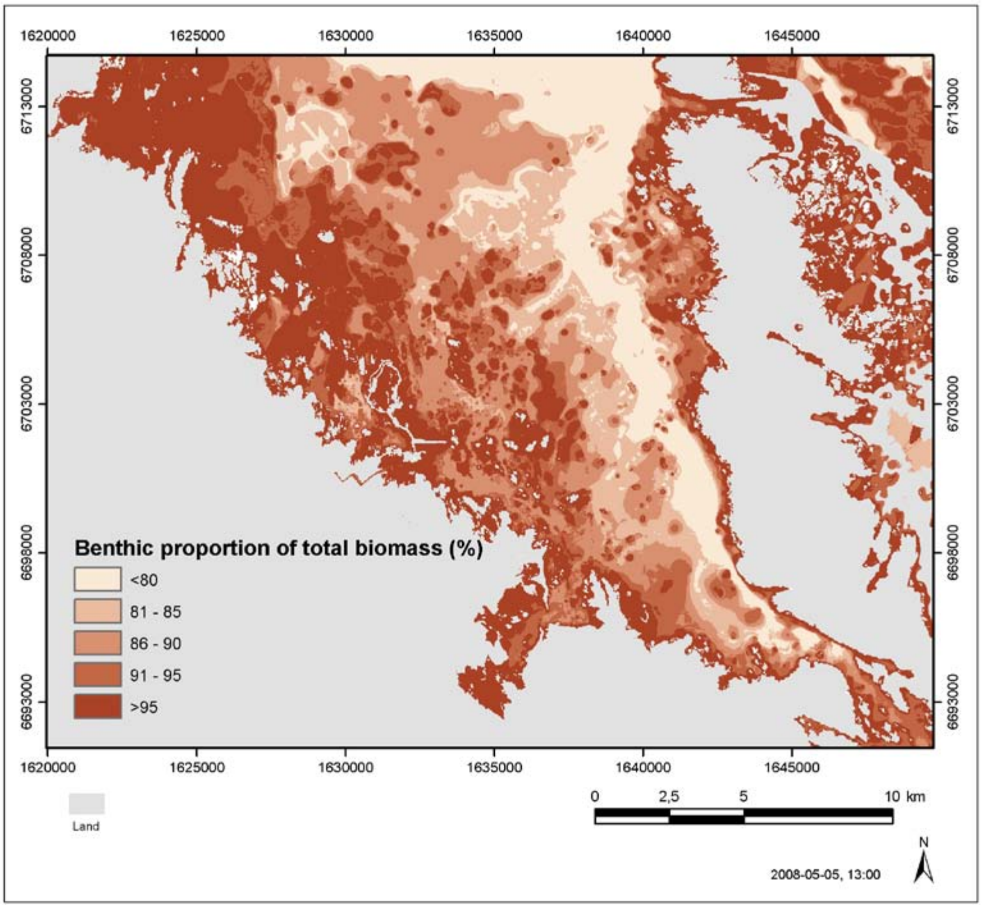


***Figure 6-3.** Proportion in (%) of the benthic component of total biomass in the Forsmark area.*

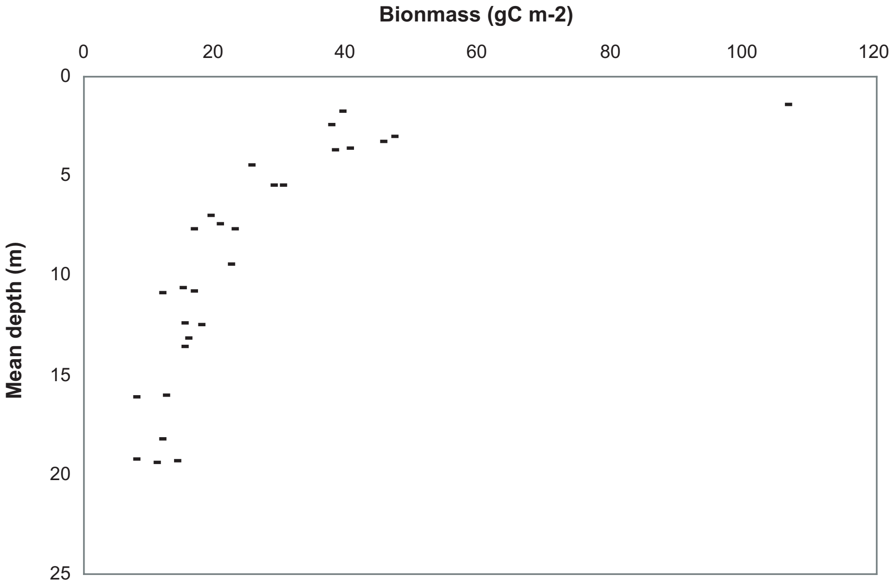


Figure 6-4. Mean biomass (gC m^{-2}) plotted against mean basin depth for all basins in the Forsmark model area.

6.1.2 Primary Production

Like biomass, net primary production (NPP) is concentrated at the shoreline, where the highest values are found, but also in the offshore areas where depth, higher water transparency and availability of nutrients permit high phytoplankton production. The mean annual NPP in the whole marine area in Forsmark is 100 gC m^{-2}. The mean NPP in separate basins ranges from 43 to 287 gC m^{-2}. The mean NPP is above the mean for the whole marine area in 12 out of 28 basins. The maximum values in individual basins (over 250 gC m^{-2}) are found along the shoreline in densely vegetated areas, e.g. in Kallrigafjärden (basin 150 and 152), but high values are also found in small areas of the deeper exposed coastal basins, see Figure 6-5. The NPP values are in the same range as reported in other studies /Gazeau et al. 2004, Pergent-Martini et al. 1994/ in the Baltic.

The benthic and pelagic components of the NPP display roughly the opposite pattern (Figure 6-6); pelagic increases and benthic decreases with depth. This is probably due to the fact that the benthic primary producers are restricted by the depth of the sea floor while increasing depth increases the volume where phytoplankton can photosynthesize and the deeper areas occur in the more outer areas where also the water transparency is greater than in the coastal zone of the area. In the whole marine model area the benthic community contributes 77% of the total NPP, which decreases with increasing depth, Figure 6-7.

6.1.3 Consumption

The most consumed component of the marine ecosystem in Forsmark is the abiotic pool of carbon, dissolved organic carbon (DOC), which is consumed mainly by bacterioplankton, followed by consumption of sediment and consumption of particulate organic carbon (POC), Figure 6-8.

The functional group that consumes the largest amount of carbon per year is bacterioplankton, followed by benthic detrivores and meiofauna, Figure 6-9. This is somewhat surprising since the bacterioplankton have a smaller biomass than the benthic bacteria. This is an indication of uncertainties in the calculations as it suggests either an overestimation of consumption by bacterioplankton or an underestimation of consumption by benthic bacteria because they are calculated in different ways (see Section 4). A modelled factor for the consumption/biomass ration was used for bacterioplankton /Sandberg et al. 2000/, while consumption by benthic bacteria was calculated using a consumption/respiration factor of 2 from /Kumblad et al. 2003/.

6.1.4 Heterotrophic respiration

The distribution of total benthic and pelagic respiration is presented in Figure 6-10. Total respiration includes only respiration by heterotrophs (consumers) as respiration by primary producers is included in the NPP presented above. Values range from 31 to 162 gC m^{-2}, with an average of 76 gC m^{-2}, in the whole marine area, which is in accordance with other reported values for respiration in the Baltic (74 gC m^{-2}) /Gazeau et al. 2004/. Respiration is not as clearly differentiated between the deep offshore areas and the coastal zone as biomass and NPP, although on a basin level, as illustrated by Figure 6-10, respiration generally increases with depth. 10 out of 28 basins have an annual mean respiration above the mean respiration for the whole area, and of these all but two are offshore basins. The two exceptions (Basin 152 and 134) are basins with high bacterial and benthic fauna biomass.

The largest component of the respiration in most basins is respiration by bacterioplankton, which on average constitutes 35% of the total annual respiration and ranges from 6 to 58% in separate basins. This result is in accordance with /Algesten 2006/, who demonstrated that the largest net flux of CO_2 emission is due to bacterial meneralistation. The second largest component of the respiration is benthic detritivores, followed by benthic bacteria with an annual average per basin of 28 and 16% of the total respiration, respectively, Figure 6-11. The same argument as in the section above (Section 6.1.3) regarding consumption by bacterioplankton and benthic bacteria can be applied here, since they are not calculated the same way and indicate an uncertainty in the calculations.

When benthic and pelagic respiration are examined separately (Figure 6-11), they display, like NPP, roughly the opposite pattern. Pelagic respiration increases and benthic respiration decreases with depth. The increase of pelagic respiration is primarily a result of higher biomass due to increasing depth. The decrease in benthic respiration is due to two factors: a smaller biomass and a decrease in temperature in the benthic habitat. The mean pelagic temperature also decreases with depth, but this is compensated for by the biomass increase. The correlation between respiration and depth is presented in Figure 6-12.

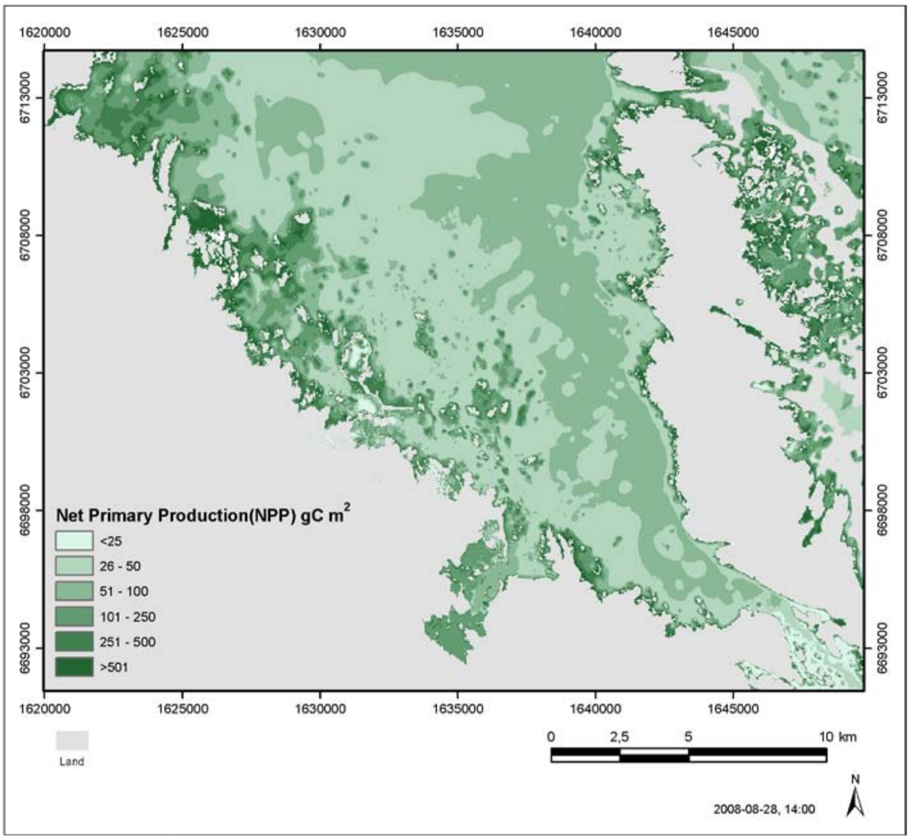
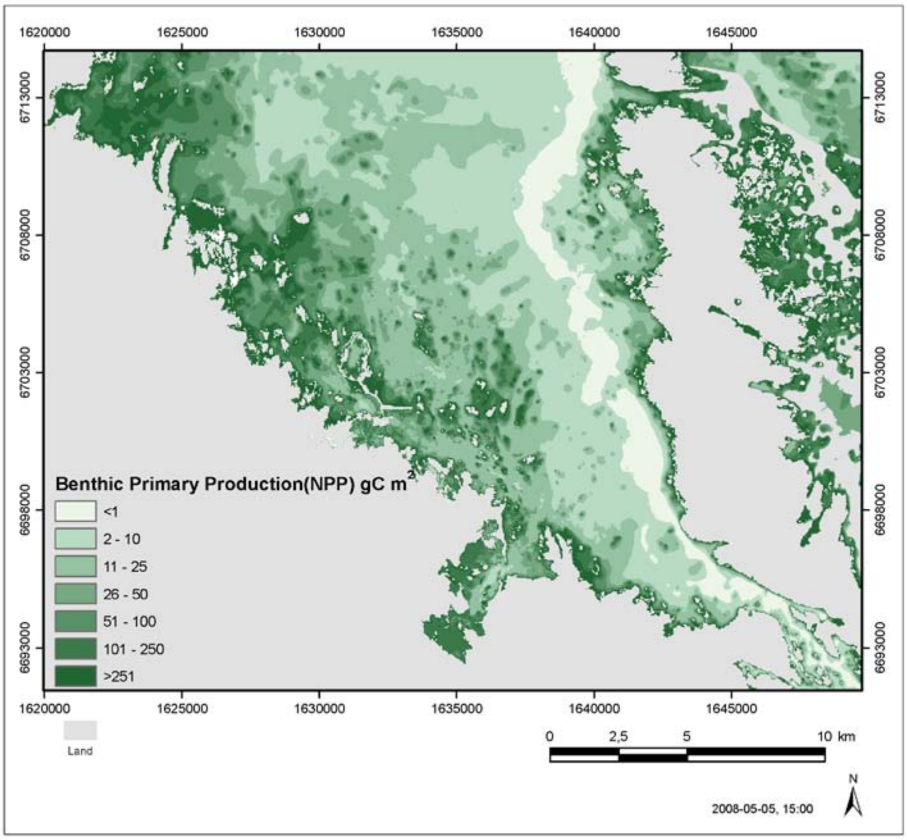


Figure 6-5. Net Primary Production (gC m^{-2} y^{-1}) in the Forsmark area. Higher NPP is indicated by increasingly dark green colour.



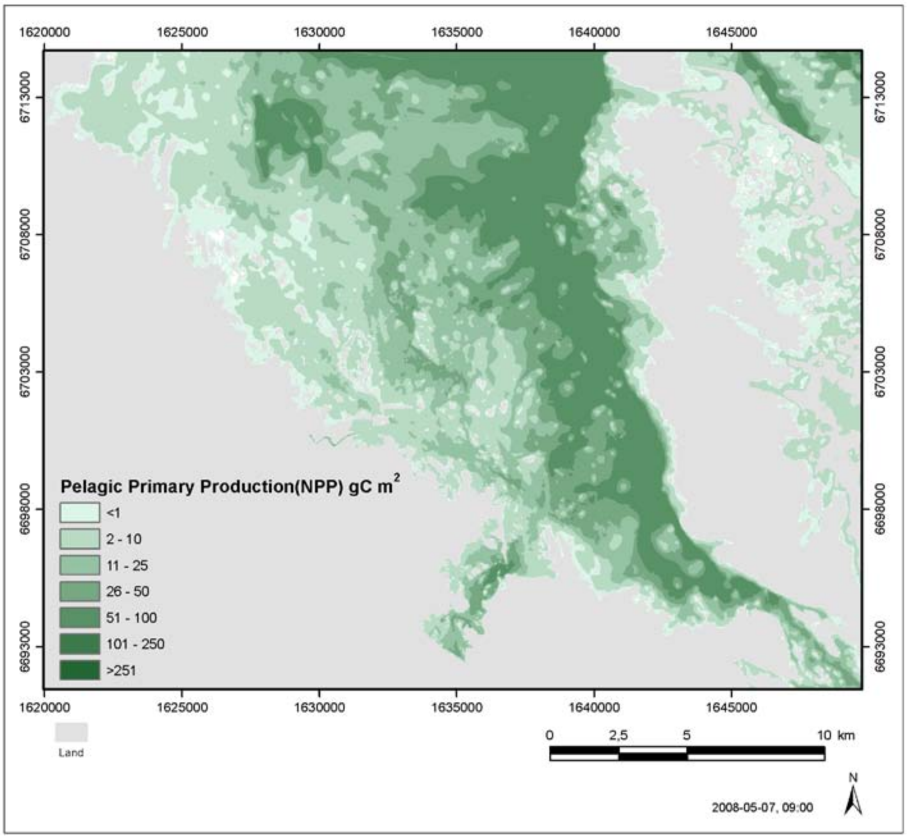


Figure 6-6. *Benthic (above) and pelagic (below) Net Primary Production (gC m^{-2} $year^{-1}$) in the Forsmark area. Higher NPP is indicated by increasingly dark green colour.*

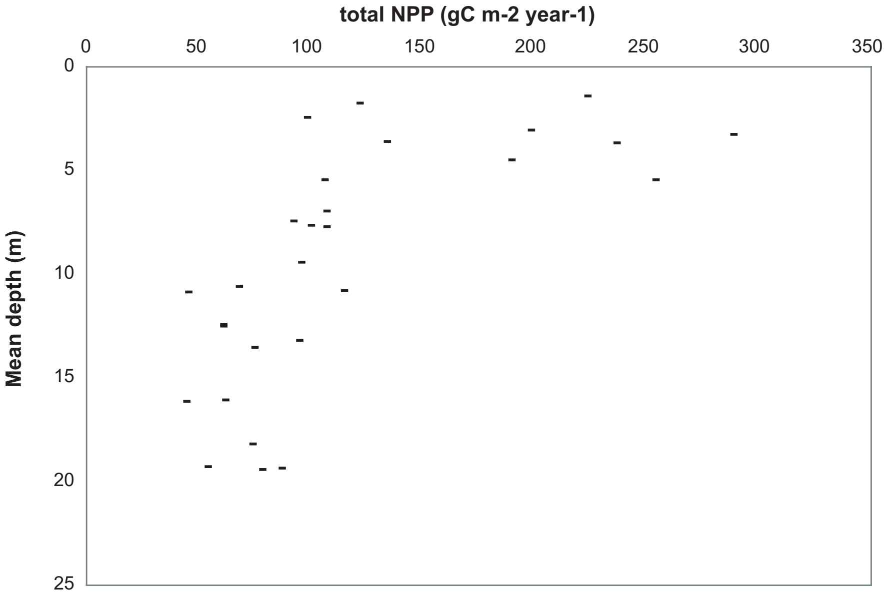


Figure 6-7. Mean NPP (gC m^2 year^{-1}) plotted against mean basin depth for all basins in the model area.

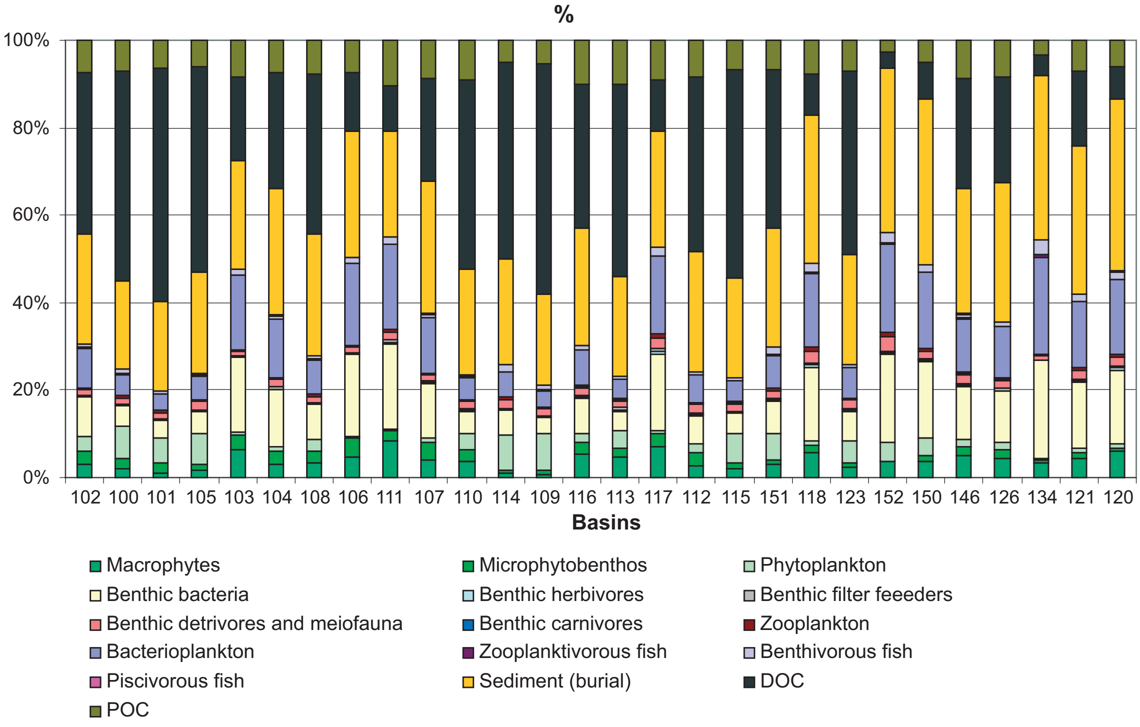


Figure 6-8. Percentage annual consumption of the biotic and abiotic pools in the ecosystem, in separate basins, in the marine area in Forsmark.

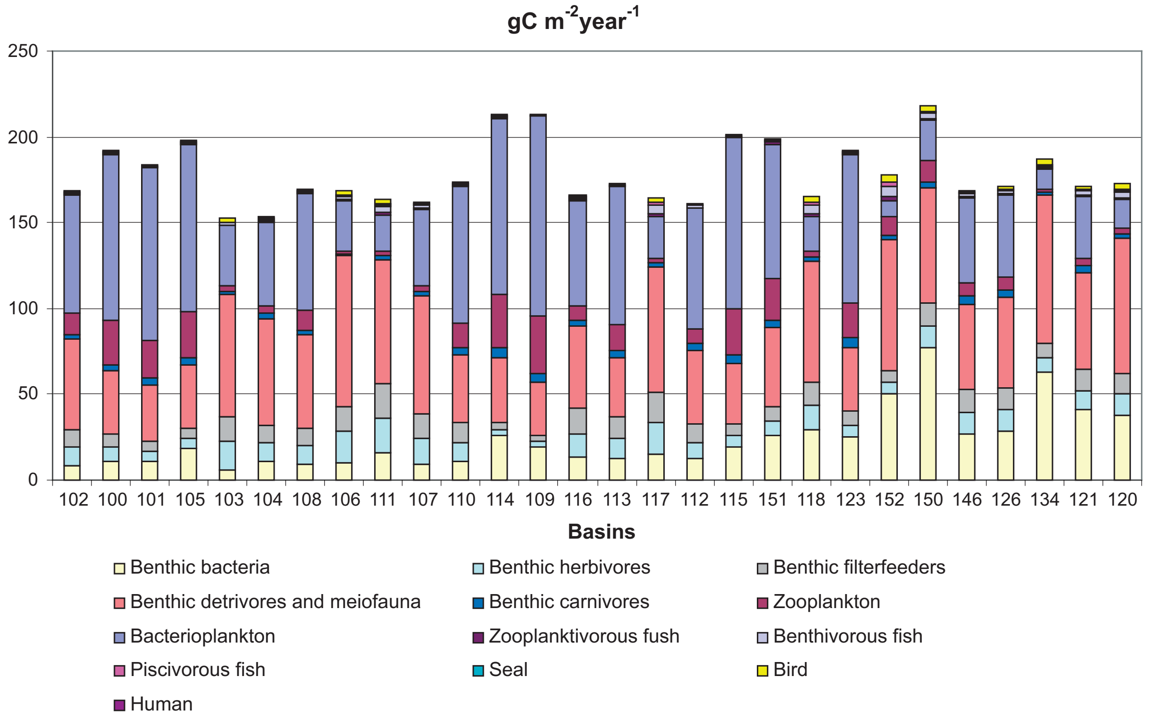


__Figure 6-9.__ The annual mean consumption, in gC m^{-2} year^{-1} in separate basins, by different consumers in the ecosystem in Forsmark.

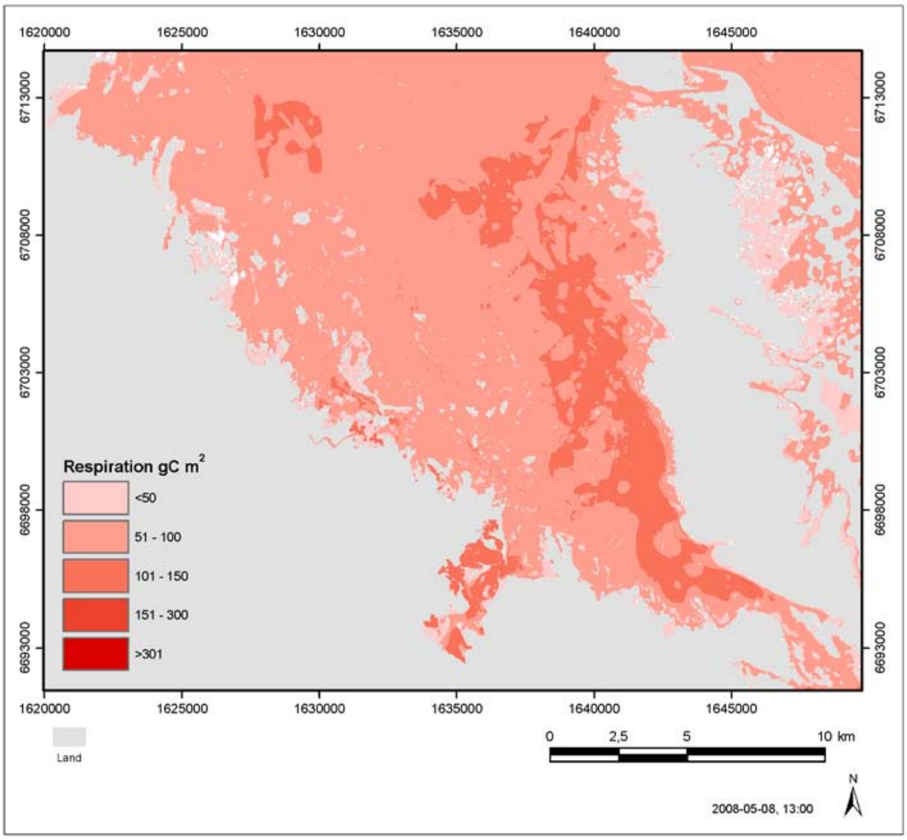
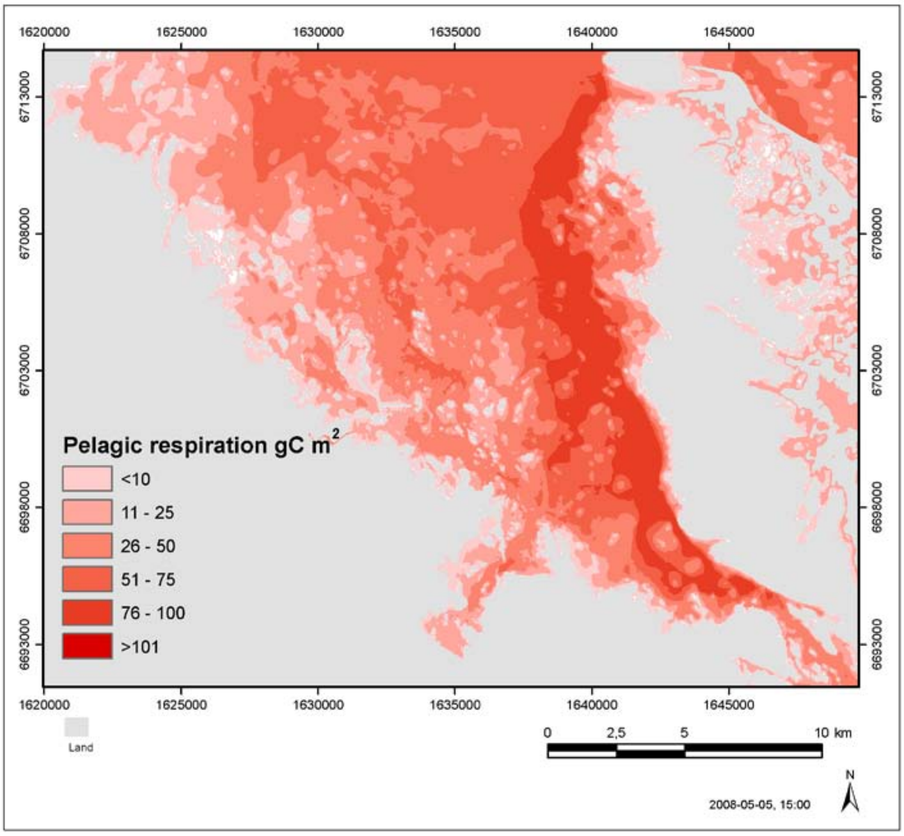


__Figure 6-10.__ The sum of heterotrophic respiration (gC m^{-2} year^{-1}), both benthic and pelagic, in the Forsmark area. Higher respiration is indicated by increasingly dark red colour.



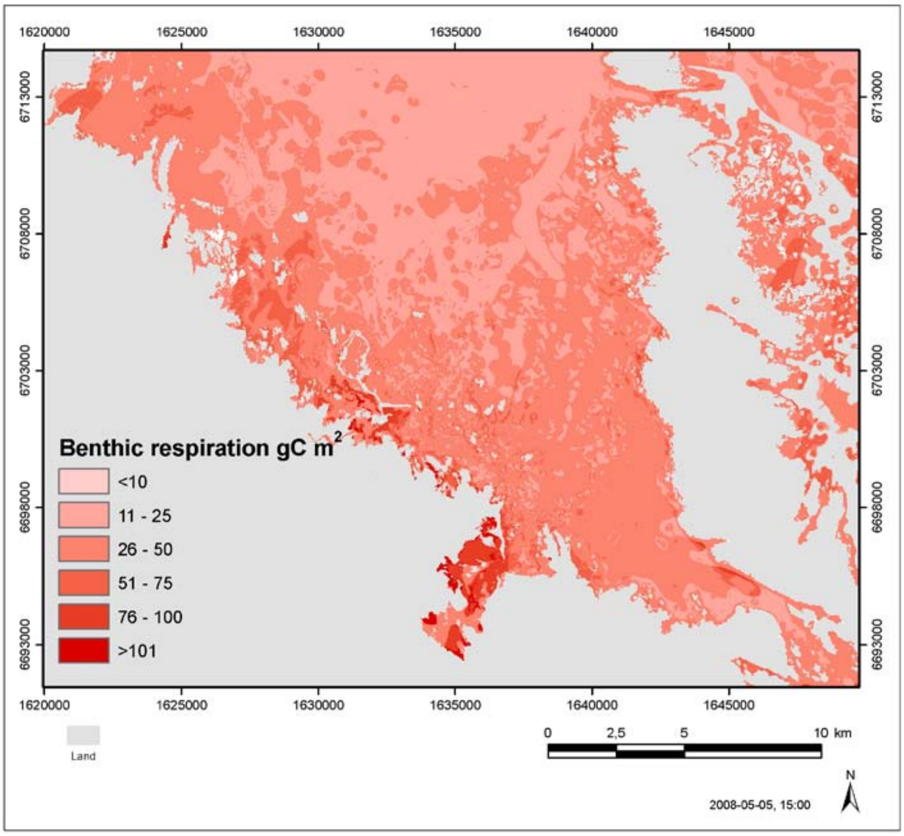


Figure 6-11. *Pelagic (above) and Benthic (below) respiration (gC m^{-2} $year^{-1}$) in the Forsmark area. The same scale is used (range: > 10 to < 150 gC m^{-2}).*

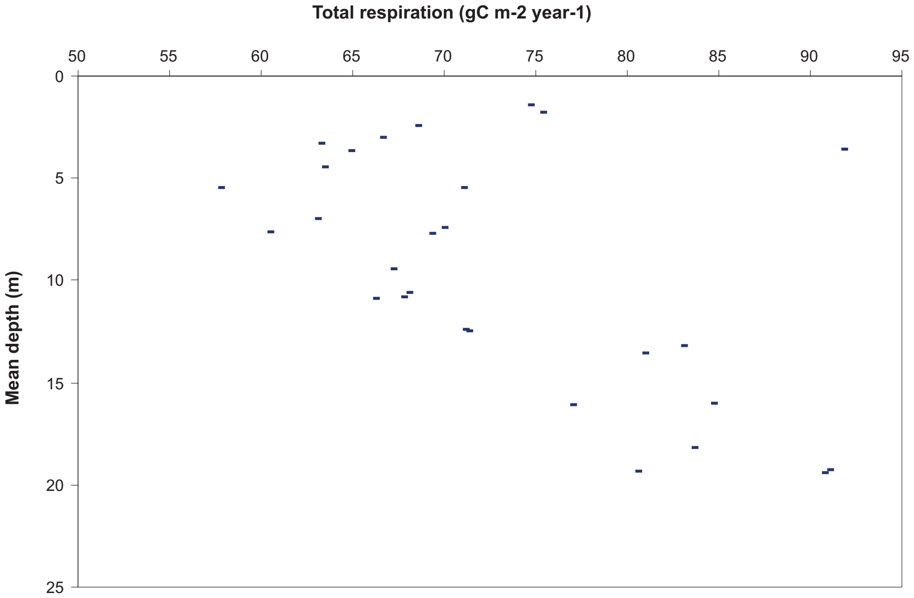


Figure 6-12. *Total heterotroph respiration (gC m^{-2} $year^{-1}$) plotted against mean depth for every basin in the Forsmark model area.*

6.1.5 Net Ecosystem Production

Net Ecosystem Production (NEP = NPP-R) for the marine area in Forsmark is presented in Figure 6-13. The results show that although most of the studied area is heterotrophic, the mean for the whole area is autotrophic, i.e. more carbon is fixed in biomass by primary producers than is released by all organisms (NEP> 1). The mean NEP in the whole model area is 24 gC m^{-2} $year^{-1}$. The annual mean in separate basins ranges between –33 and 224 gC m^{-2} $year^{-1}$. In comparison the NEP according to /Witek et al. 2003/ in the Gulf of Gdansk were 82 g Cm^{-2} $year^{-2}$. All basins on the western coast of the whole marine area are autotrophic and have an annual mean NEP above the mean NEP for the whole area. Ten out of 28 basins are heterotrophic, and they are all offshore or located on the deeper eastern coast. Thus, as Figure 6-13 suggests, the shallow coastal basins tend to be generally autotrophic, while the offshore areas are heterotrophic.

The pelagic component of the ecosystem is mainly heterotrophic, while a larger share of the benthic community along the shores is autotrophic (Figure 6-14 and 15). Both the benthic and pelagic components are heterotrophic in the deeper areas, however. This results in a lower NEP the deeper the mean depth of the basins is, as illustrated by Figure 6-16, which shows a breakeven point for NEP, where NPP equals R at a mean depth of 10–15 m. The autotrophic basins in the area serve as possible carbon sources for the more heterotrophic basins, which are sinks of carbon.

The net heterotrophy in deeper areas is supported by studies made in the Bothnian Bay suggesting that the Bothnian Bay (mean depth of 62 m) is as a whole net heterotrophic and is supplied by organic carbon from the Baltic Sea and from rivers discharging into the Bothnian Bay /Algesten et al. 2004/. Other studies in the Baltic suggest that the NEP of the whole Bothnian Sea is 0 /Gazeau et al. 2004/, i.e. all of the NPP is remineralized by the heterotrophs over an annual cycle and no net production of organic carbon takes place in the ecosystem.

6.1.6 Marine ecosystem food webs

The marine ecosystem model can be summarized and illustrated in a food web representing various biotic and abiotic pools and fluxes within the ecosystem and between the ecosystem and the surroundings. Food webs illustrating average pools and fluxes for all marine basins in the functional groups of the marine ecosystem in Forsmark are presented for C, N and P. For N and P, fluxes during net primary production have been estimated with the Redfield ratio (se Section 4) to give a rough estimate of the magnitude of these processes for these elements. The figures in the food webs represent relative (square root transformed) values of pools and fluxes, the figures are presented in Appendix 7.

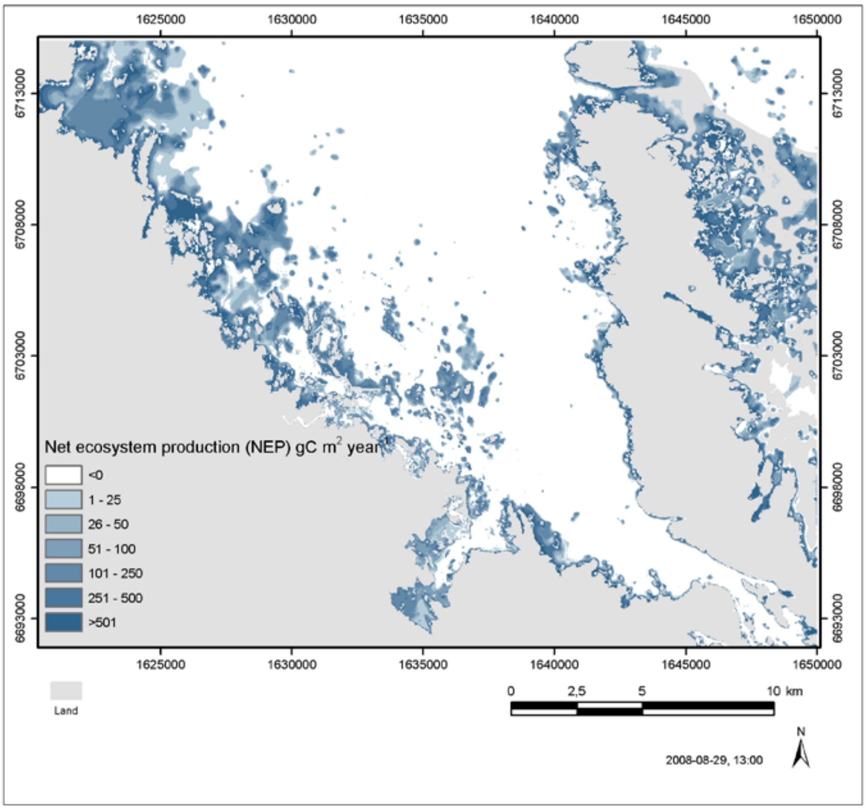


Figure 6-13. *Net ecosystem production (NEP) (gC m^{-2} y^{-1}) in the marine basins in the Forsmark area. Higher respiration is indicated by increasingly dark blue green colour.*

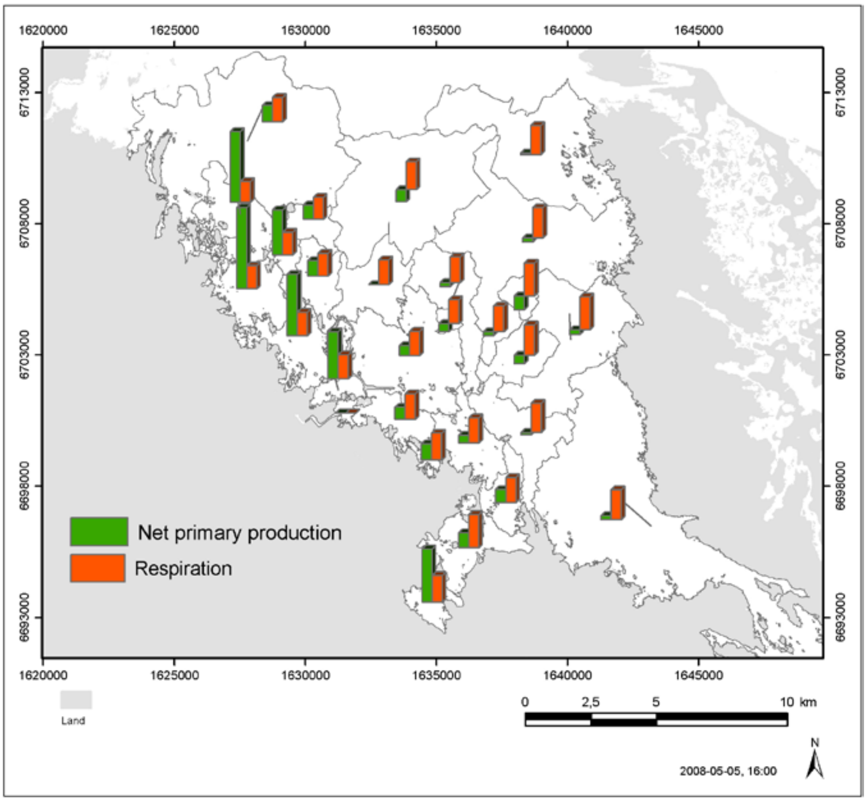


Figure 6-14. *Relative amount of Net Primary Production (NPP = green bars) and Respiration (R = red bars) (gC m^{-2} $year^{-1}$) for the marine basins in the Forsmark area.*

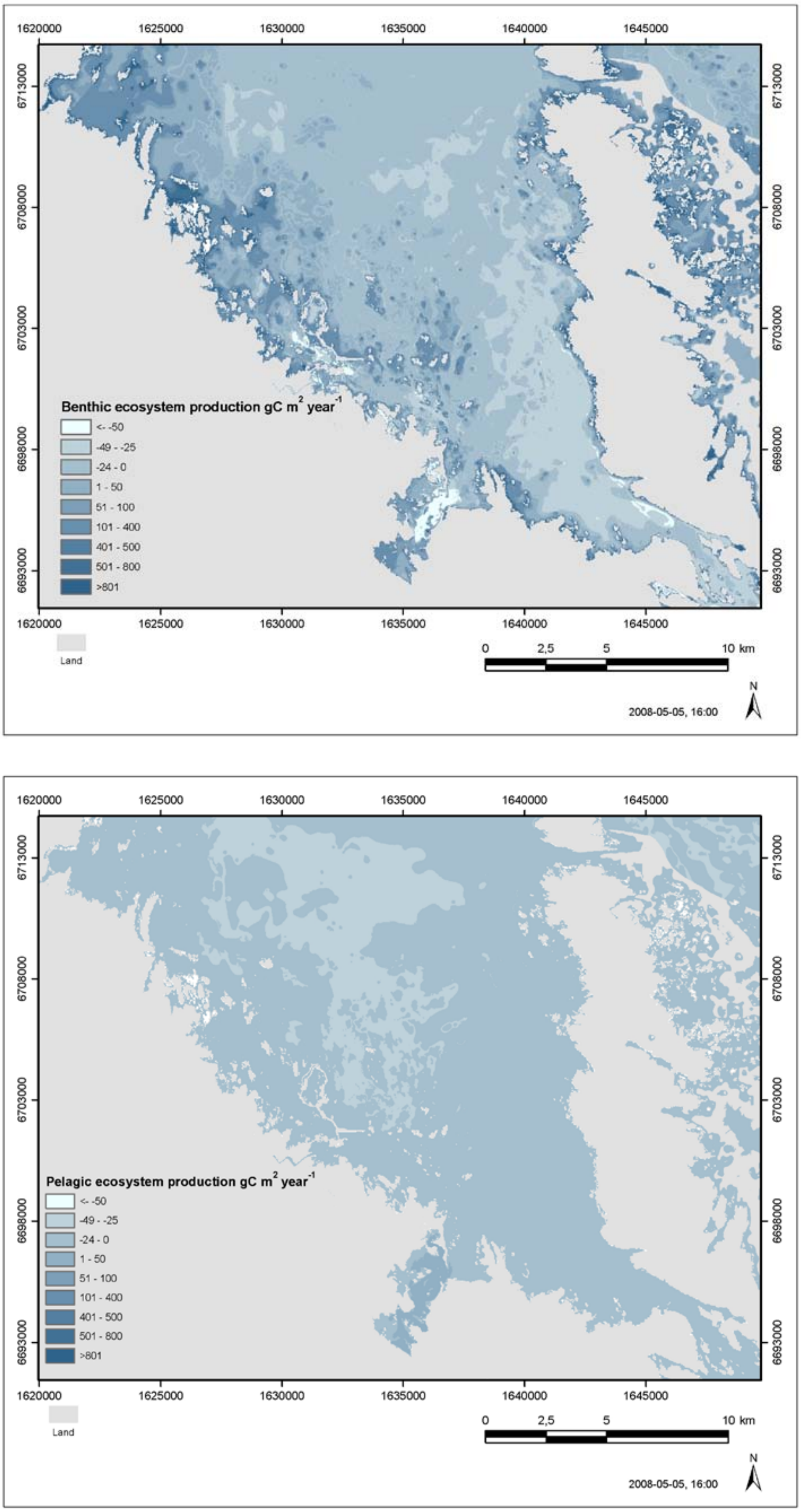


Figure 6-15. *Benthic (above) and pelagic (below) net ecosystem production (gC m^{-2} year^{-1}) in the Forsmark area.*

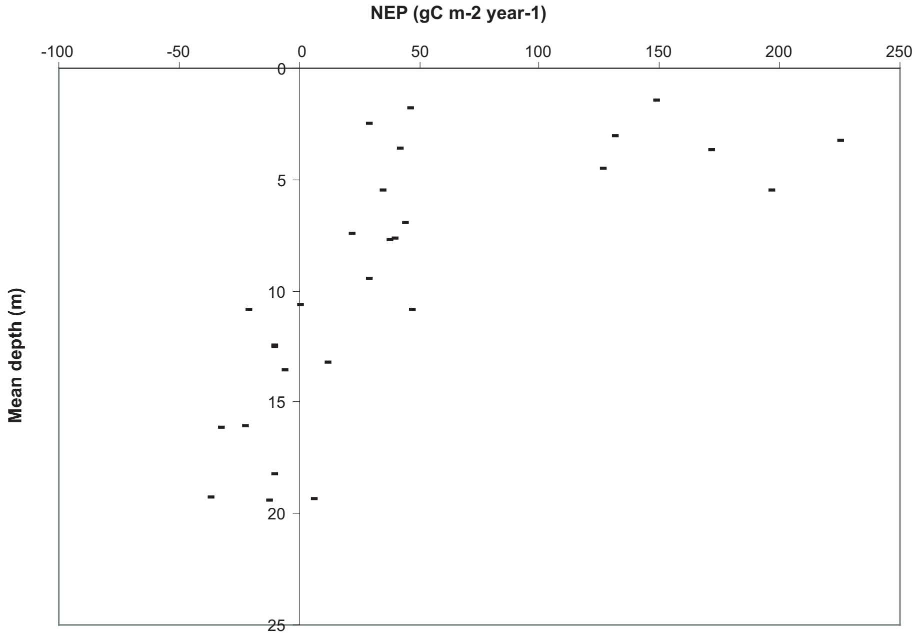


Figure 6-16. *Net Ecosystem Production (NEP) in gC* m^{-2} *year*$^{-1}$ *correlated to depth in the marine area in Forsmark.*

The largest pools of carbon in all basins in the marine area in Forsmark are the abiotic pools: sediment, DIC and DOC, followed by the largest biotic pool, the macrophytes. The largest biotic carbon flux is the fixation of carbon by primary producers, while the second largest is the consumption of DOC by bacterioplankton. The biotic fluxes are still small in comparison with advective flux, Figure 6-17.

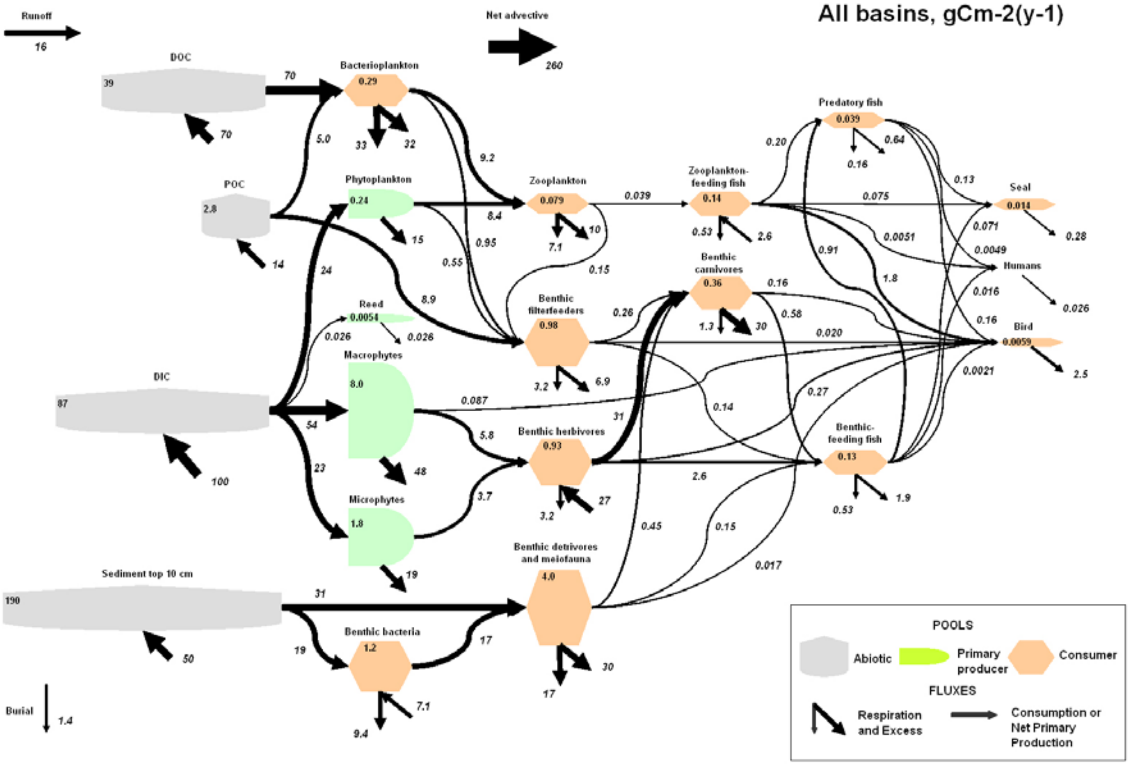


Figure 6-17. *Food web based on pools and fluxes of carbon in the whole marine model area in Forsmark. Boxes and arrows denote relative (square root transformed) size of pools and fluxes.*

On average in the marine area in Forsmark, 20% of the carbon fixed by the primary producers is transferred to the next trophic level, the herbivorous pathway in the food web. The other pathway in the food web for carbon is via consumption of POC dissolved in water or in the surface sediment, the sediment and POC pathway. The size of primary consumption by heterotrophs in this pathway is on average 4 (in separate basins) times higher than primary consumption in the herbivorous pathway. Of the total initially consumed carbon in the food web, around 4% is transferred all the way up to the top predators (piscivorous fish, seal bird and humans).

The excess (the remainder including secondary production, excretion, faeces and dead material from all functional groups and mortality) in the whole marine basin is positive. The positive excess for most of the functional groups can either result in an accumulation of biomass or, as we assume in this steady-state model, formation of POC. However, most of the excess carbon in the marine ecosystem is probably recycled internally and is not transferred to the sediments via burial. The probable fates of POC are consumption, sedimentation, resuspension or export to other basins via water movement. The excess for benthic bacteria, zooplanktivorous fish and benthic herbivores is negative in the whole basin and in most separate basins, which could be due to underestimations of biomasses, overestimations of consumption or respiration, that they are transferred from adjacent areas or that these pools are decreasing.

Most nitrogen (N) is also distributed in the abiotic pools: sediment, dissolved inorganic nitrogen DIN and particulate nitrogen PON. Large biotic fluxes of nitrogen are the consumption of sediment by benthic detrivores and benthic bacteria, consumption of benthic herbivores by benthic carnivores and bacterioplankton consumption of particulate nitrogen in water, but they are all still very small compared to the advective flux, Figure 6-18.

The transfer of N between trophic levels in the food web is similar to that of carbon.

The nitrogen excess (the remainder including secondary production, excretion and faeces and mortality) in the whole marine basin is positive. The nitrogen excess for the functional groups bacterioplankton, benthic bacteria, benthivorous- and zooplanktivorous fish is negative.

The major pool for phosphorus is sediment, although the other abiotic pools – dissolved inorganic phosphorus (DIP) and particulate phosphorus (POP) – are not so large compared to the biotic pools as for C and N. Large biotic fluxes of phosphorus are the consumption of sediment by benthic detrivores and benthic bacteria and consumption of benthic herbivores by benthic carnivores, but they are still very small compared with the advective flux, Figure 6-19.

The transfer between trophic levels in the food webs of P is similar to that of C and N, and the phosphorus excess (the remainder including secondary production, excretion and faeces and mortality) in the whole marine basin is very small but still positive.

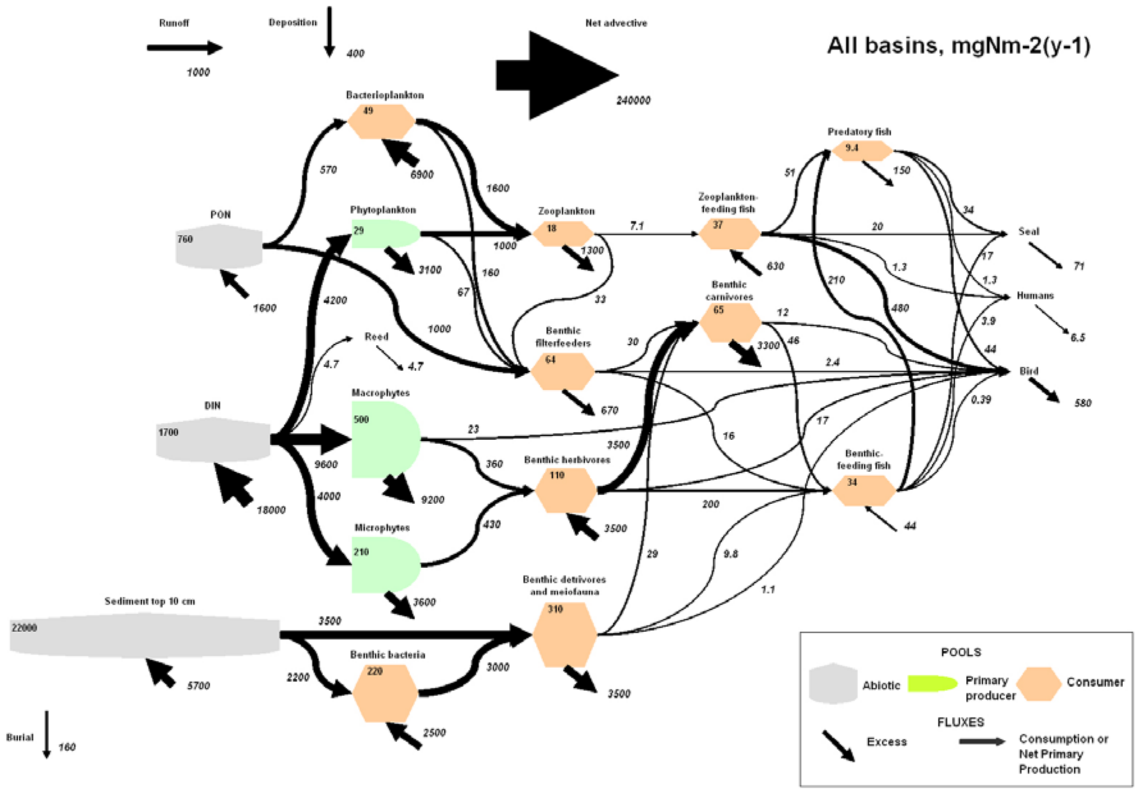


Figure 6-18. *Food web based on pools and fluxes of nitrogen in the whole marine model area in Forsmark. Boxes and arrows denote relative size of pools and fluxes.*

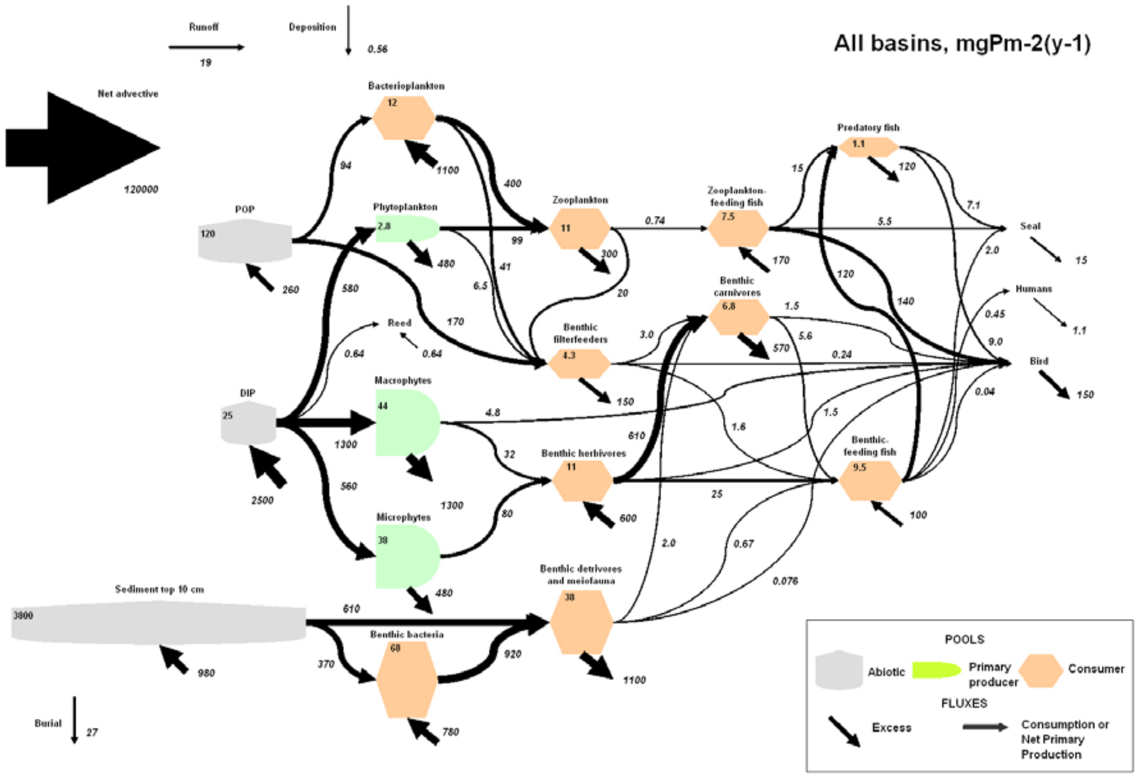


Figure 6-19. *Food web based on pools and fluxes of phosphorus in the whole marine model area in Forsmark. Boxes and arrows denote relative size of pools and fluxes.*

6.2 Marine ecosystem model – Laxemar-Simpevarp

The results of modelling are presented below on a model area scale for the Laxemar-Simpevarp model area, i.e. the marine area divided into basins (described in Chapter 4 and displayed in Figure 4-2). The results presented below for the Laxemar-Simpevarp area pertain to that model area. The food web of the marine ecosystem is presented for carbon (C), nitrogen (N) and phosphorus (P).

6.2.1 Biomass distribution

Total biomass varies from just below 2 gC m^{-2} to over 450 gC m^{-2} in the area, see Figure 6-20. Mean biomass is 91 g C m^{-2} in the whole area, resulting in an estimated total of 10,430 tonnes of carbon fixed in biota in all basins in the Laxemar-Simpevarp marine model area. In 6 (Basin 513, 514, 518, 523, 524 and 525) out of 19 basins the annual mean biomasses are above the mean biomass for the whole area, and these basins are all situated offshore in more exposed areas with high densities of *M. edulis.* The highest average biomass in the area is found among the filter feeders, which, when the substrate is suitable, form very dense colonies with high biomasses (up to above 100 gC m^{-2}).

The biomass in 8 (Basin 501, 500, 504, 502, 506, 508, 516 and 519) out of 19 basins is dominated by macrophytes, and they are all secluded bays. The average macrophyte fraction of the total biomass in all separate basins varies between 26 and 80%. In some of the more exposed basins (Basin 521, 522, 523, 524 and 525), filter feeders constitute a large portion (50–60%) of the total biomass, but for the whole marine area the filter feeders only constitute on average 28% of the total biomass. Other organisms contribute on average to less than 10% of the total biomass, see Figure 6-20 and 6-21. Basin-specific biomass data in gC m^{-2} are found in Appendix 7. The annual mean biomasses for the various functional groups are in good agreement with other reported values (see Section 3) from the Baltic, although the biomasses for phytoplankton and microphytobenthos might be a bit lower /Feuerpfeil et al. 2004/.

Figure 6-22 shows the percentage which benthic organisms comprise of the total biomass, which varies from 95 to 99% for separate basins.

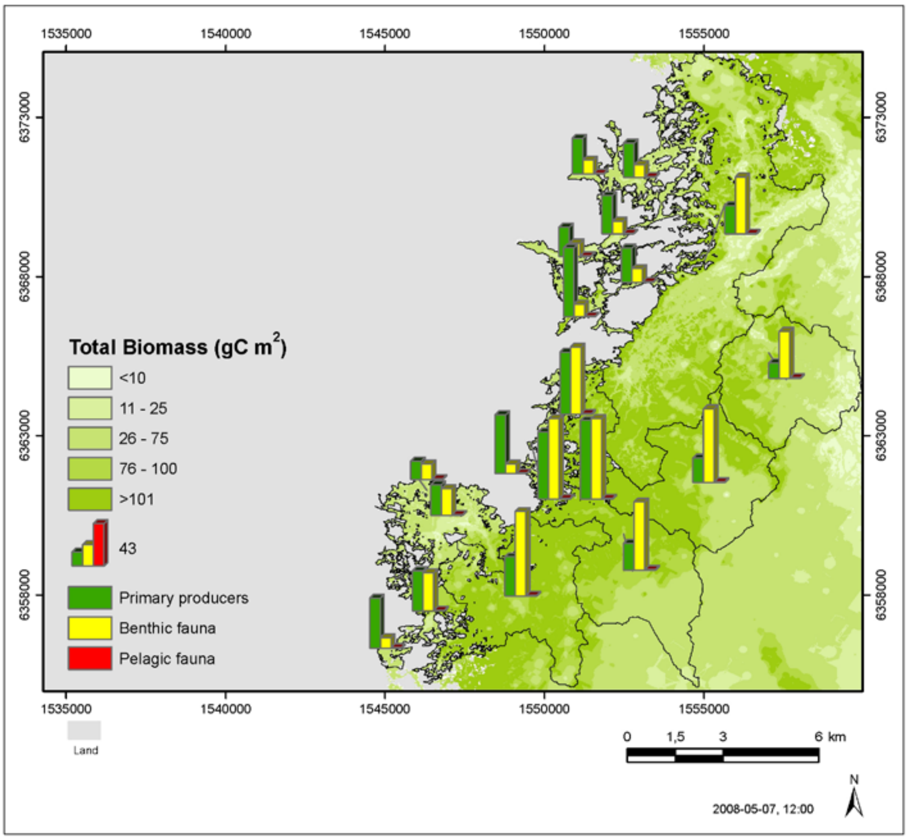


Figure 6-20. Annual average biomass of the functional groups in the ecosystem model and total biomass (shaded in background) (g C m^{-2}) for all basins in the Laxemar-Simpevarp area.

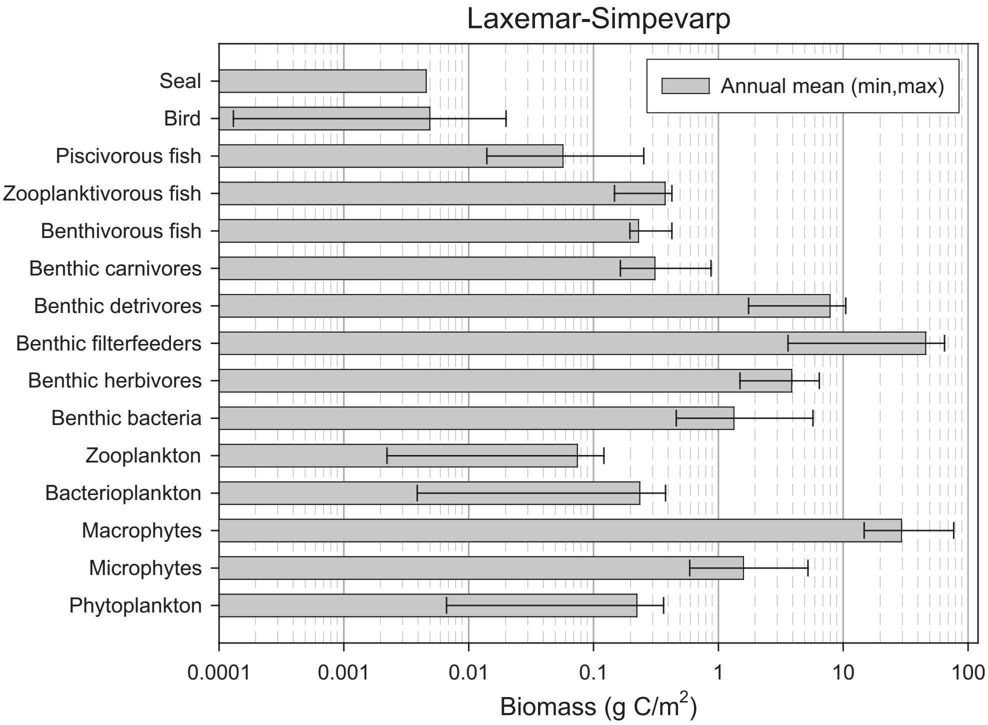


Figure 6-21. *Annual average biomass (gC m^{-2}) for functional groups of marine biota in the Laxemar-Simpevarp area.*

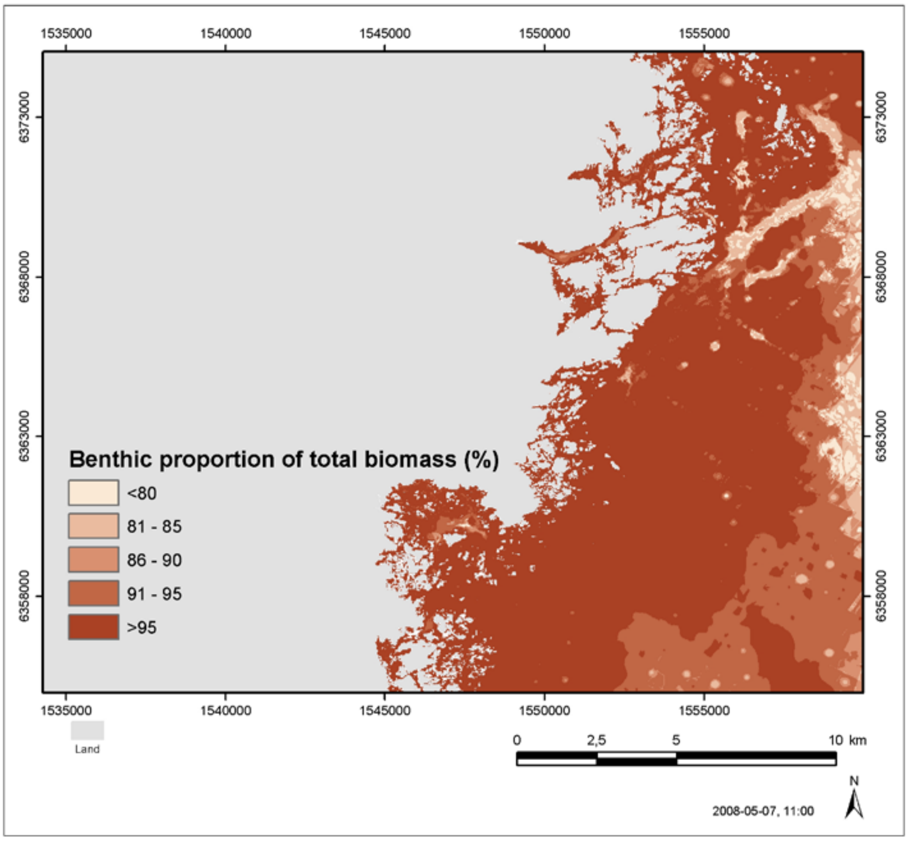


Figure 6-22. *The benthic part of the biomass component in (%) in the Laxemar-Simpevarp area.*

In Figure 6-23, biomass is plotted against mean depth in each basin. There is no evident correlation with depth, however, in areas with depth > 4 m a correlation with depth can be seen. The highest mean biomasses are found in basins with intermediate depth, 4–8 m.

6.2.2 Primary Production

Net primary production (NPP) is presented in Figure 6-24. Like biomass, NPP is concentrated at the shoreline, where the highest values are found, but also in the offshore areas where depth and higher water transparency permit high phytoplankton production. In 10 out of 19 basins, most of them located near shore (except for Basin 523, 524 and 525), the annual mean NPP exceeds the annual mean NPP for the whole marine model area. The average value for the whole marine area in Laxemar-Simpevarp is 170 gC m^{-2}. This agrees well with other reported average values of primary production in the Baltic, 160 gC m^{-2} /Feuerpfeil et al. 2004/. Some of the southern coastal basins have very high NPP values, although the data density in these basins is lower than in the more extensively examined northern basins and these values have a higher uncertainty.

The benthic and pelagic components of NPP are shown in Figure 6-25. The benthic and pelagic components display roughly the opposite patterns: pelagic increases with depth and benthic decreases with depth. In the whole marine model area the benthic community contributes 90% to the total NPP, which decreases with increasing depth along with macrophyte biomass and light penetration (Figure 6-26). In separate basins the benthic NPP varies from 64 to 100%.

6.2.3 Consumption

The most consumed component of the marine ecosystem in Laxemar-Simpevarp is POC (Figure 6-27). In the bays with a higher degree of soft bottoms, consumption of sediment and DOC is higher than consumption of POC.

The overall dominant consumers are the filter feeders in Laxemar-Simpevarp, (dominated by *M. edulis*). In average they consume from 69 to 97% of all consumed carbon in the area, Figure 6-28.

6.2.4 Heterotrophic respiration

The distribution of total respiration benthic and pelagic is presented in Figure 6-29. Total respiration includes only respiration by heterotrophs (consumers) as respiration by primary producers is included in the NPP presented above.

In the whole area the annual average respiration is 332 gC m^{-2}, and the annual average value in separate basins ranges from 56 to 486 gC m^{-2}, which is high compared with other reported values of respiration in the Baltic, 74 gC m^{-2} /Gazeau et al. 2004/. The largest component of the respiration in most basins is respiration by filter feeders, which on an annual average constitutes 48% of the total respiration and ranges from 13 to 80% in separate basins. One cause of the high respiration is the large amounts of *M. edulis* in some of the basins. The second largest component of the respiration is benthic bacteria, which are a major constituent in particular in the inner basins.

When the benthic and pelagic components of the respiration are examined separately (Figure 6-30), they display, like NPP, roughly the opposite pattern. Pelagic respiration increases and benthic decreases with depth. The increase of pelagic respiration is primarily a result of higher biomass due to increasing depth, Figure 6-31. The decrease in benthic respiration is due to two factors: a smaller biomass and a decrease in temperature in the benthic community. The mean pelagic temperature also decreases with depth, but this is compensated for by the biomass.

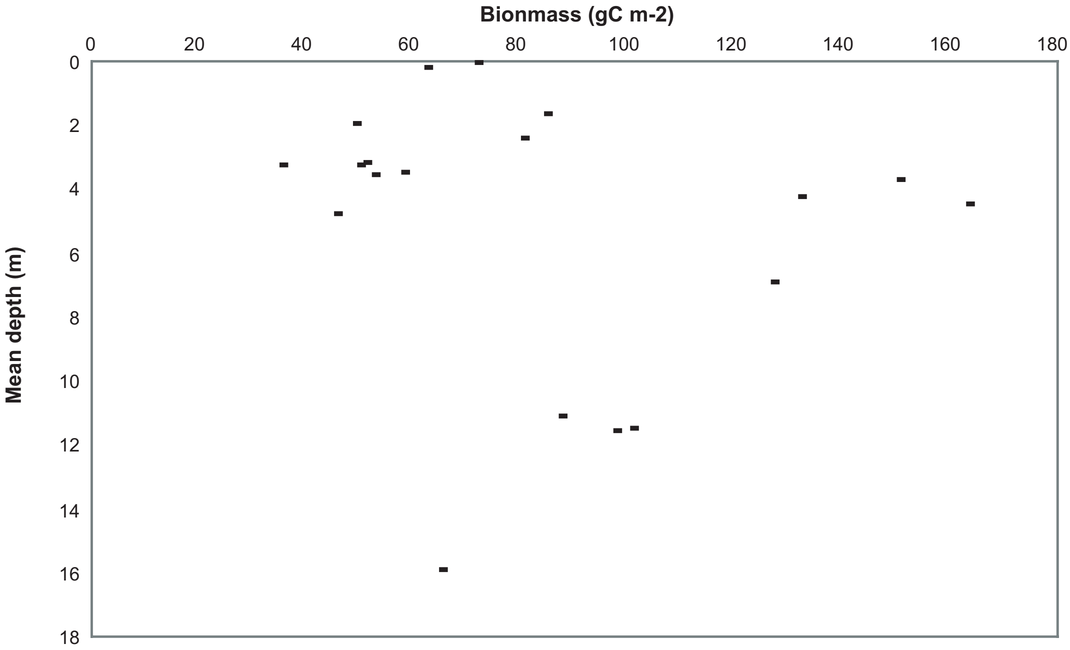


Figure 6-23. *Mean biomass (gC m^{-2}) plotted against mean basin depth for all basins in the model area.*

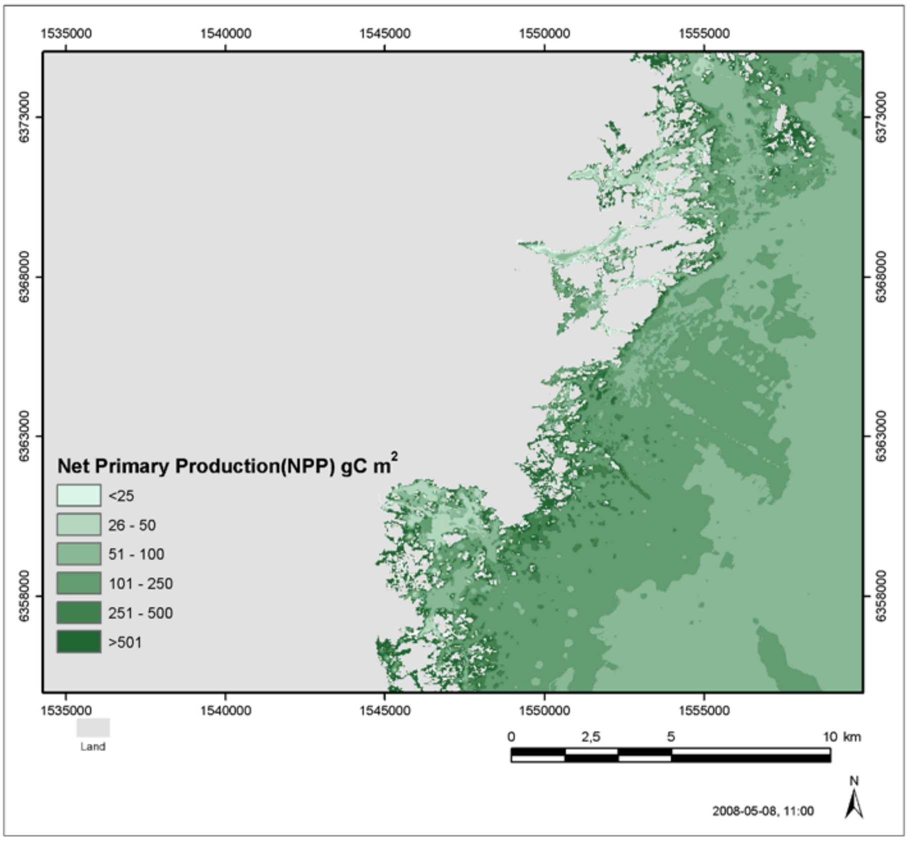
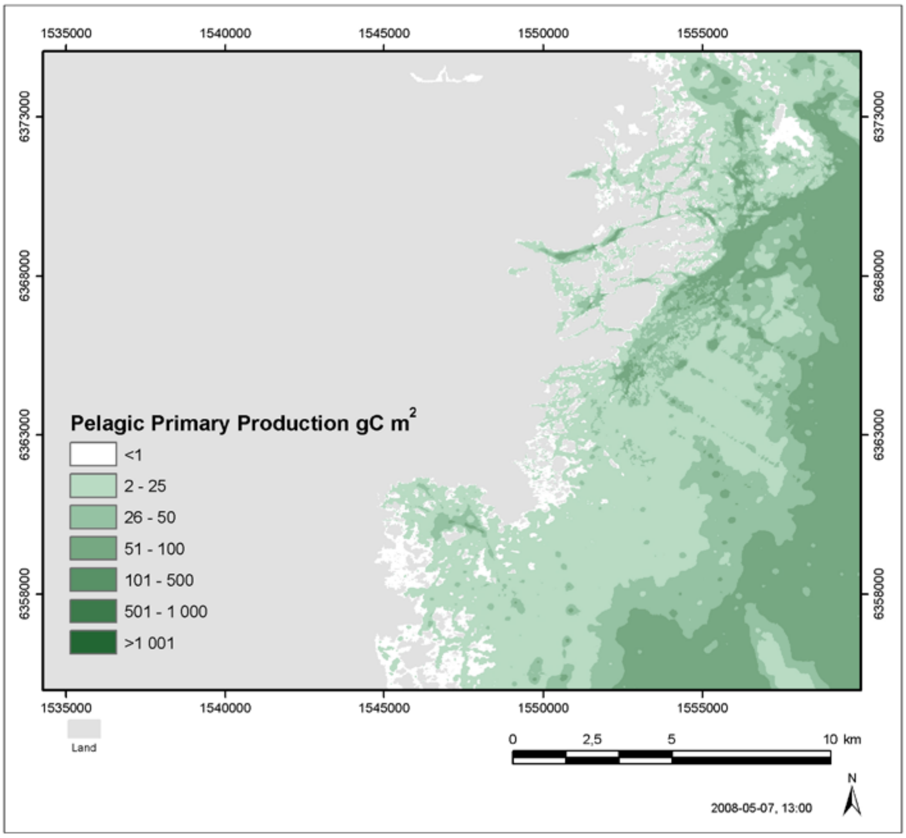


Figure 6-24. *Net Primary Production (gC m^{-2} year^{-1}) in the Laxemar-Simpevarp area. Higher NPP is indicated by increasingly dark green colour.*



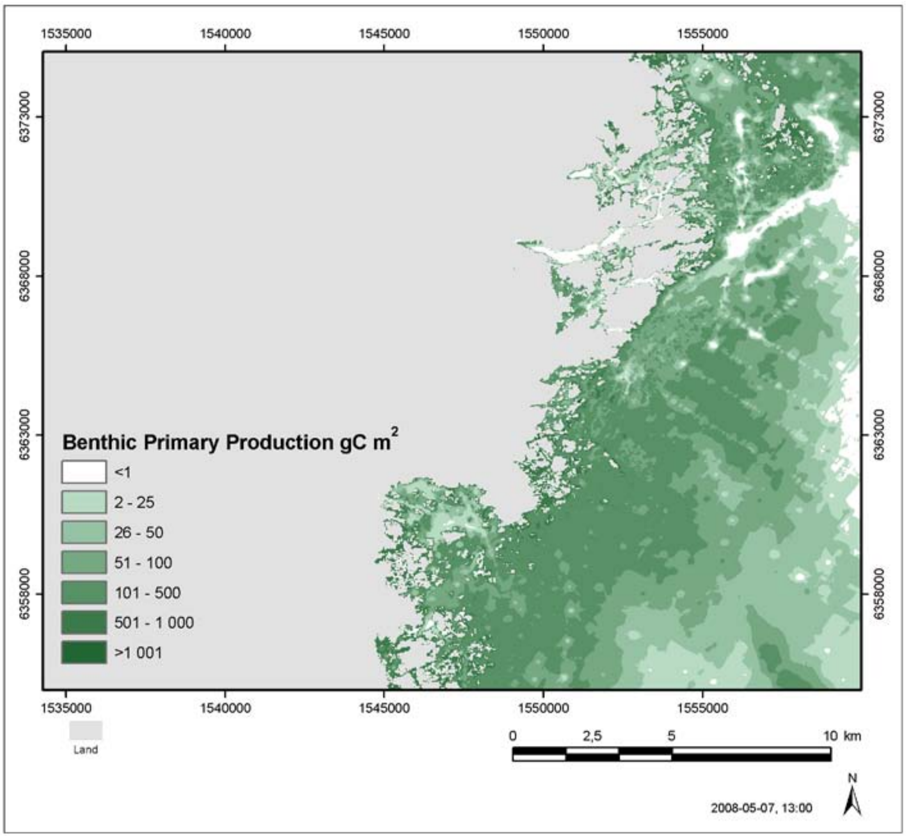


Figure 6-25. *Pelagic (above,A) and benthic (below, B) Net Primary Production (gC m^{-2} year^{-1}) in the Laxemar-Simpevarp area. Higher NPP is indicated by increasingly dark green colour.*

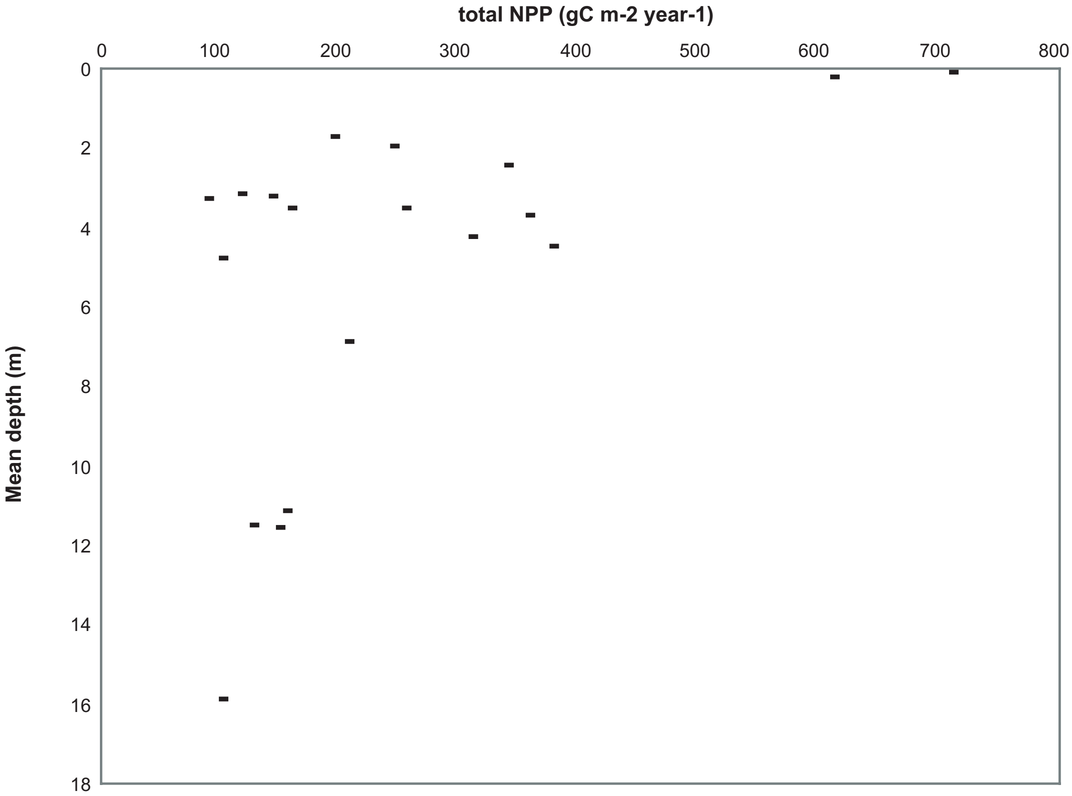


Figure 6-26. *Mean NPP (gC m^2 $year^{-1}$) plotted against mean basin depth for all basins in the model area.*

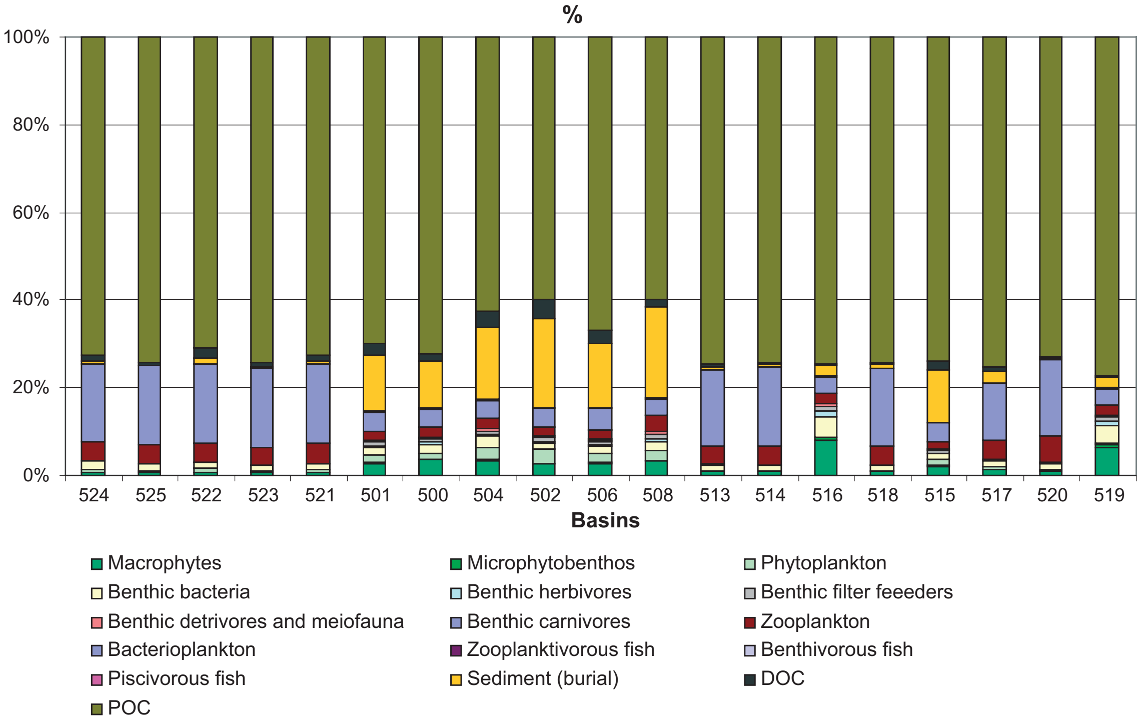


Figure 6-27. *Percentage consumption of the biotic and abiotic pools in the ecosystem, in the separate basins, in the marine area in Laxemar-Simpevarp.*

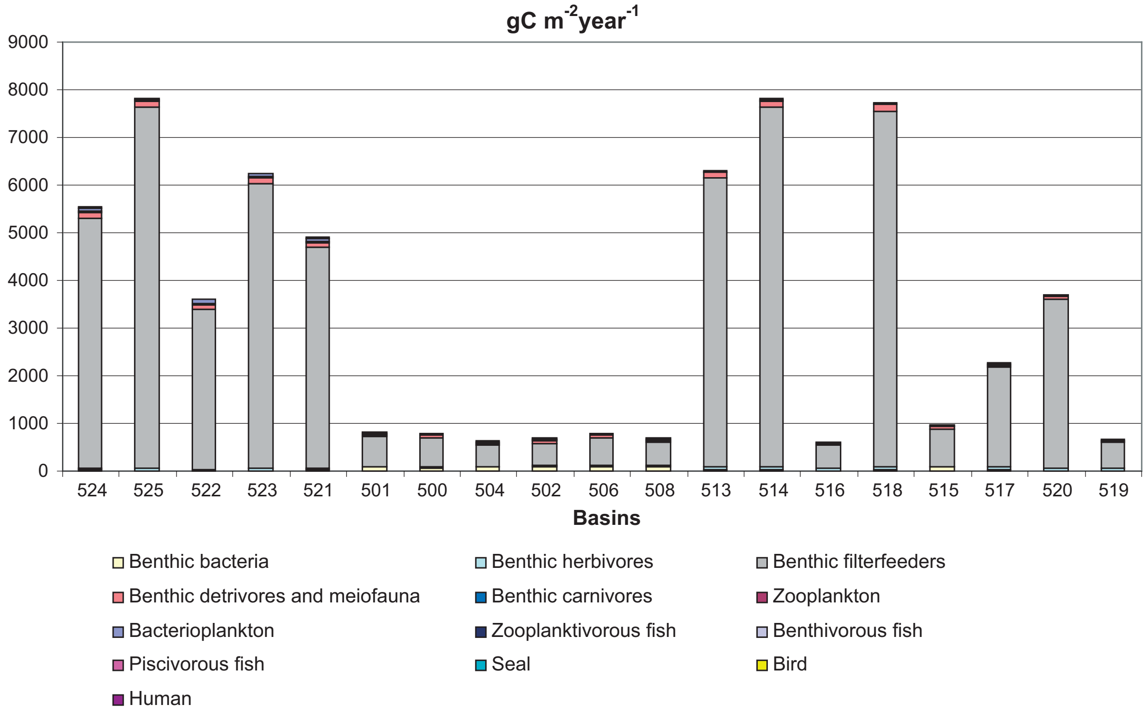


Figure 6-28. *The annual mean consumption, in gC m^{-2} year^{-1} in separate basins, by the consumers in the ecosystem in Laxemar-Simpevarp.*

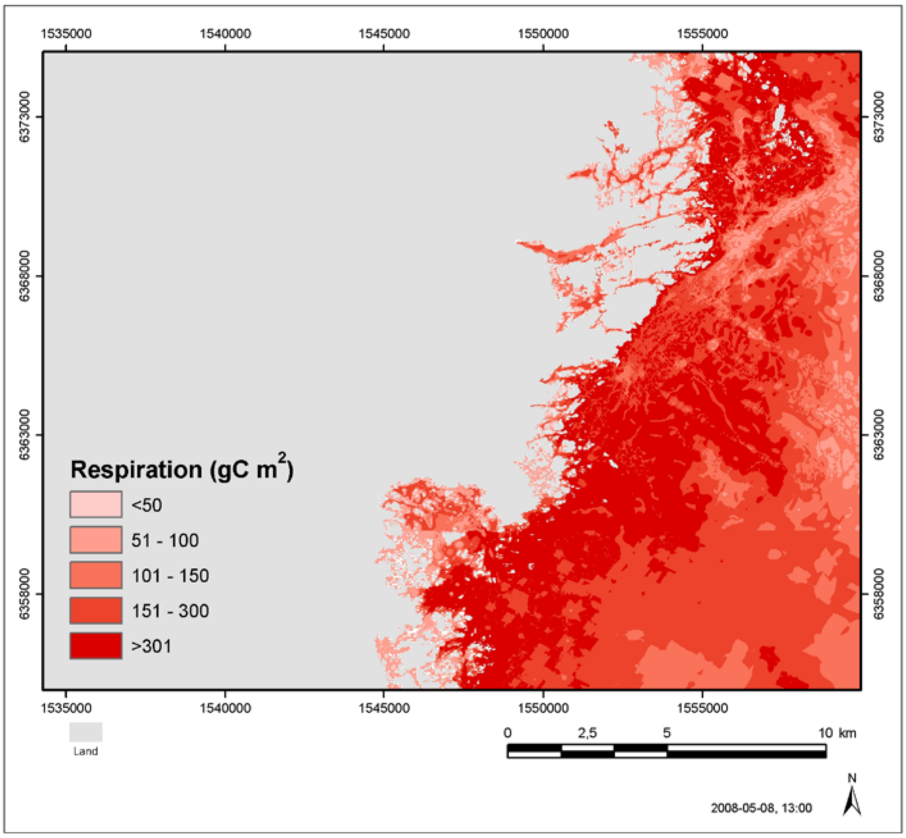
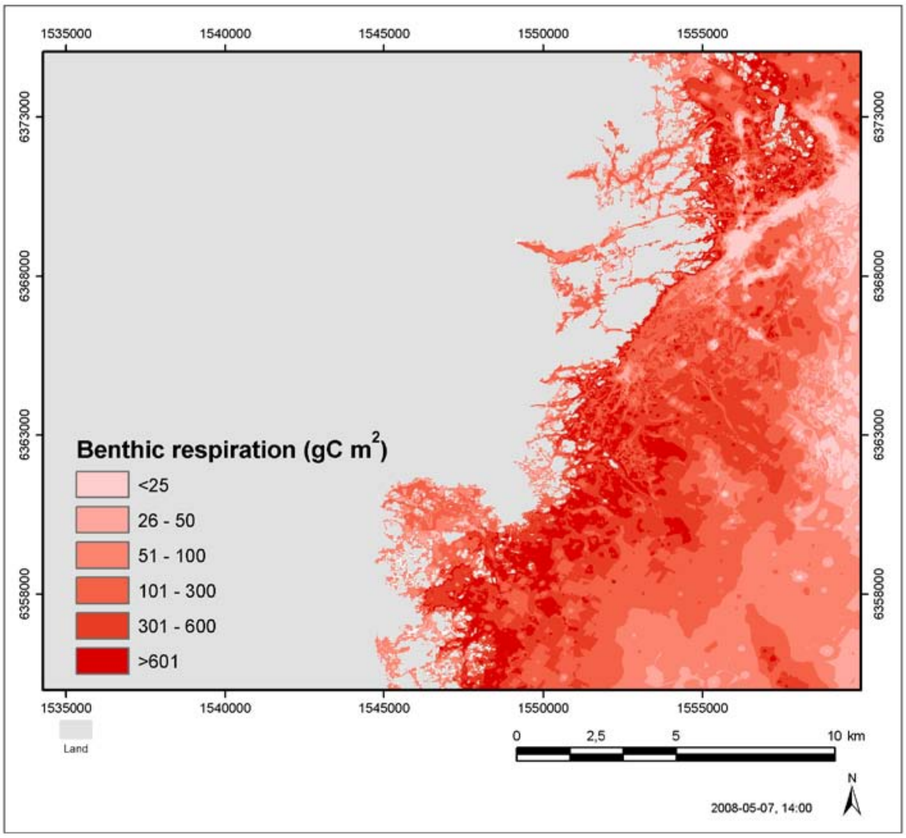


Figure 6-29. *The sum of heterotrophic respiration (gC m^{-2} year^{-1}) in the Laxemar-Simpevarp area.*



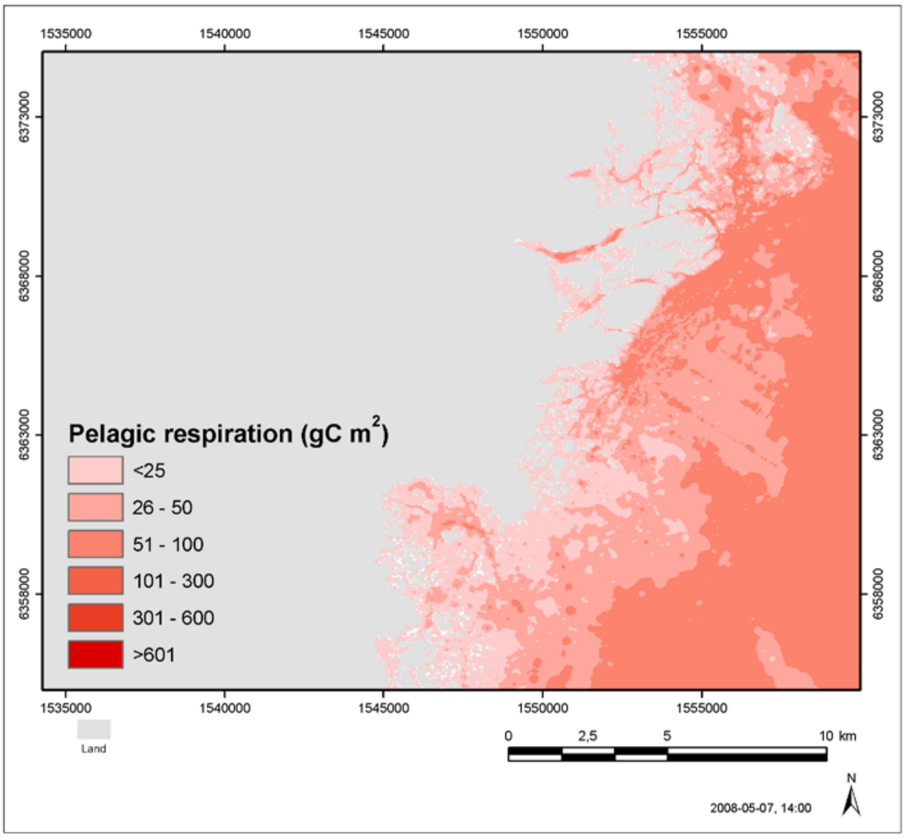


Figure 6-30. *Benthic (above) and pelagic (below) respiration (gC m^{-2} year^{-1}) in the Laxemar-Simpevarp area. The same scale is used in both figures.*

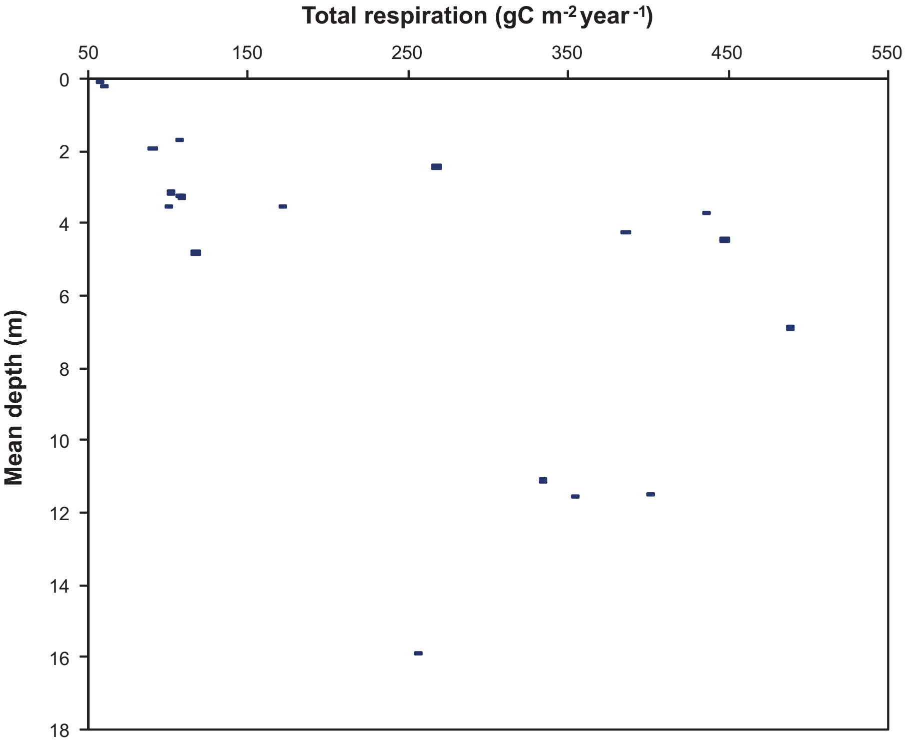


Figure 6-31. Respiration (gC m^{-2} year^{-1}) plotted against mean depth for every basin in the model area.

6.2.5 Net Ecosystem Production

Net ecosystem production (NEP = NPP-R) for the area is presented in Figure 6-32. The annual average NEP in the Laxemar-Simpevarp model area is –161 gC m^{-2} year^{-1}. In separate basins the annual mean ranges between –282 to 651 gC m^{-2} year^{-1}. The marine area as a whole is heterotrophic, i.e. more carbon is released to the atmosphere than is fixed in biomass. 9 (501, 500, 504, 508, 516, 515, 517, 520 and 519) out of 19 basins are autotrophic, all of them coastal basins with macrophyte biomass constituting more than 50% of the total biomass. The rest of the basins are heterotrophic. Thus, bays in the area tend to be autotrophic while the more offshore basins are heterotrophic.

NPP in comparison with total respiration is displayed in Figure 6-33.

The NEP decreased with mean depth of the basins, as illustrated by Figure 6-34, indicating a breakeven point for NEP, where NPP equals R at a mean depth of 3 m, Figure 6-35.

6.2.6 Marine ecosystem food webs

The marine ecosystem model can be summarized and illustrated in a food web representing various biotic and abiotic pools and fluxes in the ecosystem and between the ecosystem and the surroundings. Food webs illustrating average pools and fluxes for all marine basins in the functional groups of the marine ecosystem in Laxemar-Simpevarp are presented for C, N and P. For N and P, fluxes during net primary production have been estimated with the Redfield ratio to give a rough estimate of the magnitude of these processes for these elements.

The largest pools of carbon in the whole area in Laxemar–Simpevarp are the DIC pool, the sediment and the benthic filter feeders. The DOC pool and the macrophytes are also major contributors to the total carbon inventory in the area. Advective flux is the largest flux. The largest biotic carbon flux is the consumption of POC, phytoplankton and bacterioplankton by the filter feeders. NPP is only about 4% of the consumption by filter feeders. Runoff, diffusion, burial and precipitation are very small in comparison with the other fluxes, Figure 6-36.

I the marine ecosystem food web, consumption of primary producers in Laxemar-Simpevarp (especially the consumption of phytoplankton), is greater than production and biomass in most basins.

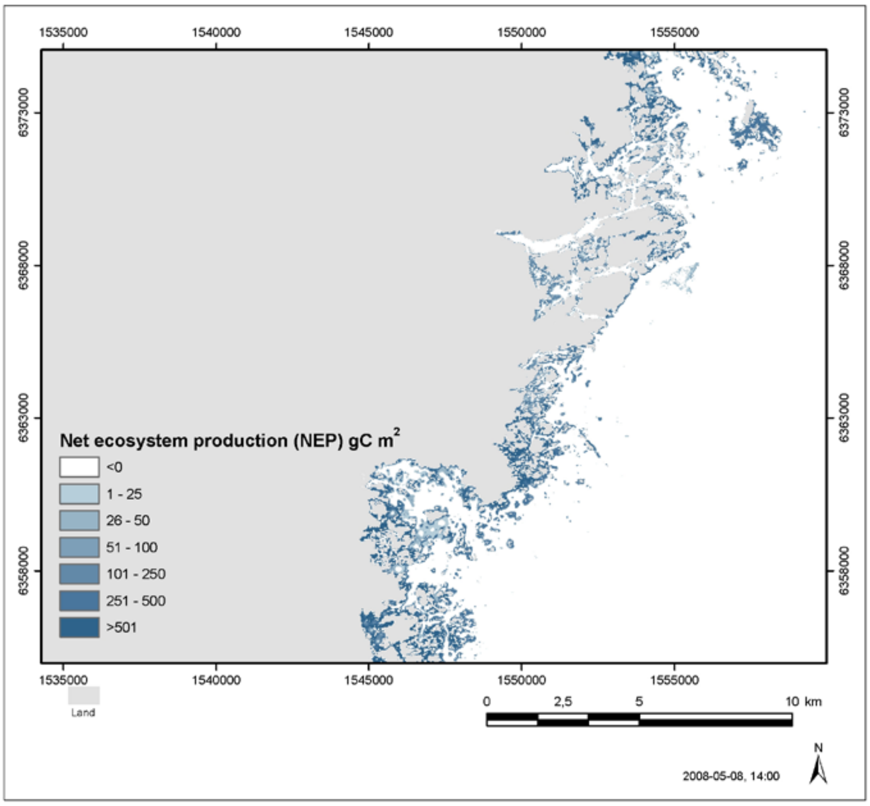


Figure 6-32. *Net Ecosystem Production (NEP = NPP-R) for the Laxemar-Simpevarp area. White colour indicates a net negative NEP.*

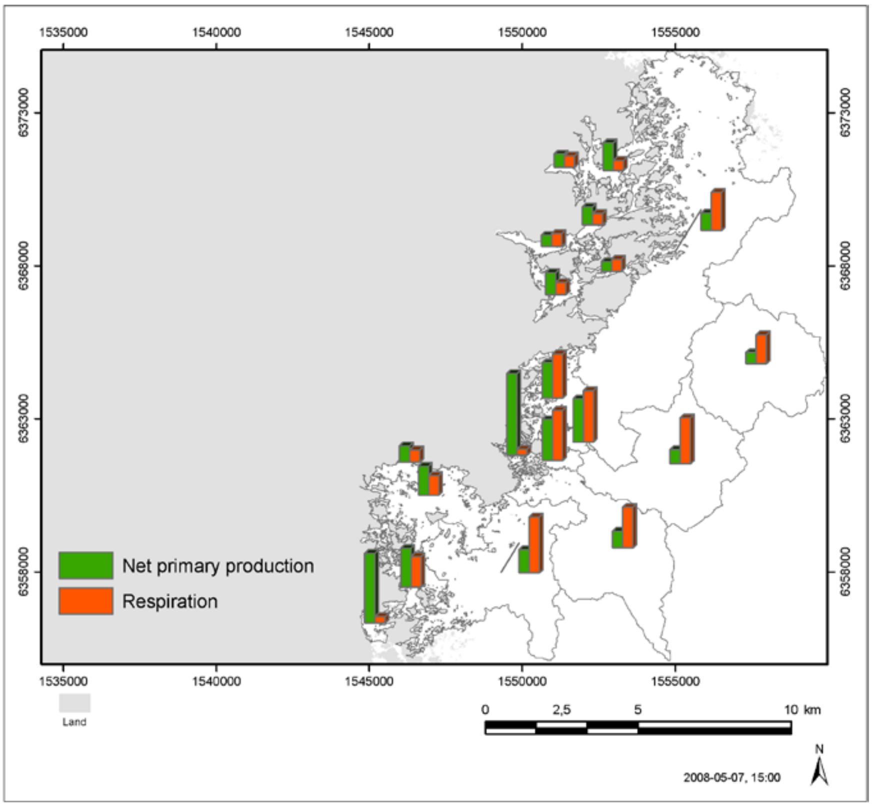


Figure 6-33. *Relative amount of Net Primary Production (NPP) and Respiration (R) (gC m^{-2} year^{-1}) for the marine basins in the Forsmark area. Green and red bars designate NPP and R, respectively.*

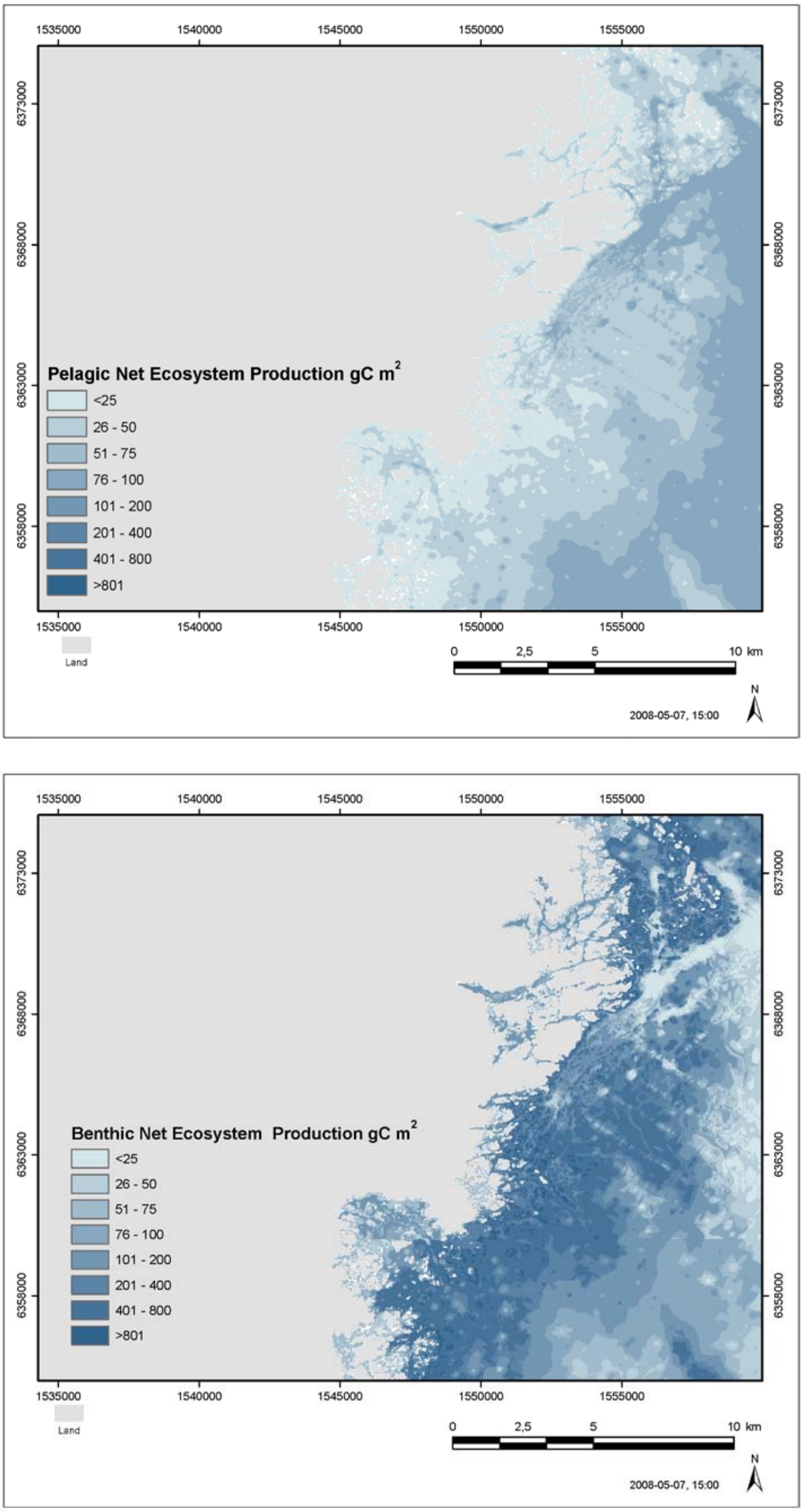


Figure 6-34. *Pelagic (above) and benthic (below) net ecosystem production (gC m^{-2} $year^{-1}$) in the Forsmark area.*

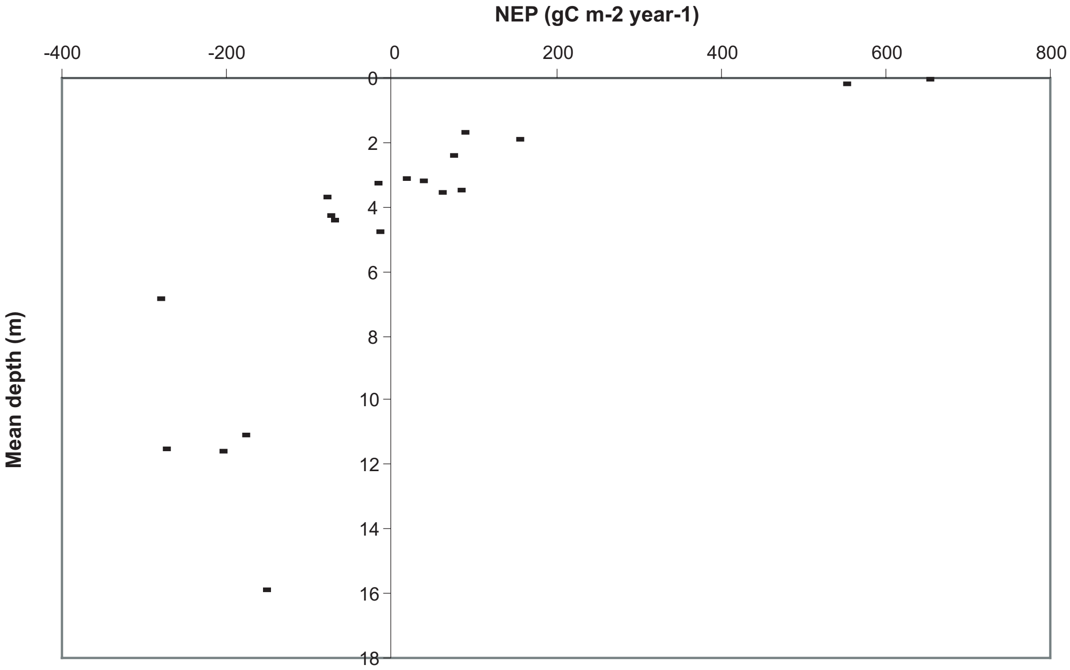


Figure 6-35. NEP (gC m^{-2} $year^{-1}$) plotted against mean depth for all basins in the model area.

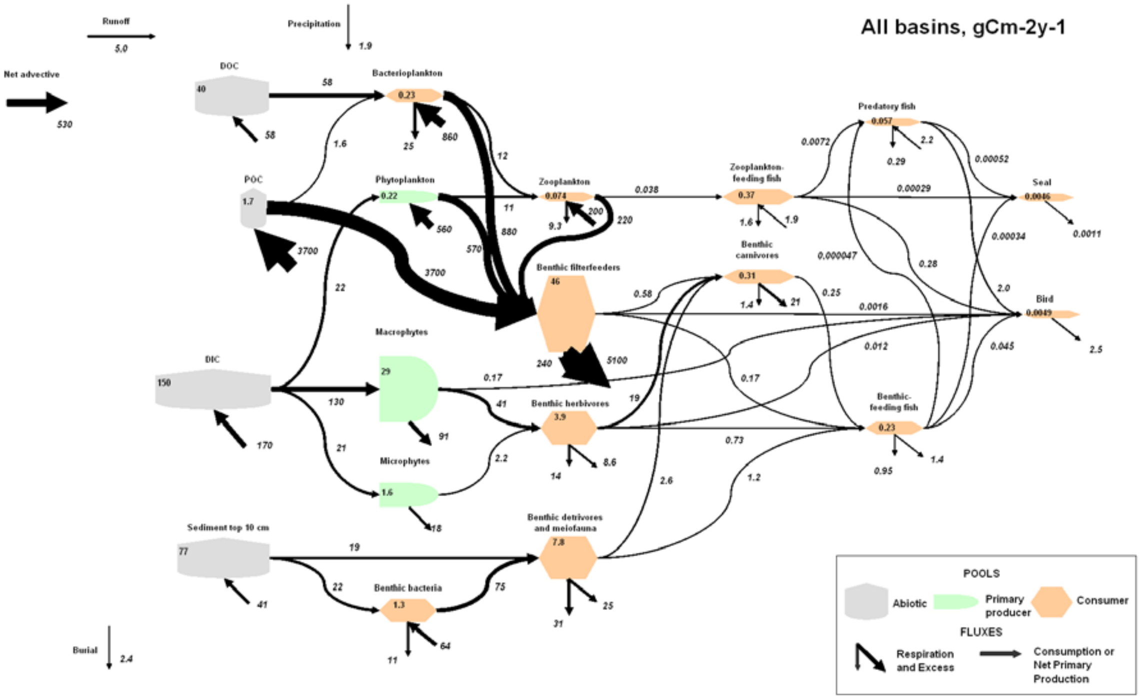


Figure 6-36. Food web based on pools and fluxes of carbon in the whole marine model area in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes respectively.

This indicates that the transfer of carbon from primary production to the first trophic level is greater than what is produced in several basins. This result is probably the result from uncertainties in input data in the calculations, and indicates that the model calculations have underestimated the primary production of phytoplankton, or the secondary production. It can also be due to an overestimation of consumption by the filter feeders. However, the consumption of filter feeders does in reality include resuspended material (some of the excess) to a higher degree than described in the model. In the model the filter feeders only consume directly from the functional groups. It may also indicate that there is a large transfer of pelagic organisms and POC from adjacent areas. The excess (the remainder including secondary production, excretion faeces and dead material from all functional groups and mortality) in the whole marine basin is positive mainly due to the filter feeders.

Of the carbon initially consumed from primary producers, POC and sediment, only 0.8% reaches the top predators (piscivorous fish, birds, seals and humans) in this food web.

The two largest pools for nitrogen are the filter feeders and the sediment and the two pools are similar in order of size. The fluxes are similar to the fluxes of carbon. The largest biotic nitrogen flux is consumption of PON, phytoplankton and bacterioplankton by filter feeders. Accumulation of N during primary production is very small in comparison with consumption by filter feeders, Figure 6-37.

The excess in the whole marine basin post is positive mainly due to the filter feeders, but a majority of the biotic functional groups have a negative excess. Since the incorporation of nitrogen during photosynthesis is represented roughly by the Redfield ratio (see Section 4), the negative excess term may indicate that this process is underestimated by this method. It can also be an uncertainty in the calculations of the pools since this is done using the ratios between carbon and nitrogen in (number of analyzed samples from 1 and 9) samples from the area (see Section 4), which might not have been representative.

For phosphorus as for nitrogen and carbon, the largest pools are the sediment and the filter feeders. The fluxes are also similar to the nitrogen food web. The largest biotic phosphorus flux is the consumption of particular organic phosphorus (POP), phytoplankton and bacterioplankton by the filter feeders. Incorporation of P during NPP is very small in comparison with consumption by filter feeders, Figure 6-38. The same reasoning considering the negative excess for many pools of nitrogen can be valid for phosphorus as well.

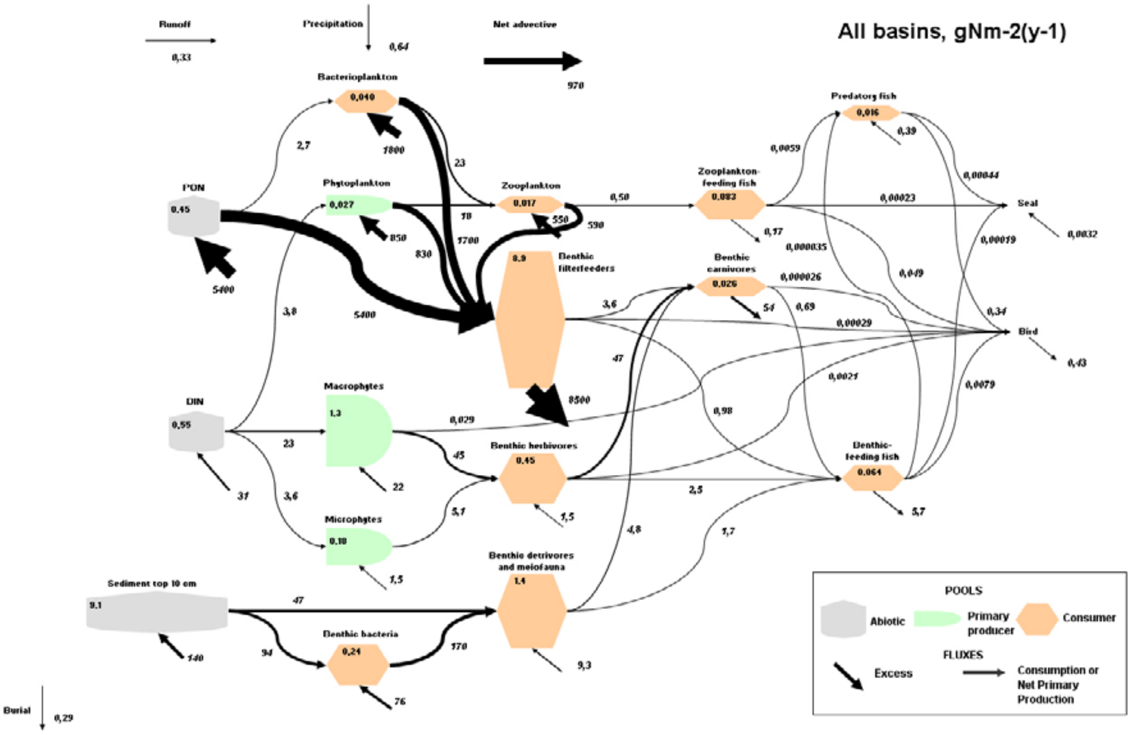


Figure 6-37. *Food web based on pools and fluxes of nitrogen in the whole marine model area in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes.*

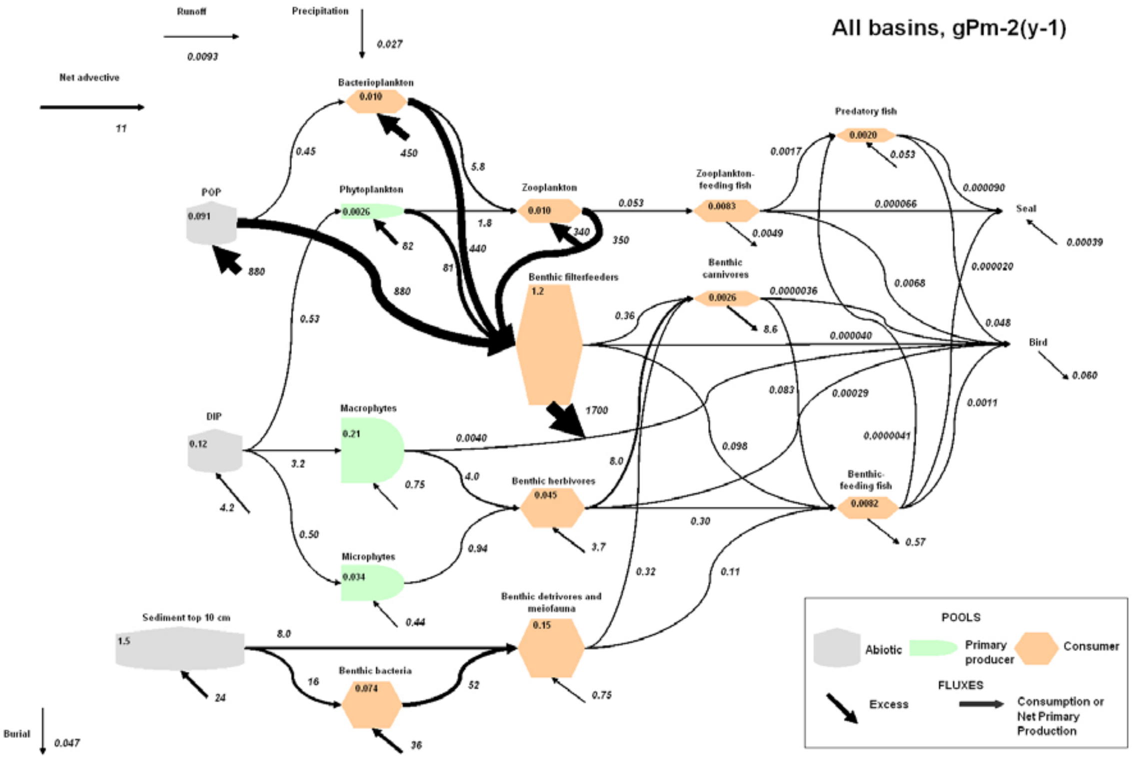


***Figure 6-38.** Food web based on pools and fluxes of phosphorus in the whole marine model area in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes.*

6.3 Mass balances for carbon and other elements – both sites

Mass balances for carbon (C), nitrogen (N), phosphorus (P), iodine (I), thorium (Th) and uranium (U) are presented in detail for the whole marine areas in Forsmark and in Laxemar-Simpevarp. Mass balances for the five selected basins at each site and additional elements are described in the following section (6.5). Mass balance data for the rest of the basins are presented in Appendix 8. Biotic and abiotic pools in the marine ecosystem were calculated in the mass balance calculations (see also Section 4) for the following biotic and abiotic pools:

- Producers (phytoplankton, microphytobenthos and macrophytes).
- Consumers (bacterioplankton, zooplankton, benthic bacteria, benthic detrivores and meiofauna, benthic herbivores, benthic filter feeders, benthic carnivores, benthic feeding fish, zooplankton feeding fish, piscivorous fish birds and seals (only for C).
- Abiotic pools (top 10 cm of the sediment, dissolved elements (for carbon DIC and DOC are counted together) and elements in the particulate phase.

The following fluxes of elements in the ecosystem were also included in the mass balance calculations where data were available:

- Net primary production (for C, N and P, see Section 4 of this report).
- Respiration (for C, see Section 4 of this report).
- Advective flow (Section 5 of this report).
- Runoff /Tröjbom et al. 2007, 2008/.
- Accumulation in the sediments (burial) (see Section 4 of this report).
- Precipitation /Tröjbom and Söderbäck 2006a, b, Pihl Karlsson et al. 2003, 2008, Knape 2001, Tyler and Olsson 2006/.
- Exchange with atmosphere via diffusion for C /Kumblad et al. 2003/.

Other flux processes such as evaporation, denitrification, volatilization etc were not considered in the mass balance due to a lack of data on these processes in a marine ecosystem. Site-specific groundwater fluxes from land to the marine basin were not ready in time to be included in the calculations.

6.3.1 Carbon, nitrogen and phosporus – Forsmark

A schematic overview of pools and fluxes of carbon, nitrogen and phosphorus in the whole marine model area is shown in Figure 6-39, 6-40, 6-41 (per m^{-2} $year^{-1}$) and summarized in Table 6-1 (in total amount in the whole area).

Carbon

The major pool of carbon in the whole marine area is sediment, followed by the dissolved water phase of carbon and the primary producers. Sediment comprises 76% of the carbon pool in the whole basin, followed by dissolved carbon (15%), macrophytes (3%), benthic detrivores and meiofauna (1.5%), and particulate carbon (1%). All other pools contain less than 1% of the total carbon inventory in the marine model area in Forsmark (see also Appendix 8). In this study the top 10 cm of sediment is assumed to be the biologically active part of the ecosystem. Although organic-rich sediment is not present in large amounts, low concentrations of carbon are found in till and other Quaternary deposits, and the great total volume of sediment make the sediment pool of carbon very large.

The major flux of carbon is the advective flux. There is a net advective outflux of carbon in the whole marine area in Forsmark (65,065 tonnes $year^{-1}$). NPP and respiration are second and third in magnitude, while runoff, diffusion, precipitation and burial are very small in comparison with other fluxes.

The total fluxes of carbon in the whole marine area, considering both influxes (runoff, advection, deposition, diffusion and net primary production) and outfluxes (advection, respiration and burial), is negative, i.e. there is a net outflux of carbon from the whole marine area of about 36,000 tonnes per year. This is equivalent to around 50 gC m^{-2} $year^{-1}$. Although not all of the basins show a net outflux (only Basins 100, 105, 103, 108, 151, 118, 150, 126 and 121, most of them in smaller volumes), some of them, like Basin 151, show a large net outflux of carbon in the mass balance calculations.

According to /Broecker and Peng 1982/, the exchange between atmosphere and sea water can be very large depending on the net outflux from the system, and the carbon needed to exhibit equilibrium between the sea water and the atmosphere is generally supplied by the atmosphere. The estimate of diffusion used is a reported mean value for the Baltic and may be an underestimate. The carbon concentrations and fluxes of water used in the mass balance calculations greatly affect the results of mass balance calculations, since a small concentration difference may cause large changes in the carbon moved by water. However, the carbon concentrations are based on a large amount of data (see Section 3) with high confidence, Figure 6-39.

Nitrogen

The sediment is the overall dominant pool for nitrogen. Sediment comprises 85% of the nitrogen pool in the whole basin, followed by dissolved nitrogen (6%), particulate nitrogen (3%), macrophytes (2%), and microphytes (1%), while all other pools contain less than 1% of the total nitrogen inventory in the marine model area in Forsmark (see also Appendix 9).

The major flux of nitrogen is the advective flux, with a net outflux in the basin (58,000 tonnes $year^{-1}$). The incorporation of nitrogen during NPP and runoff is the second and third fluxes in magnitude, while precipitation and burial are very small in comparison to the other fluxes. Processes like denitrification and exchange with atmosphere are not included. Although most of the basins show a net influx of nitrogen and are almost balanced, 7 out of 28 show a net outflux (Basins 102 and 100, see Appendix 8). The large advective flows in some of these basins contributes so much to the total result for the whole marine area that the total resulting flux is negative. Denitrification probably contributes somewhat to the release of nitrogen from sediment and PON to the dissolved phase, Figure 6-40. /Witek et al. 2003/ have reported denitrification rates in The Baltic of 18 gN m^{-2} $year^{-1}$, which is in the same magnitude as nitrogen incorporated during photosynthesis.

Phosphorus

Phosphorus is less abundant than C and N in the marine ecosystem in Forsmark, but sediment is once again the overall dominant pool for phosphorus. Sediment comprises 90% of the pool in the whole basin, followed by particulate phosphorus (3%), dissolved phosphorus (1%), macrophytes (1%), and microphytes (1%), while all other pools contain less than 1% of the total phosphorus inventory in the marine model area in Forsmark (see also Appendix 9).

As for C and N the major flux of phosphorus is the conrective flux. The incorporation of phosphorus during NPP is the second flux in magnitude. Runoff, precipitation and burial are very small in comparison with the other fluxes, Figure 6-41. There is a net influx in the whole marine area, considering all flux processes (abiotic and biotic), of around 30,000 tonnes year^{-1}. In most basins the net flux of phosphorus is very small, i.e. the fluxes are almost in balance, and in some basins the influx is very large. This could indicate that these marine basins in Forsmark may serve as a sink and accumulate P, although, since burial is still very small, this is probably due to uncertainties in the calculations. as for all other elements, the advective flux is a large term and will affect the results of the mass balance calculations greatly at even small changes in concentration and/or water volume.

Table 6-1. Pools and fluxes of carbon, nitrogen and phosphorus, in tonnes per year for the whole marine model area in Forsmark.

Area: 246 km^2, volume: 3,088×10^6 m^3, mean depth: 12.6 m

Fluxes	**C**	**N**	**P**
Runoff	3,830	248	5
Advective influx	5,390,000	736,000	59,200
Net Primary Production	25,000	4,460	608
In by precipitation	310	89	30
Advective outflux	5,460,000	794,000	28,900
Out to air, respiration	18,700	Not applicable	Not applicable
Accumulation by burial	333	38	7
Diffusion (exchange with atmosphere)	2,562	No data	No data
Net advective flux	**–65,065**	**–58,066**	**30,218**
Pools			
Phytoplankton	59	7	1
Microphytes	438	51	9
Macrophytes	1,972	123	11
Total pool producers	**2,470**	**181**	**21**
Bacterioplankton	71	12	3
Zooplankton	20	4	3
Benthic bacteria	302	54	17
Benthic herbivores	229	27	3
Benthic filter feeders	240	16	1
Benthic detrivores	974	77	9
Benthic carnivores	88	16	2
Benthivorous fish	32	8	2
Zooplanktivorous fish	34	9	2
Piscivorous fish	10	2	0
Birds	1	no data	no data
Seals	4	no data	no data
Total pool consumers	**2,000**	**226**	**42**
Top 10 cm regolith pool	47,800	5,480	938
Particulate pool	696	187	31
Dissolved pool (inorganic and organic)	31,000	410	6

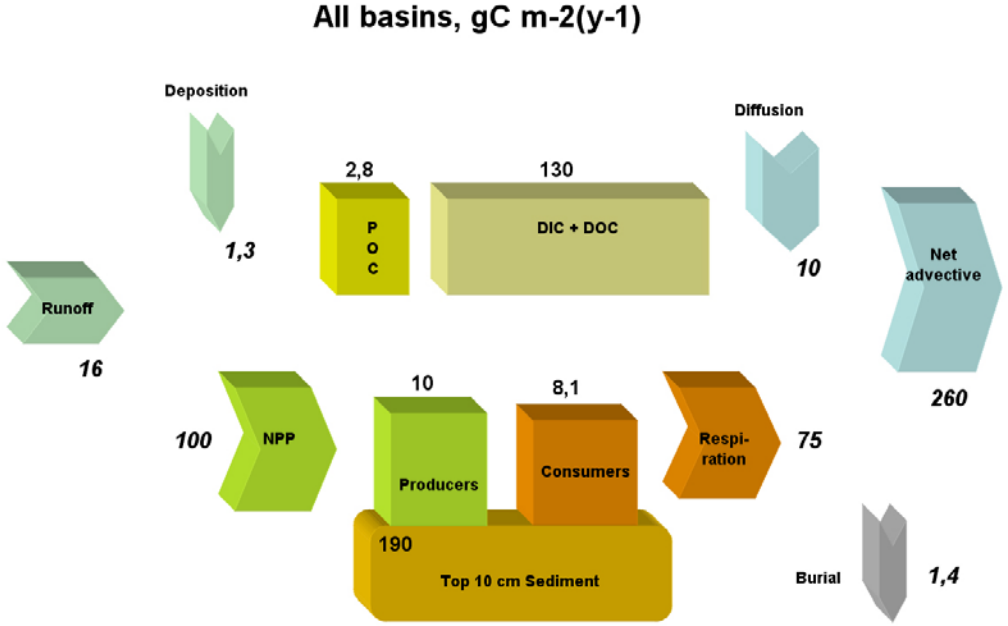


Figure 6-39. *Schematic overview of pools and fluxes of carbon in the whole marine model area in Forsmark, in g C m^{-2} year^{-1}.*

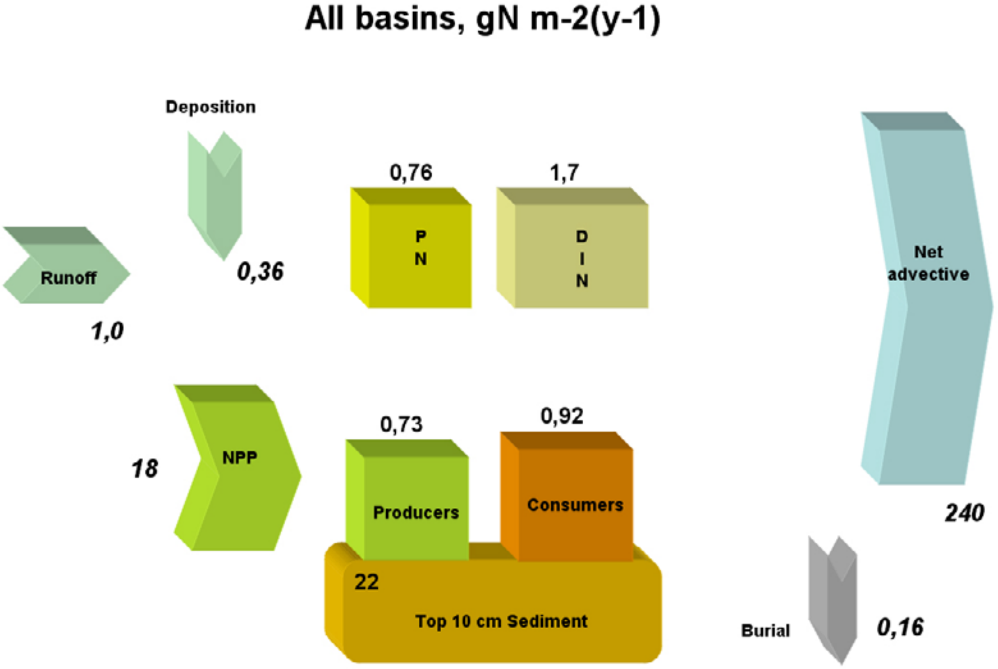


Figure 6-40. *Schematic overview of pools and fluxes of nitrogen in the whole marine model area in Forsmark, in g Nm^{-2} year^{-1}.*

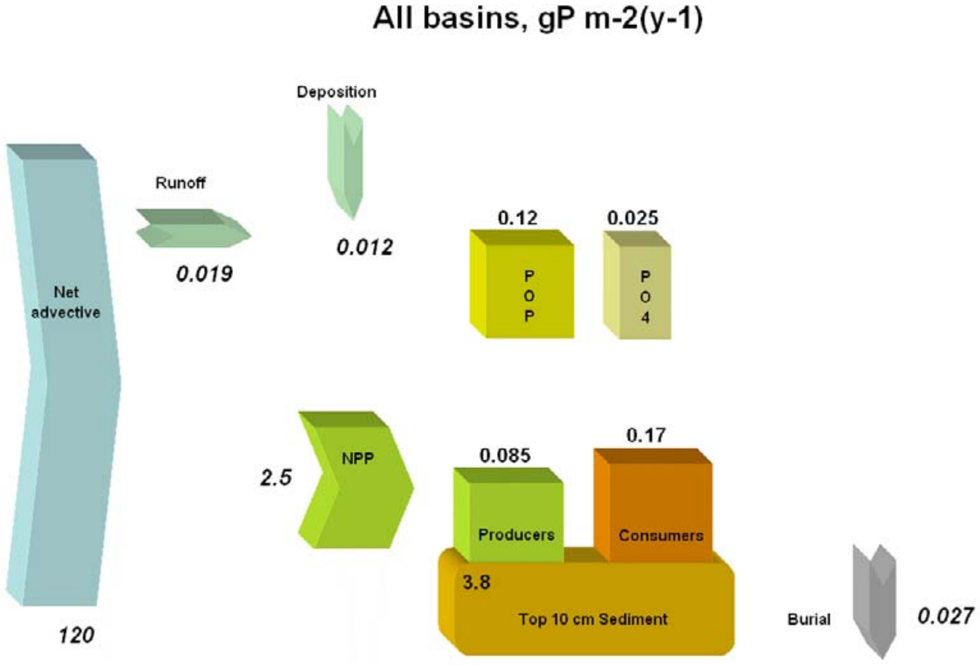


Figure 6-41. Schematic overview of pools and fluxes of phosphorus in the whole marine model area in Forsmark, in g Pm^{-2} year^{-1}.

6.3.2 Actinides and Iodine – Forsmark

For these elements the fluxes considered are advective flux, precipitation and burial. Other fluxes were not included due to a lack of data. For some functional groups (benthic bacteria, bacterioplankton, benthic filter feeders, benthic carnivores, birds and seals), no analysis data were available and are thus not included in the mass balances, which underestimates the consumer pool. Concentrations of some elements in some biota were below the detection limit, and estimated means based on half the detection limit were used to give a rough estimate. Uranium concentrations in biota have not been measured in Forsmark and data from Laxemar-Simpevarp have been used to give rough estimate. The biotic pools for which estimated means of concentrations were used are marked in Table 6-2. Data for all basins are presented in Appendix 9.

The distribution coefficients (K_d) for these elements cover a wide range: 3,200 ml/g (Th), 35 ml/g (U) and 0.6 ml/g (I) /SKB 2006a/, which is also reflected in the distribution of the elements in the marine pools. Th has the smallest pools in the water compared to the sediments and I the largest (Figures 6-42, 6-43, 6-44 and Table 6-2). The mass balances for Th, U and I indicate that there is a net outflux of these elements from the marine area in Forsmark, although processes such as runoff, incorporation during growth of biota and release during decomposition of organic material are not included and will contribute to the uncertainty of the mass balance calculations.

Thorium

For thorium the major pool is the sediment. The sediment comprises 89% of the pool in the whole basin, followed by dissolved thorium (7%), particulate thorium (2%) and the primary producers, microphytes (1%). All other pools contain less than 1% of the total thorium inventory in the marine model area in Forsmark.

The major flux of thorium is the advective flux; the model shows a net outflux in the basin (125 kg year^{-1}). Deposition and burial are very small in comparison with the advective fluxes, Figure 6-42.

Uranium

For uranium the dissolved pool in the water is the overall dominant pool, although the sediment pool is almost as large. The biotic pools are very small and the largest pool is the macrophytes, which constitute 0.004% of the total uranium pool in the marine model area in Forsmark.

The major flux of uranium is the advective flux. Burial and deposition are very small in comparison with the advective fluxes, see Figure 6-43. According to the model there is a net outflux of U from the marine model area in Forsmark of around 1,400 kg year^{-1}.

Iodine

For iodine the dissolved pool in the water is the overall dominant pool. Dissolved iodine comprises 76% of the pool in the whole basin, followed by sediment (14%), particulate iodine (6%), macrophytes (2%) and microphytes (1%). All other pools contain less than 1% of the total iodine inventory in the marine model area in Forsmark.

The major flux of iodine is the advective flux, and as in the case of Th and U, burial is very small in comparison with the advective fluxes. The model indicates a net outflux of I from the marine area in Forsmark, see Figure 6-44. The calculations of fluxes resulted in a net outflux of around 14 tonnes year^{-1}.

Table 6-2. Pools and fluxes of iodine, thorium and uranium in tonnes per year for the whole marine model area in Forsmark. Values marked with * denotes reported values below detection limit were reported value have been divided by 2 in calculations. Values marked with ** denotes data from analyses in Laxemar-Simpevarp. Values marked with * denotes that concentrations measured in macrophytes in Laxemar-Simpevarp have been used for all primary producers and that concentrations for benthic filter feeders in Laxemar-Simpevarp have been used for zooplankton and benthic fauna.**

Area: 246 km^2, volume: 3,088×10^6 m^3, mean depth: 12.6 m

Fluxes	**I**	**Th**	**U**
Runoff	no data	no data	no data
Advective influx	16,489	130	1,706
Net Primary Production	no data	No data	no data
In by precipitation	0.07	0.00121	0.0005
Advective outflux	16,503	130	1,708
Out to air, respiration	No data	no data	no data
Accumulation by burial	0.04	0.02	0.02
Net advective flux	–14	–0.1	–2
Pools			
Phytoplankton	0.01	0.0005	0.0001**
Microphytes	1	0.05	0.001**
Macrophytes	0.4	0.002	0.004**
Total pool producers	**1**	**0.05**	**0.004**
Bacterioplankton	no data	no data	no data
Zooplankton	0.003	0.00002	no data
Benthic bacteria	no data	no data	no data
Benthic herbivores	0.01	0.0002	0.0002***
Benthic filter feeders	no data	0.0001	0.0002
Benthic detrivores	0.01	0.001	0.0008***
benthic carnivores	no data	0.0001	0.0001***
Benthivorous fish	0.0001	0.0000004*	0.0000001**
Zooplanktivorous fish	0.0001	0.0000003*	0.0000001**
Piscivorous fish	0.00004	0.0000001	0.00000002*
Bird	no data	no data	no data
Seal	no data	no data	no data
Total pool consumers	**0.02**	**0.001**	**0.001**
Top 10 cm regolith pool	6*	3	3
Particulate pool	2	0.1	4
Dissolved pool	30	0.2	3

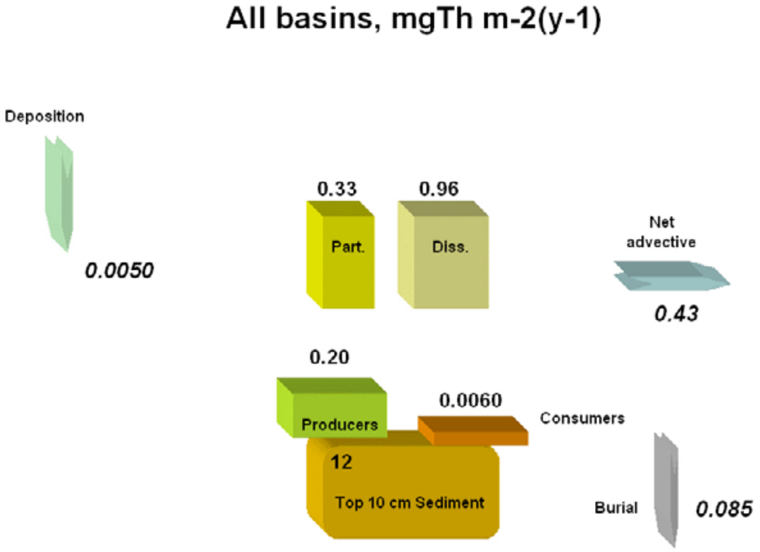


Figure 6-42. *Schematic overview of pools and fluxes of thorium in the whole marine model area in Forsmark, in mg Th m^{-2} year^{-1}.*

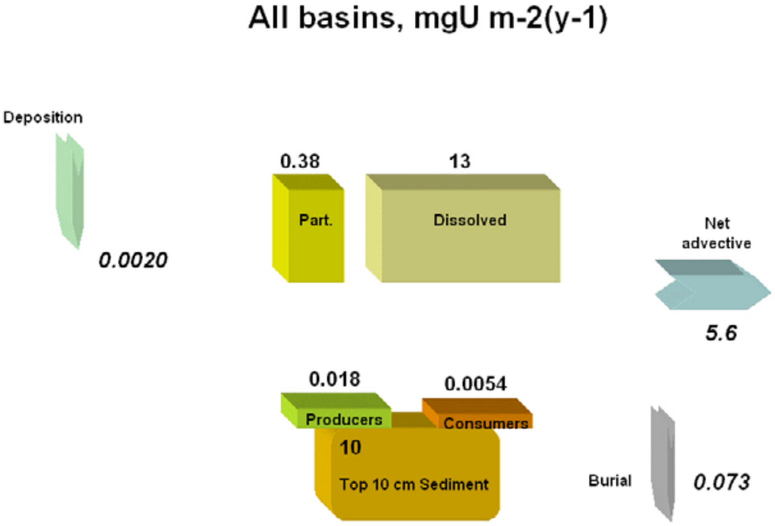


Figure 6-43. *Schematic overview of pools and fluxes of uranium in the whole marine model area in Forsmark, in mg U m^{-2} year^{-1}.*

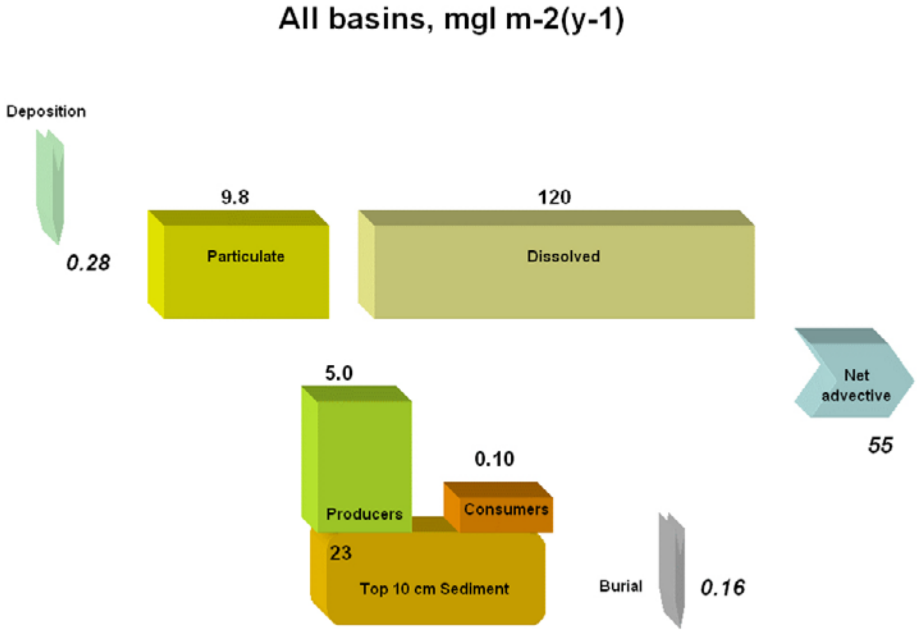


Figure 6-44. Schematic overview of pools and fluxes of iodine in the whole marine model area in Forsmark, in mg I m^{-2} $year^{-1}$.

6.3.3 Carbon, nitrogen and phosphorus – Laxemar-Simpevarp

A schematic overview of pools and fluxes of carbon, nitrogen and phosphorus in the whole marine model area is shown in Figures 6-45, 6-46, 6-47 and Table 6-3.

Carbon

In the separate basins (the inner bays) the sediment pool can be the major carbon pool but in average for the whole marine area, the dominant carbon pool is the dissolved phase. DIC and DOC, constitute in total 54% of the whole carbon pool in the area, followed by the sediment pool (21%), the consumer pool (16%, dominated by the filter feeders) and the producer pool (8.5%). Among the producers it is the macrophytes that constitute the main pool, while the other producers contribute less than 1% to the producer pool.

Considering all fluxes in the mass balance calculations (advective flux, deposition, diffusion, runoff primary production, respiration and burial), there is a net influx of carbon to the whole marine area in Laxemar-Simpevarp, equivalent to around 9 gC m^{-2} $year^{-1}$. But not all basins show this net influx, and some have a net outflux of carbon instead (11 out of 19 basins, see Appendix 8). Burial is very low, although the net influx indicates there are uncertainties in the mass balance calculations. The major flux of carbon is the advective flux.This estimate is based on very large volumes of water transferred between the basins (se Section 5) and on concentrations of C in the water from sampling during the site investigation in the area (see Sections 3 and 4),.Since the water volumes are so large even small uncertainties in these estimates will have great consequences for the mass balance. All other fluxes including burial are very small in comparison with the advective flux. There is less uncertainty in the burial term than in the advective term, hence the large net influx does not indicate that the area is a sink for carbon, Figure 6-45.

Nitrogen

Looking at the total inventory of nitrogen in the whole marine basin in Laxemar-Simpevarp, consumers constitute the major pool (49%), Table 6-3, followed by sediment (40%) and macrophytes (6%). The consumer pool is totally dominated by filter feeders. This is also true of nitrogen pools per m^2 (Figure 6-46).

The mass balance calculations show an annual net advective outflux of nitrogen in the whole marine area (around 111,000 tonnes year–1) and in 7 out of 19 basins (Appendix 8). The major flux of nitrogen is the advective flux, in comparison all other fluxes are very small. Since advection is such a large term it will have great influence on the results and even minor uncertainties will greatly affect the result. Denitrification is not included in the mass balance and could contribute to an even larger outflux in the basins.

Phosphorus

Phosphorus is quite evenly distributed between the sediment and consumer pools, which are in the same order of magnitude (43% and 44%, respectively). The third largest pool, although much smaller than the former two, is primary producers (7%). (Figure 6-47, Table 6-3).

The major flux of phosphorus is the advective flux. Runoff, burial and precipitation are very small in comparison with the other fluxes (Figure 6-47). The mass balance calculation shows a net influx of phosphorus in the whole marine area of 2,600 tonnes year^{-1}, mainly due to a large net influx in Basins 523 and 521. In most basins the net flux of phosphorus is quite low. Release of phosphorus during decomposition of organic material is not included. This could indicate that the marine basins in Laxemar-Simpevarp in some way serve as a sink and accumulate P, although as the burial is low it probably indicates uncertainties in the calculations. For all other elements, the advective flux is a large term and will affect the results of the mass balance calculations greatly at even small changes in concentration and/or water volume.

Table 6-3. Pools and fluxes of carbon, nitrogen and phosphorus, in tonnes per year for the whole marine model area in Laxemar-Simpevarp.

Area: 119 km^2, volume: 1,154×10^6 m^3, mean depth: 9.9 m

Fluxes	**C**	**N**	**P**
Runoff	598	39	1
Advective inflow	5,123,978	448,090	36,893
Net Primary Production	20,565	3,621	501
In by precipitation (deposition)	223	760	3
Advective outflow	5,060,767	563,256	35,575
Out to air, respiration	39,331	6,890	954
Accumulation by burial	287	34	6
Diffusion (exchange with atmosphere)	1,235	no data	No data
Pools			
Phytoplankton	26	3	0.3
Microphytes	189	22	4
Macrophytes	3,481	151	25
Emerging macrophytes	incl in macrphytes	incl in macrphytes	incl in macrphytes
Total pool producers	**3,696**	**176**	**29**
Bacterioplankton	28	5	1
Zooplankton	9	2	1
Benthic bacteria	158	29	9
Benthic herbivores	459	53	5
Benthic filter feeders	5,425	1,053	146
Benthic detrivores	930	170	18
Benthic carnivores	37	3	0,3
Benthic feeding fish	27	8	1
Zooplankton-feeding fish	44	10	1
Piscivorous fish	7	2	0
Birds	1	no data	no data
Seals	1	no data	no data
Total pool consumers	**7,125**	**1,334**	**183**
Top 10 cm regolith pool	9,090	1,077	178
Particulate pool	201	53	11
Dissolved pool (inorganic and organic)	4,934	66	14

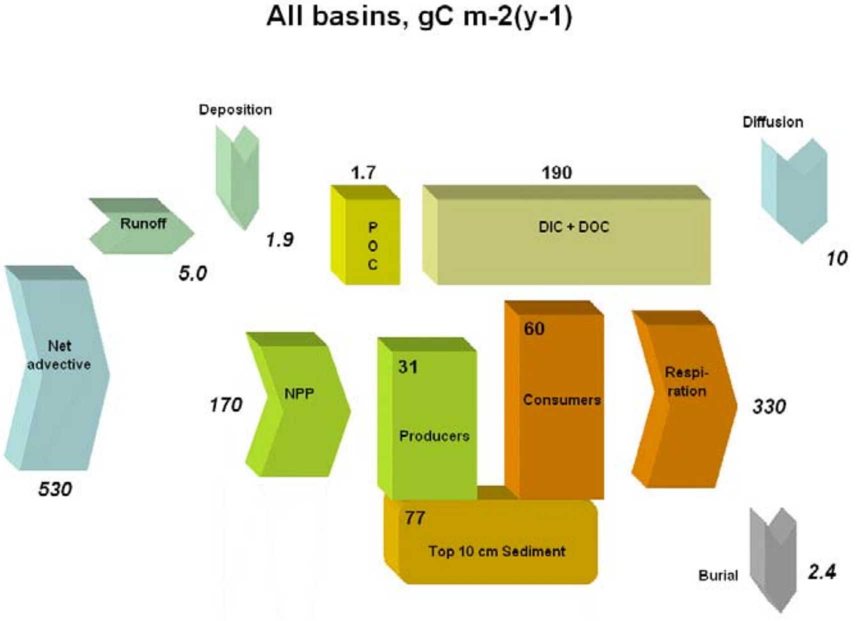


Figure 6-45. Schematic overview of pools and fluxes of carbon in the whole marine model area in Laxemar-Simpevarp, in g C m^{-2} year^{-1}.

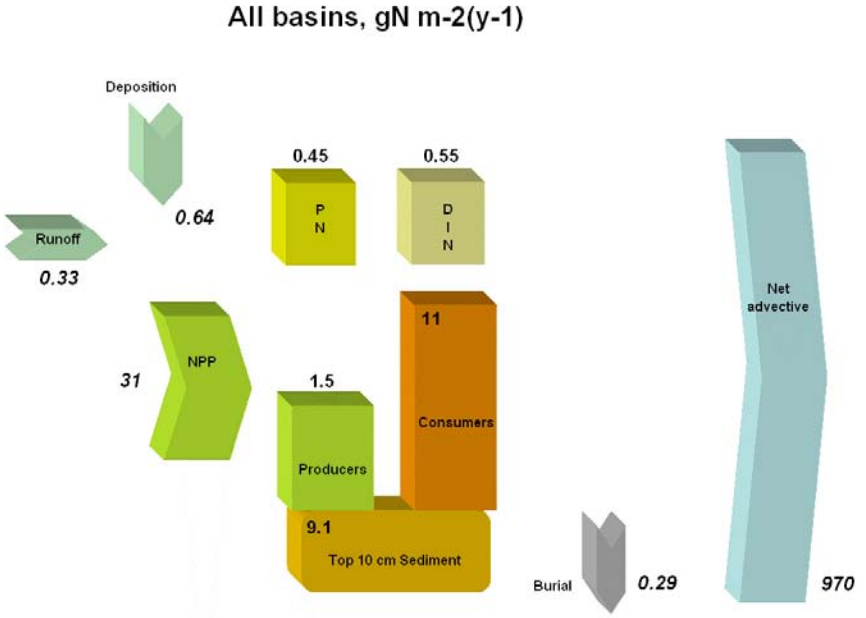


Figure 6-46. Schematic overview of pools and fluxes of nitrogen in the whole marine model area in Laxemar-Simpevarp, in g N m^{-2} year^{-1}.

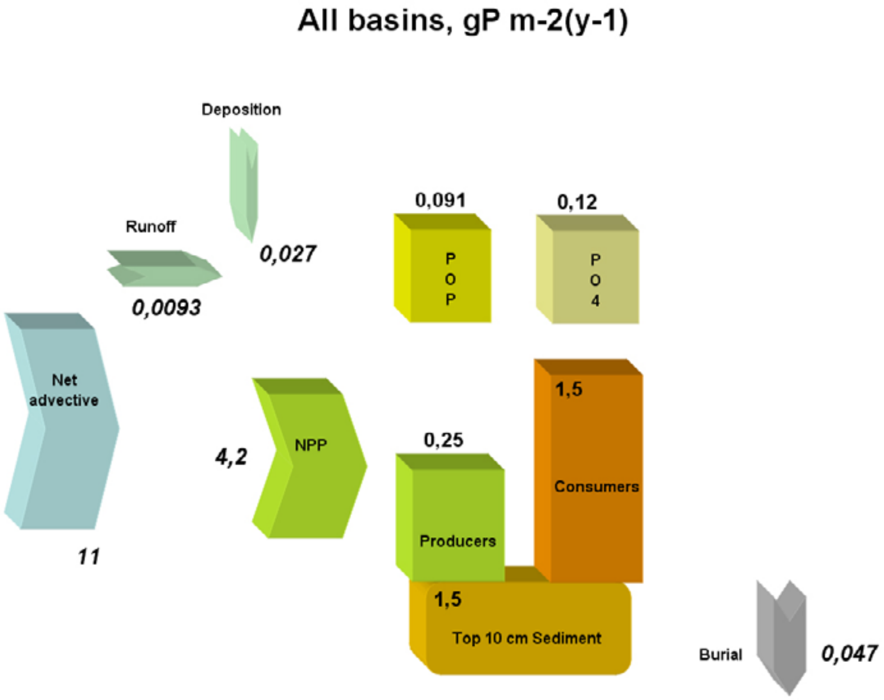


Figure 6-47. Schematic overview of pools and fluxes of phosphorus in the whole marine model area in Laxemar-Simpevarp, in g P m^{-2} year^{-1}.

6.3.4 Actinides and Iodine – Laxemar-Simpevarp

Considered fluxes are advective flow, deposition and burial. The other fluxes NPP, respiration and diffusion were not included due to a lack of data. For some functional groups (benthic bacteria, bacterioplankton, benthic filter feeders, benthic carnivores, birds and seals), no analysis data were available and they are not included in the mass balances, entailing an underestimation of the consumer pool. For some of the biotic functional groups data on uranium concentrations were not available in Laxemar-Simpevarp and therefore data from Forsmark were used for them to give a rough estimate of these pools relative to other pools. Since mainly salinity but also other chemical characteristics will affect uranium distribution, these estimates of uranium concentrations are to be regarded as very rough. Some analyses of biota were below the detection limit, and estimated means based on half the detection limit were used to give an estimate. Uranium analyses did not include all functional groups, and to give a rough estimate of pools, reported concentrations for macrophytes have been used for all primary producers and reported values for benthic filters have been used for all benthic fauna. These data are marked in Table 6-4 and in Appendix 9.

The varying distribution coefficients (Kd) for the elements, thorium, uranium and iodine, are reflected in the distribution in the marine pools in Laxemar-Simpevarp as well (Figures 6-48, 6-49 and 6-50). The mass balances for Th, U and I entail that there is a net outflux of these elements from the marine area in Laxemar-Simpevarp, although processes such as runoff, incorporation during growth of biota, and release during decomposition of organic material are not included and will contribute to the uncertainty of the mass balance calculations.

Thorium

For thorium the major pool is the sediment. The sediment comprises 90% of the pool in the whole basin, followed by particulate matter (4%), microphytobenthos (4%) and the dissolved pool (1%). All other pools contain less than 1% of the total thorium inventory in the marine model area in Laxemar-Simpevarp.

The major flux of thorium is the advective flux; the model indicates a net advective outflux in the basin (5 tonnes year^{-1}). Burial is very small in comparison with the advective fluxes, see Figure 6-48.

Uranium

For uranium the dissolved pool in the water is the dominant pool (67%). The particulate pool comprises 31% of the pool in the whole basin, followed by sediment (1%). All other pools contain less than 1% of the total thorium inventory in the marine model area in Laxemar-Simpevarp.

The major flux of uranium is the advective flux; the model indicates large net advective in flux in the basin (28 tonnes year^{-1}). The size of the net in flux is due to small concentration differences at the various sampling sites in the marine area. This will be of great importance to the results since it is connected to the large advective flows in the area. Burial is very small in comparison with the advective fluxes, see Figure 6-49.

Iodine

For iodine the dissolved pool is dominant (86% of total iodine). The producer pool constitutes only around 5%, of the total iodine in the ecosystem. That is the same order of magnitude as the sediment and particulate pools. The consumer pool constitutes 2%, while all other pools contain less than 1% of the total iodine inventory in the marine model area in Laxemar-Simpevarp.

The major flux of iodine is the advective flux; the model indicates a net advective outflux in the basin (3,333 tonnes year^{-1}). Burial is very small in comparison with the advective fluxes, see Figure 6-50.

Table 6-4. Pools and fluxes of iodine, thorium and uranium in tonnes per year for the whole marine model area in Laxemar-Simpevarp. Values marked with an * denotes reported concentrations below detection limit, were half the reported value have been used in the calculations.

Area: 119 km^2, volume: 1 154×10^6 m^3, mean depth: 9.9 m

Fluxes	**I**	**Th**	**U**
Runoff	no data	no data	no data
Advective inflow	14,958	3	987
In by precipitation	0.04	0.001	0.0002
Advective outflow	18,291	8	959
Accumulation by burial	0.02	0.01	0.01
Pools			
Phytoplankton	0.002	0.0002	0.0001
Microphytes	0.4	0.02	0.0004
Macrophytes	1	0.002*	0.008
Emerging macrophytes	incl in macrphytes	incl in macrphytes	incl in macrphytes
Total pool producers	**1**	**0.02**	**0.01**
Bacterioplankton	no data	no data	no data
Zooplankton	0.001	0.00001	no data
Benthic bacteria	no data	no data	no data
Benthic herbivores	0.02	0.0005	0.000
Benthic filter feeders	0.3	0.0004*	0.005
Benthic detrivores	0.05	0.001	0.001
Benthic carnivores	0.002	0.00007	0.00003
Benthic feeding fish	0.00006*	0.000001*	0.00000001
Zooplankton-feeding fish	0.00002*	0.0000002*	0.00000005
Piscivorous fish	0.00001	0.0000002	0.000000001*
Birds	no data	no data	no data
Seals	no data	no data	no data
Total pool consumers	**0.3**	**0.002**	**0.01**
Top 10 cm regolith pool	1	0.5	0.4
Particulate pool	1	0.02	0.01
Dissolved pool	16	0.01	1

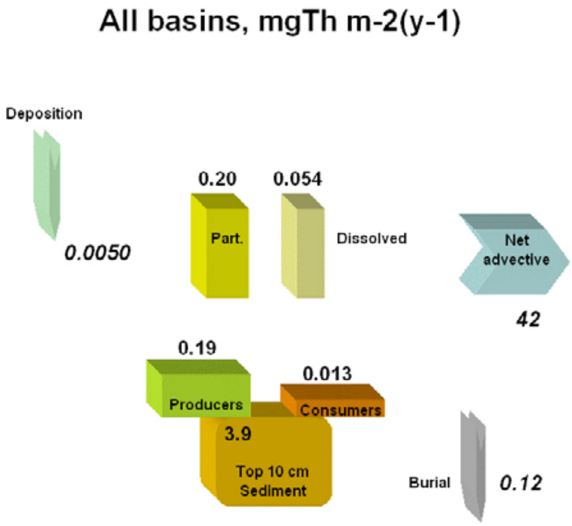


Figure 6-48. *Schematic overview of pools and fluxes of thorium in the whole marine model area in Laxemar-Simpevarp, in mg Th m^{-2} $year^{-1.}$*

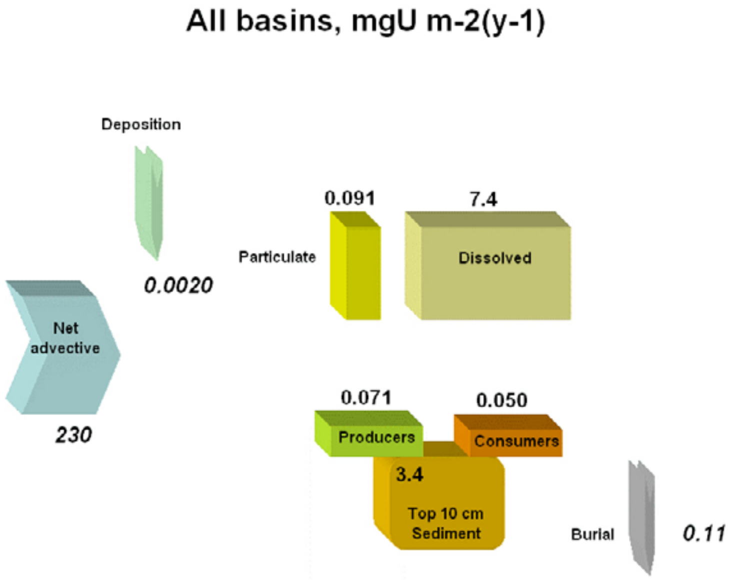


Figure 6-49. *Schematic overview of pools and fluxes of uranium in the whole marine model area in Laxemar-Simpevarp, in mg U m^{-2} $year^{-1.}$*

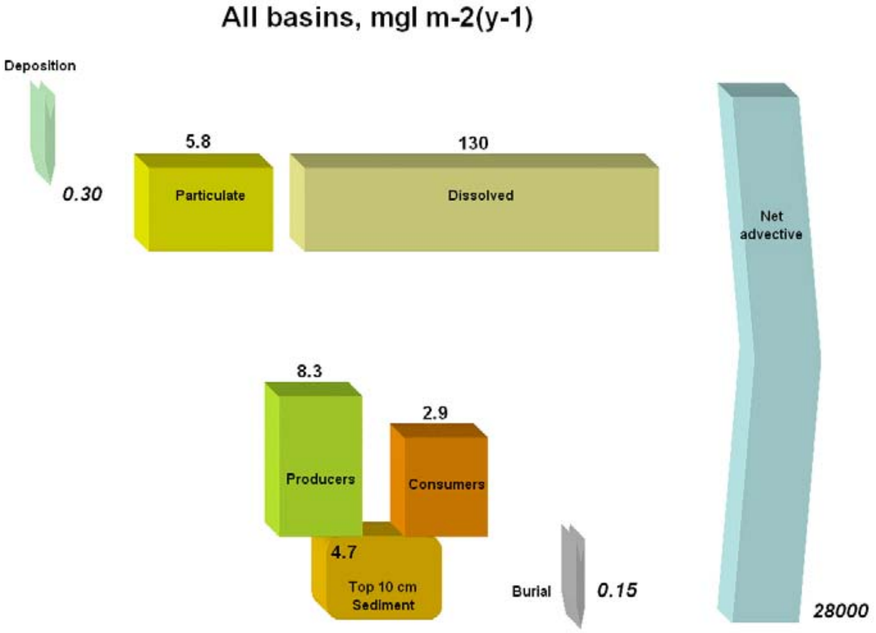


Figure 6-50. *Schematic overview of pools and fluxes of iodine in the whole marine model area in Laxemar-Simpevarp, in mg I* m^{-2} *year*$^{-1.}$

6.4 Abundance and distribution of carbon and other elements – both sites

This chapter discusses the abundance and distribution of 49 elements in the marine ecosystem in Forsmark and Laxemar-Simpevarp.

The annual average concentrations in all model pools (biotic and abiotic) are presented for the following elements (metalloids: Si, As, Se, metals: Ti, Fe, Zr, V, Co, Al, Hg, Cs, Pb, Cu, Cr, Ni, Mn, Cd, Rb, Mo, Li, Ba, K, Zn, Ca, Na, Mg, lanthanides: Dy, Ce, Pr, Gd, Sm, Yb, Ho, Eu, Er, Lu, Tm, Nd, Tb, non-metals: P, N, C, I, S, F, Br, Cl and the actinides: Th, U). C, N, P and I, Th and U will be specifically presented.

The data presented for Forsmark are based on analyses made in 2005 for the biotic pools /Kumblad and Bradshaw 2008/, sediment /Engdahl et al. 2008/ and data from the site investigations in Forsmark 2002–2006 extracted from SKB's database Sicada (dissolved and particulate phase).

The data presented for Laxemar-Simpevarp are based on analyses in /Engdahl et al. 2006/ (deposits and biota), /Nilsson 2004, Engdahl et al. 2008/ (sediment) and data from the site investigations in 2003–2008, extracted from SKB's database Sicada[5] (dissolved and particulate phase).

6.4.1 Distribution of elements in all model pools – Forsmark

The elemental composition of all pools (biota, dissolved in water, particulate and sediment (top 10 cm)), for the whole marine area is presented in Figure 6-51. Table 6-5 shows the elemental composition in figures for the whole marine area and for one separate basin, Basin 134. The most abundant elements are carbon and the major constituents are Cl, Na, Mg, S. They are present to a large extent in the dissolved phase and will therefore be very abundant due to the large water volume. Cl is the most abundant element in the marine ecosystem. On average the total Cl content in all pools constitutes 31 kg m^{-2}. The rest of the elements are minor constituents contributing less than 1% of the total weight.

The whole model area in Forsmark is compared with one separate basin, Basin 134. Basin 134 is rather small and shallow which implies rather large differences in abundance of the major sea water

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[5] SKB database Sicada Delivery #08_111 and 08_112, access might be given upon request.

Table 6-5. Elemental abundance in total mass (g) and per m^2 in all pools in the whole marine model area considered in Forsmark and specifically for Basin 134. C, N, P are presented first, followed by the rest of the elements, in order of magnitude in the whole marine area in Forsmark (all basins). Elements described in further detail below are highlighted in bold text.

Element	All basins g m^{-2}	Tonnes	Basin 134 g m^{-2}	Tonnes
C	**341**	**83,966**	**6,135**	**3,598**
N	**25**	**6,128**	**32**	**19**
P	**2**	**477**	**3**	**2**
Cl	30,806	7,589,019	4,424	2,594
Na	16,809	4,140,988	2,431	1,425
Mg	2,041	502,880	293	172
S	1,461	359,825	246	144
Ca	945	232,793	164	96
K	657	161,795	132	78
Si	410	101,037	582	341
Br	103	25,396	15	9
Al	70	17,306	99	58
Fe	44	10,763	69	40
Ba	11	2,809	1	0
Zn	9	2,100	1	0
F	4	1,097	0.7	0.4
Ti	3	795	5	3
Mn	1	193	1	1
Rb	0	87	0.2	0.1
Zr	0	74	0.4	0.3
Li	0	83	0	0.1
I	**0.2**	**39**	**0.1**	**0.0**
As	0.2	46	0.0	0.0
Pb	0.1	22	0.1	0.1
V	0.1	21	0.1	0.1
Cr	0.1	25	0.1	0.1
Cu	0.1	23	0.1	0.1
Ni	0.1	15	0.1	0.04
Ce	0.09	23	0.1	0.08
Nd	0.05	13	0.1	0.04
Mo	0.03	8	0.01	0.01
U	**0.02**	**6**	**0.02**	**0.01**
Co	0.01	3	0.02	0.01
Cs	0.01	2	0.01	0.01
Th	**0.01**	**3**	**0.0**	**0.01**
Cd	0.01	2	0.01	0.00
Pr	0.01	3	0.02	0.01
Sm	0.01	2	0.01	0.007
Gd	0.01	2	0.01	0.01
Dy	0.005	1	0.01	0.00
Er	0.004	1	0.005	0.003
Yb	0.003	0.8	0.005	0.003
Se	0.003	1	0.002	0.001
Tb	0.002	0.4	0.002	0.001
Hg	0.001	0.1	0.001	0.0004
Ho	0.001	0.3	0.002	0.001
Lu	0.0006	0.1	0.001	0.0005
Tm	0.0006	0.1	0.001	0.0004
Eu	0.002	0.4	0.002	0.001

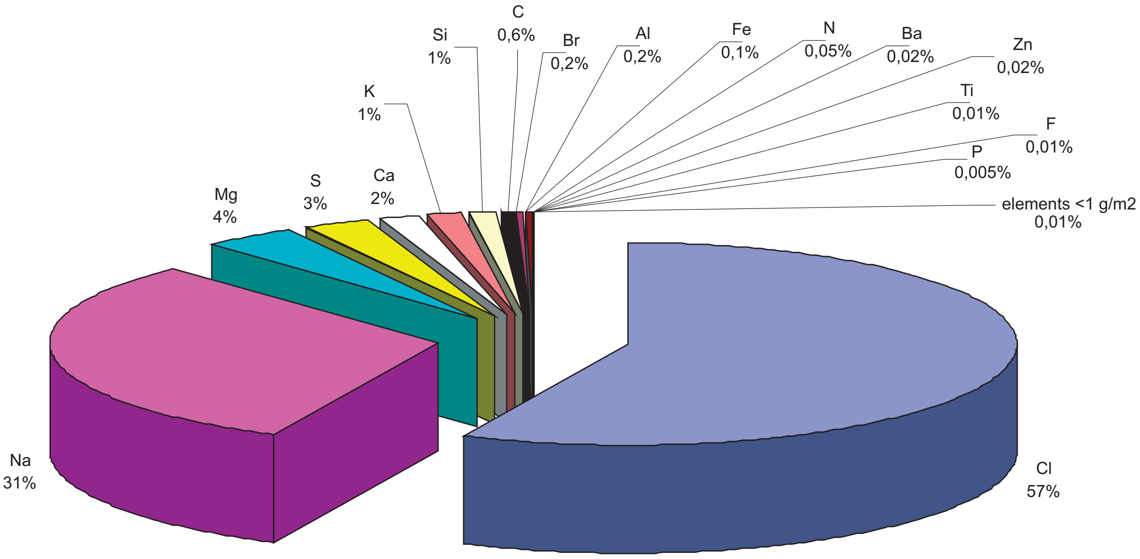

Figure 6-51. *Elemental abundance in all pools the marine model area in Forsmark, in weight percent of investigated elements and in order of magnitude. Note that the elements of water (hydrogen and oxgen) is not included.*

constituents per square metre. The elemental pools in Basin 134 are therefore presented together with the pools of the whole area in Table 6-5. There was more carbon per m^2 in Basin 134, although the nitrogen and phosphorus pools are of the same size per m^2.

Only the elements Mn, P, N, C, I, Co, Ni, Th, Cu, Fe and Ca have biotic pools larger than 1% (by weight), while 99% of all other elements are distributed in the abiotic pools considered (sediment, particulate matter and dissolved), Figure 6-52. However, analyses of some elements are missing for some biotic pools. Seals and birds are not included, only data for C, N and P were available for benthic bacteria and bacterioplankton, data for elemental composition of C, F and Br are missing for macrophytes and benthic detrivores, and since no biotic pools in Forsmark were analyzed with regard to uranium (U), data for biota in Laxemar-Simpevarp were used.

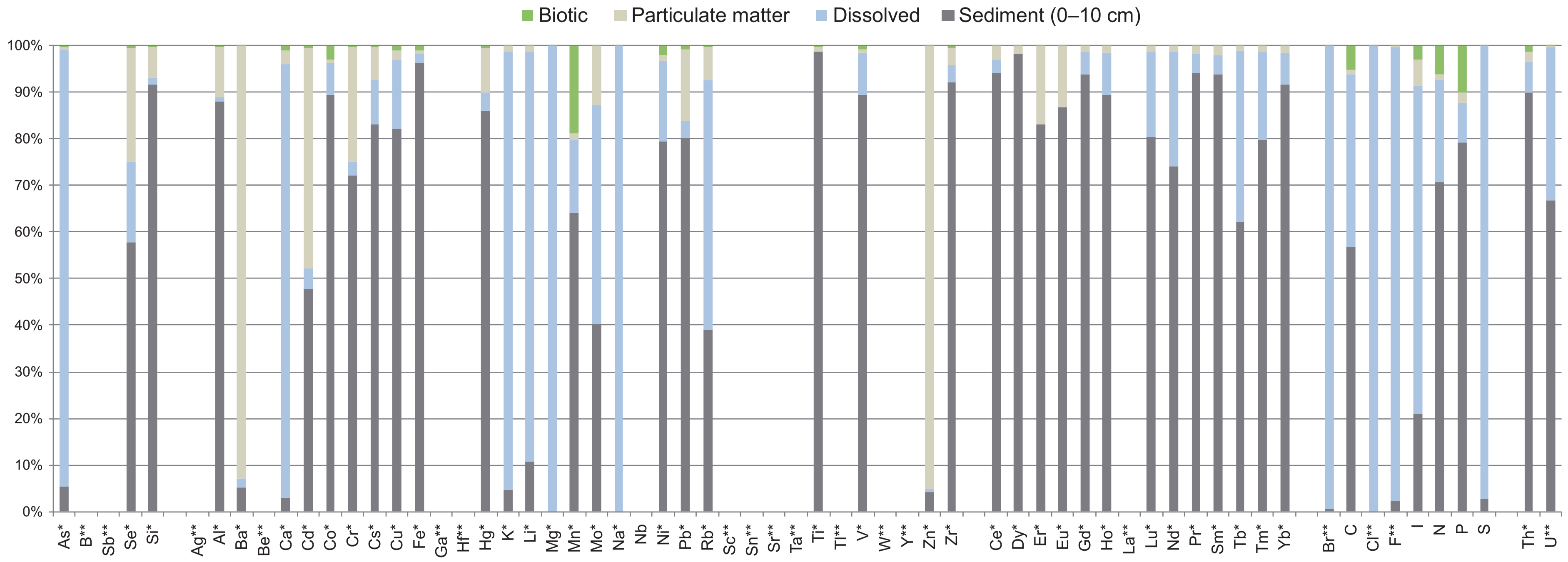

Figure 6-52. *Elemental distribution in percent of total abundance, in biotic and abiotic ecosystem pools in Forsmark model area. * Indicates that data for bacteria is missing, and ** that one or more biotic group besides bacteria is missing.*

6.4.2 Distribution of elements in abiotic pools – Forsmark

In general the abundance of various elements in abiotic pools reflects the composition of the geology at the site, and the expected abundance in this region of the Baltic was in fairly good agreement with the results from Forsmark /Pettersson and Strömberg 2007/. The ten most abundant elements in sediment in Forsmark in order of size in the three abiotic pools are: Si > C > Al > Fe > K > S > N > Ca > Cl > Ti > P; in the particulate pool: Si > Ca > Na > Al > Zn > K > C > Mg > S > N; and in the dissolved pool: Cl > Na > Mg > S > Ca > K > C > Br > Si > N.

Cd, Ba and Zn are the only elements distributed to the greatest extent in the particulate pool (> 50% of total abundance). More than 50% of the metals Rb, Mo, Li, Ba, K, Zn, Ca, Na, and Mg and the non-metals I, S, F, Br, Cl and As occur in the dissolved pool. For the rest of the elements sediments are the major abiotic pool, Figure 6-53.

6.4.3 Distribution of elements in biotic pools – Forsmark

The principal chemical constituents that make up the soft tissues of all organisms are: oxygen, hydrogen, carbon, nitrogen and phosphorus (oxygen and hydrogen have not been analyzed in this study).

In biota the dominant pool for the majority of elements is producers and especially microphytes. This distribution pattern within the producers could be attributable to some overestimation of microphyte biomass, since the sampling technique does not allow a distinction between microphytes and benthic bacteria, and there may also have been contamination of theses samples by sediment. All lanthanides have a similar distribution pattern, and benthic fauna is the dominant pool. Se, Ca, N and P are distributed to the greatest extent in consumers, see Figure 6-54. Organisms that use elements more specifically for certain purposes, such as Ca for skeletons, comprise a large pool in consumers. Data on birds and seals were only available for carbon, so other pools are underestimated.

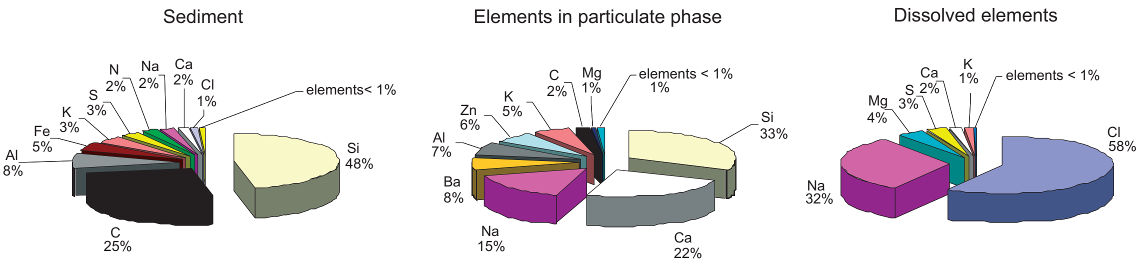

Figure 6-53. Elemental distribution in percent of total abundance in the abiotic pools of the marine ecosystem in the Forsmark marine model area. Note that the elements of water (hydrogen and oxygen) is not included.

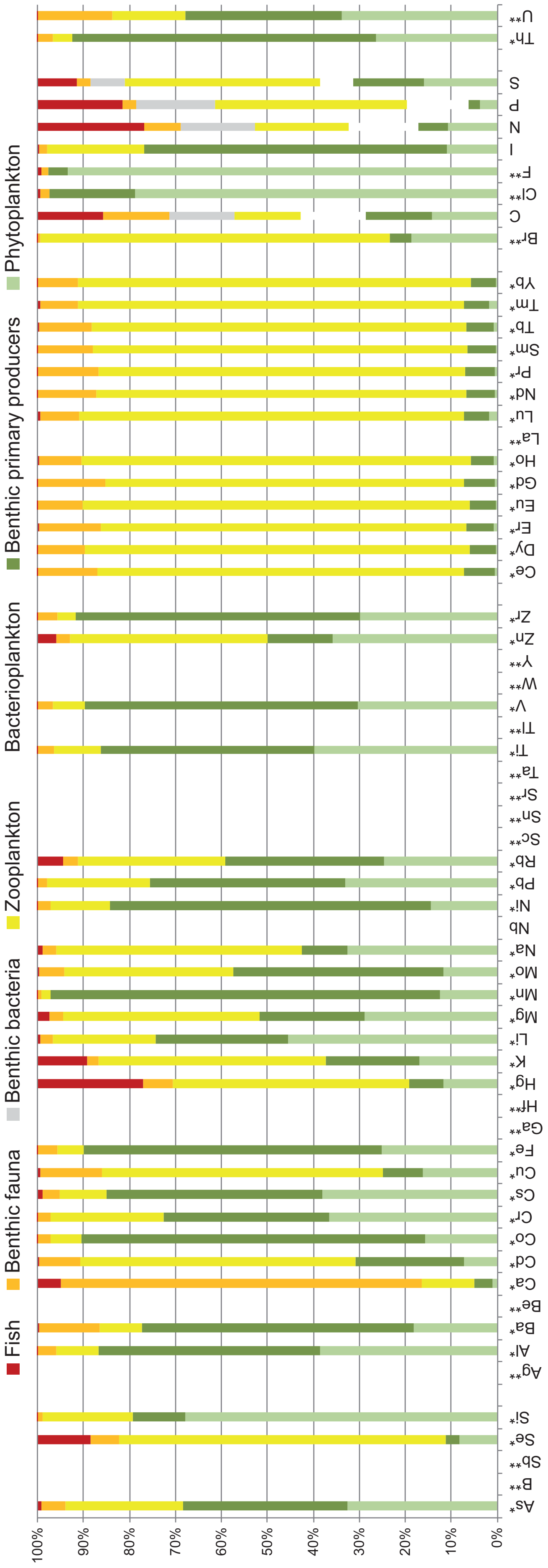

***Figure 6-54.** Elemental distribution in percent of total abundance in biotic pools in the marine ecosystem in the model area in Forsmark.*

** indicates that data for bacteria are missing and ** that one or more other groups besides bacteria are missing.*

6.4.4 Distribution of elements in all model pools – Laxemar-Simpevarp

The elemental composition of all pools (biota, dissolved in water, particulate and sediment (top 10 cm)), for the whole marine area is presented in Figure 6-55. Table 6-6 shows the elemental composition in figures for the whole marine area and for one separate basin, Basin 508. Basin 508 is compared with the whole marine basin in Laxemar-Simpevarp, since data from this basin are abundant and to illustrate the variation within the whole marine area. The major constituents such as Cl, Na, Mg, S are present to a great extent in the dissolved phase and will therefore be very abundant due to the large water volume. Cl is the most abundant element in the marine ecosystem. On average, the total Cl content in all pools is 32 kg m^{-2}. In general, minor constituents are those contributing less than 1% of the total mass.

The distribution pattern of all elements in the biotic pools – sediment, dissolved phase and particulate matter – is shown in Figure 6-56. Just over 50% of the analyzed elements have a distribution with more than 50% in the sediments. The metalloids and the non-metals are more heterogeneously distributed in the pools.

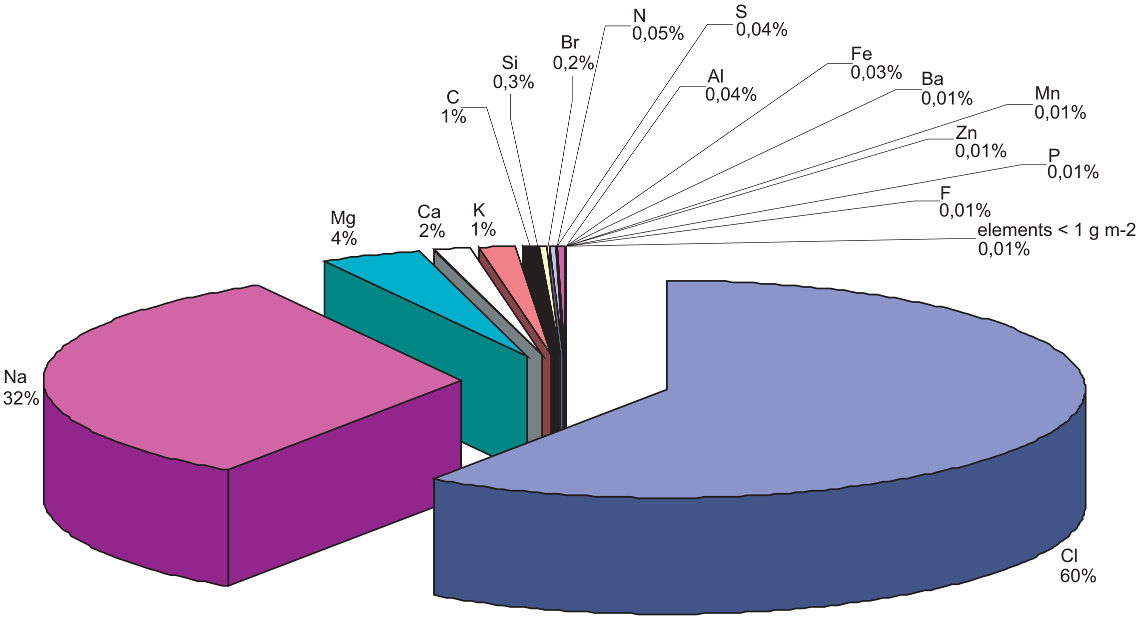

Figure 6-55. Elemental abundance in all pools the marine model area in Laxemar-Simpevarp, in weight-percent per m^2 and in order of magnitude. Note that the elements of water (hydrogen and oxygen) is not included.

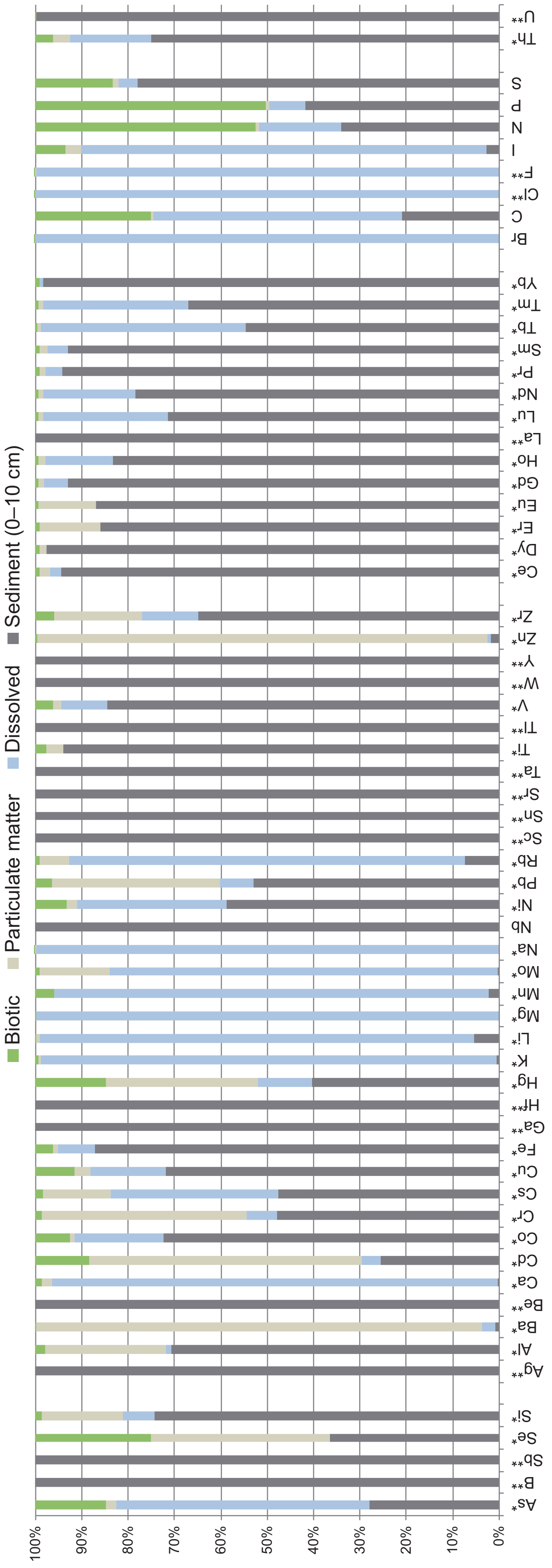

Figure 6-56. *Elemental distribution in percent of total abundance, in biotic and abiotic ecosystem pools in Laxemar-Simpevarp marine model area. * Indicates that data for bacteria is missing, and ** that one or more biotic group besides bacteria is missing.*

Table 6-6. Elemental abundance in total mass (tonnes) and per m² (g m^{-2}) in all pools in the marine model area considered in Laxemar-Simpevarp area and specifically for Basin 508. C, N, P are presented first. The other elements are presented in order of magnitude in the whole marine area in Forsmark (all basins). Elements presented specifically are highlighted with bold text.

Element	All basins g m^{-2}	Tonnes	Basin 508 g m^{-2}	Tonnes
C	**31,845**	**43,256**	**1**	**118**
N	**27**	**3,172**	**1**	**72**
P	**4**	**428**	**0.1**	**12**
Cl	31,845	3,782,910	1	177
Na	17,262	2,050,584	1	110
Mg	2,074	246,345	0.04	4
Ca	883	104,939	1	62
K	671	79,666	0.4	44
Si	146	17,361	7	799
Br	121	14,374	0.0	1
S	22	2,595	1	128
Al	20	2,382	1	106
Fe	17	1,974	1	104
Ba	7	792	0.05	6
Zn	5	595	0.04	5
F	4	518	0.0001	0.0
Mn	4	517	0.01	1
Er	0.6	71	0.0001	0.02
Ti	0.6	66	0.03	4
Ho	0.6	66	0.00005	0.006
Dy	0.5	65	0.0002	0.03
Li	0.3	36	0.001	0.1
Rb	0.2	29	0.001	0.1
I	**0.2**	**20**	**0.001**	**0.1**
Ce	0.08	9	0.004	0.5
Nd	0.05	6	0.002	0.3
Cu	0.05	5	0.002	0.2
Zr	0.04	5	0.002	0.2
Cr	0.03	4	0.001	0.1
Ni	0.03	4	0.001	0.1
Yb	0.03	4	0.002	0.2
Pb	0.03	3	0.001	0.1
V	0.02	3	0.001	0.1
Mo	0.02	2	0.00003	0.003
As	0.01	2	0.0002	0.03
Pr	0.01	1	0.0006	0.07
Co	0.008	1	0.0003	0.04
Sm	0.006	1	0.0004	0.04
U	**0.006**	**1**	**0.0003**	**0.04**
Gd	0.005	1	0.0003	0.04
Th	**0.005**	**1**	**0.0002**	**0.03**
Cd	0.004	0	0.0001	0.01
Cs	0.002	0.3	0.0001	0.01
Se	0.002	0.2	0.00004	0.005
Tb	0.001	0.2	0.00004	0.005
Eu	0.001	0.2	0.0001	0.007
Lu	0.0005	0.1	0.00002	0.003
Tm	0.0005	0.1	0.00002	0.003
Hg	0.00009	0.01	0.000002	0.0003

6.4.5 Distribution of elements in abiotic pools – Laxemar-Simpevarp

The ten most abundant elements in Laxemar-Simpevarp in order of size in the three abiotic pools are in sediment: Si > C > Cl > S > Fe > Al > Na > N > K > Ca; in the particulate pool: Si < Ca > Na > Ba > Al > Zn > K > C > Mg > S; and in the dissolved pool: Cl > Na > Mg > Ca > K > C > Br > Si > N > F.

In the abiotic pools, Si dominates the particulate and sediment pools and Cl the dissolved pool, see Figure 6-57.

6.4.6 Distribution of elements in biotic pools – Laxemar-Simpevarp

In biota, the dominant pool for the majority of elements is producers and especially microphytes. This distribution pattern within the producers could be attributable to some overestimation of microphyte biomass, since the sampling technique did not allow distinction between microphytes and benthic bacteria. The lanthanides exhibit a very similar distribution pattern in Laxemar-Simpevarp. Se, Ca, N and P are mainly distributed in consumers, see Figure 6-58. Data on birds and seals were only available for carbon, so other pools are underestimated.

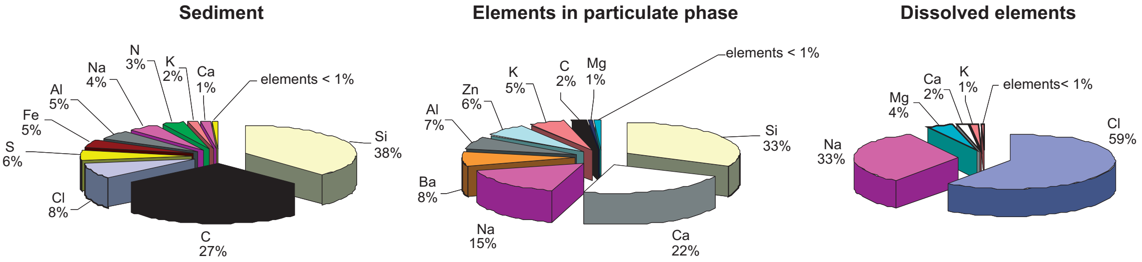

Figure 6-57. Elemental distribution in percent of total abundance in the abiotic pools in the marine ecosystem in the Laxemar-Simpevarp marine model area.

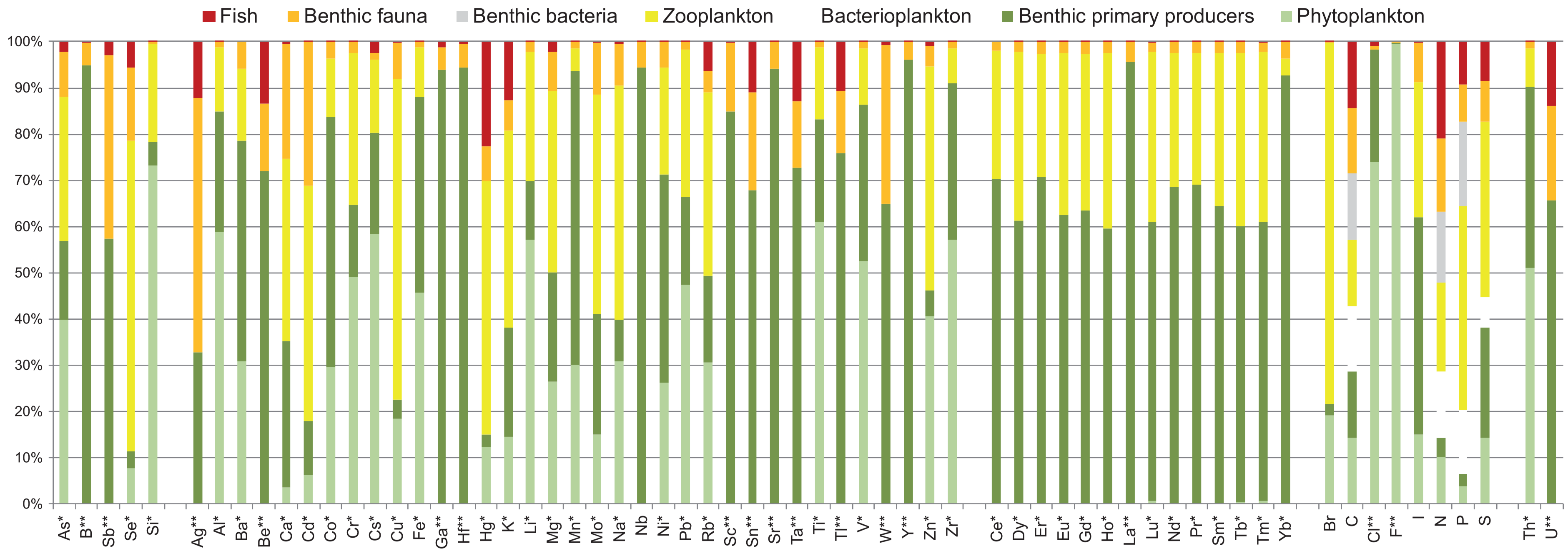

Figure 6-58. *Elemental distribution in biotic ecosystem pools in the marine model area in the Laxemar-Simpevarp area.*
** indicates that data for bacteria are missing and ** that one or more other groups besides bacteria are missing.*

6.5 Marine basins – both sites

In this section, ecosystem food webs, mass balances with pools and fluxes are specifically presented for separate basins in Forsmark and Laxemar-Simpevarp. The selected basins fulfil two criteria: (i) the density of site-specific in data is high and (ii) they are located where exit points for radionuclides were located in a preliminary safety assessment, see /SKB 2005/. In Forsmark, Basin 134 is presented graphically and numerically together with four additional basins (116, 120, 121 and 126) in Table 6-7. In Laxemar-Simpevarp, Basin 508 is presented graphically and numerically together with four additional basins (520, 502, 504 and 506) in Table 6-8. Detailed data tables are presented for all basins in Appendix 8 and 9.

Food webs for C, N and P and mass balances, pools and fluxes for C, N, P, I, Th and U and are presented for the basins. Pools and fluxes are also presented for some other elements representing general elemental groups in the periodic table.

6.5.1 Basins – Forsmark

In Figure 6-59, the selected basins are marked and the adjacent catchment areas are shown.

In Table 6-7, basic physical characteristics for basins 116, 120, 121, 126 and 134 are presented.

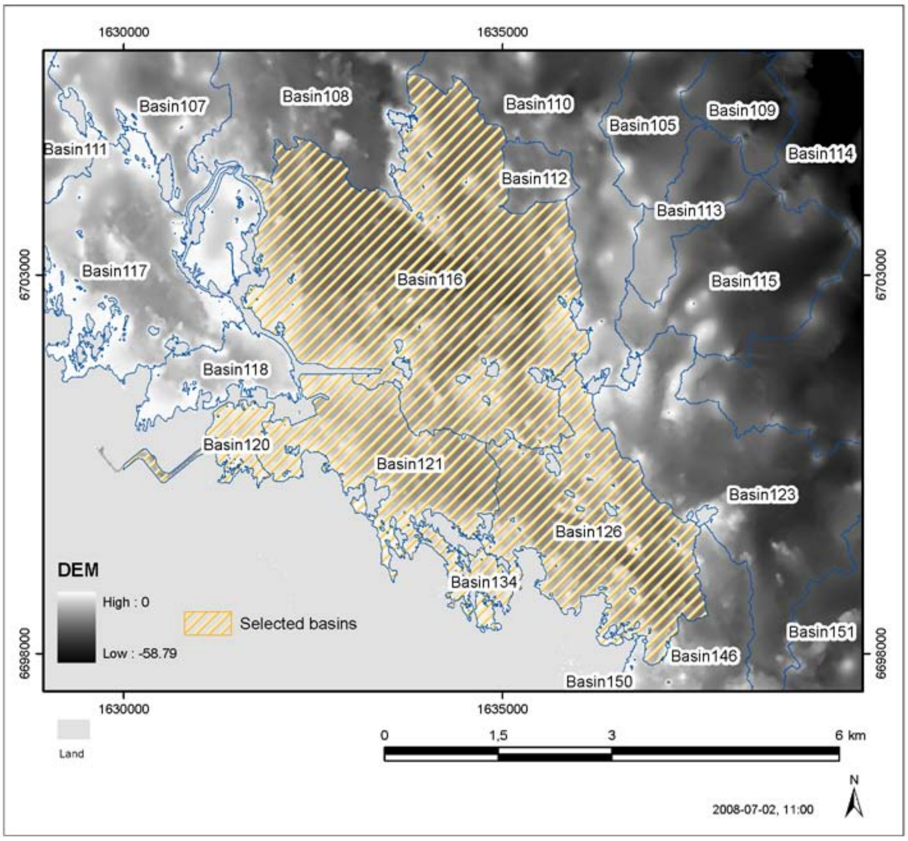

Figure 6-59. *Basins 116,120,121, 126 and 134 in Forsmark presented in this chapter.*

Table 6-7. Basic characteristics for five basins in Forsmark marine model area.

	Basin 116	Basin 126	Basin 134	Basin 121	Basin 120
Marine basin area (m^2)	13,534,000	5,440,400	586,400	3,692,400	729,200
Mean depth (m)	9	7	2	6	2
Max. depth (m)	19	16	6	13	12
Volume (m^3)	128,153,311	40,604,153	1,052,611	20,313,960	1,815,453
Total catchment area (m^2)	14,101,600	7,232,000	1,957,600	13,983,600	10,336,400
Runoff (m^3 $year^{-1}$)	19,222,997	6,090,623	157,892	3,047,094	272,318
Advective outflow (m^3)	52,142,360,552	22,217,768,523	1,017,417	8,073,976,047	26,125,590
Advective inflow (m^3)	52,082,246,480	22,194,479,015	862,217	8,058,725,774	24,685,617

Basin specific food webs – carbon, nitrogen and phosphorus

Food webs illustrating the C, N, P pools and fluxes in the marine ecosystem in Basin 134 are presented in Figure 6-60, 6-61 and 6-62. Food webs for the four other basins are presented in Appendix 8.

Pools and fluxes of carbon in the marine ecosystem food web in Basin 134 are similar to those for the average food web for the whole area, although some differences occur. The largest fluxes are the biotic fluxes, with NPP being the largest followed by consumption by benthic bacteria and of herbivores by benthic carnivores. The abiotic fluxes are generally smaller than the biotic fluxes in Basin 134. Burial is larger than the small net advective outflux and larger than burial on average for the whole marine area. In comparison with the whole marine area, macrophytes account for a larger portion of the NPP flux, consumption by birds is larger and consumption by herbivores and zooplankton is smaller.

The pools and fluxes of nitrogen in the marine ecosystem food web in Basin 134 are somewhat different than the average nitrogen pools and fluxes in the whole marine area in Forsmark. In comparison with the other pools in Basin 134, macrophytes, DIN and PON are larger than the average for the whole marine area. There is a positive net advective influx of nitrogen into the basin in contrast to

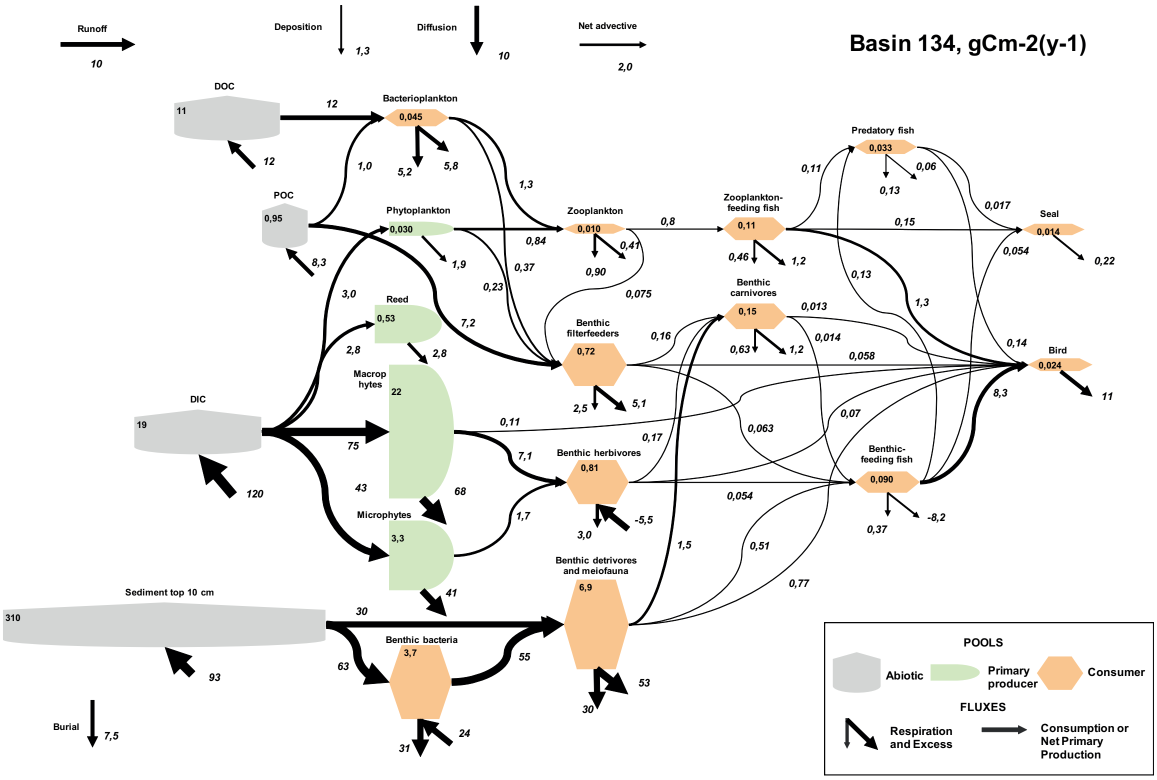

Figure 6-60. Food web based on pools and fluxes of carbon in Basin 134 in Forsmark. Boxes and arrows designate relative size of pools and fluxes.

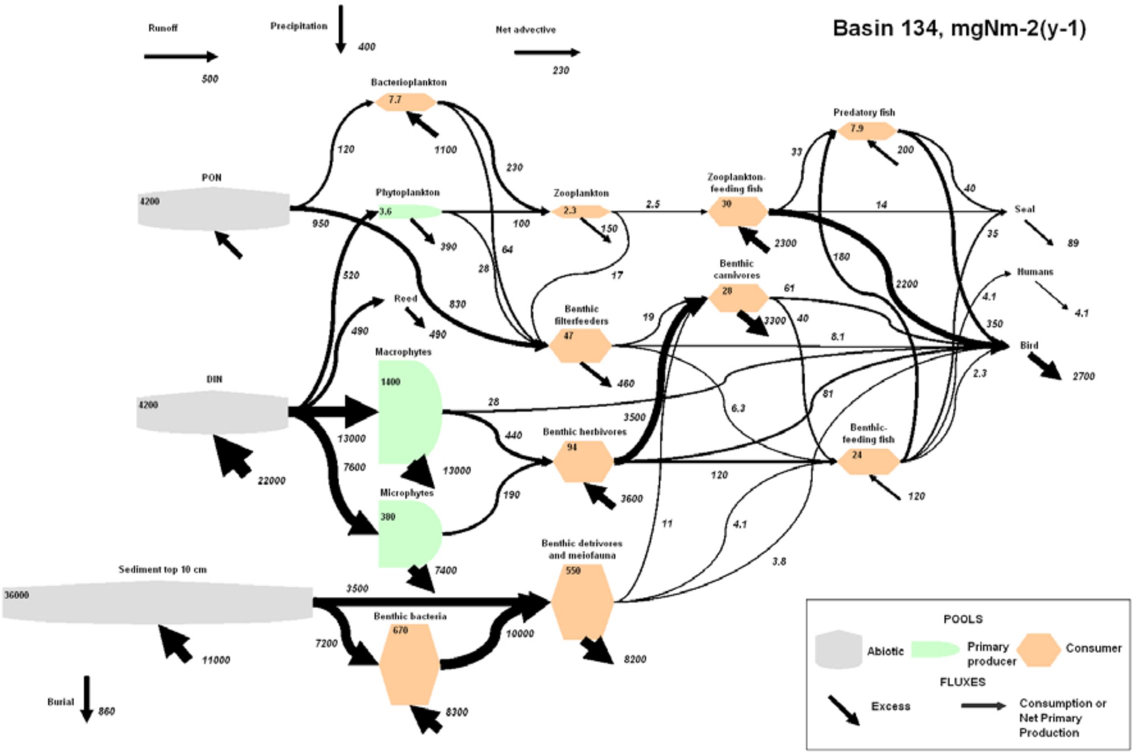

Figure 6-61. *Pools and fluxes of nitrogen in Basin 134 in Forsmark. Boxes and arrows denote relative size of pools and fluxes.*

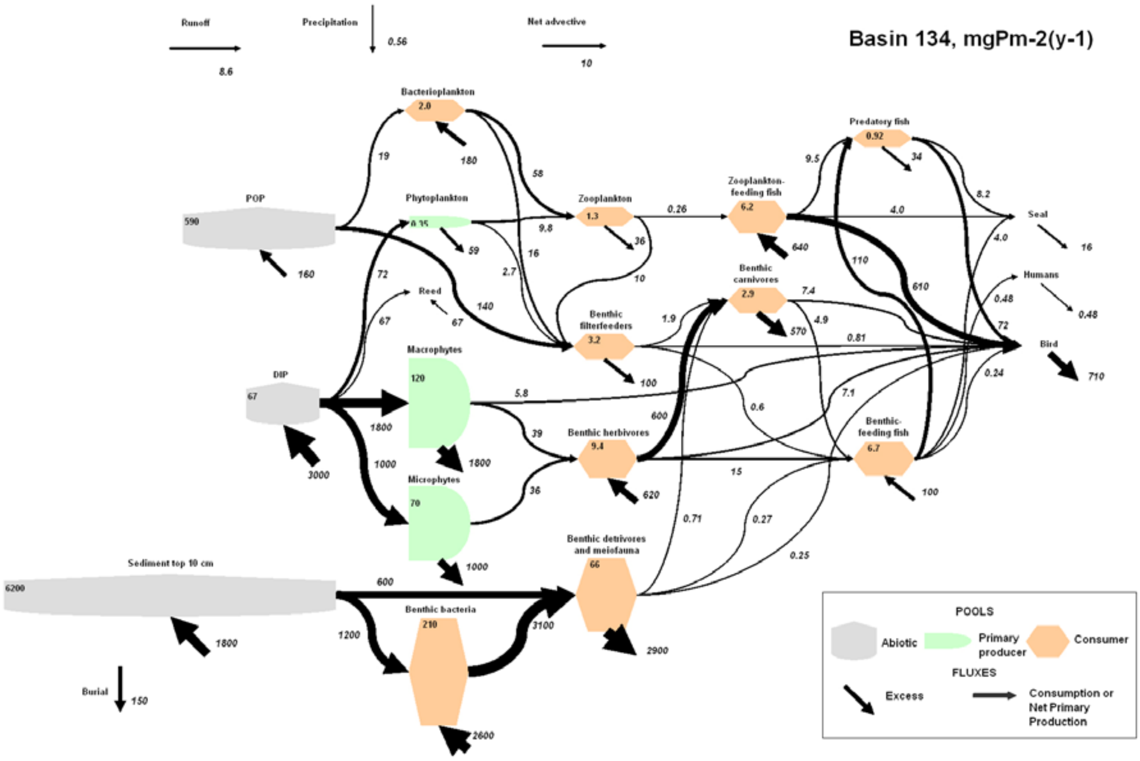

Figure 6-62. *Pools and fluxes of phosphorous in Basin 134 in Forsmark. Boxes and arrows denote relative size of pools and fluxes.*

the average net outflux in the whole marine area. Burial is the largest abiotic flux, although it is much smaller than the accumulation of nitrogen in primary producers during photosynthesis, which is the largest flux of nitrogen. The excess term is also large for nitrogen in Basin 134, especially from benthic fauna such as carnivores and detrivores. This is also true of the average food web for the whole basin. As for fluxes of carbon, the flux of nitrogen due to consumption by birds is larger in this basin.

The pools and fluxes of phosphorus in the marine ecosystem food web in Basin 134 are similar to those in the food web of nitrogen in Basin 134, but with some differences. In Basin 134, the pools of greatest magnitude are the DIP-and sediment pool. These pools in this basin are larger in relation to the other pools, in comparison to the general relation between pools in the whole marine area. The phosphorus pools in macrophytes, microphytes and benthic bacteria are much larger than average for the whole basin, and the phytoplankton, bacterioplankton and zooplankton pools in the pelagic organisms are much smaller. As for nitrogen and carbon, the flux due to consumption by birds is larger than on average in the marine area.

Basin-specific mass balances – carbon, nitrogen and phosphorus

Pools and fluxes of carbon, nitrogen and phosphorus in Basin 134 are shown in Figures 6-63, 6-64 and 6-65 and Tables 6-8, 6-9 and 6-10.

Carbon

The carbon pools in the fives basins are dominated by sediment in three of the basins (126, 134 and 121). In Basins 116 and 120 the DIC and DOC pools are larger in relation to the sediment; see Table 6-8 and Appendix 8. The sediment pool is followed by the DIC pool (5–32%), the macrophyte pool (3–17%) , the DOC pool (3–12%), benthic detrivores and meiofauna (2–6%) and microphytes (1–2%). All other pools contain less than 1% of the total carbon in the five basins.

The fluxes to and from the basins are clearly dominated by advective flux in the three basins 116, 121 and 126 (see Table 6-8). The model also indicates a net outflux of carbon in these basins. NPP is the largest flux in Basin 134, and NPP is of the same order of magnitude as the advective flux in Basin 120. There is also a small advective influx of carbon in these basins. Runoff makes a very small carbon contribution to all basins except for Basin 120, where it contributes about 80% of the net influx of carbon. Burial is small relative to other fluxes. It is negligible in Basins 116, 121, and 126, but a bit larger in Basins 121, 120 and 134, approximately 10% of the outflux from biota (i.e. respiration). Considering all fluxes in and out, according to mass balance calculations (runoff, deposition, advection, diffusion, NPP, respiration and burial), there is a total net influx of carbon in two of the five basins (Basins 134 and 120). In the others there is a net outflux of carbon.

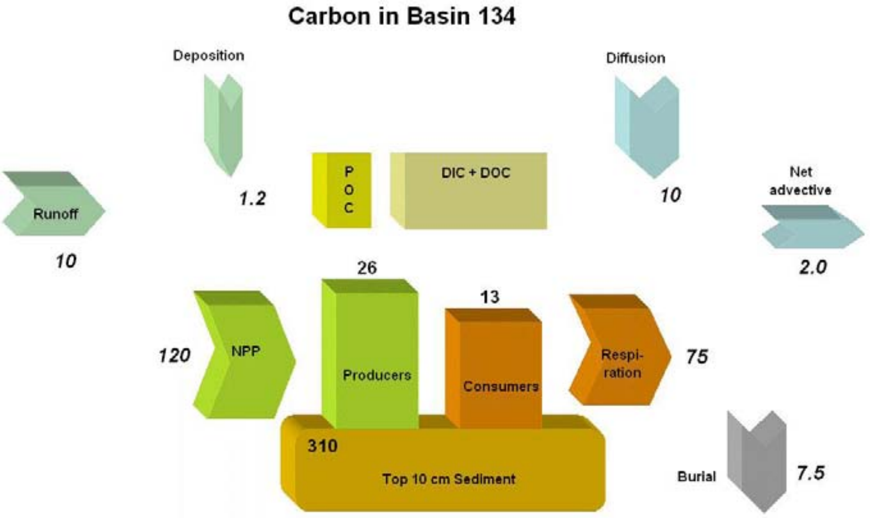

Figure 6-63. Schematic overview of pools and fluxes, mass balances, of carbon on average per m^2 in Basin 134 in Forsmark.

Table 6-8. Pools and fluxes of carbon, mass balances, in total tonnes per year and basin for five basins in the Forsmark marine model area.

	Tonnes C basin^{-1} y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	1	4	6	55	33
Advective influx	165,877	75,385	3	27,095	89
Net Primary Production	1,286	494	71	388	71
In by deposition	17	7	1	5	1
Advective outflux	166,951	82,509	4	29,265	95
Out to air, respiration	908	380	44	262	50
Accumulation by burial	1	1	4	12	6
Pools					
Phytoplankton	2	1	0.02	0.2	0.03
Microphytes	32	14	2	11	2
Macrophytes	150	45	13	56	17
Total pool producers	**183**	**59**	**15**	**67**	**19**
Bacterioplankton	3	1	0.03	1	0.05
Zooplankton	1	0.2	0.01	0.1	0.01
Benthic bacteria	11	9	2	9	2
Benthic herbivores	18	6	0.5	4	1
Benthic filter feeders	20	7	0.4	4	1
Benthic detrivores	52	23	4	16	4
Benthic carnivores	4	2	0.1	1	0.1
Benthic feeding fish	3	1	0.1	1	0.4
Zooplankton feeding fish	1	1	0.1	1	0.1
Piscivorous fish	1	0.4	0.02	0.4	0.1
Birds	0.1	0.04	0.01	0.05	0.02
Seals	0.2	0.1	0.01	0.1	0.01
Total pool consumers	**114**	**51**	**7**	**37**	**8**
Top 10 cm regolith pool	1,718	1,012	184	609	38
Particulate pool	27	11	1	6	1
Dissolved pool	1,134	140	6	74	23

Nitrogen

The nitrogen pools in the fives basins are dominated by sediment, as in the whole marine basin. Sediment comprises between 56 and 88% of the nitrogen pools in the five basins, and similar results are found in all other basins (see Table 6-9 Appendix 9). In most basins the dissolved pool is larger than the particulate pool, but in Basin 134 they are of the same magnitude. The largest biotic pool is macrophytes (2–20%), benthic detrivores and meiofauna (1–4%), microphytes (1–4%) and benthic bacteria (1–4%). All other pools contain less than 1% of the total nitrogen inventory in the five basins.

In four of the basins the total pool of producers is larger than the total pool of consumers, although in Basin 126 the consumer pool is slightly larger, Table 6-9.

The fluxes to and from the basins are clearly dominated by advective flux in three of the basins (see Table 6-9) and the model indicates a large net advective influx of nitrogen to all but one basin (Basin 116). Runoff makes the largest nitrogen contribution in Basin 120, while in Basin 134 it is incorporation of nitrogen during photosynthesis, see Figure 6-64 and Table 6-9. Considering all fluxes in the mass balance calculations, there is a positive net influx of carbon in all basins, but Basin 116.

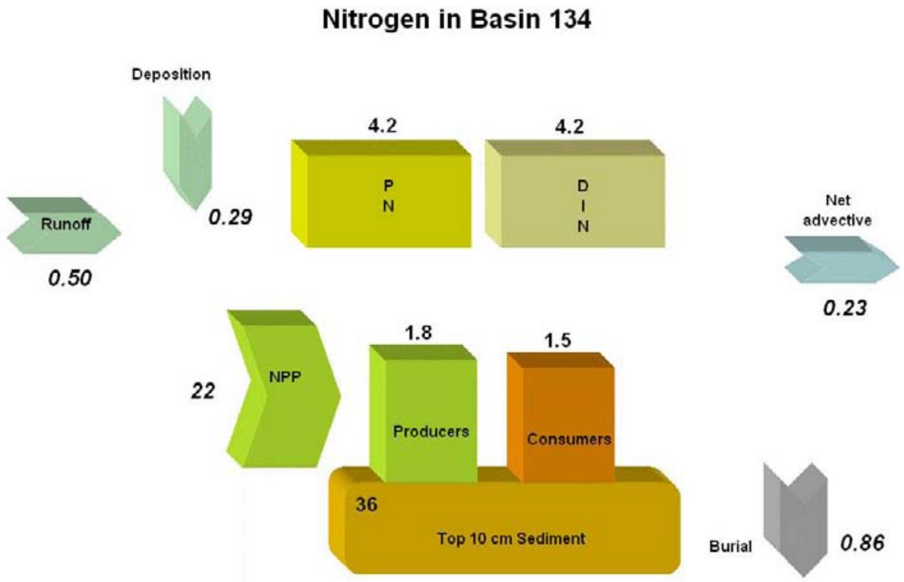

Figure 6-64. *Schematic overview of pools and fluxes of nitrogen on average per m^{-2} in Basin 134 in Forsmark.*

Table 6-9. Pools and fluxes of nitrogen (total for the whole basin in kg) for five basins in the Forsmark marine model area.

	Kg N basin^{-1} y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	0.0	574	2,348	13,742	191,951
Advective influx	23,579,843	9,525,289	233	3,497,284	6,665
Net Primary Production	226,501	87,042	12,453	68,324	74,610
In by deposition	4,872	1,959	211	1,329	263
Advective outflux	24,600,649	7,776,219	366	2,179,974	12,326
Accumulation by burial	100	86	503	1,324	662
Pools					
Phytoplankton	190	65	2	29	4
Microphytes	3,727	1,617	224	1,250	212
Macrophytes	9,312	2,777	812	3,491	1,064
Total pool producers	**13,229**	**4,459**	**1,038**	**4,770**	**1,280**
Bacterioplankton	545	173	5	86	8
Zooplankton	119	41	1	18	3
Benthic bacteria	1,988	1,705	395	1,614	275
benthic herbivores	2,059	720	55	429	92
Benthic filter feeders	1,298	451	28	282	50
Benthic detrivores	4,123	1,836	320	1,280	343
Benthic carnivores	810	339	16	222	23
Benthic feeding fish	667	299	14	299	94
Zooplankton feeding fish	347	211	18	162	27
Piscivorous fish	199	99	5	100	23
Birds	no,data	no data	no data	no data	no data
Seals	no data	no data	no data	no data	no data
Total pool consumers	**12,157**	**5,875**	**857**	**4,492**	**936**
Top 10 cm regolith pool	197,108	116,124	21,124	69,919	4,408
Particulate pool	1,760	1,592	2,480	59	832
Dissolved pool	3,907	3,535	2,480	71	416

Phosphorus

The phosphorus pools in the fives basins are dominated by sediment. Sediment comprises between 84 and 90% of the phosphorus pools in the five basins, and similar results are found in all other basins (see Table 6-10 and Appendix 9). The sediment pool is followed by the particulate pool in Basins 134 and 120 (8–10%), but for the rest of the basins the abiotic pools contain around or less than 1% of the total phosphorus inventory. The biotic pools are quite large for phosphorus, and the total consumer pool is larger than the producers in all basins, Table 6-10.

The fluxes to and from the basins are clearly dominated by advective flux in the three Basins 116, 121 and 126 (see Table 6-10). In Basins 116 and 121 there is also a net outflux of phosphorus. NPP is the largest flux in Basin 134. There is a small influx of phosphorus in Basins 121 and 126. Runoff makes a very small phosphorus contribution to all basins. Burial is small relative to other fluxes, but in Basins 120 and 134 it is larger in comparison with other fluxes. Considering all fluxes, there is a net outflux of phosphorus in 3 out of 5 basins (116, 134 and 120).

Table 6-10. Pools and fluxes of phosphorus (total for the whole basin in kg) for five basins in the Forsmark marine model area.

	Kg P basin^{-1} y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	1	4	5	41	23
Advective influx	864,928	351,836	9	129,872	269
Net Primary Production	31,346	12,046	1,723	9,456	1,722
In by deposition	164	66	7	45	9
Advective outflux	896,032	305,336	15	87,833	449
Accumulation by burial	17	15	86	227	113
Pools					
Phytoplankton	18	6	0	3	0
Microphytes	687	298	41	230	39
Macrophytes	818	244	71	307	94
Emerg macrophytes	no data	no data	no data	no data	no data
Total pool producers	**1,524**	**548**	**113**	**540**	**133**
Bacterioplankton	138	44	1	22	2
Zooplankton	70	24	1	11	2
Benthic bacteria	613	526	122	498	85
Benthic herbivores	205	72	5	43	9
Benthic filter feeders	87	30	2	19	3
Benthic detrivores	498	222	39	155	41
Benthic carnivores	85	35	2	23	2
Benthic feeding fish	189	85	4	85	27
Zooplankton feeding fish	71	43	4	33	6
Piscivorous fish	23	12	1	12	3
Birds	no,data	no data	no data	no data	no data
Seals	no data	no data	no data	no data	no data
Total pool consumers	**1,980**	**1,092**	**180**	**899**	**179**
Top 10 cm regolith pool	33,718	19,864	3,613	11,960	754
Particulate pool	290	263	345	10	118
Dissolved pool	58	53	40	2	29

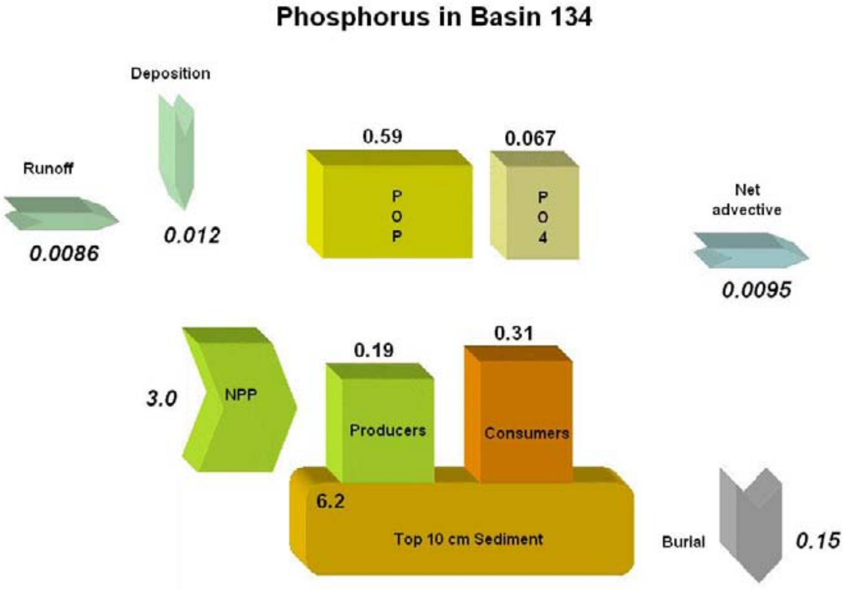

Figure 6-65. Schematic overview of pools and fluxes of phosphorus on average per m^2 in Basin 134 in Forsmark.

Actinides and iodine

The fluxes considered are advective flow and burial. The other fluxes were not included due to a lack of data. For some functional groups (benthic bacteria, bacterioplankton, benthic filter feeders, benthic carnivores, birds and seals) no concentration data were available and they are not included in the mass balances, which entails an underestimation of the consumer pool. Some analyses of biota were below the detection limit, and estimated means based on half the detection limit were used to give a rough estimate (estimated mean). The biotic pools for which estimated means of concentrations were used are marked in Tables 6-11 to 6-13.

Thorium

In four of the five basins, the thorium pools are dominated by sediment (~ 90%). Except in Basin 120, the sediment and the dissolved phase are of the same order of magnitude (50% and 43%, respectively). The particulate pool varies from 0.5 to 3% of the total thorium inventory in the basins. Except for microphytobenthos (2–4%), the biotic pools do not exceed 1% of the total thorium inventory in the basins, see Table 6-11.

In Basins 134 and 121 there is an according to the model net outflux of thorium, considering all fluxes, while in the rest of the basins there is a net influx. Burial is a small flux, but in Basin 134 it is larger than the advective flux and in Basin 120 it is about 25% of the advective flux, see Table 6-11 and Figure 6-66.

Table 6-11. Pools and fluxes of Thorium (in kg) for five basins in the Forsmark marine model area. Pool marked with * denotes reported concentrations below the detection limit, were half of the reported value have been used in the calculations.

	Kg Th basin^{-1} y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Advective influx	4,091	1,824	0.1	620	3
In by deposition	0.07	0.03	0.003	0.02	0.004
Advective outflux	4,012	1,710	0.1	821	2
Accumulation by burial	0.1	0.05	0.3	1	0.4
Pools					
Phytoplankton	0.01	0.004	0.0001	0.002	0.0003
Microphytes	3	1	0.2	1	0.2
Macrophytes	0.2	0.05	0.01	0.1	0.02
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**4**	**1**	**0**	**1**	**0**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	0.001	0.0002	0.00001	0.0001	0.00001
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	0.02	0.006	0.0005	0.004	0.001
Benthic filter feeders	No data	No data	No data	No data	No data
Benthic detrivores	0.1	0.03	0.004	0.02	0.005
Benthic carnivores	No data	No data	No data	No data	No data
Benthic feeding fish*	0.00003	0.00001	0.000001	0.00001	0.000004
Zooplankton feeding fish*	0.00001	0.00001	0.000001	0.000005	0.000001
Piscivorous fish	0.000006	0.000003	0.0000001	0.000003	0.000001
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**0.08**	**0.03**	**0.005**	**0.02**	**0.01**
Top 10 cm regolith pool	109	64	12	39	2
Particulate pool	3	1	0.1	1	0.1
Dissolved pool	2	2	1	0.1	2

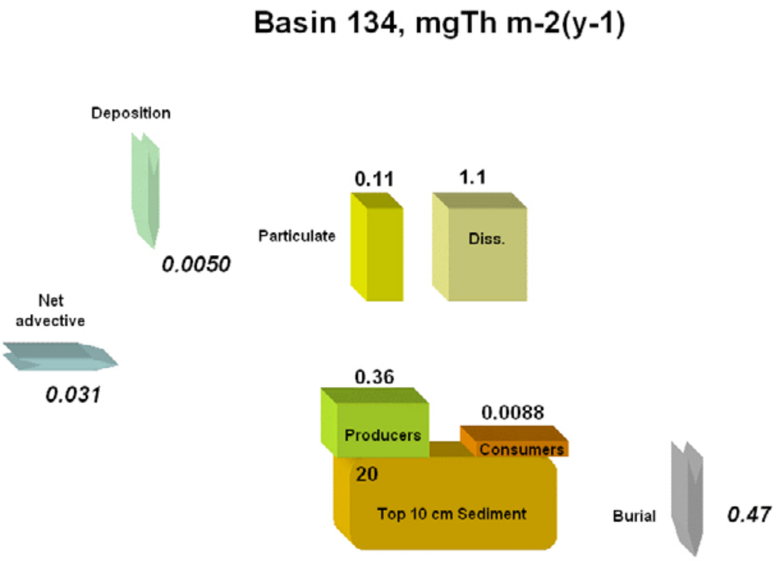

Figure 6-66. *Schematic overview of pools and fluxes, in mg per m^2, of thorium in Basin 134 in Forsmark.*

Uranium

The uranium pools in three of the five basins (116, 126 and 120) are dominated by sediment (66–96%). In Basins 134 and 120, sediment constitutes 25% and 13%, respectively. In all the basins, the major part of the remaining uranium is distributed in the dissolved pool. The biotic pools are very small even for the primary producers, see Table 6-12. Data for the biotic pools are from Laxemar-Simpevarp, due to lack of data for these groups in Forsmark.

According to the model there is a net outflux of uranium in all but one basin (Basin 121). Burial is a small flux, but in Basin 134 it is of the same order of magnitude as the advective fluxes, see Figure 6-67 and Table 6-12.

Table 6-12. Pools and fluxes of uranium (in kg) for five basins in the Forsmark marine model area. Functional groups marked with an * denotes reported analyses below detection limit, were half the reported concentration was used in the calculations.

	Kg uranium basin^{-1}y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes Area (km^2):	**14**	**5.4**	**0. 6**	**3.7**	**0.7**
Advective inflow	51,555	20,866	0.6	8,153	17
In by precipitation	0.03	0.01	0.001	0.01	0.001
Advective outflow	52,755	22,479	0.7	5,432	26
Accumulation by burial	0.05	0.04	0.2	1	0.3
Pools					
Phytoplankton	0.003	0.001	0.00003	0.00044	0.0001
Microphytes	0.06	0.03	0.004	0.02	0.003
Macrophytes	0.3	0.08	0.02	0.1	0.03
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**0.3**	**0.1**	**0.03**	**0.1**	**0.03**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	0.000	0.0002	0.00001	0.0001	0.00001
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	0.02	0.005	0.0004	0.003	0.001
Benthic filter feeders	No data	No data	No data	No data	No data
Benthic detrivores	0.05	0.02	0.003	0.01	0.004
Benthic carnivores	No data	No data	No data	No data	No data
Benthic feeding fish	0.000005	0.000002	0.0000001	0.000002	0.000001
Zooplankton feeding fish	0.000002	0.000001	0.0000001	0.000001	0.0000002
Piscivorous fish*	0.000002	0.000001	0.00000004	0.000001	0.0000002
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**0.06**	**0.03**	**0.004**	**0.02**	**0.004**
Top 10 cm regolith pool	93	55	10	33	2
Particulate pool	1	1	0.03	0.3	0.1
Dissolved pool	30	27	30	0.9	14

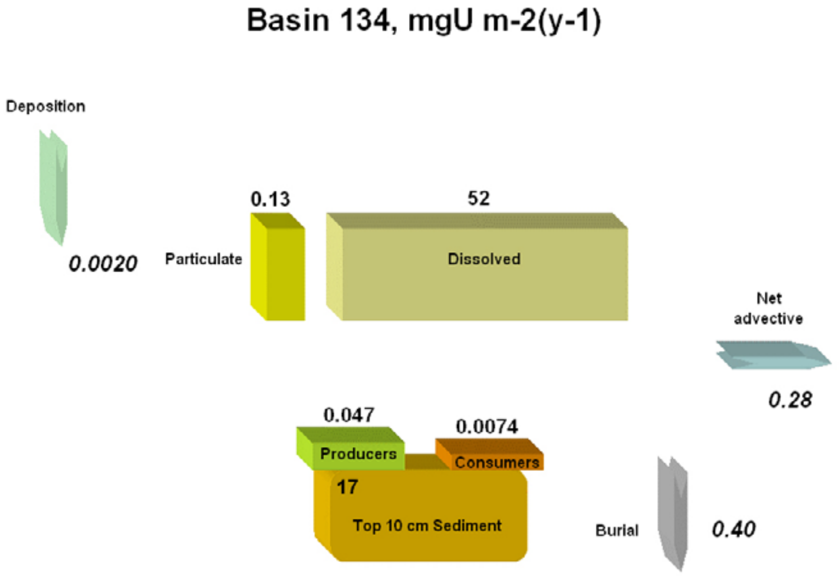

***Figure 6-67.** Schematic overview of pools and fluxes of, in mg per m², of uranium in Basin 134 in Forsmark.*

Iodine

In four of the five basins, the iodine pools are dominated by the dissolved phase (43–94%), but in Basin 121 the dissolved phase constitutes only 8% and sediment is the major pool (54%). The four other basins have sediment pools varying from 2 to 30%. The particulate pool varies from 1 to 14% of total iodine inventory in the basins. The producer pool is a much larger pool for iodine than the consumer pool. The total pool of consumers constitutes less than 1%, while the total producer pool constitutes 2–23%, see Table 6-13.

According to the model there is a net advective influx of iodine in three of five basins (116, 126 and 120), while for the others there is a net outflux of iodine. Burial is a small flux in all basins, including Basin 134 (see Figure 6-68).

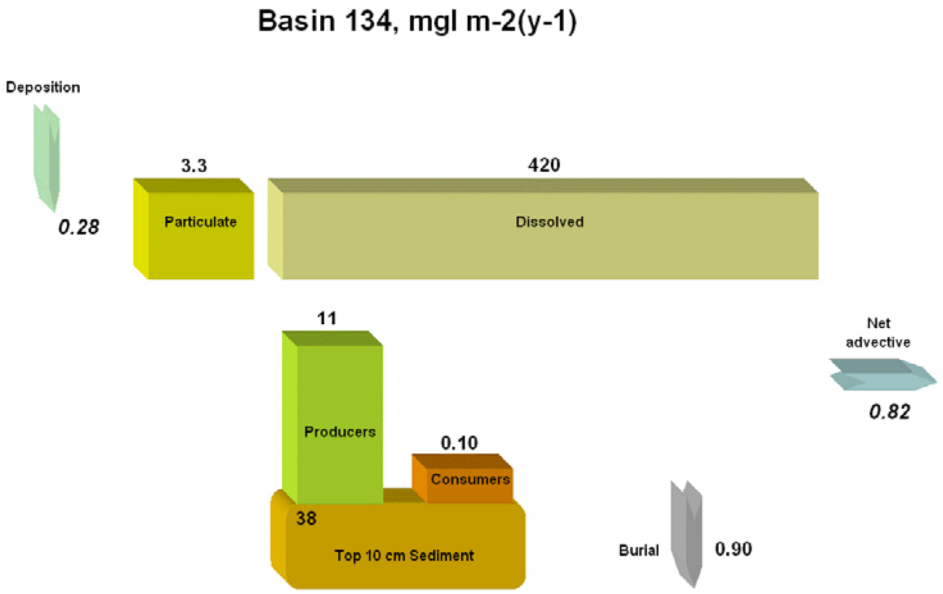

***Figure 6-68.** Schematic overview of pools and fluxes, in mg per m², of iodine in Basin 134 in Forsmark.*

Table 6-13. Pools and fluxes of iodine (in kg) for five basins in Forsmark marine model area.

	Kg I basin^{-1} y^{-1}				
	Basin 116	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Advective inflow	511,199	220,598	9	78,658	262
In by precipitation	4	2	0.2	1	0.2
Advective outflow	508,943	216,860	10	85,637	255
Accumulation by burial	0.1	0.1	1	1	1
Pools					
Phytoplankton	0.1	0.05	0.002	0.02	0.003
Microphytes	62	27	4	21	4
Macrophytes	30	9	3	11	3
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**92**	**36**	**6**	**32**	**7**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	0.09	0.03	0.001	0.01	0.002
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	0.9	0.3	0.02	0.2	0.04
Benthic filter feeders	No data	No data	No data	No data	No data
Benthic detrivores	0.5	0.2	0.04	0.1	0.04
Benthic carnivores	No data	No data	No data	No data	No data
Benthic feeding fish	0.01	0.003	0.0001	0.003	0.001
Zooplankton feeding fish	0.002	0.001	0.0001	0.001	0.0002
Piscivorous fish	0.003	0.002	0.0001	0.002	0.0004
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**1**	**1**	**0.1**	**0.3**	**0.1**
Top 10 cm regolith pool	206	121	22	73	5
Particulate pool	92	38	2	20	4
Dissolved pool	286	259	248	11	221

Metalloids

Si and Se are included in the chemical group metalloids, together with As. They have properties of both metals and non-metals. They are generally not distributed similar to each other in the pools of an ecosystem and are therefore presented separately. These metalloids are regarded as recycled elements, i.e. elements that are incorporated into soft tissues or into skeletal material and will be more or less depleted in surface waters and enriched in the deep ocean. Si is also classified as biolimiting together with P and N, while the others can be considered as biointermediate /Bearman 2005/.

Si is the most abundant element of the analyzed metalloids and is also the metalloid with the largest biotic pools (1–2%). Sediment is the major pool for Si (78–97%), followed by the particulate pool (2–18%). The dissolved pool dominates (52–93%) for As, followed by the sediment pool (6–44%). Se is least distributed in the biotic pools of the metalloids, with less than 1% in all but one basin. Se is more evenly distributed in the three abiotic pools, see Table 6-14.

The net advective flux of all metalloids in all basins is almost +/– 0. Burial is a small flux for Se and As but important for Si. Since Si and Se are widely used among organisms they are specifically presented in Table 6-14.

Table 6-14. Pools and fluxes of Si and Se, in Basin 116, 126, 134, 121 and 120 in Forsmark in kg basin^{-1} year^{-1}.

Kg Si basin^{-1} y^{-1}	Basin 116	Basin 126	Basin 134	Basin 121	Basin 120
Fluxes					
Runoff	991	2,370	9,686	56,692	791,902
Advective inflow	39,062	16,646	1	6,044	19
In by precipitation	113	46	5	31	6
Advective outflow	39,107	16,663	1	6,055	20
Accumulation by burial	1,600	1,372	8,058	21,234	10,615
Pools					
Total pool producers	**24,819**	**9,947**	**1,570**	**8,301**	**1,667**
Total pool consumers	**1,201**	**479**	**59**	**309**	**71**
Top 10 cm regolith pool	3 160,554	1,862,014	338,709	1,121,119	70,680
Particulate pool	400,483	164,077	8,351	87,916	16,011
Dissolved pool	95,518	30,264	785	15,141	1,353

Kg Se basin^{-1} y^{-1}	Basin 116	Basin 126	Basin 134	Basin 121	Basin 120
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	3	1	0.00005	0.4	0.001
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	3	1	0.0001	0.4	0.001
Accumulation by burial	0.01	0.005	0.03	0.08	0.04
Pools					
Total pool producers	**0.2**	**0.08**	**0.01**	**0.1**	**0.01**
Total pool consumers	**0.2**	**0.09**	**0.01**	**0.06**	**0.02**
Top 10 cm regolith pool	11	7	1	4	0.3
Particulate pool	9	4	0.2	2	0.4
Dissolved pool	7	2	0.1	1	0.1

Metals

Mg, Na, Ca, K, Li and Mo are metals that are concentrated into the dissolved pool, Zn and Ba are concentrated in the particulate pool and for the rest of the metals the sediment pool dominates.

For all metals except Ca, the dominant biotic pool is producers. To exemplify metal pools and fluxes, Fe, Mg and Ca are presented in Table 6-15 because they represent various distributions within the chemical group of metals.

Ca and Mg, which are major constituents of marine water, are distributed to a very large extent in the dissolved water pool (around 99% for Mg and between 74 and 94% for Ca). Fe is mainly distributed in the sediment pool (90–98%). Fe is the only metal (of these three) with a biotic pool of over 1%, see Table 6-12.

The net advective flux of Fe, Mg and Ca is around +/– 0 in all basins. Burial is an important flux for iron in several basins, but for the other elements it is small compared with the advective flux, see Table 6-15.

Table 6-15. Pools and fluxes of Fe, Mg and Ca, in Basin 116, 126, 134, 121 and 120 in Forsmark, in kg basin^{-1} year^{-1}.

Kg Fe basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	4,062	1,731	0.1	629	2
In by precipitation	244	98	11	67	13
Advective outflow	4,067	1,733	0.1	630	2
Out to air, respiration	No data	No data	No data	No data	No data
Accumulation by burial					
Pools					
Total pool producers	**9,731**	**4,159**	**594**	**3,275**	**577**
Total pool consumers	**310**	**132**	**20**	**90**	**23**
Top 10 cm regolith pool	371,022	218,584	39,761	131,610	8,297
Particulate pool	2,476	1,014	52	543	99
Dissolved pool	9,995	3,167	82	1,584	142
Kg Mg basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	1,209	2,893	11,825	69,214	966,813
Advective inflow	8,475,084	3,611,597	140	1,311,356	4,017
In by precipitation	620	249	27	169	33
Advective outflow	8,484,866	3,615,386	166	1,313,838	4,251
Accumulation by burial	53	46	268	706	353
Pools					
Total pool producers	**6,176**	**2,186**	**465**	**2,201**	**555**
Total pool consumers	**456**	**181**	**18**	**118**	**24**
Top 10 cm regolith pool	4	2	0,4	1	0
Particulate pool	8,210	3,364	171	1,802	328
Dissolved pool	20,853,772	6,607,319	171,286	3,305,593	295,420
Kg Ca basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	1,209	2,893	11,825	69,214	966,813
Advective inflow	3,706,803	1,579,628	61	573,556	1,757
In by precipitation	2,270	912	98	619	122
Advective outflow	3,711,081	1,581,285	72	574,642	1,859
Accumulation by burial	61	52	305	803	402
Pools					
Total pool producers	**12,181**	**4,494**	**887**	**4,308**	**1,025**
Total pool consumers	**133,224**	**54,331**	**7,408**	**36,494**	**8,773**
Top 10 cm regolith pool	119,551	70,433	12,812	42,408	2,674
Particulate pool	280,717	115,009	5,854	61,625	11,223
Dissolved pool	9,120,945	2,889,884	74,917	1,445,788	129,210

Lanthanides

Lanthanides are regarded as trace elements in the marine ecosystem. The lanthanides have similar distribution in the marine ecosystem. Like many of the other elements the lanthanides (Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Tm, Yb, Lu) are most abundant in the sediments. Ce, Tb and Er have been selected to illustrate the distribution of lanthanides, see Table 6-16.

Lanthanide distribution is fairly similar within the pools. However, Tb hasa slightly smaller sediment pool and a larger dissolved pool. All of them have very small biotic pools, see Table 6-16.

The net advective fluxes of Ce, Er and Mg are +/– 0 in all basins, see Table 6-16.

Table 6-16. Pools and fluxes of Ce, Er and Tb, in Basin 116, 126, 134, 121 and 120 in Forsmark.

Kg Ce basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	12	5	0.0002	2	0.01
Net Primary Production	No data	No data	No data	No data	No data
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	13	5	0.0002	2	0.01
Out to air, respiration	No data	No data	No data	No data	No data
Accumulation by burial	0.4	0.3	2	5	3
Pools					
Total pool producers	**0.1**	**0.05**	**0.01**	**0.04**	**0.01**
Total pool consumers	**0.1**	**0.05**	**0.01**	**0.04**	**0.01**
Top 10 cm regolith pool	783	461	84	278	18
Particulate pool	27	11	1	6	1
Dissolved pool	31	10	0.3	5	0.4

Kg Er basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	1	0.4	0.00002	0.2	0.0005
Net Primary Production	No data	No data	No data	No data	No data
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	1	0.4	0.00002	0.2	0.001
Out to air, respiration	No data	No data	No data	No data	No data
Accumulation by burial	0.01	0.01	0.1	0.2	0.1
Pools					
Total pool producers	**0.1**	**0.002**	**0.0003**	**0.001**	**0.0003**
Total pool consumers	**0.1**	**0.002**	**0.0002**	**0.001**	**0.0003**
Top 10 cm regolith pool	461	17	3.0	10	1
Particulate pool	11	2	0.1	1	0.2
Dissolved pool	10	1	0.02	0.4	0.04

Kg Tb basin^{-1} y^{-1}	**Basin 116**	**Basin 126**	**Basin 134**	**Basin 121**	**Basin 120**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	3	1	0.00004	0.4	0.001
Net Primary Production	No data	No data	No data	No data	No data
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	3	1	0.0001	0.4	0.001
Out to air, respiration	No data	No data	No data	No data	No data
Accumulation by burial	0.004	0.004	0.02	0.06	0.03
Pools					
Total pool producers	**0.001**	**0.001**	**0.0001**	**0.0005**	**0.0001**
Total pool consumers	**0.001**	**0.001**	**0.0001**	**0.0004**	**0.0001**
Top 10 cm regolith pool	9	5	1	3	0.2
Particulate pool	0.2	0.1	0.003	0.04	0.01
Dissolved pool	6	2	0.1	1	0.1

6.5.2 Basins – Laxemar-Simpevarp

The selected marine basins in Laxemar-Simpevarp are marked in Figure 6-69.

The basic physical characteristics of Basins 521, 504, 502, 506 and 508 are presented in Table 6-17. Physical data for the rest of the basins are presented in Appendix 7.

Table 6-17. Basic characteristics of five basins in the Laxemar-Simpevarp marine model area.

	Basin 521	Basin 504	Basin 502	Basin 506	Basin 508
Marine basin area (m^2)	38,044,800	608,000	1,126,800	334,400	1,374,800
Mean depth (m)	11.1	3.6	4.8	3.3	1.7
Max depth (m)	45.1	16.1	18.1	12.1	8.1
Volume (m^3)	425,691,909	2,187,558	5,461,854	1,105,921	2,387,159
Total drainage area to basin (m^2)	1,538,000	1,948,000	34,675,000	951,000	46,517,000
Runoff (m^3 $year^{-1}$)	338,360	428,560	7,628,500	209,220	10,233,880
Advective outflow (m^3)	226,170,479,016	228,477,024	89,939,160	309,264,480	60,906,168
Advective inflow (m^3)	355,090,217,688	229,423,752	90,254,736	302,637,384	55,225,800

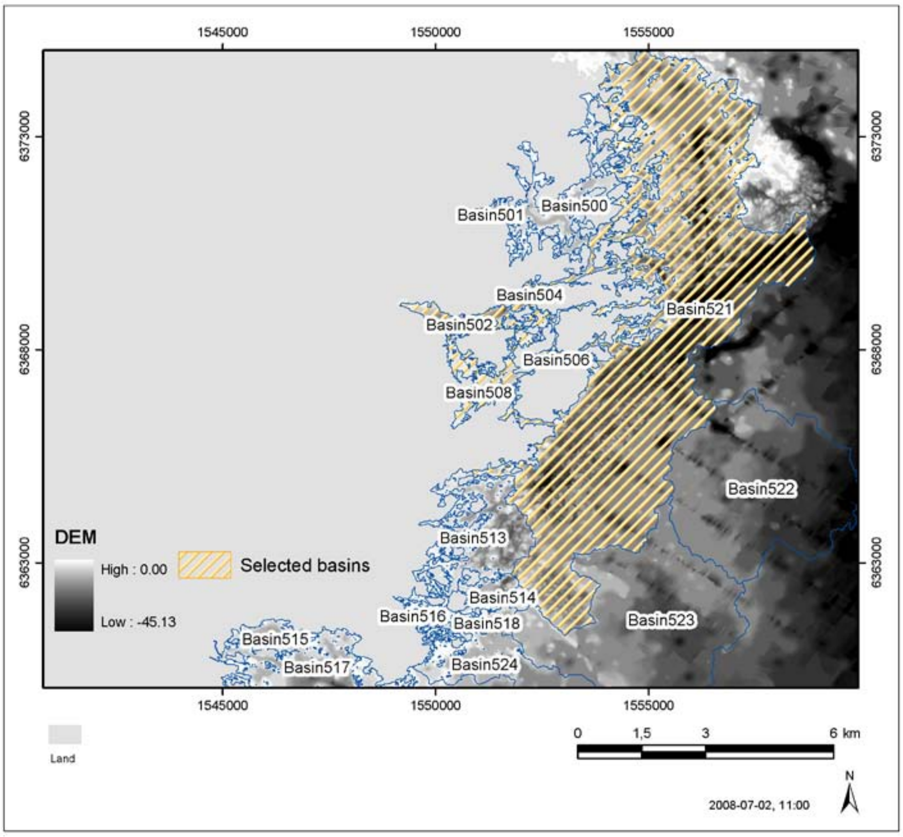

__Figure 6-69.__ Basins 502, 504, 506, 508 and 521 in Laxemar-Simpevarp and their catchment areas are presented in this chapter.

Basic specific food webs – carbon, nitrogen and phosphorus

Food webs illustrating the sizes of C, N, P pools and fluxes in the ecosystem are presented in Figure 6-70, 6-71 and 6-72, and data for pools and fluxes of C, N and P in Appendix 9.

The largest pool in the 5 basins is the sediment (from 66–76% of the total carbon pool), followed by the DIC and DOC pools. Basin 521 is more Filter feeders constitute a major part of the carbon biomass in the whole marine area, as in Basin 521. However, in the other four selected basins filter feeders constitute around 1% of the total carbon pools and the macrophyte pool is in turn larger. The fluxes in Basin 508 are similar to the average fluxes in the whole marine basin, although consumption by the filter feeders is smaller and consumption by birds is larger. Consumption by filter feeders is the largest biotic flux of carbon, see Figure 6-70.

Even more than for carbon, the sediment in the 5 basins constitutes the largest nitrogen pool followed by the biotic pools of benthic filter feeders and macrophytes. The fluxes in Basin 508 are similar to the fluxes in the whole marine basin on average, although consumption by filter feeders is smaller and burial and consumption by birds are larger. Consumption by filter feeders is the largest biotic flux of nitrogen, see Figure 6-71.

As in the case of carbon and nitrogen, the sediment in the 5 basins constitutes the largest phosphorus pool, followed by the biotic pools of benthic filter feeders and macrophytes. The fluxes in Basin 508 are similar to the fluxes in the whole marine basin on average, although consumption by filter feeders is smaller and consumption by birds is larger, as is burial. Consumption by filter feeders is the largest biotic flux of phosphorus, see Figure 6-72.

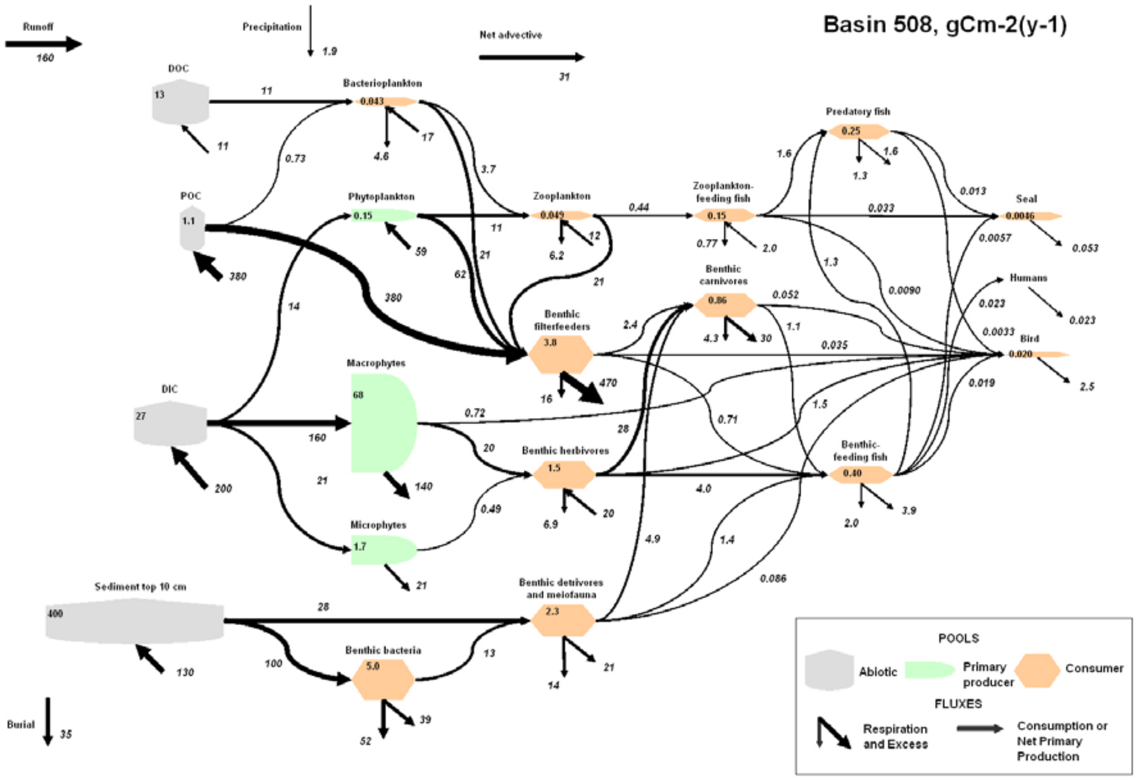

Figure 6-70. *Pools and fluxes of carbon in basin 508 in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes. Fish and benthic fauna are summarized in one pool.*

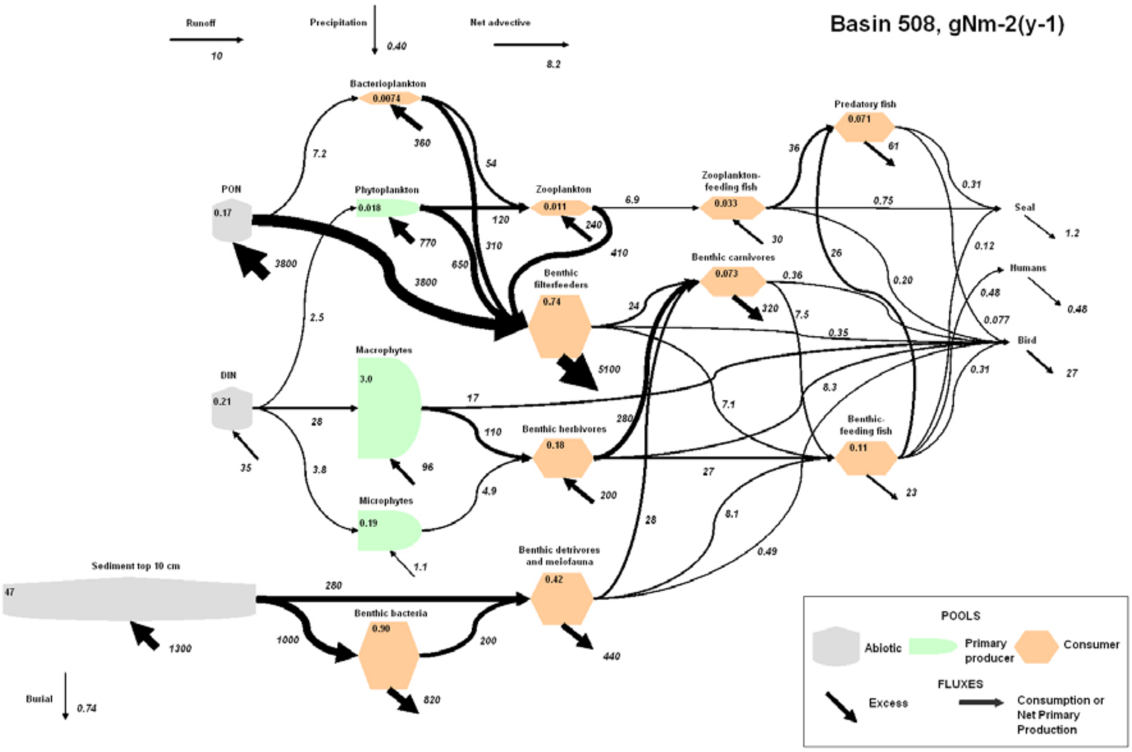

Figure 6-71. Pools and fluxes of nitrogen in basin 508 in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes. Fish and benthic fauna are summarized in one pool.

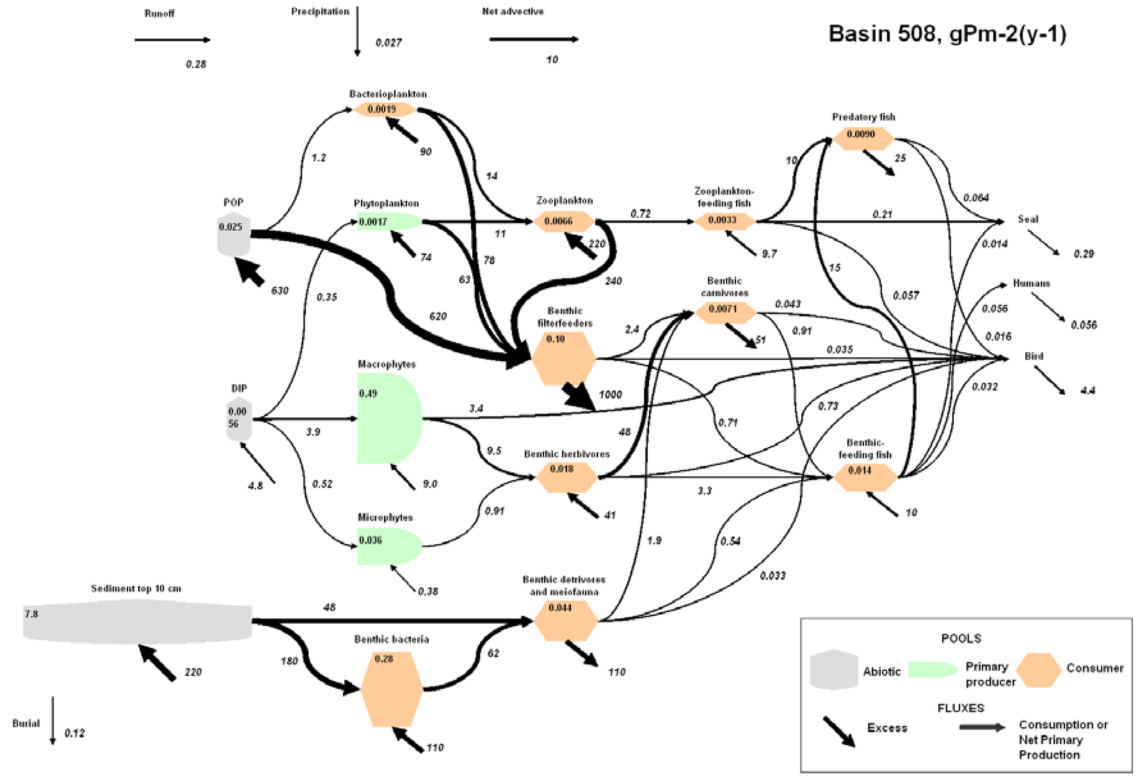

Figure 6-72. Pools and fluxes of phosphorus in basin 508 in Laxemar-Simpevarp. Boxes and arrows denote relative size of pools and fluxes. Fish and benthic fauna are summarized in one pool.

Basin-specific mass balances – carbon, nitrogen and phosphorus

Overviews of pools and fluxes of carbon, nitrogen and phosphorous in Basin 508 are given in Figures 6-73, 6-74 and 6-75 and Tables 6-18, 6-19 and 6-20.

Carbon

Considering all fluxes in the mass balance calculations (see Table 6-18 and Appendix 9), there is a net outflux of carbon in 3 of the five basins (521, 504 and 506). The fluxes to and from the basins are dominated by advective flux in all basins. Carbon burial is very small in all basins except for 521, where it constitutes about 50% of the net outflux of carbon. Runoff is small relative to other fluxes, but in Basin 508 it is approximately 50% of the advective influx of carbon.

Table 6-18. Pools and fluxes of carbon (in tonnes basin^{-1} year^{-1}) for five basins in Laxemar-Simpevarp marine model area.

	Tonnes C basin^{-1} y^{-1}				
	Basin 521	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	6	8	162	4	213
Advective influx	897,247	1,179	689	1,393	411
Net Primary Production	5,824	96	112	29	265
In by deposition	72	1	2	1	3
Advective outflux	923,369	1,757	657	2,326	454
Out to air, respiration	12,655	60	130	36	145
Accumulation by burial	25	15	51	2	48
Pools					
Phytoplankton	10	0.1	0.3	0.1	0.2
Microphytes	51	1	1	0.4	2
Macrophytes	1,023	23	33	11	94
Emerg macrophytes	no data	no data	no data	no data	no data
Total pool producers	**1,084**	**24**	**34**	**12**	**96**
Bacterioplankton	10	0.1	0.1	0.03	0.1
Zooplankton	3	0.04	0.1	0.02	0.1
Benthic bacteria	43	3	6	2	7
Benthic herbivores	139	1	2	1	2
Benthic filter feeders	1,714	2	4	2	5
Benthic detrivores	296	1	3	1	3
Benthic carnivores	10	0.4	1	0.2	1
Benthic feeding fish	8	0.2	0.4	0.1	1
Zooplanktonfeeding fish	15	0.1	0.2	0.05	0.2
Piscivorous fish	1	0.2	0.3	0.1	0.3
Birds	0.1	0.01	0.01	0.005	0.03
Seals	0.2	0.003	0.01	0.002	0.01
Total pool consumers	**2,240**	**8**	**17**	**5**	**20**
Top 10 cm regolith pool	3,465	178	560	84	545
Particulate pool	70	1	3	1	1
Dissolved pool	1,718	16	39	8	17

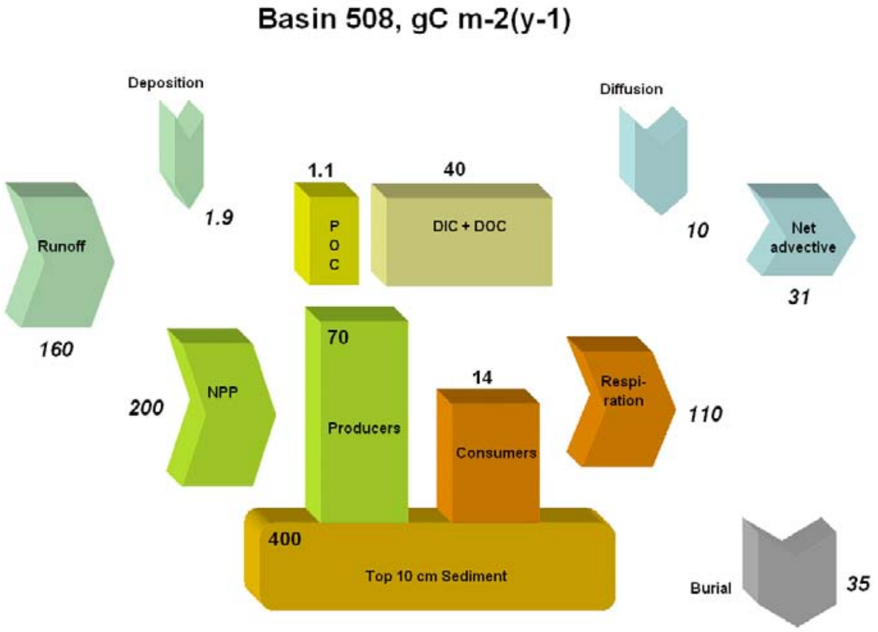

Figure 6-73. *Schematic overview of pools and fluxes of carbon in gC m^{-2} $year^{-1}$ in Basin 508 in Laxemar-Simpevarp.*

Nitrogen

Sediment, primary producers and benthic filter feeders constitute the major pools. The rest of the pools constitute less than 1% of the total nitrogen in the marine basin. Basin 521 has an almost even distribution between the sediment pool and consumers (46 and 47%, respectively), followed by producers (5%), and the dissolved pool (1%), see Table 6-19.

The fluxes to and from the basins are dominated by advective flux, followed by primary production followed by precipitation (deposition) or burial. Deposition of nitrogen is quite an important flux, especially in Basin 521. Considering all fluxes (see Table 6-§19), all basins but one (Basin 506) show a net influx of nitrogen, especially Basin 521, mainly due to high accumulation during NPP.

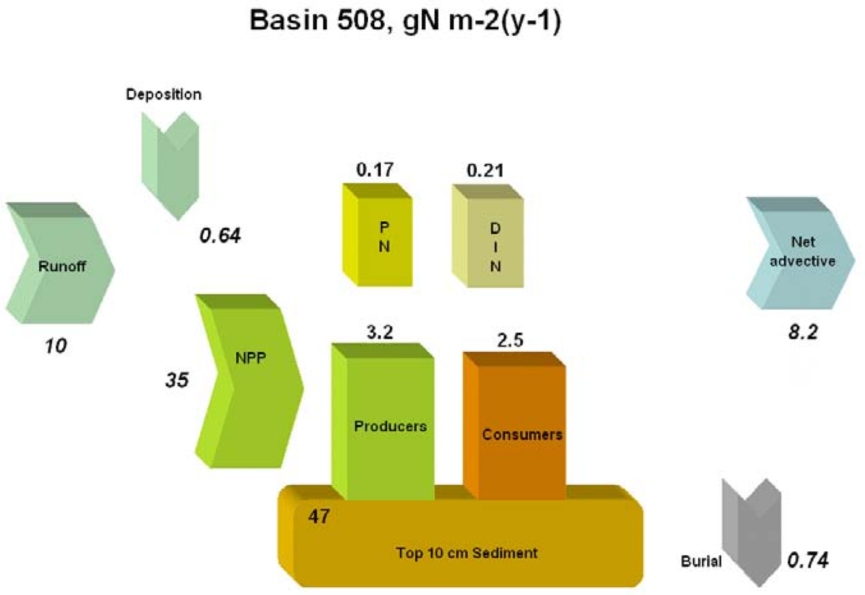

Figure 6-74. *Schematic overview of pools and fluxes of nitrogen in gN m^{-2} $year^{-2}$ in Basin 508 in Laxemar-Simpevarp.*

Table 6-19. Pools and fluxes of nitrogen (in kg year^{-1}) for five basins in Laxemar-Simpevarp marine model area.

	Kg N basin^{-1} y^{-1}				
	Basin 521	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	240	366	10,285	207	14,027
Advective influx	84,093,648	82,845	47,214	99,925	27,962
Net Primary Production	1,025,626	16,865	19,659	5,099	46,669
In by precipitation	24,349	389	721	214	880
Advective outflux	62,719,560	111,268	48,407	150,612	39,194
Accumulation by burial	2,910	1,723	6,098	294	5,664
Pools					
Phytoplankton	1,217	13	32	7	24
Microphytes	5,955	111	126	45	266
Macrophytes	44,323	981	1,419	485	4,069
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**51,495**	**1,106**	**1,577**	**536**	**4,359**
Bacterioplankton	1,703	9	23	5	10
Zooplankton	762	8	20	4	15
Benthic bacteria	7,826	468	1,163	278	1,231
Benthic herbivores	16,106	119	195	66	245
Benthic filter feeders	332,820	429	850	320	1,018
Benthic detrivores	54,071	256	500	133	576
Benthic carnivores	833	37	67	20	101
Benthic feeding fish	2,321	57	104	35	153
Zooplankton feeding fish	3,372	20	37	11	45
Piscivorous fish	385	43	80	24	98
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**420,199**	**1,446**	**3,039**	**895**	**3,491**
Top 10 cm regolith pool	410,404	21,044	66,285	9,983	64,489
Particulate pool	7,819	138	378	70	238
Dissolved pool	9,034	172	562	87	283

Phosphorus

In Basin 508, sediment dominates the phosphorus pool. All other pools are considerably smaller, see Figure 6-75.

The fluxes to and from the basins are dominated by advective flux, although NPP is quite an important flux (see Table 6-20), followed by deposition and burial. Considering all fluxes of phosphorus the model indicates that there is a net influx in all but one basin, Basin 508, which has a small net outflux.

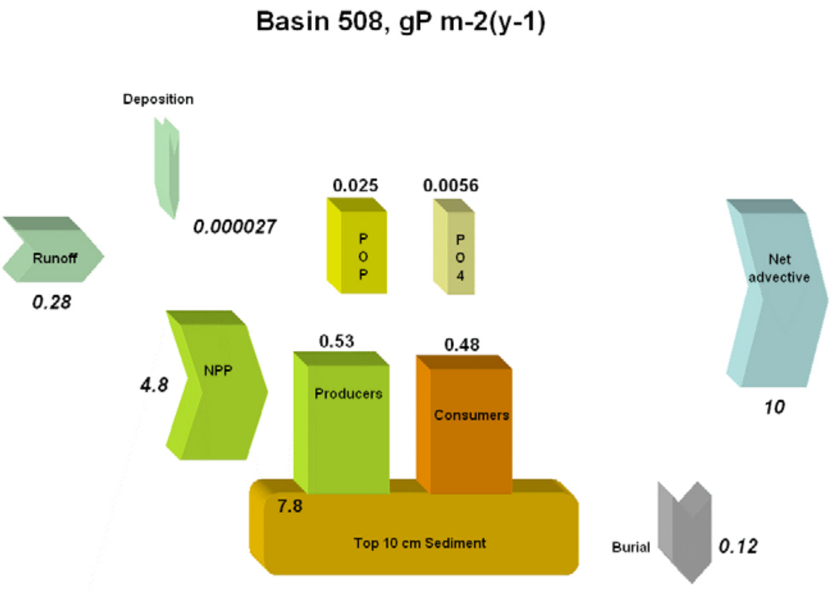

***Figure 6-75.** Schematic overview of pools and fluxes of phosphorus in P m^{-2} $year^{-1}$ in Basin 508 in Laxemar-Simpevarp.*

Table 6-20. Pools and fluxes of phosphorus (in kg $year^{-1}$) for five basins in the Laxemar-Simpevarp marine model area.

	Kg P $basin^{-1}$ y^{-1}				
	Basin 521	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
434. **Fluxes** **435.**					
Runoff	6	9	295	6	391
Advective influx	6,559,145	6,266	7,454	17,070	1,669
Net Primary Production	141,939	2,334	2,721	706	6,459
In by deposition	1,027	16	30	9	37
Advective outflux	5,664,998	6,626	2,900	8,969	15,909
Accumulation by burial	482	286	1 011	49	939
Pools					
Phytoplankton	118	1	3	1	2
Microphytes	1,098	20	23	8	49
Macrophytes	7,307	162	234	80	671
Emerg macrophytes	no data	no data	no data	no data	no data
Total pool producers	**8,523**	**184**	**260**	**89**	**722**
Bacterioplankton	431	2	6	1	3
Zooplankton	450	5	12	2	9
Benthic bacteria	2,413	144	359	86	380
Benthic herbivores	1,605	12	19	7	24
Benthic filter feeders	46,147	60	118	44	141
Benthic detrivores	5,652	27	52	14	60
Benthic carnivores	81	4	7	2	10
Benthic feeding fish	295	7	13	4	19
Zooplankton feeding fish	335	2	4	1	4
Piscivorous fish	49	5	10	3	12
Birds	no data	no data	no data	no data	no data
Seals	no data	no data	no data	no data	no data
Total pool consumers	**57,458**	**268**	**600**	**165**	**663**
Top 10 cm regolith pool	68,023	3,488	10,986	1,655	10,689
Particulate pool	1,418	28	107	14	35
Dissolved pool	6,970	20	43	10	8

Actinides and iodine

The fluxes considered are advective flux, precipitation and burial. The other fluxes were not included due to lack of data. For some functional groups (benthic bacteria, bacterioplankton, benthic filter feeders, benthic carnivores, birds and seals), no data were available and therefore some functional groups are not included in the mass balances, which suggests an underestimation of the consumer pool. Data on uranium concentrations in some of the biotic functional groups were not available for Laxemar-Simpevarp, so data from Forsmark were used to give a rough estimate of these pools relative to others. Since salinity in particular but also other chemical characteristics will affect the uranium distribution, these estimates of uranium concentrations are to be regarded as very rough. Some analyses of biota were below the detection limit, and estimated means based on half the detection limit were used to give a rough estimate (estimated mean). For the biotic pools half the detection limit was used as estimated means of concentrations and they are marked in the tables.

Th has the smallest pools in water and I the largest, compared with sediments, see Figures 6-76, 6-77 and 6-78 and Tables 6-21, 6-22 and 6-23.

Thorium

The major pool for thorium is sediment in all basins. Sediment comprises 91–98% of the pool in the whole basin, followed by the particulate pool (1–4%), and producers (1–3%). All other pools constitute less than 1% of the total thorium inventory in the marine model area in Laxemar-Simpevarp (see also Appendix 9).

The major flux of thorium is the advective flux. Burial is a small flux in comparison with advection in all basins except Basin 508, but larger than deposition. Considering all fluxes there is according to the model a total net outflux of thorium in all but one basin, Basin 521, see Figure 6-76 and Table 6-21.

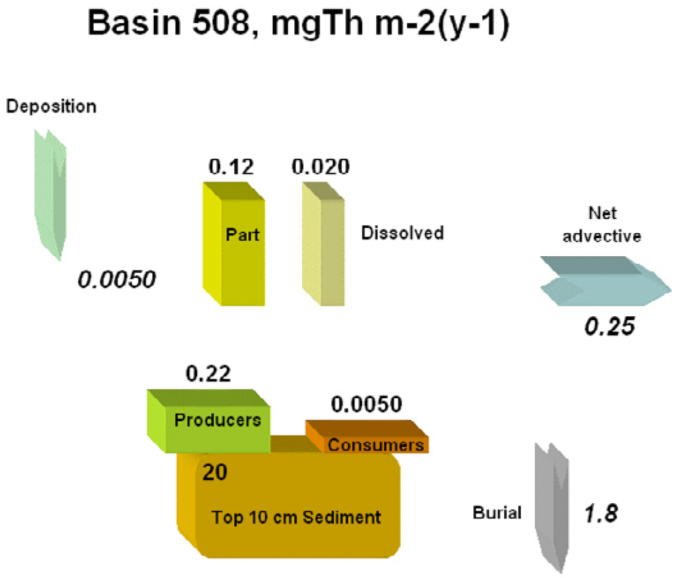

Figure 6-76. *Schematic overview of pools and fluxes of Thorium in mgTh* m^{-2} *year*$^{-}$*, in Basin 508 in Laxemar-Simpevarp.*

Table 6-21. Pools and fluxes of Thorium (in kg and kg year^{-1} respectively) for Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

	Kg Th basin^{-1} y^{-1}				
	Basin 521	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective influx	689	1	1	1	0.4
In by deposition	0.2	0.003	0.006	0.002	0.007
Advective outflux	622	2	1	2	1
Accumulation by burial	1	0.7	3	0.1	2
Pools					
Phytoplankton	0.1	0.001	0.002	0.0004	0.002
Microphytes	5.3	0.1	0.1	0.04	0.2
Macrophytes	0.7	0.02	0.02	0.01	0.1
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**5**	**0.1**	**0.1**	**0.04**	**0.2**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	0.004	0.00005	0.0001	0.00002	0.00008
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	0.1	0.001	0.002	0.0006	0.002
Benthic filter feeders	0.1	0.0001	0.0003	0.0001	0.0004
Benthic detrivores	0.2	0.001	0.002	0.0005	0.002
Benthic carnivores	0.02	0.001	0.002	0.0004	0.002
Benthic feeding fish	0.0002	0.000005	0.00001	0.000003	0.00001
Zooplankton feeding fish	0.0001	0.0000005	0.000001	0.0000003	0.000001
Piscivorous fish	0.00003	0.000004	0.000007	0.000002	0.00001
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**0.5**	**0.003**	**0.01**	**0.002**	**0.01**
Top 10 cm regolith pool	178	9	29	4	28
Particulate pool	8	0.2	0.4	0.1	0.2
Dissolved pool	1	0.02	0.03	0.01	0.03

Uranium

For uranium, the sediment pool is the dominant pool for four of the basins, followed by the dissolved pool. However, in Basin 521 the dissolved pool is largest (66%), followed by sediment (32%). All other pools constitute less than 1% of the total thorium inventory in the marine model area in Laxemar-Simpevarp. This is also true in Basin 508, see Figure 6-77 and Table 6-22.

The major flux of uranium is the advective flux. Considering all fluxes, all basins except Basin 504 have a net outflux of uranium according to the model In most basins the net outflux is quite small, except for Basin 521, where it is quite large. Burial is very small in comparison with the advective fluxes, see Figure 6-77 and Table 6-22.

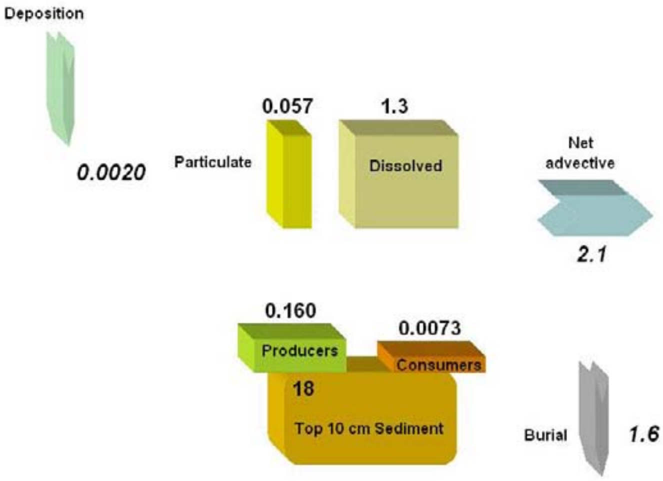

Figure 6-77. Schematic overview of pools and fluxes of Uranium in mgU m^{-2} year^{-1} in Basin 508 in Laxemar-Simpevarp.

Table 6-22. Pools and fluxes of uranium (in kg and kg year^{-1} respectively) for five basins in Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

	Kg uranium basin^{-1} y^{-1}				
	Basin 521	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes Area (km^2):	14	5.4	0. 6	3.7	0.7
Runoff	No data	No data	No data	No data	No data
Advective influx	173,495	177	68	232	42
In by deposition	0.08	0.001	0.002	0.001	0.003
Advective outflux	174,604	174	69	235	45
Accumulation by burial	1	0.7	2	0.1	2
Pools					
Phytoplankton	0.02	0.0002	0.001	0.0001	0.0005
Microphytes	0.1	0.002	0.002	0.001	0.01
Macrophytes	2	0.05	0.07	0.03	0.2
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**0.1**	**0.002**	**0.003**	**0.001**	**0.006**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	No data	No data	No data	No data	No data
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	0.1	0.001	0.001	0.0005	0.002
Benthic filter feeders	1	0.002	0.004	0.001	0.005
Benthic detrivores	0.3	0.001	0.002	0.0006	0.003
Benthic carnivores	0.01	0.000	0.001	0.0002	0.001
Benthic feeding fish	0.000002	0.00000004	0.0000001	0.00000002	0.0000001
Zooplankton feeding fish	0.00002	0.0000001	0.0000002	0.0000001	0.0000002
Piscivorous fish	0.0000003	0.00000003	0.0000001	0.00000002	0.0000001
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**2**	**0.004**	**0.01**	**0.003**	**0.01**
Top 10 cm regolith pool	156	8	25	4	24
Particulate pool	4	0.1	0.2	0.04	0.1
Dissolved pool	329	2	4	0.8	2

Iodine

For iodine the dissolved pool in water is the dominant pool for of the basins (521, 502 and 506). In Basin 521 the domination iodine pool is producers (78%), while in Basin 508 the majority of the iodine is distributed in the sediment (36%), followed by the dissolved pool (34%) and the producer pool (23%). The particulate pool varies between 2 and 9% in the basins, while all other pools, including all consumers, contain less than 1% of the total iodine inventory, Table 6-23.

The major flux of iodine is the advective flux. In three of five basins there is a net outflux of iodine, according to the model. In Basin 521 there is a large net influx of iodine on an annual basis. Burial is very small in comparison with the advective fluxes, see Figure 6-78.

Table 6-23. Pools and fluxes of iodine (in kg and kg year^{-1} respectively) for Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

Kg I basin^{-1} y^{-1}	Basin 521	Basin 504	Basin 502	Basin 506	Basin 508
Fluxes					
Advective influx	2,751,206	3,132	1,336	3,519	917
In by deposition	11	0.2	0.3	0.1	0.4
Advective outflux	2,555,726	3,495	1,689	4,731	800
Accumulation by burial	1.5	0.9	3	0.2	3
Pools					
Phytoplankton	0.9	0.01	0.02	0.005	0.02
Microphytes	99	2	2	1	4
Macrophytes	180	4	6	2	17
Emerg macrophytes	No data	No data	No data	No data	No data
Total pool producers	**280**	**6**	**8**	**3**	**21**
Bacterioplankton	No data	No data	No data	No data	No data
Zooplankton	0.6	0.01	0.01	0.003	0.01
Benthic bacteria	No data	No data	No data	No data	No data
Benthic herbivores	7	0.1	0.08	0.03	0.1
Benthic filter feeders	No data	No data	No data	No data	No data
Benthic detrivores	15	0.07	0.1	0.04	0.16
Benthic carnivores	0.5	0.02	0.04	0.01	0.06
Benthic feeding fish	0.02	0.0004	0.0008	0.0003	0.0011
Zooplankton feeding fish	0.01	0.00004	0.0001	0.00002	0.0001
Piscivorous fish	0.003	0.0003	0.0006	0.0002	0.0007
Birds	No data	No data	No data	No data	No data
Seals	No data	No data	No data	No data	No data
Total pool consumers	**23**	**0**	**0.3**	**0.1**	**0.3**
Top 10 cm regolith pool	213	11	34	5	33
Particulate pool	240	5	11	2	5
Dissolved pool	4,810	33	103	17	31

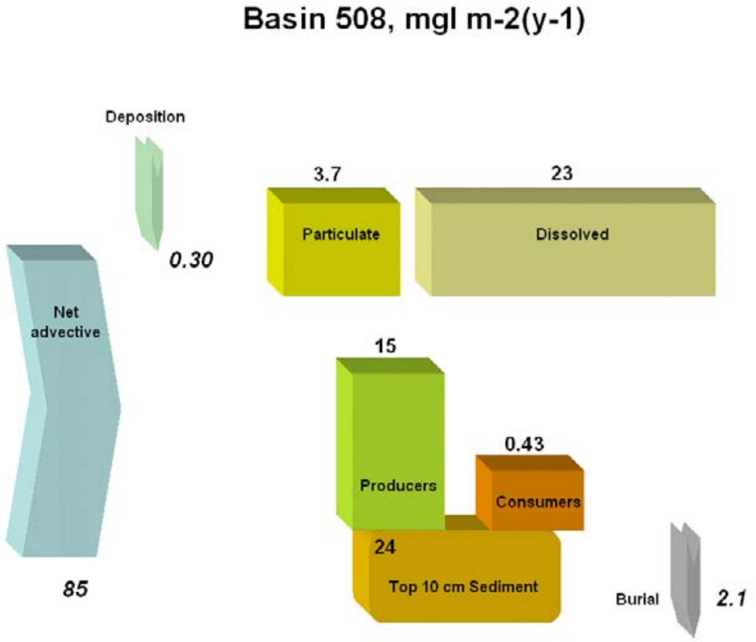

Figure 6-78. *Schematic overview of pools and fluxes of Iodine in Basin 508 in mg I m^{-2} year^{-1} in Laxemar-Simpevarp.*

Metalloids

Si and Se are included in the chemical group metalloids, together with As. They have properties of both metals and non-metals. They are generally not distributed similar to each other in the pools of an ecosystem and are therefore presented separately. These metalloids are regarded as recycled elements, i.e. elements that are incorporated into soft tissues or into skeletal material and will be more or less depleted in surface waters and enriched in the deep ocean. Si is also classified as biolimiting together with P and N, while the other metalloids can be considered as biointermediate.

In the fives basins Si is mainly distributed in the sediment pool (75–96%), followed by the particulate pool (3–16%), see Table 6-24. The rest of the pools contain around 1% or less of the total inventory of Si in the basins.

Se and As are, in comparison to Si, slightly less abundant in the sediment pool (40–85% for Se and 29–86% for As) and more abundant in the particulate and dissolved pools (11–38% for Se and 29–86% for As). In Basin 521, Se is quite abundant in the consumer pool (20%), but much less so in the other biotic pools. For As, the producer pool constitutes the largest biotic pool (93%).

According to the model there is a net outflux of the metalloids Si and As (no site specific data for Se is available) in all basins, except for Basin 521 where there is a large influx. Burial is important (for both Si and As) and is the largest flux in all basins but Basin 521. Since Si and Se are essential for organisms they are specifically presented in Table 6-24.

Table 6-24. Pools and fluxes of Si and Se, in Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

kg Si basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	1,910	2,419	43,065	1,181	57,772
Advective inflow	365,743	236	93	312	57
In by deposition	1,240	20	37	11	45
Advective outflow	232,956	235	93	319	63
Accumulation by burial	34,903	20,573	73,070	3,519	67,820
Pools					
Total pool producers	66,956	1,291	1,779	587	4,189
Total pool consumers	10,678	60	114	32	132
Top 10 cm regolith pool	4,916,632	252,107	794,087	119,602	772,574
Particulate pool	**1,044,009**	**20,721**	**49,622**	**10,281**	**21,946**
Dissolved pool	438,401	2,253	5,625	1,139	2,458
kg Se basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	No data	No data	No data	No data	No data
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	No data	No data	No data	No data	No data
Accumulation by burial	0.2	0.1	0.4	0.02	0.3
Pools					
Total pool producers	**1**	**0.03**	**0.04**	**0.01**	**0.1**
Total pool consumers	**13**	**0.02**	**0.04**	**0.02**	**0.1**
Top 10 cm regolith pool	25	1	4	1	4
Particulate pool	24	0.5	1	0.2	1
Dissolved pool	No data	No data	No data	No data	No data

Metals

For Mg, Na, Ca, K, Li and Mo for the dissolved pool dominates. For Zn and Ba it is the particulate pool, and for the rest of the metals the sediment pool dominates (Appendix 9).

For all metals except Ca, the dominant biotic pool is producers. To exemplify metal pools and fluxes, Fe, Mg and Ca are presented in Table 6-25 because they represent various distributions of elements in the metals chemical group.

Ca and Mg, which are major constituents of marine water, are distributed to a high degree in the dissolred water pool (around 99% for Mg and between 77 and 96% for Ca). Fe is mainly distributed in the sediment pool (88–98%), and Fe is the only metal (of these three) with a biotic pool of over 1%, see Table 6-25.

According to the model there is a net outflux of Fe, Mg and Ca in all basins but Basin 521. In Basin 521 there is a large net influx of Fe, Mg and Ca. Burial is an important flux for iron in several basins, but for other metals this flux is very small compared with the advective flux, see Table 6-25.

Table 6-25. Pools (kg) and fluxes (kg year^{-1}) of Fe, Mg and Ca, in Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

Kg Fe basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Advective influx	35,509	23	9	30	6
In by deposition	1,432	23	42	13	52
Advective outflux	22,617	23	9	31	6
Accumulation by burial	4,653	2,743	9,741	469	9,041
Pools					
Total pool producers	**20,220**	**394**	**486**	**169**	**1,143**
Total pool consumers	**1,324**	**6**	**10**	**3**	**12**
Top 10 cm regolith pool	655,447	33,609	105,862	15,944	102,994
Particulate pool	6,453	128	307	64	136
Dissolved pool	58,502	301	751	152	328

Kg Mg basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	437	554	9,859	270	13,226
Advective influx	75,694,582	48,906	19,240	64,513	11,772
In by deposition	4,946	79	146	43	179
Advective outflux	48,212,761	48,704	19,172	65,926	12,983
Accumulation by burial	1,588	936	3,324	160	3,085
Pools					
Total pool producers	**41,477**	**900**	**1,282**	**437**	**3,587**
Total pool consumers	**30,417**	**72**	**140**	**44**	**165**
Top 10 cm regolith pool	17	1	2.8	0.4	3
Particulate pool	21,402	425	1,017	211	450
Dissolved pool	90,744,796	466,322	1,164,304	235,749	508,871

Kg Ca basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	2,231	2,825	50,292	1,379	67,467
Advective influx	31,027,783	20,047	7,886	26,444	4,826
In by deposition	15,941	255	472	140	576
Advective outflux	19,762,776	19,964	7,859	27,024	5,322
Accumulation by burial	1,171	690	2,452	118	2,276
Pools					
Total pool producers	**180,841**	**3,967**	**5,678**	**1,942**	**16,108**
Total pool consumers	**282,873**	**2,023**	**3,670**	**1,108**	**4,875**
Top 10 cm regolith pool	165,009	8,461	26,651	4,014	25,929
Particulate pool	731,795	14,524	34,783	7,207	15,383
Dissolved pool	37,199,011	191,159	477,283	96,641	208,601

Lanthanides

Lanthanides are regarded as trace elements in the marine ecosystem. The lanthanides seem to be distributed similarly in the marine ecosystem (see Section 6.2). Like many of the other elements, the lanthanides (Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Tm, Yb, Lu) are most abundant in the sediments (Appendix 9). Ce, Tb and Er have been selected to illustrate the distribution of lanthanides, see Table 6-26.

Ce and Er are distributed with their major pool in the sediment (except in Basin 521, who has a huge dissolved pool), while Tb seems to have a slightly smaller sediment pool and a larger dissolved pool. All of them have very small biotic pools, see Table 6-26.

According to the model there is a net influx of Ce, Tb and Er in Basin 521. In the other basins there is a net outflux due to the large burial term. Burial is quite an important flux for Ce and Tb, but the advective flux is still of major importance, see Table 6-26.

Table 6-26. Pools (kg) and fluxes (kg year^{-1}) of Ce, Er and Tb, in Basin 521, 504, 502, 506 and 508 in Laxemar-Simpevarp.

Kg Ce basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	71	0.05	0.02	0.1	0.01
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	45	0.05	0.02	0.1	0.01
Accumulation by burial	24	14	50	2	46
Pools					
Total pool producers	**23**	**0.50**	**0.7**	**0.3**	**2**
Total pool consumers	**1.3**	**0.003**	**0.01**	**0.002**	**0.01**
Top 10 cm regolith pool	3,361	172	543	82	528
Particulate pool	71	1	3	1	1
Dissolved pool	88	0.5	1.1	0.2	0.5

Kg Er basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	21,589	14	5	18	3
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	13,751	14	5	19	4
Accumulation by burial	0.75	0.44	1.6	0.1	1.5
Pools					
Total pool producers	**0.7**	**0.02**	**0.02**	**0.008**	**0.06**
Total pool consumers	**0.1**	**0.0001**	**0.0002**	**0.0001**	**0.1**
Top 10 cm regolith pool	106	5	17	3	17
Particulate pool	14	0.3	0.6	0.1	0.3
Dissolved pool	25,886	133	332	67	145

Kg Tb basin^{-1} y^{-1}	**Basin 521**	**Basin 504**	**Basin 502**	**Basin 506**	**Basin 508**
Fluxes					
Runoff	No data	No data	No data	No data	No data
Advective inflow	36	0.02	0.01	0.03	0.01
In by precipitation	No data	No data	No data	No data	No data
Advective outflow	23	0.02	0.01	0.03	0.01
Accumulation by burial	0.2	0.1	0.5	0.02	0.5
Pools					
Total pool producers	**0.2**	**0.004**	**0.0062**	**0.0021**	**0.0178**
Total pool consumers	**0.02**	**0.00003**	**0.0001**	**0.00002**	**0.0001**
Top 10 cm regolith pool	33	2	5	1	5
Particulate pool	0.4	0.01	0.020	0.004	0.01
Dissolved pool	26	0.1	0.3	0.1	0.1

6.6 Confidence and uncertainties

The biomass distributions of the various functional groups in the marine ecosystems at the two sites are based on data from extensive site investigations and can be considered reliable for most groups. The annual cycle of some organism may not have been covered and it is possible that for example the yearly maximum densities of phyto- and zooplankton have been missed. However, since the data is site specific it has quite good reliance regarding magnitude.

The calculations of primary production in various macrophyte communities were based on extensive site specific measurements and have good confidence. The calculated values for primary production in the various macrophyte communities were in good agreement with other studies /Binzer et al. 2006/ (see also discussion in Section 4.6.1), and with measurements of primary production at the sites.

Respiration was calculated from biomass and average annual temperature, using conversion factors (from T days to respiration) /Kautsky 1995/ and consumption was estimated from respiration using reported conversions factors /Kumblad et al. 2003, 2006/. Human consumption was estimated from fishery catch. Since these calculations are based on extensive data from site investigations regarding temperature and biomass and reliable conversion factors the confidence is fairly good. Small differences in the conversion factors used will greatly influence the size of the biotic fluxes, for most elements the biotic fluxes are small compared to advective flux and the altered conversion factor will not greatly influence the massbalance.

In the food webs the various organisms are expected to consume all potential food items available, i.e. if there are as many benthic detrivores and herbivores as benthic carnivores the benthic feeding fish are expected to consume the same amount of each. In reality it is more likely that a consumer have a certain food preference and select prey that are easy to find or with the highest food quality. However, this assumption that consumers don’t select their food items (in detail) gives a rough estimate of the flow of matter in the food web, but with some uncertainty.

The estimations of pools and fluxes of different elements in the marine ecosystems at the two investigated sites are based on data from extensive site investigations. Site-specific water chemistry data for most elements are available for the period November 2002–July 2007 (Forsmark) and October 2002–April 2007 (Laxemar-Simpevarp), giving these estimates a relatively good resolution both in time and space. The estimated pools of various elements in the marine basins have, when possible, been calculated with data from a sample site within the basin. When no sample site where located in a basin a mean value for the whole marine area were used.

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 considered reliable estimates with good resolution in time and space. The estimated pools of other elements in particulate matter and sediment are, on the other hand, based on a single sampling performed in spring 2008 and on a limited amount of sediment samples. The use of the results from this sampling to estimate the mean annual pool of different elements in particulate matter and sediment implies of course a relative high uncertainty in the estimates. However, as data are site-specific it gives a high confidence in the magnitude of the pools of element.

Sediment pool estimates depend on the spatial distribution mapping of the various sediment types and their stratigraphy, an assumption of bioactive layer depth, and on the chemical element analyses and their representativity. Given that the spatial distribution rests on e.g. seismic sonar, the certainty regarding sediment distribution must be considered relatively good. The active layer depth could probably be better justified locally and possibly sediment type specific. Element and water content analyses could have been better distributed spatially and across sediment types. Thus, and in any case since also further bioavailability of the various elements (e.g. labile or refractory nutrients) is probably less certain than the pool estimates, derived results need to be considered as being within at least half an order of magnitude.

The largest uncertainty in pools of element in the biotic component is the lack of data on chemical composition of bacteria for all elements except phosphorus, nitrogen, sulfur and carbon. This of course leads to uncertainties in the distribution of elements within the biotic component. For other organisms, the elemental composition data for biotic pools are reliable estimate since it is mainly site specific. There are relatively few replicates, which induce some uncertainties, but the available replicates show small deviations from each other. When estimating the pools of different elements, biomass data are used together with the chemical composition. Although small, uncertainties are of course also connected with the biomass data.

Mass balances for a large number of elements have been constructed for five of the marine basins in Forsmark and Laxemar-Simpevarp. The mass balance calculations for the basins are in general not well balanced, due to several reasons, but probably mainly due to that not all fluxes which may occur are included. For example is the exchange between sea surface and atmosphere is only included for carbon and only with a general value for exchange in the Baltic Sea. This process can according to /Baes et al. 1985/ be much larger depending on how much is needed to reach equilibrium. The large advective fluxes in the sea do also convey large uncertainties. The fluxes of elements, calculated with water chemistry data and oceanographic estimates of water fluxes, can be considered as relative reliable (see Section 5.6 for discussion of uncertainties in advective flux). However, since the volumes of water moved in the advective fluxes are so large, this flux has a great impact on the results in the mass balance. Even if the concentration of respective element in the water is reliable, just a minor concentration difference will largely affect the advective flux of the element. Thus the advective fluxes of elements have contributes to the uncertainty in the mass balance calculations.

The estimates of burial rely on a mapping of the sea-floor, both spatial and vertical, and on the estimation (and applicability) of the relationship between gross accumulation and net burial. The former depends on both a fairly crude sediment classification, however relatively well mapped spatially and locally also on thickness modeling. The latter relationship draws upon on few core dating and analyses only. The outcome can probably be considered rough order-of-magnitude estimates.

The site specific data on atmospheric deposition includes only a few elements. Thereby this flux is missing for many elements. For most elements (except phosphorus) this flux is small and probably does not alter the mass balance in any significant way. However, for the lanthanides atmospheric deposition has not been estimated for a single element. Even though, the possibility that the atmospheric deposition is high for this group of elements is less likely it cannot be excluded. 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.

7 Long term development of marine ecosystems

The long term development of marine ecosystems in the Baltic Sea is considered to be driven mainly by the factors climate change and shoreline displacement /SKB 2010a/. The aim of this chapter is to describe the effects of the major forcing factors on the long term development of marine ecosystems, the historical development and the potential future development of the marine ecosystems at Forsmark and Laxemar-Simpevarp. The aim is also to evaluate the possible effects of future climate change and shoreline displacement on important processes used in the radionuclide model Chapter 10 in /Andersson 2010/. These two major forces in combination strongly affect a number of processes, which in turn determine the development of ecosystems (e.g. salinity and water turnover). The shoreline displacement is mainly a secondary effect of climate variations. It is caused by the interaction between glacially induced isostatic variations on the one hand, and eustatic sea level variations on the other. Periodically, shoreline displacement has strongly affected the Forsmark and Laxemar-Simpevarp areas, both before and after the latest deglaciation, and it is likely that the areas repeatedly has been situated below the sea level for long periods (cf. Chapter 3 in /Söderbäck 2008/). Discussions of ecosystem properties in this chapter relate mainly to processes of potential importance for the distribution of radionuclides in the marine environment, and these may not always coincide with processes of importance for ecosystem functioning.

The long term temporal perspective considered covers a glacial cycle estimated to be around 120,000 years. The radionuclide model /Andersson (ed) 2010, Chapter 10/ used in the safety assessment (SR-site) performed by SKB describes the dose to humans during a glacial cycle, i.e. under varying climatic conditions. In the safety assessment it is assumed that the extremes within which Swedish climate has varied in the past, will serve as a framework for climatological conditions during a glacial cycle. Therefore, the SR-Site primary approach of handling the complex issue of future climates is by constructing a *reference glacial cycle (the reference case)*, which constitutes a repetition of the climate reconstructed for the latest glacial cycle, in Europe called Weichsel and the subsequent warm period Holocene. Covering a period of around 120,000 years, the case provides an example of how climate characteristics are likely to develop during a future glacial cycle including full glacial conditions. The reference case, which starts at present time, gives input on timing, function and feedbacks of climate-related phenomena like ice sheets, permafrost and shoreline displacement (further described in the **Climate report**). In addition to the reference case, a *Global warming case* is considered in SR-site. The global warming case exhibits the same sequence of climate, although the initial temperate period is somewhat warmer and wetter and has a longer duration than in the reference case. Fundamental for the climate cases considered is the division of conceivable climate-related conditions in *climate-driven process domains* /Boulton et al. 2001/, in the following referred to as *climate domains.* The purpose of identifying climate domains is to create a framework for the assessment of issues of importance for repository safety associated with particular climatically determined environments that may occur in Sweden. Three different climate domains considered in SR-site are; a temperate (an environment neither covered by ice sheet, nor influenced by permafrost), a periglacial (with permafrost) and a glacial (ice-covered) domain. In addition periods of submerged conditions, when the whole model area is beneath sea surface, following upon the regressions of the glacial climate ice-sheet will occur. The specific order and duration in which the various climate domains appear in a future time perspective the climate cases are further elaborated in Section 7.4, and described in the **Climate report** and /Lindborg 2010/. The model starting point is at the end of last glacial cycle, corresponding to the situation 8800 years BC when both Forsmark and Laxemar-Simpevarp were deglaciated and submerged by sea water.

The description of the historical long term development of the landscapes in Forsmark and Laxemar-Simpevarp is generally taken from /Söderbäck 2008/ and mainly based on the elevation model, the shoreline displacement equation (cf. /Påsse 1997/), old cadastral maps and site-specific information on Quaternary deposits.

The descriptions of the future evolution are based on existing knowledge of the past, known processes (e.g. shoreline displacement) and knowledge of the current situation e.g. existing ecosystems (Chapters 3–6 in this report), climate (climate models **Climate report** and /Kjellström et al. 2009/), the geometry and geology of the seafloor /Lindborg 2010/. All these descriptions involve uncertainties. Moreover, the future development of the area may be different than expected based solely on history, due to e.g. climate change caused by increased greenhouse gas-induced warming. Thus, the descriptions presented here are potential future cases that are logically coherent, but the temporal and spatial extension of various climatic conditions is uncertain due to limitations in underlying data and conceptual models (e.g. /Kjellström et al. 2009/).

7.1 General effects of major abiotic factors on marine ecosystems

The Baltic Sea is not a steady state system and since its formation it never has been. External drivers acting on different time scales force major changes in the marine ecosystem structure and function. Postglacial isostatic and eustatic processes have shaped the Baltic Sea's coastline, topography, basic chemistry and sedimentary environment on millennium scales. Climate variability acts on all time scales and, at least over the last 150 years, overlaps with human activities in the drainage basin and the coastal zone, leading to considerable changes in the biogeochemistry of this semi-enclosed sea /BACC 2008/.

Changes in abiotic forcing factors like substrate, depth, nutrient conditions, salinity and temperature, may indirectly or directly be the result of shoreline displacement and climate change, and will generate changes in the ecosystem structure and functioning. Accordingly this is the case in the coastal areas in Forsmark and Laxemar-Simpevarp, were shoreline displacement continuously transforms the offshore sea bottom to near-shore coastal areas and climate conditions adds further impact on the abiotic factors controlling ecosystem development. The total effect of the forcing abiotic factors on the marine ecosystems will be enhanced or attenuated during various conditions.

Following the deglaciation, starting condition for marine ecosystem succession begins in the deep sea when the ice is gone and the model area is submerged below deep sea water. Although conditions are less variable than on land, the limits of tolerance of most marine organisms are comparatively narrow and their distribution is determined primarily by the interrelated effects of water depth, latitude and distance from shore. Hence, the development of the marine habitats is strongly dependent on the bathymetrical conditions. Low points on the seafloor accumulate sediments (accumulation bottoms), to a higher degree than higher-lying 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 (soft bottoms), while the finer fractions are washed out from more wave-exposed open shorelines (hard bottoms). The benthic soft- and hard bottom ecosystems of the Baltic Sea in general, have due to the abiotic boundary conditions, different ecosystem structure and composition as well as the shallow and deep bottom types. The different abiotic conditions dependent upon bottom substrate, and depth generates a zonation of marine ecosystems. Thus, one common way to categorise the benthic ecosystems can be according to depth and bottom substrate.

In deep soft bottoms (> 20 m) the light is generally to sparse to allow any vegetation and the ecosystem is dominated by benthic heterotrophic organisms, e.g. benthic bacteria, Baltic clam (*Macoma baltica*), isopods, amphipods and polychaete. Large areas of deep soft bottoms may also be oxygen free and is then only inhabited by benthic bacteria.

In shallow soft bottoms where the salinity often due to influence from land runoff lower than in more offshore areas, the vegetation is often extensive and dominated by rooted freshwater vegetation in subsurface meadows (Figure 7-1).The shallow soft bottom fauna generally consists of snails, insects and insect larvae, which serve as food resource for fish and fry.

On hard bottoms the subsurface zone generally is occupied by the green algae, deeper down followed by the brown algae like *Fucus* (see Figure 3-31), and below them the red algae grow (see Figure 3-32). The algae belts provide good habitats for among others; mussels, crustaceans, snails and bryozoans. Deeper hard bottoms with insufficient light conditions for algae and with sufficient salinity is often totally dominated by the blue mussle (*Mytilus edulis,* see Figure 3-38) in the Baltic Sea.

At present soft bottoms is the most extensive bottom substrate in Forsmark, and in Simpevarp-Laxemar the hard bottoms dominate the outer basins, although the substrates in the bays are generally soft bottoms.

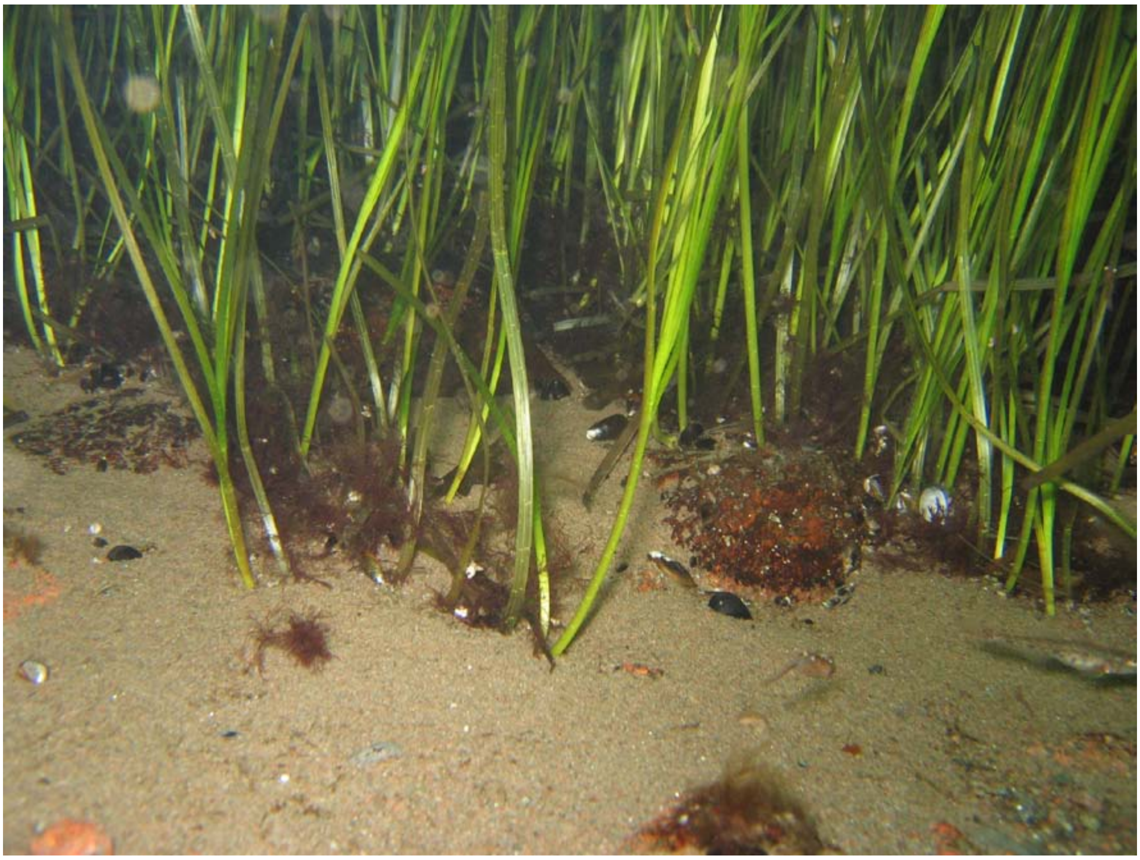

Figure 7-1. *Shallow soft bottom meadow of Zostera marina.*

The clear zonation seen in the marine benthic ecosystems is not as visually evident in the pelagic ecosystem. In the shallower coastal marine ecosystem, the effects of runoff and wave exposure often result in lower water transparency, lower salinity and high nutrient load. The incidence of freshwater species is larger than further out and the photic depth is smaller. The pelagic offshore ecosystem will be inhabited by more marine species, the water transparency is deeper and the water more saline.

Following the long term development with a regressive shore line, the deeper marine areas will be transformed to more shallow coastal areas or bays. The deep soft or hard bottoms will become shallow soft or hard bottoms or, hence, at some point during the development, there might be a shift from one bottom substrate to another due to altered bathymetric conditions. The 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 connected to the sea until sedimentation, vegetation growth and shoreline displacement transforms it into a wetland. The subsequent development of marine areas in terrestrial areas and lakes, is described in /Andersson 2010/ and /Löfgren 2010/ and may follow different trajectories depending on factors such as fetch during the shallow marine stage, slope and surrounding topography.

7.2 Climate change

Climate variation is caused by factors external to the Earth's climate system and by the complex response of the climate system's components and internal dynamics to those forces. Examples of external natural factors affecting climate in the time perspective of interest for the safety assessment are volcanism, solar variability and changes in insolation due to variations of the Earth's orbital parameters. Another example of an external, but anthropogenic, factor is the burning of fossil fuel, increasing concentrations of greenhouse gases in the atmosphere. Internal dynamics affecting the climate include those associated with atmospheric and ocean circulation, the waxing and waning of ice sheets and feedback processes such as those relating to temperature – water vapour, ice – albedo, vegetation – albedo and vegetation – precipitation.

The Earth climate system is also closely linked to the carbon cycle, i.e. the continued exchange and reactions of carbon in the terrestrial biosphere, atmosphere, hydrosphere, and sediments, the latter including fossil fuels. There are important feed-back mechanisms in the carbon transfer processes between these carbon reservoirs, many of which have an impact on climate. Global warming could for example suppress terrestrial carbon uptake, which would result in higher carbon dioxide levels in the atmosphere /Friedlingstein et al. 2006/. This is a topic within climate research that is developing rapidly. A recent update on this and related issues is found in /Thorne and Kane 2006/.

During the Quaternary period, i.e. the last 2.6 million years, the climate has been characterized by large and sometimes fast changes of global temperature (cf. Chapter 3 in /Söderbäck 2008/). One effect of the large climate variations is the waxing and waning of large ice sheets, especially in the mid-latitudes of the Northern Hemisphere. Results from studies of the isotopic composition of deep-sea sediment cores suggest as many as fifty glacial/interglacial cycles during the Quaternary /Shackelton 1997/. The climate during the past c 700,000 years has been colder than during the earlier part of the Quaternary, and it has been characterised by 100,000 yearlong glacial periods interrupted by interglacials lasting for approximately 10,000–15,000 years (Figure 7-2). Accordingly, Sweden has repeatedly been covered by glacial ice and this has had a great impact on the distribution of loose deposits and on the shaping and morphology of the landscape. This has in turn affected the near-surface hydrology and the local distribution of soils and vegetation.

As described above, the past climatic variations during the Quaternary are fairly well known, especially for the latter parts of the period. In contrast, the timing and extent of any future climate changes are highly uncertain due to the complexity and non-deterministic aspects of the climate system. Additional uncertainty is introduced by the unclear impact and duration of human influence on the climate due to emissions of greenhouse gases. It is not possible to predict the evolution of the climate in a 120,000-year time perspective and any presented long term future climate evolution is associated with large uncertainties. However, the extremes within which the climate of Sweden may vary can be estimated with reasonable confidence. Within these limits, characteristic climate-related conditions of importance for repository safety can be identified. The conceivable climate-related conditions can be represented as climate-driven process domains /Boulton et al. 2001/ where such domain is defined as a climatically determined environment in which a set of characteristic processes of importance for repository safety appear. In the following these climate driven process domains are referred to as climate domains. The identified domains are denominated:

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

The purpose of identifying climate domains is to create a framework for the assessment of issues of importance for repository safety associated with particular climatically determined environments that may occur in Sweden. By taking the sequence of climate domains into account it is possible to cover potential changes in ecosystem properties at the site. However, a changing climate adds further variation to the existing span in estimates of ecosystem properties representing the different successional stages occurring at the sites. In order for the dose modelling to cover a period of 120,000 years, a broader approach must be taken to cover extremes within expected future climate variations (see the **Climate report**).

The temperate climate domain is defined as regions without permafrost or the presence of ice sheets. It is dominated by a temperate climate in a broad sense, with cold winters and either cold or warm summers. Precipitation may fall at any time of the year, i.e. there is no dry season. The precipitation falls either as rain or snow. The temperate domain has the warmest climate of the three climate domains. Within the temperate domain, a site may also at times be submerged by the sea or by an ice-dammed lake. The global warming case does also fall into the temperate climate domain /Näslund 2010/.

The periglacial climate domain is defined by the presence of permafrost. It is a cold region but without the presence of an ice sheet. Although true for most of the time, regions belonging to the permafrost domain are not necessarily the same as regions with a climate that supports permafrost growth. For example, for a certain area, at the end of a period with permafrost domain the climate may be relatively warm, not building or even supporting the presence of permafrost. Instead, permafrost may be diminishing. However, as long as permafrost is present, the region is defined as

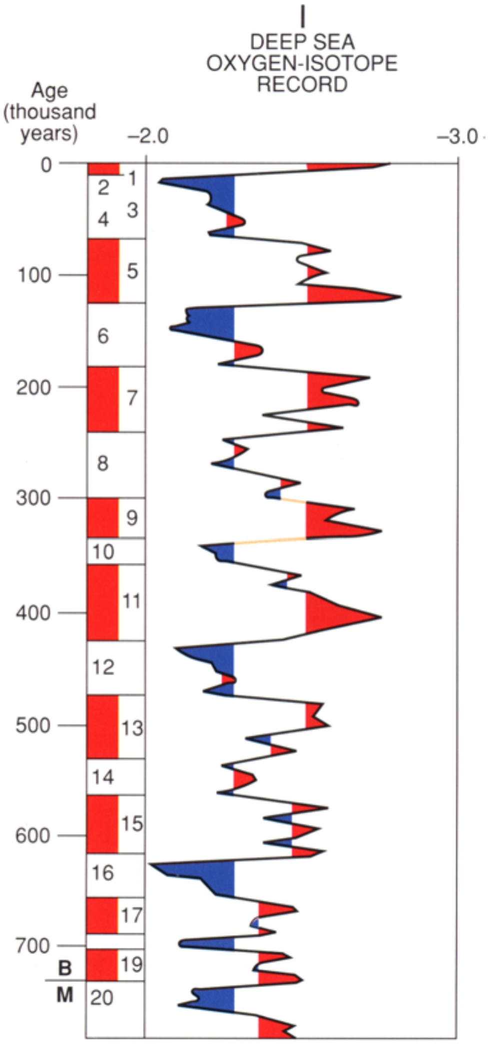

Figure 7-2. *A deep-sea isotope stratigraphy showing climate variations during the past 700,000 years. The red peaks represent warm or relatively warm interstadials and interglacials, whereas the blue peaks represent periods with a relatively cold climate. The interglacials are represented by the most pronounced red peaks (from /Andersen and Borns 1997/).*

belonging to the permafrost domain, regardless of the prevailing temperature at the ground surface. This way of defining the domain is used because, in this case the presence of the permafrost is more important for the safety function of the repository than the actual temperature at the ground surface. In general, the permafrost domain has a climate colder than the temperate domain and warmer than the glacial domain. Precipitation may fall either as snow or rain (see the **Climate report**).

The glacial domain is defined as regions that are covered by ice sheets. Within the glacial domain, the ice sheet may in some cases be underlain by sub-glacial permafrost. In line with the definition of the permafrost domain, areas belonging to the glacial domain may not necessarily at all times have a climate that supports the presence of ice sheets. Furthermore, for a certain area, at the end of a period in a glacial domain the ice-edge may be located within the area although the climate conditions in the open sea during this situation are considered as periglacial. However, in general, the glacial domain has the coldest climate of the three climate domains. Precipitation normally falls as snow in this domain (see the **Climate report**).

It is currently not possible to make confident predictions of future long term climate, particularly taking into account the potential long term significance of inferred current human-induced perturbations of the natural climate system. It is, however, likely that the three climate domains will appear repeatedly during the one million year assessment period, i.e. any reasonable evolution will have to address them, and transitions between them.

7.2.1 Climate cases

The 6 different SR-site climate cases are presented in the **Climate report**. Four of the cases focus on climate effects on the geological repository. Two of these are considered relevant in order to describe the future evolution of the surface system in Forsmark: the reference case and the global warming case. These cases, the reference case and the global warming case, comprise the same climate domains, e.g. temperate, periglacial (permafrost) and glacial, although in the global warming case the temperate domain prevails for a longer time. Together, these cases cover the full range of potential climate effects associated with surface ecosystems. The climate cases also include a submerged stage, where all objects in the area are below sea surface.

Reference case

In the reference case, describing the repetitive development and duration of climate domains during the last glacial cycle, The Weichselian-Holocene, the site is subject to the different climate domains: glacial, periglacial and temperate, see Figure 7-3, from the **Climate report**. The Figure 7-3 shows climate domains at Forsmark as colour coded segments of a succession bar. The Forsmark site is dominated by temperate climate domain (green) for the first ~ 25 kyrs, although shorter periods of periglacial climate domain (blue) occur around 10 kyrs after present. Subsequently, up to the first period of glacial climate domain (~60,000 after present, white or light grey), temperate conditions are gradually replaced by periglacial conditions. Climate conditions within the temperate climate domain vary and include conditions both colder and warmer, as well as both wetter and drier than today's climate. Subsequently, the periods with temperate climate conditions are succeeded by progressively longer periods of permafrost conditions. The glacial conditions are succeeded by submerged conditions, followed by a period dominated by permafrost conditions. After that, the main phase of ice sheet cover (glacial domain) ensues, starting at around 90,000 years into the reference case. At the end of this glacial cycle, around 120,000 AD, the site is again deglaciated (see the **Climate report**).

Global warming case

In addition to the reference case, a global warming case has been developed, which starts with a prolonged initial temperate period that prevails for about 60,000 years before the first period with permafrost conditions (periglacial climate domain). After that, the same sequence of events occurs as in the reference case evolution (see the **Climate report**). In addition to prolonging the periods with temperate conditions, a global warming variant may of course alter the temperature to warmer condi-

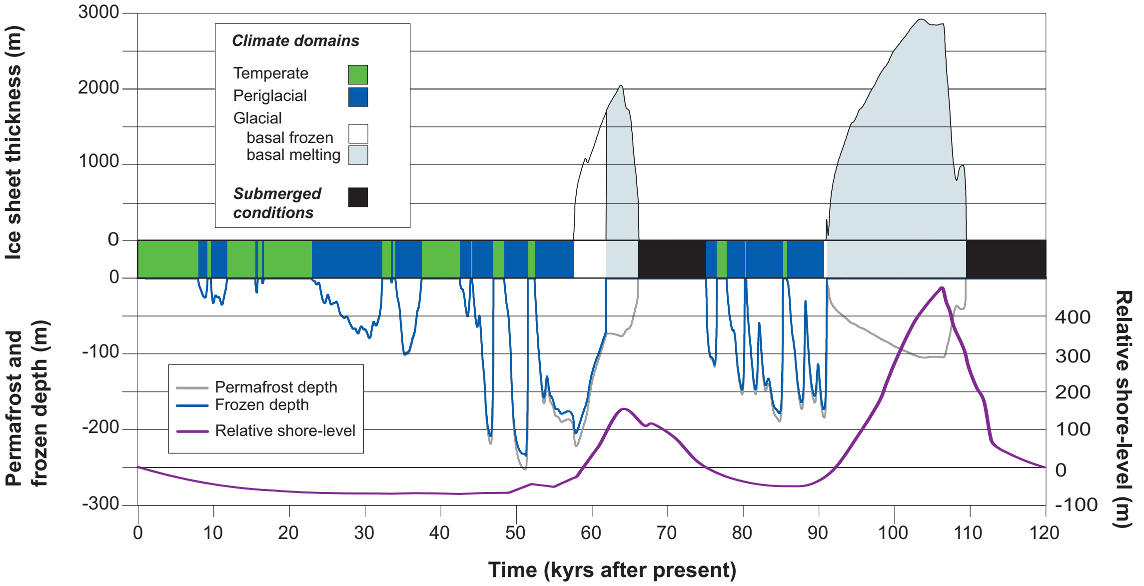

Figure 7-3. *Evolution of important climate-related variables at Forsmark for the coming 120 kyrs in the SR-Site reference glacial cycle.*

tions. Although, the climate may be warmer the climate domain will still be temperate. In the dose modelling, the prolongation of the temperate conditions, i.e. temperate climate domain, was chosen to represent global warming. The arguments for this are discussed below for the marine ecosystem.

7.2.2 Simulated climate conditions of 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 stage where all objects in the area are submerged. In order to estimate the extremes within which the climate of Sweden may vary and to generate climate data describing conditions during the relevant climate domains, climate models for Forsmark and Laxemar-Simpevarp have been used /Kjellström et al. 2009/. 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. The setup of forcing conditions for the model simulations was based on the selected separate periods during the Weichselian (the last glacial cycle) and the Holocene (i.e. the present interglacial starting about 10,000 BP). 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 represent the climate at the site during a temperate climate domain.

Altogether, examples from three climate domains were studied by /Kjellström et al. 2009/ and compared with data from the recent past (temperate climate domain):

1. Temperate (recent past) climate domain – a period corresponding to recent past climate representative of the present temperate climate domain.
2. Global warming – except for prolonging the temperate domain (discussed in 7.4), global warming will give rise to a period of a few thousand years into the future with increased greenhouse gas concentrations and enhanced temperature.
3. Periglacial climate domain – a climate domain corresponding to the conditions at year 44,000 BP during the Greenland Stadial (GS), i.e. representing the permafrost climate domain.
4. Glacial climate domain – a period corresponding to the conditions at 21,000 BP during the Last Glacial Maximum, i.e. representing the glacial domain.

Temperate climate domain

The climate in the recent past is used as an estimate of temperate conditions (Table 7-1). The temperate climate 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. Hence, present-day conditions are assumed to be relevant to use for estimation of biological parameters in the marine habitat in future temperate periods.

Global warming

In the simulations of global warming conditions, the seasonal mean temperature was calculated to be up to 5°C warmer in the summer and up to 7.5°C warmer in the winter over Scandinavia during the simulated period with global warming as compared with the recent past /Kjellström et al. 2009/. The annual mean temperature in Forsmark and Laxemar-Simpevarp were calculated to increase by about 3.6 and 3.2 degrees respectively at the sites, and the precipitation to increase by between 15–28% at both sites. The runoff from land will also increase by around 40% and 17%, respectively (Table 7-1).

The simulated climate of the global warming 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 during the global warming period are large, and neither lower nor higher greenhouse gas concentrations than the ones used can be ruled out. Differences between the modelled mean annual temperature and precipitation, during global warming and the temperate climate domain (recent past) are presented in Table 7-2 for Forsmark and Laxemar-Simpevarp.

Table 7-1. 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 (+/–) of the nine grid boxes closest to the location is shown in parentheses.

Simulation of climate domains	T (°C)	PR (mm/year)	R (mm/year)
Forsmark			
Temperate (recent past)	4.7 (0.6)	666 (93)	175 (113)
Global Warming variant/case	8.0 (0.3)	852 (66)	249 (102)
Periglacial (permafrost)	–7.8 (0.9)	438 (53)	170 (40)
Glacial (last glacial maximum)	–20.3 (1.0)	564 (161)	–
Laxemar-Simpevarp			
Temperate (recent past)	6.2 (0.3)	806 (192)	242 (158)
Global Warming variant/case	9.2 (0.5)	929 (196)	283 (168)
Periglacial (permafrost)	–3.2 (0.5)	582 (117)	218 (80)
Glacial (last glacial maximum)	–13.2 (1.0)	581 (71)	–

Table 7-2. 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 (∆Tagm) and the maximum of the Atlantic Meridional Overturning Circulation (AMOC) below 500 m depth are both taken from a global model. From /Kjellström et al. 2009/.

Simulation	Annual means for two sites in Fennoscandia			
	Forsmark		Laxemar-Simpevarp	
	∆T (°C)	∆PR (%)	∆T (°C)/	∆PR (%)
Temperate (recent past)	0	0	0	0
Global Warming	+3.6	+21	+3.2	+12
Periglacial (permafrost)	–12.5	–34	–9.4	–29
Glacial (last glacial maximum)	–25.0	–15	–19.3	–33

During global warming, there will be climate effects on the marine ecosystem affecting the abiotic boundary conditions, like for example; reduced/eliminated ice-cover season, increased runoff, a higher incidence of extreme runoff situations and a higher frequency of days per year with wind speed over the normal. These factors will in turn affect the rate of nutrient supply, vertical mixing and upwelling /BACC 2008/. Global warming conditions may also decrease the effect of shoreline displacement, although, according to /Milne et al. 2009/ it is likely that the shore line development for the reference case and the global warming case shows identical development (see Section 7.3, Figure 7-4).

Periglacial climate domain

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. 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/. The permafrost may be interrupted by unfrozen areas below lakes, so called taliks. Also the sea may be underlayed by permafrost in various extensions depending on the climate. The periglacial domain in marine ecosystems means a marine environment with lower water temperature, a short ice-free season (60–100 days) and with a smaller area of open sea.

In the periglacial climate domain, Forsmark and Laxemar-Simpevarp are assumed to be situated outside the ice sheet, in areas relatively distant, ~100 km Forsmark and > 200 km for Laxemar-Simpevarp,) from the ice sheet margin. The cold and dry climate with partially snow-free conditions provides favourable conditions for development of permafrost at both sites.

During the simulated periglacial climate domain, Forsmark and Laxemar-Simpevarp have annual mean temperatures of around –8°C and –3°C, respectively (Table 7-1). Precipitation is also low compared with the recent past (temperate climate domain) and during glacial conditions. In the periglacial climate domain, there will also be less evaporation and less precipitation (27 and 35% lower in Laxemar-Simpevarp and Forsmark, respectively), although runoff is similar to runoff in the temperate climate domain (Table 7-1).

The main climate factors affecting the marine ecosystem, during periglacial conditions, are the decreased temperature and the presence of sea ice. These factors will among other things affect the exchange of CO_2 between the atmosphere and the sea surface, primary production and mixing conditions /Anderson and Kaltin 2001/. There seems to be less weathering during permafrost conditions, which could result in lower concentrations of ions. This could mean less input of nutrients from land to the marine ecosystem than during temperate conditions. Although, the incidence of upwelling effects during summer periods may increase and in turn increase the nutrient supply by mixing of surface waters with deep nutrient rich water /BACC 2008/.

The glacial climate domain

Essentially the glacial climate domain, simulated as during the last glacial maximum, entails that the areas of Forsmark and Laxemar-Simpevarp are covered by an ice sheet. It is therefore assumed that no vegetation is present and the sea is covered all year around with a thick ice sheet. In addition to the low temperatures, production in these systems is not only dependent on temperature but may also be limited by nutrients and light (e.g. /Vincent 1981/).

Simulation results for glacial conditions, represented by the last glacial maximum, at the sites are presented in Table 7-1. The annual mean temperatures are below –20°C and –13°C in Forsmark and Laxemar-Simpevarp respectively. The precipitation is quite high and there is evidently no runoff. Nevertheless, at some point during glacial conditions the ice edge may be located in the marine areas of Forsmark and Laxemar-Simpevarp. The colder and harsher climate would probably not be suitable for humans to live in, but theoretically it can be hunting and fishing along the ice edge and on the open sea which could constitute a potential exposure pathway for radionuclides. In order to have a cautious approach, periglacial conditions for the ecosystems in the sea is assumed during this climate domain.

7.3 Shoreline displacement

Shore-line displacement followed the melting of the Weichselian ice sheet (the last glacial period in northern Europe, occurring approximately 115,000–10,000 years before present (BP)), and is the interaction between isostatic recovery on the one hand and eustatic sea level variations on the other. 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 marine ecosystems, e.g. salinity (Section 7.4) and water turnover (Chapter 5 and 9). 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 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/.

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 they decrease to levels less than 20 m.a.s.l. in southernmost Sweden. Both Forsmark and Laxemar-Simpevarp are situated below the highest coastline.

The eustatic sea level in general in oceans, 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. In the Baltic basin, the eustatic sea level is also dependent upon the two shallow sill areas: the

Darss Sill in the Belt Sea area and the Drogden Sill in the Sound, which regulates the inflow of water from the North Sea. 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/. However, since the sea level in Forsmark according to /Milne et al. 2009/ hardly will be affected at all, even if all of the ice on Greenland will melt, development of the shore line for the reference case and the global warming case shows identical development (Figure 7-4). As the modelling covers 120,000 years, the entire Forsmark area will rise above the surface of the sea whether global warming occurs or not.

7.4 Salinity changes in the Baltic Sea

The evolution of the Baltic basin since the last deglaciation is characterized by changes in salinity caused by changes in location of discharge into the Atlantic, decreasing supply of glacial melt water and variations in height of thresholds. These variations have in turn affected the ecosystems, reflected in the remnants of organisms found in sediment and raised shorelines from the different Baltic Sea stages. This history has therefore been divided into four main stages /Björck 1995, Fredén 2002/, summarized in Table 7-3.

The Baltic Ice Lake stage was characterized by freshwater conditions. Weak brackish conditions prevailed 11,300–11,100 years ago during the Yoldia Sea stage (e.g. /Andrén et al. 2000/). The salinity of the water in the central Yoldia Sea was between 10‰ and 15‰ /Schoning et al. 2001/. The Baltic Sea was thereafter characterized by freshwater conditions until the onset of the Littorina Sea around 9,500 years ago /Fredén 2002, Berglund et al. 2005/. The salinity of the Baltic Proper since the onset of the Littorina period has been reviewed by /Westman et al. 1999, Gustafsson 2004a/ with an updated chronology from /Fredén 2002/. Freshwater conditions prevailed during most of the deglaciation of Sweden. Salinity was probably low during the first 1,000 years or so of the Littorina Sea stage but started to increase 8,500 years ago. Salinity variations since the onset of the Littorina Sea are shown in Figure 7-6. The most saline period occurred 6,000–5,000 years ago when the surface water salinity in the Baltic proper (south of Åland) was 10–15‰ compared with approximately 7‰ today. Variations in salinity during the Littorina Sea stage have mainly been caused by variations in freshwater input and changes in the cross-sectional areas in the Danish Straits (cf. /Westman et al. 1999/).

The present site specific salinity measurements (see Chapter 3) shows an average annual salinity of 4.5 ‰ and 6.4 ‰ in Forsmark and Laxemar-Simpevarp respectively, which can be compared with the present general salinity gradient in the Baltic Sea free from /Bernes 1996/ presented in Figure 7-5.

The future salinity the Baltic Sea is sensitive to changes in the freshwater supply, as well as to changes in the water exchange with the ocean. This was modelled by /Gustavsson 2004a/ in a sensitivity analysis of the Baltic Sea salinity to climate changes. The postglacial isostatic rebound in southernmost Sweden today is negligible and it will therefore not affect the future salinity in the southern Baltic Sea. However, a conclusion from the study was that the possible range of future salinity in the southern Baltic Sea is between freshwater conditions and a salinity of 15 psu, depending on the combination of climate conditions and sea level. Accordingly, any long term forecast of the future salinity will be utterly uncertain, since information on the climate development is lacking. In contrast, the isostatic recovery in central and northern Sweden is significant /Påsse 2001/. Due to the rising of the Southern Kvark sill, i.e. the most narrow part of the Baltic Sea between Åland and Sweden where the maximum depth today is c 40 m, we can anticipate large changes in the exchange of water between the Bothnian Sea and the Baltic Proper in the future. Accordingly, isostatic recovery will relatively soon dominate salinity variations north of Åland, regardless of prevailing climate conditions, and the uncertainty in the prediction of future salinity is therefore considerably lower for the Bothnian Sea than for the Baltic Proper. Extrapolation of the shoreline displacement models for sites situated both east and west of Åland /Påsse 2001/ indicates that the present Bothnian Sea will become a freshwater lake around 25,000 AD (Figure 7-6). Although, it takes about 12,000 years to transfer the entire Forsmark area from fully submerged just before the first islet emerges above the sea surface (1000 BC), until the last marine embayment is turned into a lake (11,000 AD).

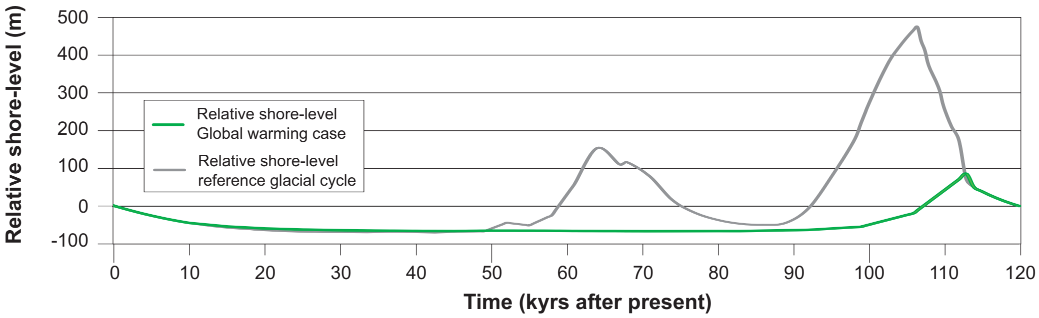

Figure 7-4. *Shore level evolution at Forsmark for the global warming case of the reference evolution. For comparison, the shore level evolution for the reference glacial cycle (the reference case) is also shown. Negative numbers indicate that the area is situated above the contemporary sea-level.*

Table 7-3. Summary of the stages of the Baltic Sea /Fredén 2002, Westman et al. 1999/. Note that altitudes and ages are approximate values, based on regional extrapolations and interpolations. BP = Before Present.

Baltic Stage	Calendar year	Salinity	Environment in Forsmark	Environment in Laxemar-Simpevarp
Baltic Ice Lake	15,000–11,550 BP	Glacio-lacustrine	Covered by inland icenot applicable in Forsmark	Regressive shoreline from 40 m.a.s.l. to 20 m.a.s.l.
Yoldia Sea	11,500–10,800 BP	Lacustrine/ Brackish/ Lacustrine	Deglaciation, regressive shoreline from about 150 m.a.s.l. Minor (or no) influence of brackish water.	Deglaciation. Regressive shoreline from about 100 m.a.s.l. to 40 m.a.s.l.
Ancylus Lake	10,800–9500 BP	Lacustrine	Regressive shoreline from about 140–75 m.a.s.l.	This period started with a transgressive shoreline reaching 30 m.a.s.l. and was followed by a regression to 20 m.a.s.l.
Littorina Sea sensu lato	9500 BP–present	Brackish	Regressive shoreline from 75–0 m.a.s.l. Most saline period 6,500–5,000 calendar years BP. Present-day Baltic Sea for approximately the last 2,000 years.	Regressive shoreline interrupted by transgression

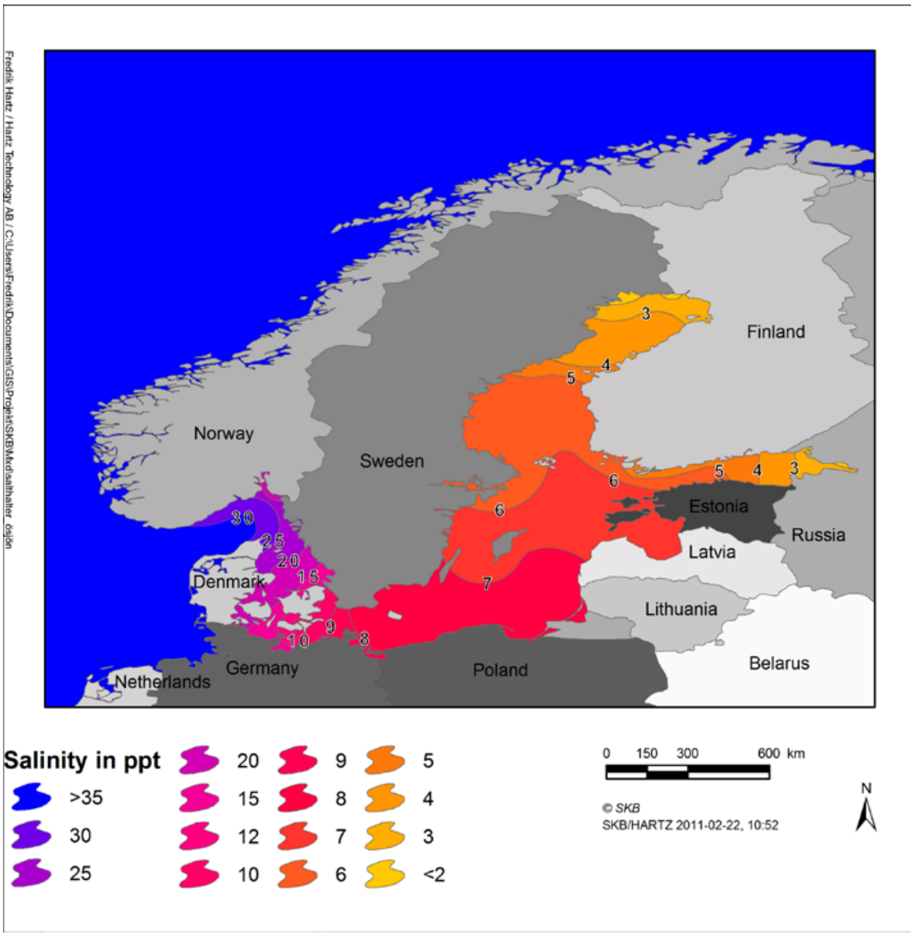

Figure 7-5. Present salinity in the Baltic Sea from /Bernes 1996/.

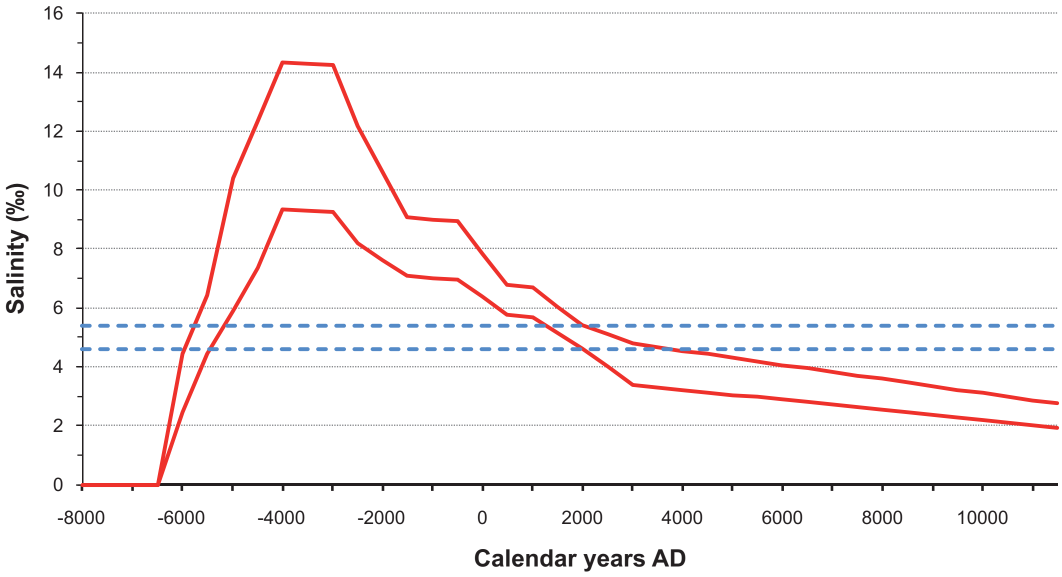

Figure 7-6. Estimated range for salinity in the open Bothnian Sea from the freshwater Ancylus Lake stage until the sea has disappeared from the modelled area in Forsmark. Present max and mean salinity in Forsmark is indicated by horizontal lines. Estimates of historical salinity are based on /Westman et al. 1999/, whereas the prediction of the future assumes that present salinity will decrease linearly until the Bothnian Sea is isolated from the Baltic Sea around 25,000 AD. It should be noted that any prediction of the future salinity is highly uncertain; the upper limit of the future salinity assumes constant climate conditions, whereas the lower limit is assumes 30% higher precipitation as an effect of greenhouse warming.

7.5 Effects on marine ecosystem development

The effects from the major forcing factors, the climate and shoreline displacement, are immense although, in the following text the aim is to focus on those factors that may lead to differences in the transfer and accumulation of radionuclides. Although great changes in ecosystem properties may occur during long term development, they will not necessarily lead to great changes in the transfer and accumulation of radionuclides. The climate domains of interest here will along with shore-line displacement convey various abiotic boundary conditions to the ecosystems, which in turn will induce various changes in the structure and functioning of the ecosystems.

There are a variety of means by which climate can affect marine biota, directly or indirectly. Examples of the former include temperature, which affects the metabolism and distribution of organisms; wind-driven currents, which transport planktonic organisms; and sea ice, providing higher predators with a platform for birthing or foraging. Indirect means by which climate can affect biota are those climate processes that affect nutrient levels and surface mixed layer depth, which in turn influence primary and secondary productivity, and ultimately food availability to the higher trophic levels. The timing of sea-ice formation and melting, as well as temperature and mixing conditions, may influence the timing, location, and intensity of biological production /ACIA 2005/.

The effects on the ecosystems can be detected in the whole ecosystem perspective but also in the perspective of functional groups or on an individual level. The functional group perspective and to some degree the whole ecosystem perspective is of importance for the safety assessment, i.e. it is important if fish production increased whereas it may not be important if certain fish species are favoured as humans may feed on several fish species and thus the functional groups may be important but not the individuals. The whole ecosystem production is an important driving factor for the exchange of e.g. carbon over the air/water interface and may thereby be of importance for the transport of that radionuclide (C-14).

7.5.1 Temperate climate domain

The temperate climate domain is assumed to be represented by present-day conditions in the marine ecosystem, described in Chapter 3 of this report. The variation due to shoreline displacement and the ensuing effects is assumed to be included in the ecosystem properties existing at the sites today. The temperate climate domain properties of the marine ecosystem are therefore not discussed further in this section.

Human interactions may affect the marine ecosystem in various ways; in the form of emissions due to industrial activities, forestry and agriculture, by more mechanical impacts as shipping or dredging and by fishing and hunting.

Historically the region's iron or ore mines (since 16th century until the iron works shut down in the 1890s) caused emissions to the marine environment. Due to the sparsely population of the area mainly due to the general scarcity of rich soils /Miliander et al. 2004a/, the area was sparsely settled until the construction of the nuclear power plant in the 1970s, and impact of nutrient loads from forestry and agriculture is moderate in comparison to other areas along the coast. The shipping and dredging of the area is not extensive at present. Today the cooling water emissions from the nuclear power plant cause the most significant impact on the ecosystem.

Today, both commercial and sport fishing occur in the area. The main commercial fish today is Baltic herring. The area in Forsmark is more affected by to large scale overfishing in the Baltic Sea than by local exploitation of the fish. The large scale over fishing, affects both species composition and fish production in the marine ecosystem in the whole Baltic Sea and thereby also in Forsmark. Along with the salinity decrease during the long term development in the area, the fish catches will most likely have a larger part of fresh water species, although the magnitudes of the catches will probably be similar as today.

Potential other food sources may be birds, seals, crustaceans, mussels and sea weed, although, today no significant catches of these occur in the area. Mussels and crustaceans in the area are very small and more energy has to be put in to catch them than is gained by eating them. The sea weed of the Baltic Sea in general is not tasty. The seals and birds may potentially be a food source but is not presently part of the normal diet for humans in the area, and the seal population is not very dense.

7.5.2 Temperate climate domain – Global warming

Warmer climate conditions during a temperate climate domain are valid for the global warming case, further elaborated in Section 7.2.1. The global warming case involves a future were anthropogenic emissions causes the present temperate domain to extend by around 50,000 years. However, since the sea level in Forsmark according to /Milne et al. 2009/ hardly will be affected at all, even if all of the ice on Greenland will melt (see Figure 7-4), modelled development of the shore line development for the reference case and the global warming case shows identical development and basically the same illustrations presented for a climate of today will be valid for a somewhat warmer climate (Figure 7-3).

As discussed in Section 7.5.2 above, the annual mean temperature is assumed to increase along with precipitation in a global warming domain. The consequence of increasing precipitation is twofold; increased precipitation may result in a decrease in salinity and in an increase of nutrient leakage and associated eutrophication /BACC 2008/. However, it is difficult to estimate the nutrient concentrations in runoff, which is influenced by e.g. accumulation and decomposition on land. Consequently, although runoff in terms of water quantity increases by about 17–40% according to simulations in the **Climate report**, it is not certain that nutrient runoff will increase accordingly, although the increased fresh water inflow will probably lead to reduced salinity.

Increase in precipitation and thereby runoff due to climate warming will not necessarily increase carbon sequestration/burial, however, as the geological composition of the drainage area and the flow are both controlling factors. Increased precipitation may lead to increased dissolved inorganic carbon (DIC) delivery, although the fate of it depends on the timing and intensity of the freshwater flow into the sea. Sequestration/burial will occur in adjacent ocean basins if the carbon is transported offshore by ocean currents, or turbidity currents /ACIA 2005/.

Decreased timing and extent of sea ice, increased water temperature, increased freshwater input, and wind stress will affect the rate of nutrient supply through their effect on vertical mixing and upwelling. Changes in vertical mixing and upwelling will affect the timing, location, and species composition of phytoplankton blooms, which in turn will affect the zooplankton community and the productivity of fish. Increased primary production does not necessarily lead to increased net ecosystem productivity if the respiration also increases, since bacterial respiration is temperature-dependent, the increased temperature will most likely be followed by increased bacterial respiration in the pelagic and benthic marine ecosystem /BACC 2008/. In addition higher respiration rate at the bottoms induced by increased primary production and temperature may lead to oxygen-free bottoms, which in turn will affect the reproduction for many fish species, which are dependent on oxygen-rich bottoms for reproduction. Another negative effect for fish dependent on the spring bloom for successful reproduction is that the earlier start of the season might shift the start of the spring bloom, causing a mismatch between primary producers and consumers, which will have effects along the food chain reducing fish productivity. For other fish species, the higher temperature will mean a higher growth rate and a longer growth season, and for these species production is expected to be higher.

Changes in the timing of the primary production will determine whether this production is utilized by the pelagic community, exported and utilized by the benthos or accumulated in the sediments. The retention to export ratio also depends upon the advection and temperature preferences of grazing zooplankton, which together determine the degree of match or mismatch between primary and secondary production /ACIA 2005/.

Projected increased temperatures, especially during winter months, will lead to changes in growth and reproduction parameters for fauna and flora, many of which are of boreal origin, i.e. adapted to low temperatures. The following changes are considered possible /BACC 2008/:

- Increased temperature stimulates pelagic bacterial growth more than primary production, thus the ratio between bacteria biomass to phytoplankton is expected to increase with increasing temperature.
- Diatom spring blooms are subjected to change in species composition when winters become milder. Furthermore, it has been suggested that the diatom bloom itself may disappear after milder winters and be replaced by dinoflagellates.
- Increasing summertime temperatures may enhance cyanobacterial blooms.
- Elevated winter temperatures may prevent convection in late winter and early spring with the result that nutrients are not mixed into the upper euphotic zone.

Because of its ecological and evolutionary history, the Baltic Sea predominantly receives species originating from both the adjacent inland waters and the oceanic coasts but also from remote seas. Most of recent invaders in the Baltic Sea originate from warmer climates. In conditions of increasing water temperature, not only spontaneously spreading European invaders but also exotics from warmer regions of the world can be expected to become established in the Baltic Sea /BACC 2008/.

It is likely that the thermocline in most coastal areas will be moved further out during the summer. As a result, the warm water species will extend their habitats at the expense of the cold water species. A similar spread of freshwater species at the expense of species with higher salinity optima is also likely to occur due to the decrease in salinity. A lower salinity in the Baltic Sea, with great spatial and temporal variation, has effects on biodiversity. The range of marine species will be shifted further south and may decrease, at the same time as the range and biomass of freshwater species will increase. Today's population of cod in the Baltic Sea is very low in comparison with historical populations, mainly due to overfishing and smaller areas for reproduction. In a global warming case, the cod population will probably be extinct /SOU 2007/. Thus, since the climate effect is generally on the composition of the functional groups in the ecosystem and not the functioning or magnitude of ecosystem processes, this effect is not further discussed in the scope of transfer and accumulation of radionuclides.

In the case of marine mammals, a reduction in the extent of ice cover during the winter will lead to reduced reproduction, since they need ice to breed their cubs. The grey seal can also breed on land, although the survival rate of the cubs is substantially lower on land. Modelling studies describe the extinction of southern subpopulations of the Baltic ringed seal as a probable effect of diminishing ice cover suitable for breeding. The Grey seal, however, has been shown to have the capability of breeding extensively on land, even in the Baltic Sea basin /BACC 2008/. At present the marine mammals has only a small part in the marine ecosystems at the sites and a potential decrease in abundance will only generate very small change in the properties of the marine ecosystem and is assumed not to have any effect on the general transfer and accumulation of radionuclides.

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

The land use by humans during global warming conditions will probably be very similar to present conditions, i.e. generally fish from the area is consumed in the same magnitude, although the degree of freshwater species caught is probably larger.

The effects of a global warming domain on the marine ecosystem are very complex and hard to predict /BACC 2008/. In Figure 7-7, an attempted to schematically describe potential effects of global warming in a marine ecosystem is presented.

7.5.3 Periglacial climate domain

In the reference case, the climate domain is assumed to be temperate until ~9400 AD (see Section 7.2). At this time there will be a very small marine area in Forsmark. Although during the reference case, periglacial climate domain will appear repeatedly and at times when the area will exhibit a more extensive distribution of the marine ecosystem. The periglacial domain in marine ecosystems means a marine environment with lower water temperature, a shorter ice-free season and a smaller area of open sea. In order to describe a marine ecosystem in Forsmark and Laxemar-Simpevarp during a periglacial, regions of today with climate similar to periglacial conditions have been used. Since not only the climate will change from temperate to periglacial, but the salinity will and the Forsmark area will become a freshwater lake around 11,500 AD (see Section 7.4), it is hard to find a perfect match region of today to compare with. Nevertheless, assuming marine conditions, marine ecosystems in Greenland would be relevant with regard to climate conditions. However, since the Baltic Sea is a semi-enclosed sea with a limited exchange of water with adjacent more saline seas and specific mixing and stratification conditions, it is not completely evident to compare with Greenland conditions. Another analogue region is today's marine ecosystems in the Bothnian Bay, with low salinity and somewhat lower temperatures, even if the climate will be even colder during periglacial conditions. Therefore a short description of the marine ecosystems at these sites follows and these two regions will be used to describe a likely marine ecosystem during periglacial climate domain in Forsmark.

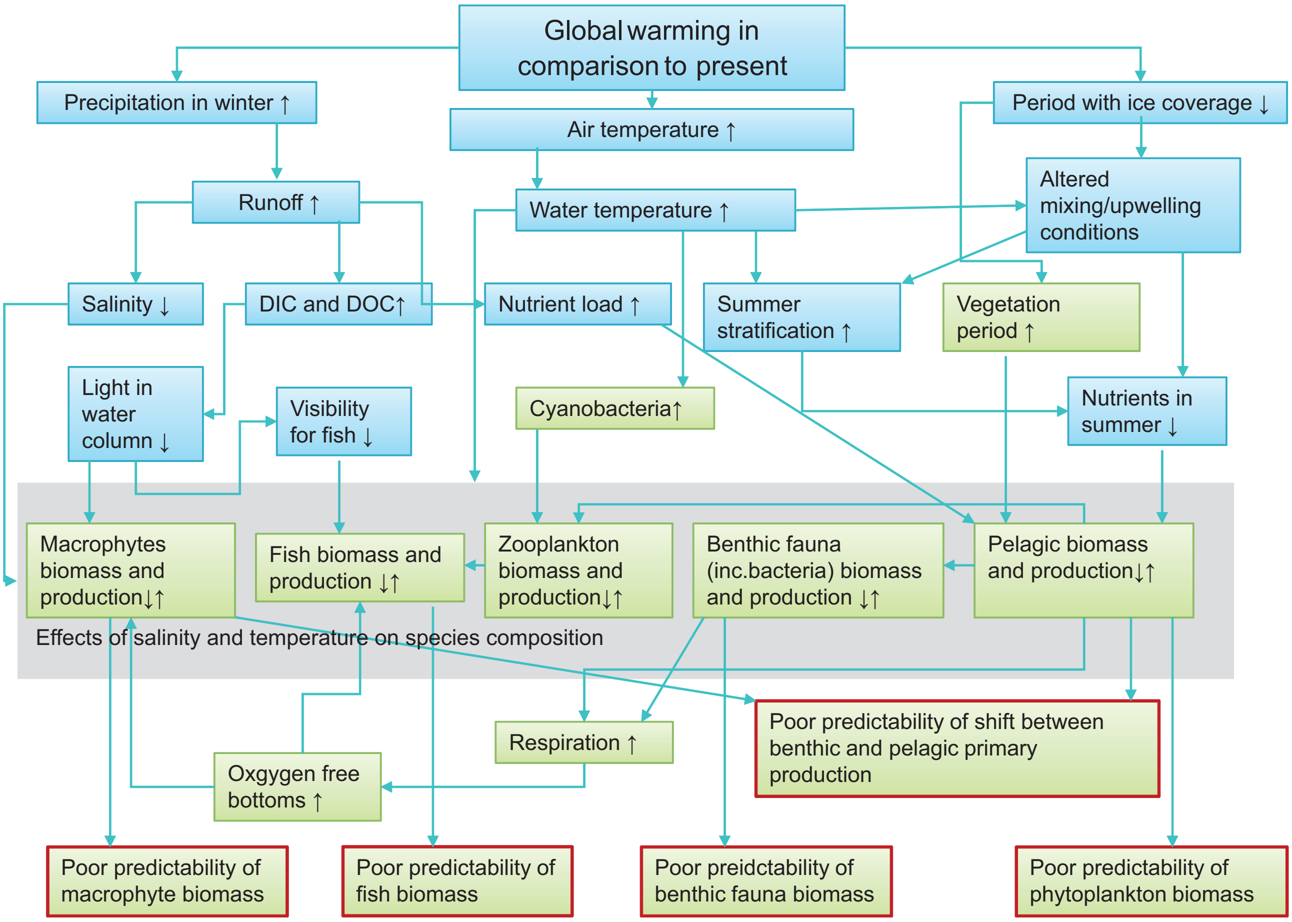

Figure 7-7. *Major effects of global warming on marine ecosystems compared to present situation in temperate regions. Note that although effect on abiotic factors (blue boxes) are determined with relatively high confidence, the effect on biotic parameters (green boxes) are less confident due to many interactions in the ecosystem between abiotic and biotic parameters as well as between different biotic components. Red frame indicates very poor predictability. Modified after /BACC 2008/.*

Greenland has a marine shelf ecosystem intermediate between the cold Polar water masses of the Arctic region and temperate water masses of the Atlantic and is located in the high latitude areas of the world with the highest marine primary production, in spite of lower temperatures and shorter growing season. This is mainly due to the upwelling of nutrient rich deep water with an origin in nutrient rich runoff from land /Huston and Wolverton 2009/. The growth period is short (60–100 days, salinity 35 ‰) in Greenland. Light and nutrient limitations are more important than temperature during ice free conditions. Moreover, the melting of sea ice in spring results in a stratification of the upper water column that promotes primary production. Ice algae does also contribute to primary production, and benthic diatoms have been shown to be productive even when light penetration is very low /Thomas and Dieckmann 2002/. The zone seaward of the ice edge is important for plankton production and planktivorous crustaceans and fish. Sea ice and the ice edge is also of major importance as a habitat for marine mammals (large whales, seals and walruses) and the location of ice edges is extremely important to seabirds. In addition sea ice together with snow cover controls the exchange of heat, CO_2 and other properties between the atmosphere and ocean. The marine areas of Greenland are important fishing grounds and are characterized by relatively few dominant species, which interact strongly /Buch et al. 2005/.

In comparison with Forsmark today, the Bothnian Bay has a longer ice-covered season (100–190 days/year in comparison to 98 days/year in Forsmark), lower annual water temperature and salinity (2–3 ‰), as well as lower species diversity, biomasses and primary production. There is a higher degree of freshwater species in Bothnian bay than in Forsmark. In the outer parts of the Bothnian Bay the ice moves and scrapes away the vegetation (down to 1–2 m depth), causing a higher proportion of annual primary producers than in less ice-affected areas more southwards in the Baltic Sea, were perennial algal occur frequently. The growing season is also significantly shorter (4–5 months compared to 8–9).

In northern and temperate seas the retrieval of nutrients from the sea floor is especially effective due to the sinking of the heavy colder surface water during winter, initiating the nutrient rich warmer bottom water to ascend. This is likely to occur in Forsmark during the periglacial domain, although depending on the out- and inflow through the entrance areas (the Danish sills and the sill between the Bothnian Bay and the Baltic proper the Kvark), river runoff, net precipitation and large-scale atmospheric circulation it is unpredictable in to what degree this will change from present conditions. The primary production could, due to nutrient conditions be higher, lower or similar as today. Nevertheless, it is likely that it will be within the range of today's estimates. In addition a likely development is that respiration will decrease along with temperature and thereby the net ecosystem production will be similar to present. The growing season will be shorter and the ice will provide an increased habitat for breeding of marine mammals. The bird fauna has been very stable in the Baltic during the recent interglacial /BACC 2008/ and will probably be similar. The sea bound flora and fauna will probably have a dominance of freshwater species and a higher degree of species able to adapt to colder climates. The colonization of new marine species will probably be very limited due to the semi enclosed character of the Baltic Sea, although, new freshwater species may colonize. In Table 7-4, marine ecosystem parameters are listed along with potential changes during a periglacial climate domain. In Figure 7-8, a schematic presentation of potential effects on the marine ecosystem during a periglacial climate domain, in comparison to present climate are presented.

In the marine areas around Greenland there is an extensive fishing. In the 20th century Greenland experienced two great transitions, the first from seal hunting to cod fishery, and then from cod to a shrimp fishery. In recent years a new fishery for snow crab (*Chionoectes opilio*) shows a steep increasing trend /Buch et al. 2005/. Fishing occurs also in the Bothnian Bay but in much more modest magnitudes than around Greenland. In a periglacial domain in Forsmark it will be possible to fish and to hunt seal and birds. Thus, depending on the salinity conditions the fish species will vary.

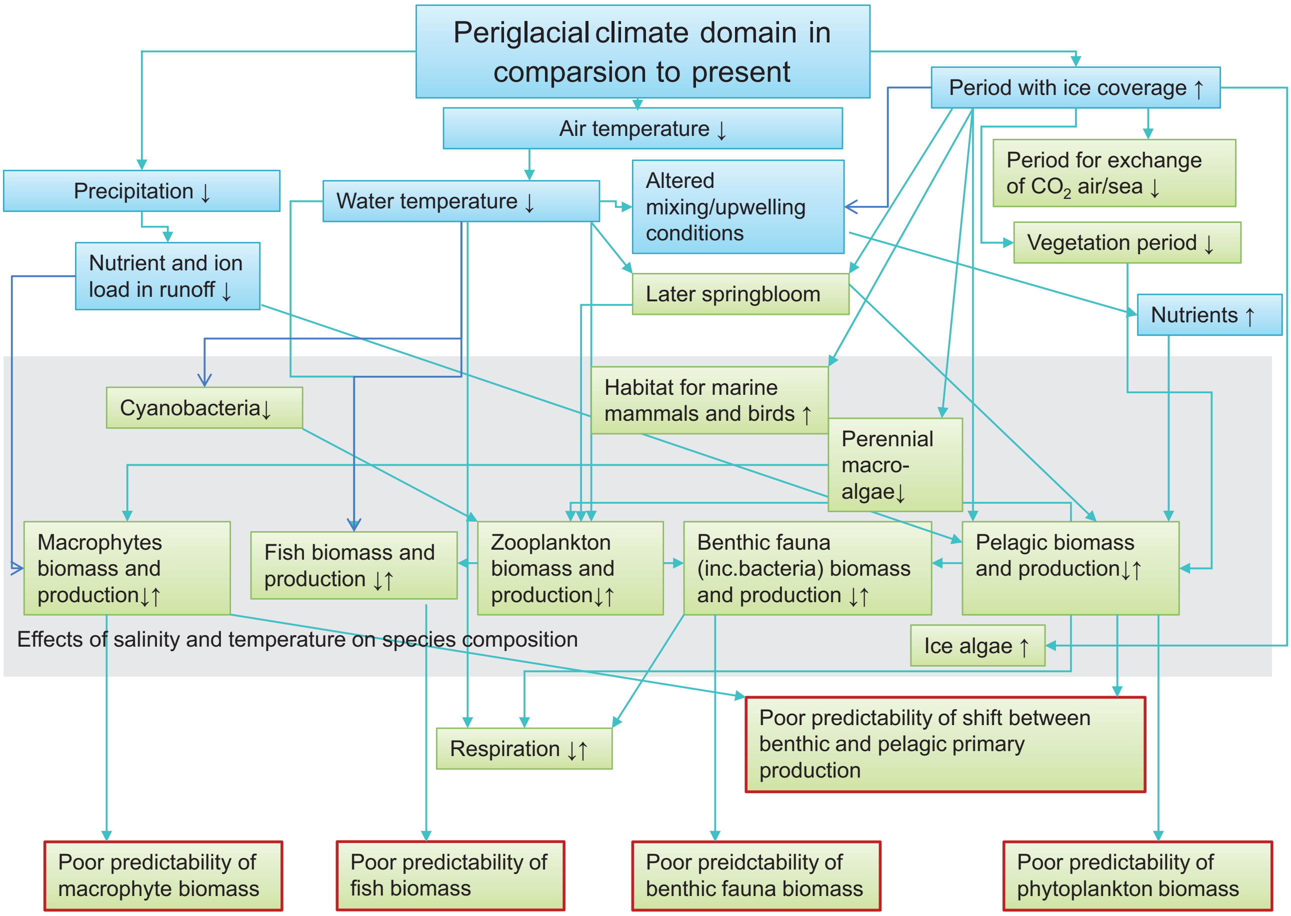

***Figure 7-8.** A schematic description of potential effects on the components of the marine ecosystem during a periglacial climate domain of components in the marine ecosystem. Note that although effect on abiotic factors (blue boxes) are determined with relatively high confidence, the effect on biotic 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. Red frame indicates very poor predictability. (modified after /BACC 2008/).*

7.5.4 Glacial climate domain

As discussed above (7.2.2), the simulated annual mean temperature in the glacial climate domain is assumed to decrease by about 20°C in Forsmark and 13°C in Laxemar-Simpevarp. The precipitation will be slightly less than during temperate conditions. It is therefore assumed, that no vegetation is present and the sea is covered all year around with a thick ice sheet. Nevertheless during some point in the glacial climate domain the ice edge will be located in the marine areas of Forsmark and Laxemar-Simpevarp, and even though it is unlikely for humans to inhabit this environment, it is assumed in order to have a cautious approach, that humans may hunt and fish along the ice edge and on the open sea which could constitute a potential exposure pathway for radionuclides. The marine environment and the land use along the ice-edge are assumed to be similar as during periglacial climate domain.

7.6 Summary

Although many factors may lead to increased primary production, other probable outcomes is that ecosystem production is assumed to remain the same magnitude or be included in the variation in present-day temperate conditions, i.e. the predicted change in ecosystem properties of relevance for dose modelling during climate change may span from present conditions to increases and to decreases, depending on a complex net of factors and interactions. At present the ecosystem change due to climate change occupy a large part of the environmental science society /BACC 2008, AICA, 2008/, and yet it is not possible to make confident predictions of the development. Thus, the most confident approach at present is to assume that data and parameters (see Chapter 10) for the marine ecosystem during present temperate conditions will include variations due to the climate change (periglacial domain and global warming) and that there is more confidence in using data and parameters for present temperate conditions in the dose modelling than in making potential predictions. The composition of the parameters may vary, but the values are assumed to be in the same range. This is based on the assumption that the variation due to the climate change mainly affects species composition and distribution, while the magnitude of material transfer between the functional groups and the abiotic components is similar. Nevertheless, in Table 7-4, a compilation of potential development of some marine ecosystem parameters during climate change is presented.

Table 7-4. Expected parameter values at different climate domains compared to present (temperate). Note that values represent mean values and values in brackets represent range of values measured during the site investigations performed by SKB in the marine areas in Forsmark and Laxemar-Simpevarp (see Chapter 3). Values denoted with an * includes other measurements performed in the areas, ** denotes values calculated from measured values in the areas (see Chapter 6).

Parameter Abiotic	Temperate Forsmark	Temperate Laxemar-Simpevarp	Global warming Bothnian Sea/Baltic proper	Periglacial	Glacial
Period with ice coverage (days)	98	1–4 months	1–2 months shorter or absent	9–10 months	365
Total nitrogen concentration (mg L^{-1})	0.5 (0.2–2.8)	0.5 (0.2–1.4)	Probably higher	Probably lower	Lower
Total phosphorus concentrations (mg L^{-1})	0.02 (0.007–0.06)	0.03 (0.01–0.4)	Probably higher	Probably lower	Lower
DOC concentrations (mg L^{-1})	5 (1–21)	6 (2–26)	Similar to present, higher or lower	Probably lower	Lower
DIC concentrations (mg L^{-1})	11 (0.3–27)	15 (4–22)	Similar to present, higher or lower	Probably lower	Lower
Particulate matter (kg dw/m^3)	0.4 (0.08–2.2)	0.4 (0.02–2.4)	Similar to present or higher	Probably lower	Lower
Oxygen free bottoms			More	Similar to present	–
Salinity (‰)	4.4 (0.2–5.4)	6.4 (0.3–6.4)	< present/0–15	< present/0–15	–
Light penetration (m)	2.7 (0.3–6.4)	5.5 (1–23)	Similar to present or lower	Probably higher	
Biotic parameters	**Temperate**	**Temperate**	**Global warming**	**Periglacial**	**Glacial**
Phytoplankton biomass (g C m^{-3})	0.2 (0.02–0.5)	0.2 (0–0.4)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Chlorophyll (ug L^{-1})	1–4	2–8	Similar to present, higher or lower	Similar to present, higher or lower	
Microphytobenthos biomass (g C m^{-2})	2 (0.5–5)	2 (0.6–5)	Similar to present, higher or lower	Similar to present or lower	Lower
Benthic macroalage and macrophytes (g C m^{-2})	8 (0.3–93)	29 (0–77)	Similar to present, higher or lower	Similar to present or lower	Lower
Bacterioplankton biomass (g C m^{-3})	0.3 (0.04–0.5)	0.2 (0–0.4)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Benthic bacterial biomass (g C m^{-2})	1 (0.4–4)	1 (0.5–6)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Zooplankton biomass (g C m^{-2})*	0.08 (0.01–0.2)	0.1 (0–0.1)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Fish biomass (g C m^{-2})*	0.3 (0.06–1)	0.7 (0.4–1)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Seal biomass (g C m^{-2})*	0.01	0.005	Similar to present, higher or lower	Similar to present or higher	lower
Bird biomass (g C m^{-2})*	0.006	0.005	Similar to present	Similar to present	lower
Benthic fauna biomass (g C m^{-2})*	6 (0–12)	56 (0–82)	Similar to present, higher or lower	Similar to present or lower	Lower
Pelagic Primary production (g C m^{-2} y^{-1})**	17 (2–46)	14 (1–36)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Benthic primary production by macroalgae (g C m^{-2} y^{-1})**	69 (1–228)	206 (55–640)	Similar to present, higher or lower	Similar to present or lower	Lower
Benthic primary production by microphytobenthos (g C m^{-2} y^{-1})**	29 (5–60)	26 (7–68)	Similar to present, higher or lower	Similar to present or lower	Lower
Pelagic respiration (g C m^{-2} y^{-1})**	33 (7–66)	22 (3–57)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Benthic respiration (g C m^{-2} y^{-1})**	40 (25–73)	207 (53–460)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Net ecosystem productivity (g C m^{-2} y^{-1})**	46 (–38–225)	18 (–275–652)	Similar to present, higher or lower	Similar to present, higher or lower	Lower

7.7 Historical development of the Baltic Sea

Following the last deglaciation, the marine environment of the Baltic basin (the depression now occupied by the Baltic Sea) has varied due to climatic and salinity variations. The evolution of the Baltic basin since the last deglaciation is characterized by changes in salinity caused by changes in location of discharge into the Atlantic, decreasing supply of glacial melt water and variations in height of thresholds. These variations have in turn affected the ecosystems. The salinity variations have in turn affected the ecosystems (see Section 7.4). It has been shown that the bottoms of the Baltic basin were anoxic below the halocline during a large part of the Littorina Sea stage (e.g. /Sohlenius and Westman 1998/). The anoxic conditions probably caused high concentrations of nutrients in the bottom water. There are several studies of sediment cores showing that primary productivity in the Baltic proper increased during the transition from the freshwater Ancylus Lake to the brackish water Littorina Sea (e.g. /Sohlenius et al. 1996/). This increase was caused by displacement of the nutrient-rich bottom water to the photic zone. It is also possible that phosphorus-rich oceanic water contributed to the relatively high productivity in the Baltic during the Littorina Sea stage. The periods with highest productivity seem to coincide with the most saline phase of the Littorina Sea. Several papers report the occurrence of nitrogen-fixing cyanobacteria in the Baltic since the onset of the Littorina Sea /Bianchi et al. 2000, Westman et al. 2003/. The occurrence of these bacteria indicates that the concentration of phosphorous in the surface water has been high, at least occasionally, since the beginning of the Littorina Sea.

7.7.1 Historical development of marine areas in Forsmark

When the last deglaciation occurred in Forsmark in approximately 8800 BC, the closest shore was situated about 100 km to the west. At that time, the Forsmark area was situated about 150 m below the surface of the Yoldia Sea. Since most of the Forsmark regional model area was covered by water until c. 500 BC, the post-glacial 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 7-9). 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 about 30 km west of the regional model area, indicate a local humid and cold climate around this time /Ingmar 1963/.

At c. 0 AD, the Bothnian Sea still covered the Forsmark area, whereas the islands in the western part of the regional model area had started to emerge (Figure 7-9). 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 AD 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 2003/.

At ~1000 AD, the mainland had emerged further in the south-western part of the area (Figure 7-9). The isolation process of the Lake Eckarfjärden basin was initiated (see map in Appendix 1 for the location of present-day lakes in the area), but the bay still had an open connection with the sea to the north (cf. /Hedenström and Risberg 2003/). The area west of Lake Eckarfjärden currently occupied by the Stenrösmossen mire had emerged, and a short lake phase was succeeded by invasion of reed (cf. /Fredriksson 2004/).

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 7-9). 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 with 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 around 1650 AD, most of the candidate area was situated above sea level.

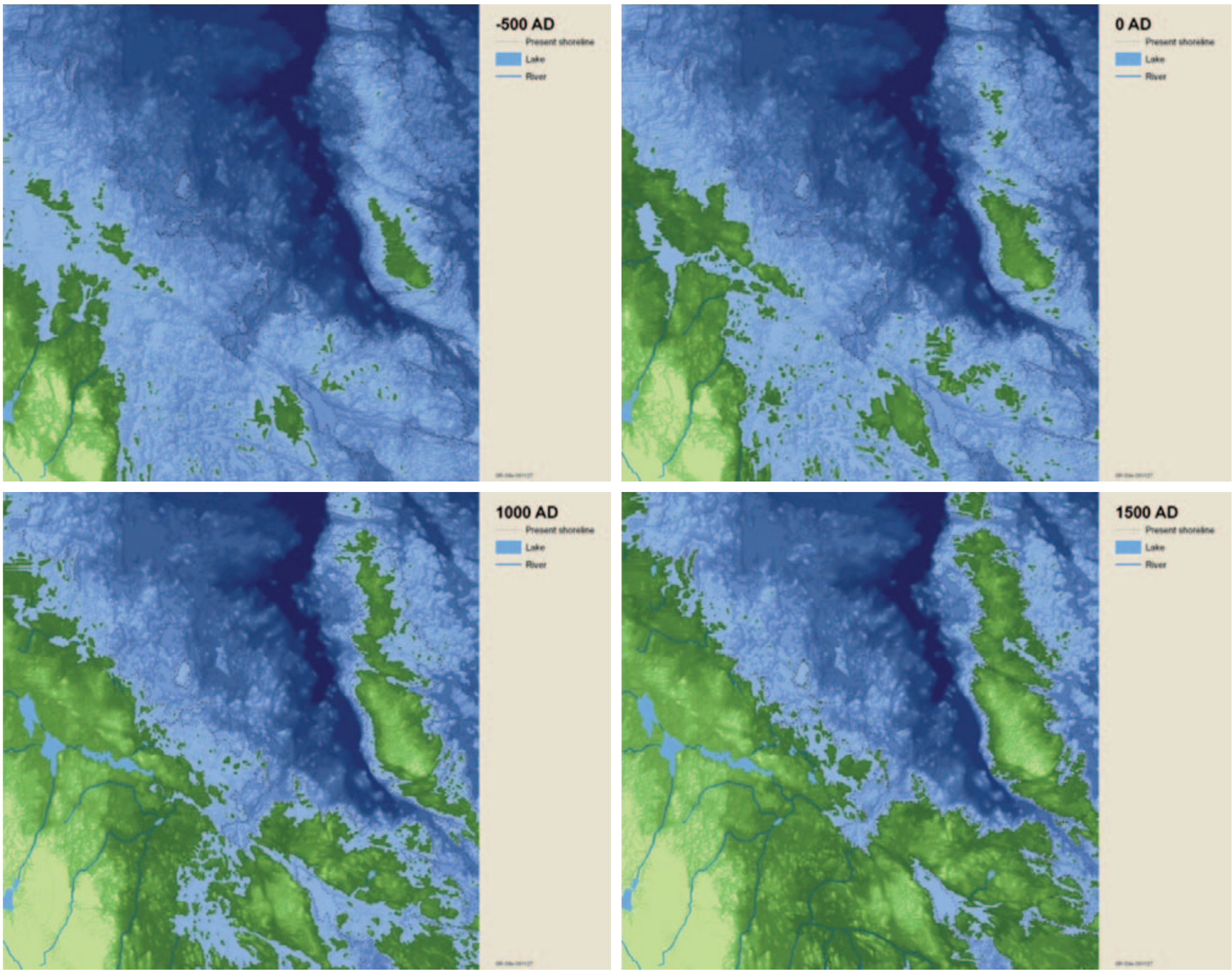

Figure 7-9. *The distribution of land and sea in the Forsmark area at 500 BC, 0 BC, 1000 AD and 1500 AD.*

7.7.2 Historical development of marine areas in Laxemar-Simpevarp

The latest deglaciation in the Laxemar-Simpevarp area took place about 14,000 years ago, and at that time the whole area was submerged by water. The first islands in the area emerged from the sea around 9400 BC.

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 total amplitude of around 11 m. At around 8000 BC, in the middle of the lacustrine Ancylus Lake stage, the shoreline was situated marginally over 20 m.a.s.l. thus the western part of the Laxemar-Simpevarp regional model area was free of water. Between 8000 BC and 5000 BC, the first part of the Littorina Sea stage, shoreline displacement was mainly regressive, although there are indications of several minor transgressions during that period (cf. Section 3.3). At 5000 BC, when the shoreline was situated about 15 m.a.s.l. the central parts of the regional model area were free of water, but the fissure valleys still constituted long and narrow coastal bays intersecting the area. At 2000 BC, most of today's terrestrial areas had emerged from the sea and the coastal bays had been considerably reduced in size. Since 0 BC the sea level has dropped about 3 m, but this has resulted in only minor changes in the distribution of land and sea in the regional model area.

As in the Forsmark area, the post-glacial development of ecosystems in the Laxemar-Simpevarp area are principally determined by the climate, the development of the Baltic basin and shoreline displacement. The first terrestrial ecosystems appeared around 9000 BC, and the succession of both the terrestrial and aquatic ecosystems has in all essentials followed the general patterns outlined above.

7.8 Future development – the reference case

The future development of Forsmark has a more extensive description since Forsmark has been the main concern in SR-site and at the time for the writing of this report, the analyse of the Laxemar-Simpevarp results is not completed.

7.8.1 Forsmark – next 500 years

During the next 500 years, the regression process will continue and new land areas will be created, predominantly in the northern part of the area (Figure 7-10). At 2400 AD, Tixelfjärden will be isolated. The inner parts of Kallrigafjärden will also become land. At ~2100 AD, the channel for cooling water will become isolated into a freshwater lake /SKB 2010a/. Simulations of the bathymetric, and hydrographical development in the Forsmark area (/Brydsten and Strömgren 2010/, Chapter 9 in this report), estimates that the average mean depth in the marine basins in Forsmark will in average be 1.7 m lower, the photic area will in average be 10% larger and the estimated retention time of the water in the marine basins will be around 7% lower at 2500 AD, in comparison to present conditions. The salinity is estimates by /Gustavsson 2004a/ to be between 3.6 and 4.5 ‰ (see Section 7.2) assuming unaltered runoff to the Bothnian Sea. This means that a marine ecosystem more similar to the Northern Quark will be present, with somewhat lower species diversity and primary production.

The land areas will expand around the sea bay west of the biotest basin, but the basin will still be a part of the Baltic Sea.

The ongoing change in proportion between land and sea will continue with the emergence of new land, forming new and larger islands.

7.8.2 Forsmark – 2500 AD until periglacial climate domain

Most probably, however, the shoreline displacement will continue to be regressive during the next 1000 years. With the predicted rate of 6 mm/year, the coastline will move around 1 km from the repository to 3000 AD. Thus, parts of the former seafloor will become land. According to the SR-Site reference case, temperate conditions will remain in Forsmark until 10,000 AD. During this period, the regressive shoreline displacement is assumed to continue, but at a gradually declining rate /Lindborg 2010/. Initially, the coastline will move at a rate of approximately 1 km per 1,000 years. This will strongly influence the landscape, especially during the first part of the period, and eventually it will result in a situation where the planned repository is located inland rather than at the coast (see Figure 7-10).

The strait at Öregrund, south of the modelled area, is expected to be cut off about 3000 AD and Öregrundsgrepen will turn into a bay. This will affect the water circulation, and due to the continued narrowing of the bay the water turnover will be further restricted (see Chapter 9). During the period from 3000 to 5000 AD, a semi-enclosed archipelago is expected to develop northeast of the repository. Around 5000 AD, many straits in this archipelago will become closed and a number of lakes are isolated from the sea. At 5000 AD, the Öregrundsgrepen bay has withdrawn ca 5 km from the repository. During the period up to 7000 AD, the coast will extend along the island of Gräsö, the coastline will be about 7 km from the central Forsmark area and the bay will gradually shrink to form two large and 20–30 m deep lakes. In the last period until 10,000 AD, the Öregrundsgrepen bay gradually shrinks to finally form a short and narrow bay along the island of Gräsö (Figure 7-10).

The salinity of the sea will continuously decrease due to the isostatic rebound of the shallow sills (The Kvarkarna) between Ålands hav and the Baltic Proper (see Figure 7-6). Around 6000 AD, the salinity is expected to have decreased down to around 3–4 ‰, accumulation of sediments will occur both on bottoms at large water depths and on shallow bottoms inside the belt of the skerries which are sheltered from wave power, whereas erosion occurs mainly on shallow bottoms exposed to waves. Transport bottoms can be found in all places between these two extremes, i.e. at intermediate depth with moderate wave exposure. Accordingly, the seafloor in the model area shows a characteristic evolution over time, beginning with a period of accumulation due to large water depth early after deglaciation. Then comes a period with transport, after which erosion dominates when the water depth decrease even more. Finally, transport and accumulation may occur in sheltered locations during a short period before the sea bottom becomes land. This means that there are very limited parts of the model area that show continuous accumulation of sediments throughout the whole marine period. The small areas with continuous accumulation are situated in the deepest parts of Öregrundsgrepen /Brydsten and Strömgren 2010/. The shoreline withdrawal means that the area for fishery is continuously reduced.

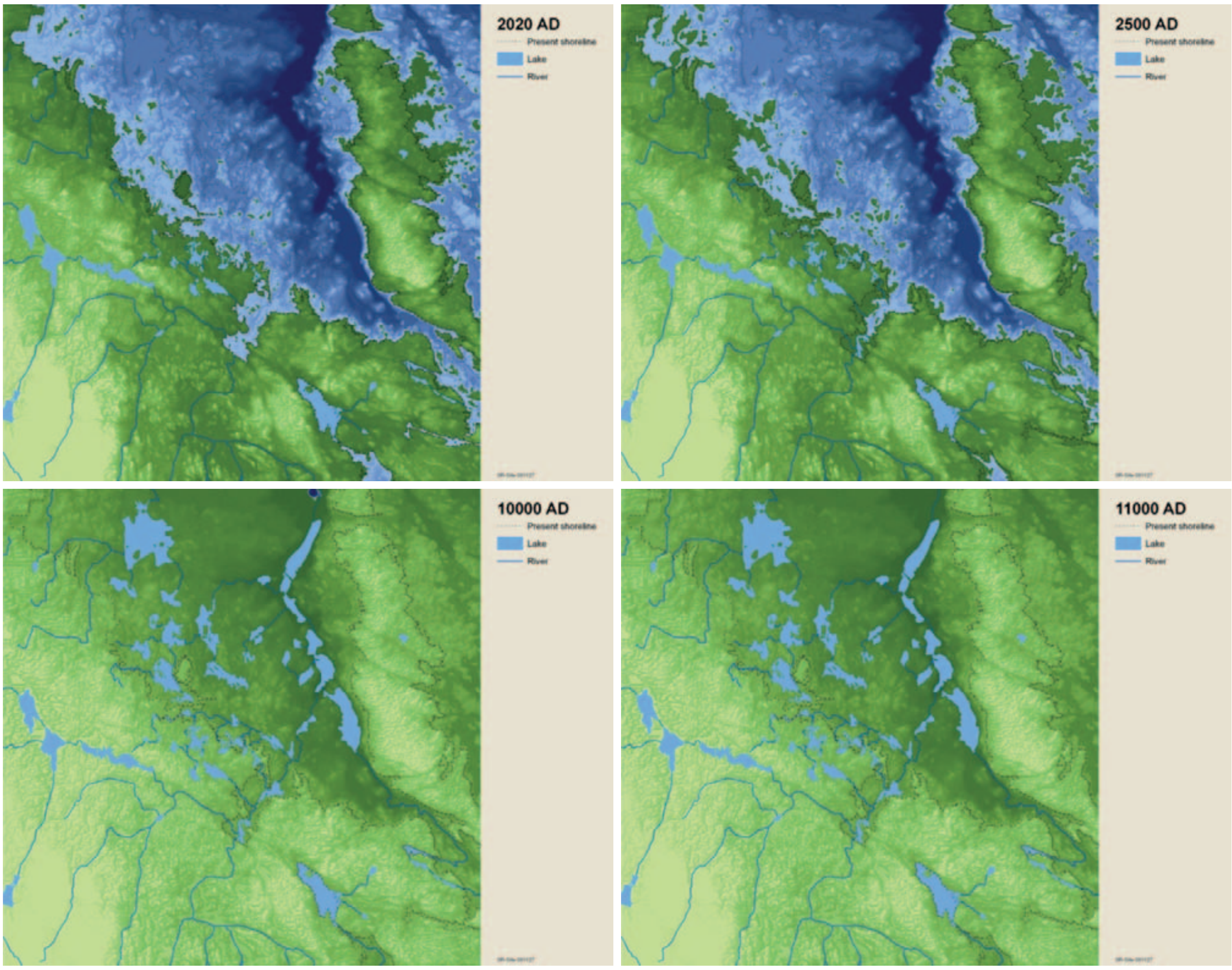

Figure 7-10. *The distribution of land and sea in Forsmark at 2020 AD, 2500 AD, 10,000 AD and 11,000 AD.*

7.8.3 Forsmark – 10,000 AD until glaciation

Around 11,500 AD, the entire Bothnian Sea, including Öregrundsgrepen, is predicted to consist of freshwater /Gustafsson 2004b/. Öregrundsgrepen will in general be a limnic ecosystem. According to the reference glacial case (see **Climate report** and Section 7.2.1), Forsmark will from 10,000 AD and forward go through a number of climate changes from temperate, periglacial (permafrost) and glacial. After glaciation, a new period of submerged conditions is also predicted (Figure 7-4).

During glacial periods Forsmark will be covered by an ice sheet. At the ice-margin, a productive aquatic community may exist. This can sustain a fish population which can be exploited by the animals living on the ice (e.g birds, polar foxes, polar bears) and humans. The populations of vertebrates and humans are likely to migrate over large areas due to low food production or severe weather conditions. In most cases, a human population will probably comprise occasional visitors, due to the hostile environment and the variable ice-situation. However, it is possible that a population could be present for longer periods close to the ice margin along the coast and live on fish.

In the reference glacial case (see **Climate report** and Section 7.2.1), two periods of submerged conditions is identified. During these periods Forsmark is covered by sea. The submerged conditions follows always direct after the ice sheet has withdrawn and the Forsmark bedrock is depressed by the ice load. The submerged conditions will have two phases, one first phase during ca 8,000 years when the whole area is submerged, and one that continues during 12,000 years when the sea gradually withdraws and the land area accordingly expands. A submerged condition is not a climate domain. It is a state when the processes and properties related to the aquatic ecosystem (marine or limnic depending on salinity) is dominating at Forsmark. The aquatic ecosystem types are not expected to change dramatically due to change in climate except for long term change in salinity. Therefore, the submerged future landscape is treated as historical and present aquatic ecosystems at Forsmark.

7.8.4 Laxemar-Simpevarp – next 500 years

Due to the relatively low rate of land uplift in the Laxemar-Simpevarp area today, in combination with the generally relatively deep areas near today's coastline, no major changes in the landscape due to the shoreline displacement are to be expected during the next 500 years. The Laxemar site is today close to the sea and the shoreline is expected to move eastwards only to a limited extent. However, bays will be isolated in the vicinity to the site. Although in the marine area the salinity may decrease and the average depth of the marine area and thereby the photic zone and water retention will be somewhat restricted.

7.8.5 Laxemar-Simpevarp – from 2500 AD until periglacial (permafrost)

The Laxemar-Simpevarp area will probably continue to be situated at, or at least near, the coast for the whole period until the next permafrost period. The most important change in the future landscape will be the isolation of the inner coastal basins from the Baltic Sea, which means that a number of new lakes will be formed. At 4000 AD, the bays north and south of Äspö are expected to become isolated from the sea and form large lakes. A terrestrial landscape will subsequently dominate the surroundings of the repository, The coastline on the seaward side of the Simpevarp peninsula will also change only slightly (Figure 7-11).

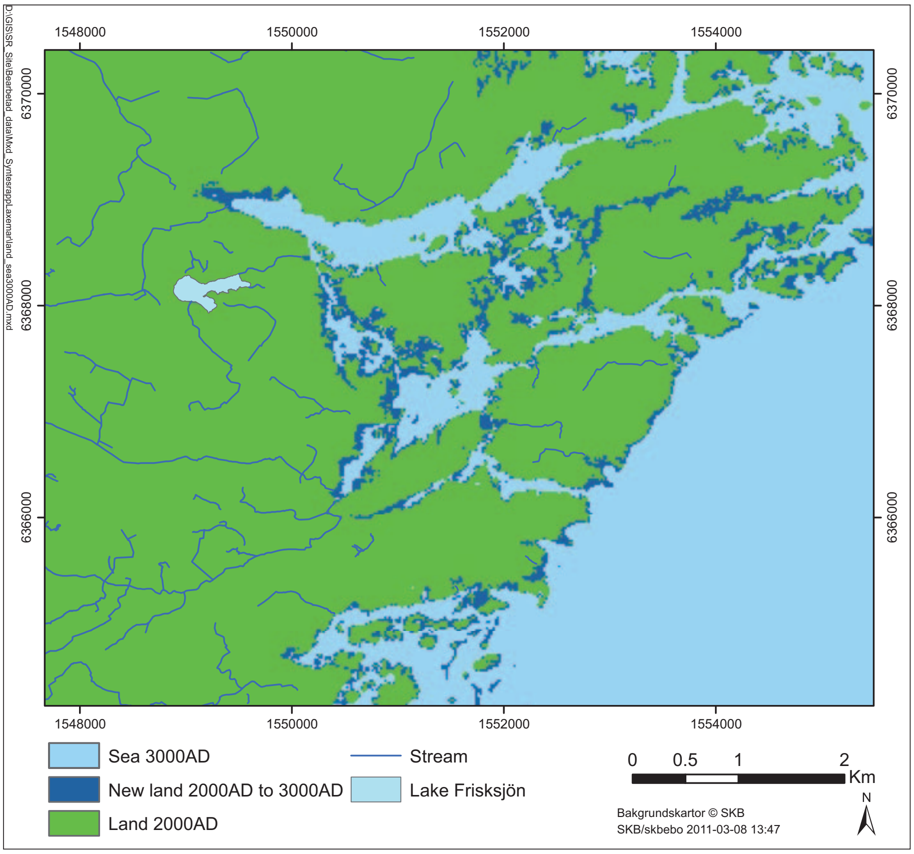

Figure 7-11. *The landuplift in Laxemar-Simpevarp until 3000 AD.*

8 Important processes for transport and accumulation of radionuclides – a comparison with the radionuclide model

8.1 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. 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 of processes. Full definitions of all processes discussed here can be found in /SKB 2010b/.

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 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 probably will decrease at colder climate and agricultural use of land will not be possible at periglacial 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

8.2 Concept of the interaction matrix

The general principles of an interaction matrix (IM) are illustrated in Figure 8-1. 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 8-1. 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 2010b/.

8.3 The limnic/marine/terrestrial interaction matrices

An aquatic IM for the limnic and marine ecosystems is presented in Figure 8-2, and an terrestrial IM for the terrestrial ecosystems is presented in Figure 8-3. The IMs are based on the general biosphere IM presented in /SKB 2010b/ and processes common to all three ecosystems are described together in Section 8.5. When the relevance of a process for a specific ecosystem differs, this is noted in the description in Section 8.5.

The aquatic and terrestial IMs includes 15 diagonal elements and 51 processes. The colour coding used in Figures 8-2 and 8-3 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.

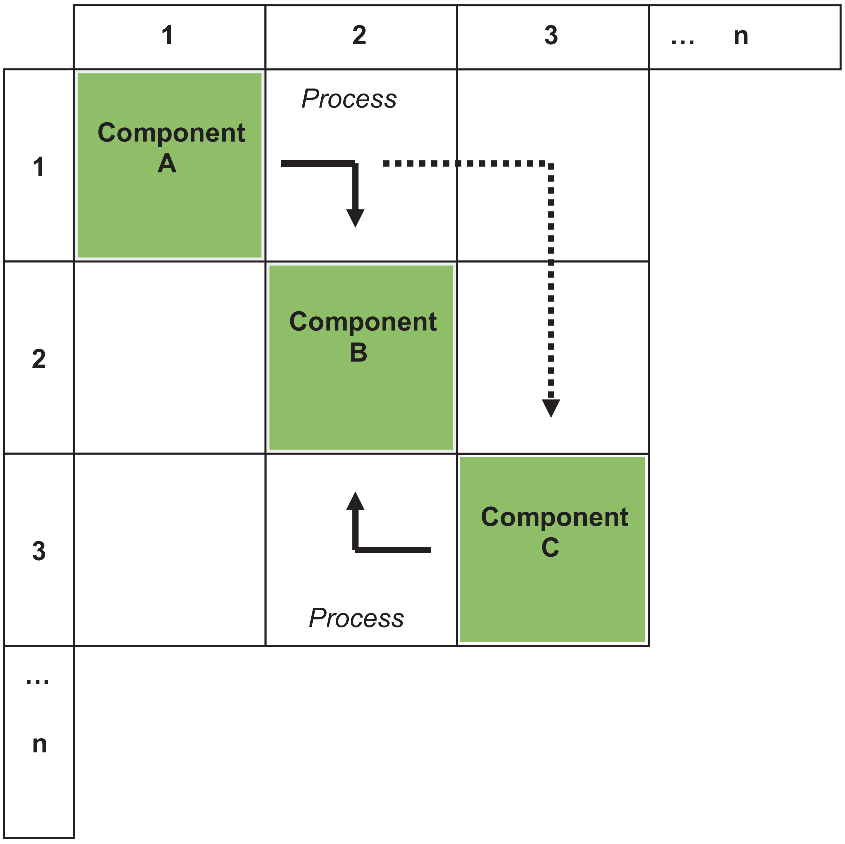

Figure 8-1. Conceptual illustration of an interaction matrix (IM). The diagonal elements A, B and C are key components of the ecosystem and are placed on the diagonal. The off-diagonal elements (white boxes) represent processes. The arrows illustrate e.g. how Component A (1:1) affects Component B (2:2) 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 8-2. *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 8-3. *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**

8.4 Diagonal elements in the interaction matrix

In the biosphere IM, 15 diagonal elements are identified (Figure 8-2 and 8-3). The diagonal elements with ecosystem-specific examples are described in Table 8-1. 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 2010b/.

Table 8-1. 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 8-2 and 8-3).

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. External conditions include surrounding ecosystems and the atmosphere above and beyond the lateral boundaries of the local atmosphere. They also include global conditions global climate and solar insulation.

8.5 Processes in the interaction matrix

In total, 51 processes were identified in the biosphere IM. Biosphere processes are listed in Table 8-2 together with a short definition whereas a comprehensive description of the processes is given in /SKB 2010b/. In Table 8-2, a reference is also given to where in the IM the processes occur. Figure 8-4 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 8-2 and is also used in Figure 8-4.

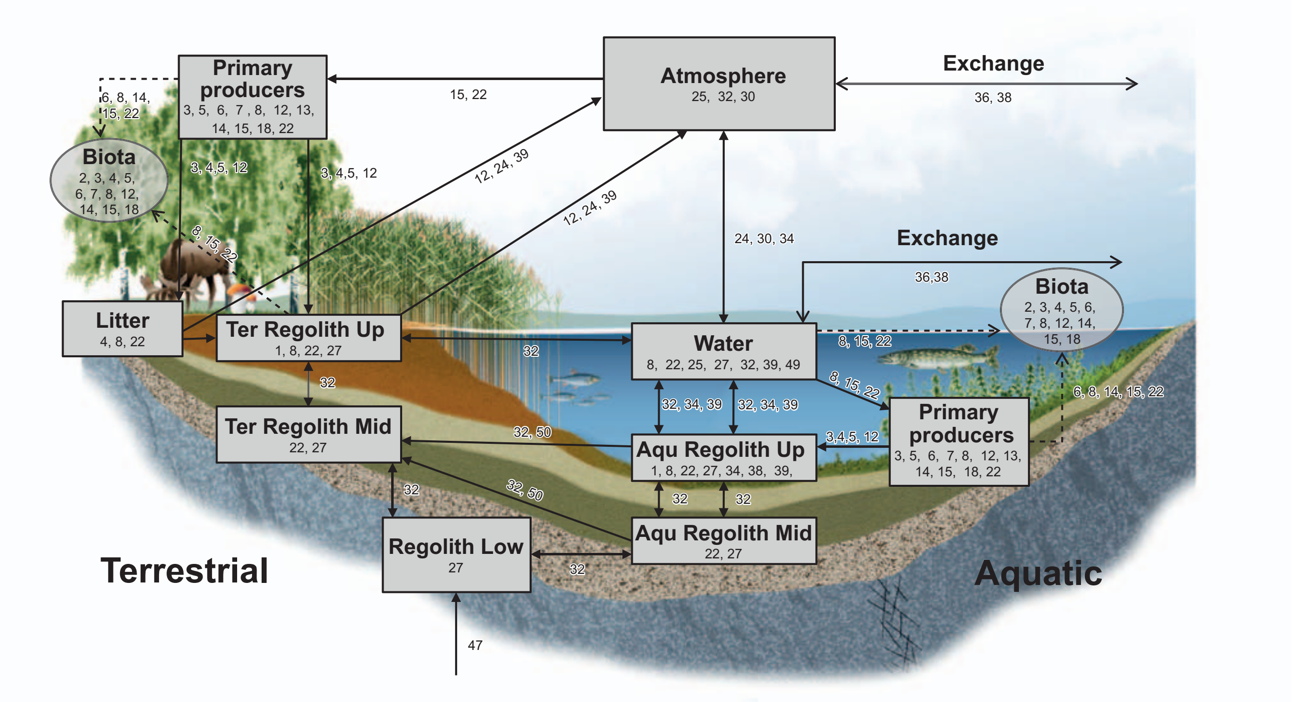

Figure 8-4. Conceptual illustration of the Radionuclide model for the biosphere and the location of processes identified as important (represented by numbers according to Table 8-2). Processes may occur in more locations than pointed out in the figure, because only the major occurrence is shown in the 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 in /Andersson (ed) 2010/. 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 8-2. 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 8-2 and 8-3) 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 8-2 and/or 8-3)	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, 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

8.6 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 8-2 and 8-3, 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 that need to be considered in the radionuclide modelling are listed for each ecosystem (limnic, marine and terrestrial) and how the processes have been included in the radionuclide model or the parameterization of the model. The boxes in the interaction matrix are numbered according to row:column (see Figure 8-2 and 8-3).

1:1 Geosphere is a diagonal element (further described in Section 8.3). 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 and the **FEP report**, SKB 2006c/ 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 4.3.7 of this report and Section 3.3.3 in /Andersson 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 9 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 in /Andersson 2010/). (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 8.3. 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 /Andersson 2010/).

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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 Chapters 3 and 4 in this report, in Chapter 3 in /Andersson 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 Chapters 10 and 11 in /Andersson 2010/, Chapter 13 in /Löfgren 2010/ and Chapter 10 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 this report, and for limnic ecosystems in Section 3.7.4 in /Andersson 2010/. 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/, 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 (Chapters 10 and 11 in /Andersson 2010/, Chapter 10 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 in /Andersson 2010/). 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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

3:3 Primary producers is a diagonal element further described in Section 8.3. 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 limnic crayfish is included in the radionuclide model (see Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 10 in this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this reportand Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, in /Andersson 2010/). and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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. Primarly 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Nordén et al. 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/). 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 10 in this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 10 in this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 10 in this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report and Chapter 10 and 11 in /Andersson 2010/). 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 10 in this report, Chapter 13 in /Löfgren 2010/ and Chapter 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/.

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Lindborg 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).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 /Andersson 2010/).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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 /Andersson 2010/).

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 /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/). 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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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 this report, Chapter 13 in /Löfgren 2010/ and Chapters 10 and 11 in /Andersson 2010/).

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.

8.7 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 8-3, Figure 8-4). 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 8.6 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 8-3. 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 8-2.

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.

9 High-resolution hydrodynamic modelling of the marine environment at Forsmark between 6500 BC and 9000 AD, and complementary ecosystem- and radionuclide models

The main scope of this chapter is to describe the high-resolution modelling of the hydrodynamic processes in the marine environment for present conditions and projections between 6500 BC and 9000 AD in Forsmark. In addition, a marine ecological C:N:P model and a model for transport and accumulation of radionuclides in the marine ecosystem are briefly presented . The results from the hydrodynamic model are used as input to the radionuclide model (Chapter 10 in /Andersson 2010/). The ecosystem model is used to illustrate the spatial and temporal variation in important processes and parameters, as well as constituting a complement to previous modelling approaches.

This chapter summarizes the model setups, data, assumptions and results of the hydrodynamic model. For the other two models a brief description of model setup, data and assumptions is presented along with some general results. Detailed descriptions and further validations and results of the models are presented in the technical reports /Karlsson et al. 2010, Erichsen et al. 2010/.

These high-resolution, three-dimensional models have been developed based upon the available marine ecosystem data (Chapter 3), the conceptual ecosystem models (Chapter 4) and previous oceanographic modelling (Chapter 5).

9.1 Modelling framework

The model area that encompasses the marine environment at Forsmark is defined as the semi-enclosed area that exists today between the mainland and the island of Gräsö. This area is called Öregrundsgrepen (see Figure 4-1). The extent of this area varies significantly over geological time scales, primarily due to land uplift. Thus, the area now identified as Öregrundsgrepen was part of an open coastal sea at 6500 BC and will probably disappear completely due to land uplift at about 11,000 AD /Brydsten and Strömgren 2010/.

To estimate water exchange for the period from 6500 BC to 1000 BC, an existing Baltic Sea model was used together with a basin-based transport model. For the period from 0 AD to 9000 AD, a hydrodynamic model was developed using MIKE by DHI software MIKE 3 FM. The ecosystem and radionuclide food web models for the present-day situation (2020 AD) have been implemented in MIKE by DHI software ECO Lab, based mainly on data collected during a single year (2004). Conceptually, the ecosystem model and the radionuclide model have been developed based on the general food web structure developed in earlier modelling studies within the area (e.g. Kumblad and Kautsky 2004, Chapters 4 and 6 in this report), but this high-resolution analysis considers only six selected radionuclides.

9.2 Hydrodynamic processes in the marine environment – present conditions (2020 AD) and projections between 6500 BC and 9000 AD

9.2.1 Methodology

The purpose of the hydrodynamic modelling effort was to provide the physical forcing for other models: estimates of the basin exchange for the years 6500 BC to 9000 AD to be used by the Radionuclide model (see Chapter 10 in /Andersson 2010/) and detailed hydrodynamic flow fields for 2020 AD to be used by the high-resolution ecosystem and radionuclide models (see below). To achieve these purposes the hydrodynamic models must calculate

1. the time-varying flow field, represented by currents and turbulent mixing, and
2. the time-varying fields of physical properties of the water, represented by sea levels, salinities and temperatures, where the latter two in turn determine the density field.

To accurately compute the above variables, the hydrodynamic models also calculate heat exchange with the atmosphere, turbulent kinetic energy, bottom friction and several other variables and processes /Karlsson et al. 2010/.

The overall methodology was as follows. The time period from 6500 BC to 9000 AD was divided into 13 years, see Table 9-1 below. For each year a hydrodynamic model was run for one calendar year using the same external forcing by the atmosphere, the surrounding sea and land. The difference between the models is the bathymetry – depths and shoreline location – which was determined from a digital elevation model (DEM) /Strömgren and Brydsten 2008/ that describes the changes over the given time period, mainly due to land uplift. Note that the marine model area changes over time as basins are lifted above sea level and become land drainage basins. For the earliest year (6500 BC) all basins are located in the sea /Brydsten and Strömgren 2010/.

During the BC years (6500, 3000 and 1000 BC) Öregrundsgrepen is not a semi-enclosed well-defined area as it is during the AD years. Instead, the basins shown in Figure 9-1 are located in an open coastal sea area. Thus, the hydrodynamics of this area is not governed by local conditions and well-defined boundary forcing, but is instead dependent on the large-scale circulation in the pre-Baltic Sea. In fact, the basins are only arbitrary volumes of water, since variations in the bottom topography are small compared with the total depth and are thus of little importance to the circulation. The flow field is likely to vary over spatial scales larger than the size of the individual basins. As the area rises and land forms, flow field variations on smaller scales become increasingly important.

For this reason, two different model approaches have been used for the three BC years and the ten AD years. For the BC years, a large-scale hydrodynamic model for the entire Baltic Sea has been used to produce flow fields which then have been interpolated to determine the basin exchange. For the AD years, a local high-resolution hydrodynamic model of Öregrundsgrepen has been used, which in turn has been forced on its lateral boundaries by the results from the Baltic Sea model.

The main deliverables of the hydrodynamic modelling have been the following:

- Mean annual volume flows between neighbouring basins, including a division into mean annual inflow and mean annual outflow.
- A measure of the mean residence time for Öregrundsgrepen, including the spatial distribution over all basins.
- Detailed flow fields to be used as forcing in the high-resolution ecosystem and radionuclide models (see following sections in this chapter).

Table 9-1. Overview of the time period 7000 BC to 9500 AD and the modelled years. S stands for salinity.

Calendar year	7000 BC	6500 BC	6000 BC	5500 BC	5000 BC	4500 BC	4000 BC	3500 BC	3000 BC	2500 BC	2000 BC	1500 BC	1000 BC	500 BC	0	500 AD	1000 AD	1500 AD	2000 AD	2500 AD	3000 AD	3500 AD	4000 AD	4500 AD	5000 AD	5500 AD	6000 AD	6500 AD	7000 AD	7500 AD	8000 AD	8500 AD	9000 AD	9500 AD
Baltic Sea phase	***Mastogloia Sea***			***Litorina Sea***					***Limnea Sea***							***Baltic Sea***			***Baltic Sea with "current" land rise***							***Baltic Sea without Bothnian Bay***								
State of Baltic Sea	sills open; lake -> brackish sea; low S			Deepening sills; increasing S. Maximum of ca 10-15 PSU at about 5000-2500 BC					Uplift exceeds sea level rise; decreasing S										Gradual closing off of Bottenviken, shallowing of Ålands hav and deepening of sills							Bottenviken a lake; Ålands hav a narrowing sound and gradually deepening sills								
State of Forsmark area	***Open sea (> 10 km to coast)***												***Gradually forming archipelago***			***Grepen exists***			***Öregrundssund gradually closing***					***Narrowing; lakes forming from west until only deep channel remains***						***Lakes forming northward until Öregrundsgrepen consists of only lakes***				
Model years		*6500 BC*							*3000 BC*				*1000 BC*		*0 AD*		*1000 AD*		*2020 AD*		*3000 AD*		*4000 AD*		*5000 AD*		*6000 AD*		*7000 AD*		*8000 AD*		*9000 AD*	

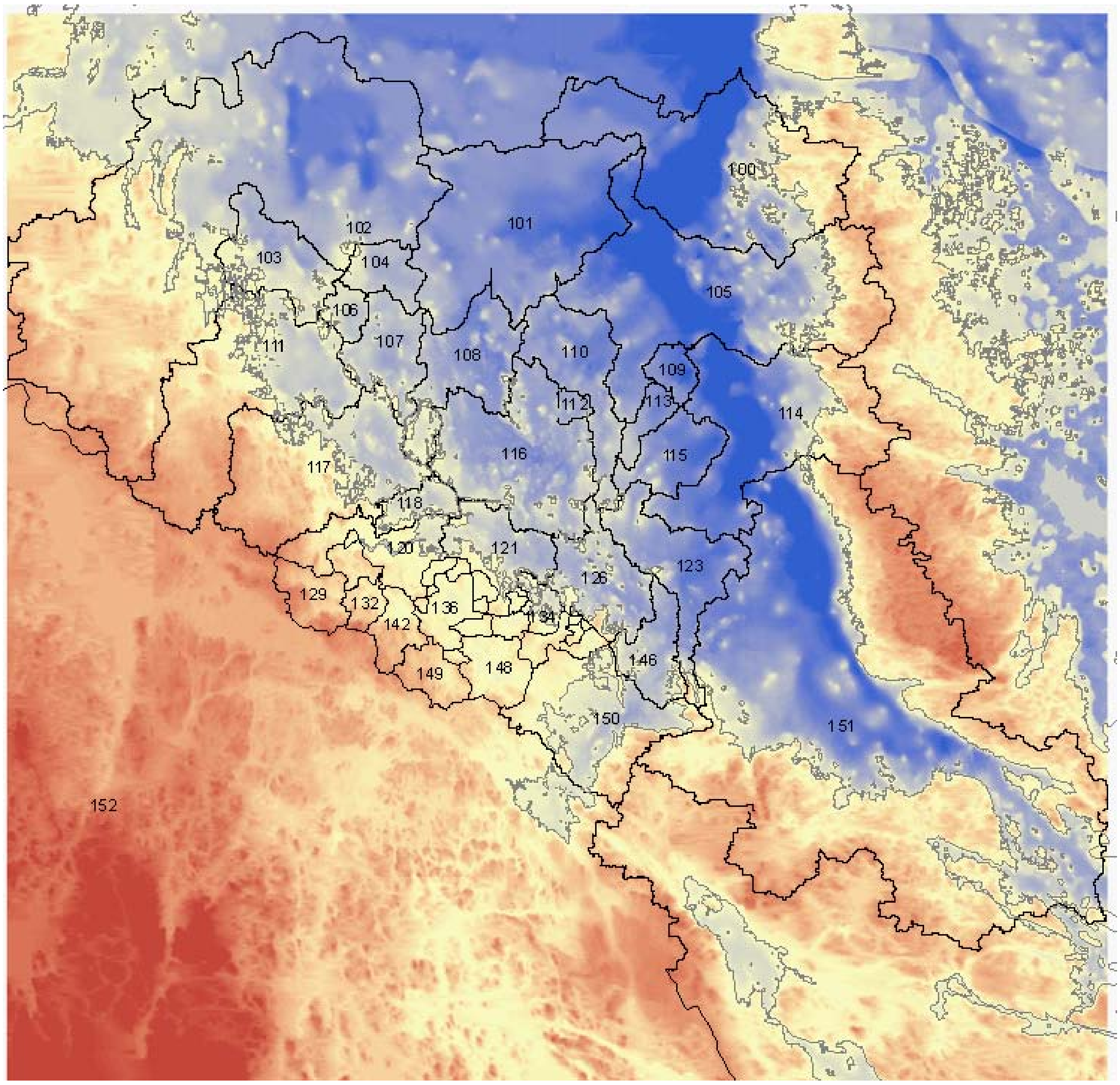

Figure 9-1. *Basins in Öregrundsgrepen.*

Both the modelling approaches, i.e. for BC and AD years, produce one-year time series of volume flows through the common boundaries between neighbouring basins. The time resolution is one hour. Depending on the year, different numbers or parts of basins are active, i.e. located within the marine environment. For example, for the BC years all 52 basins are active, yielding over 200 connections (interfaces) between neighbouring basins, and thus an equal number of time series of volume flows. From these time series the annual mean of all occasions with positive net flow, the mean of all occasions with negative net flow and the mean of the entire time series are calculated. The mean annual flows constitute a low estimate of the exchange. This is because they are based on the net exchange at a given instant in time, which means that simultaneous inflows and outflows over the same boundary (e.g. at different depths) may cancel each other. The annual means of negative and positive volume flows indicate whether the total mean is the result of large flows in both directions or primarily a flow in one direction only.

The measure of residence time used is the so-called average age (AvA). This describes the average time that water parcels have spent within a given volume. To calculate this for the basins in Öregrundsgrepen, an age tracer is used. Outside Öregrundsgrepen, the tracer concentration is set to zero, which means that water from outside the modelled basins is assumed to have zero age and is termed exogenous. In each computational point there is an age tracer source equal to one, i.e. for a closed off basin the concentration will increase monotonously at the same rate as the passing of time. This age tracer is transported and mixed in the model just as any other conservative substance, e.g. salinity. Thus the concentration of the age tracer represents the age of the water, relative to the water outside Öregrundsgrepen, at that particular point in space and time. After an initial increase (the spin-up period), a quasi-steady state will be reached between ageing and mixing with exogenous water. Thus the age tracer concentration will eventually fluctuate around some average value. Taking this average value – defined as the temporal mean over the period February to December (January constituting the spin-up period) – and calculating the volume-weighted average for each basin, yields the AvA for each basin relative to the exogenous water. Note that this measure is the same as the one termed "collective AvA" in Chapter 5 of this report. The AvA results in this study are thus not comparable to the "individual AvA" computed for the basins in Chapter 5, where the definition of exogenous water is different (see section "Results" below and /Karlsson et al. 2010/).

9.2.2 Description of models

The Baltic Sea model AS3D /Engqvist and Andrejev 2008/ was used to determine the basin water exchange for the BC years, i.e. the open sea phase. The resolution of the hydrodynamic model is 2×2 nautical miles, which means that the Forsmark area is covered by 9×10 grid points (see Figure 9-2). For more details see appendix in /Karlsson et al. 2010/.

The computed hourly 3-D time series of current components (east-west and north-south) for the Forsmark area were then interpolated to the midpoints of all cross-sections connecting neighbouring basins, using nearest neighbour interpolation, producing time series of vertical profiles of current speed for each connection. The corresponding vertical profiles of the cross-sectional area for each connection were determined from the high-resolution DEM. Time series of volume flow for each cross-section were calculated from the interpolated currents and the area profiles.

To calculate the basin AvA, a simple model describing the temporal evolution of the concentration of an age tracer has been set up for the 52 interconnected basins 100 to 151. For each basin i the age tracer concentration C_i is given by

$$\frac{dC_i}{dt} = 1 + \frac{(Q_i^{in} - Q_i^{out})}{V_i}$$

where Q_i^{in} is the sum of mass inflows of tracer from surrounding basins to i, Q_i^{out} is the sum of mass outflows of tracer to surrounding basins from i and V_i is the volume of i.

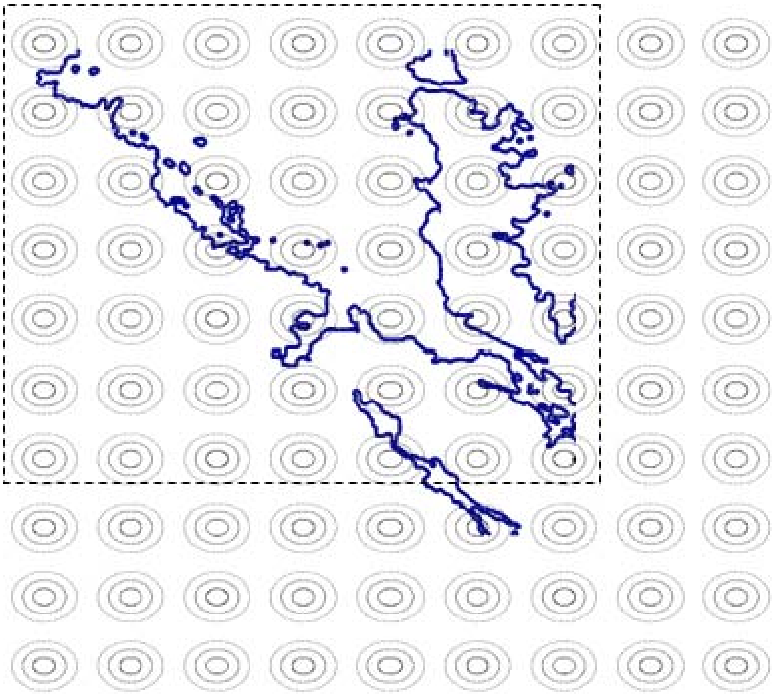

Figure 9-2. Locations of velocity grid points in the Forsmark area relative to present-day shoreline for Öregrundsgrepen.

- This constitutes a set of 52 ordinary differential equations, which have been solved numerically using the previously calculated volume flows. If there is no exchange with neighbouring basins then the age tracer concentration increases linearly with time. The age tracer concentration is fixed at zero outside the 52 basins. Basin 152 is also considered part of the exterior area.
- A high-resolution flexible mesh model (MIKE 3 FM) has been applied to calculate circulation and water exchange for the years when the Öregrundsgrepen area progresses from partially open water to the closing of the Öregrundsgrepen (0 AD to 9000 AD, see Figure 9-4). The extent of the model mesh has been chosen such that there are two open boundaries, one in the north between Örskär and Klungsten (approx. N 60º 31' 46") and one in the south between Vässarön and Storskäret. The water volume in the model area is divided into a number of prism-shaped computational cells where sea level, currents, salinity, temperature, density, and turbulence are calculated in three dimensions. The model resolution (i.e. the size of the cells) varies and has been chosen to represent the topography and pre-defined basins in the area as accurately possible while retaining a reasonable run time. Resolution is finer in straits and shallow areas and coarser in the deeper more open water areas, see example in Figure 9-3.
- The hydrodynamic model accounts for
  - Density stratification due to temperature and salinity variations.
  - Density-driven currents.
  - Wind forcing on the surface.
  - Currents driven by sea level variations.
  - Fresh water runoff and cooling water discharge.
  - Heat exchange with the atmosphere.
  - Turbulence and Coriolis force.

The dynamics of the age tracer (as described above) have been computed using an add-on module termed ECO Lab. The vertically and horizontally integrated flows through each interconnecting cross-section as well as the 3-D field of age tracer concentration are calculated and output as time series by the model.

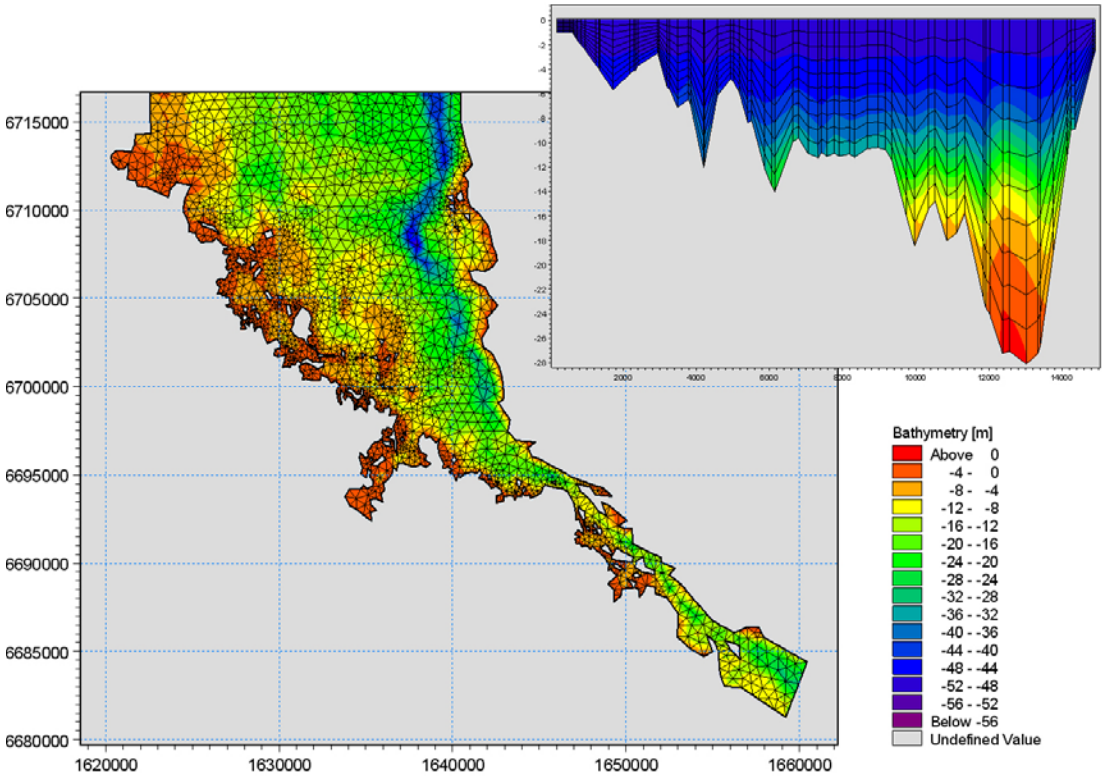

***Figure 9-3.** Computational mesh for 2020 AD showing horizontal and vertical resolution. Resolution is higher in areas with small basins and straits. The vertical resolution varies with depth as the water column is described by 10 layers. The layer thicknesses vary in proportion to the local depth.*

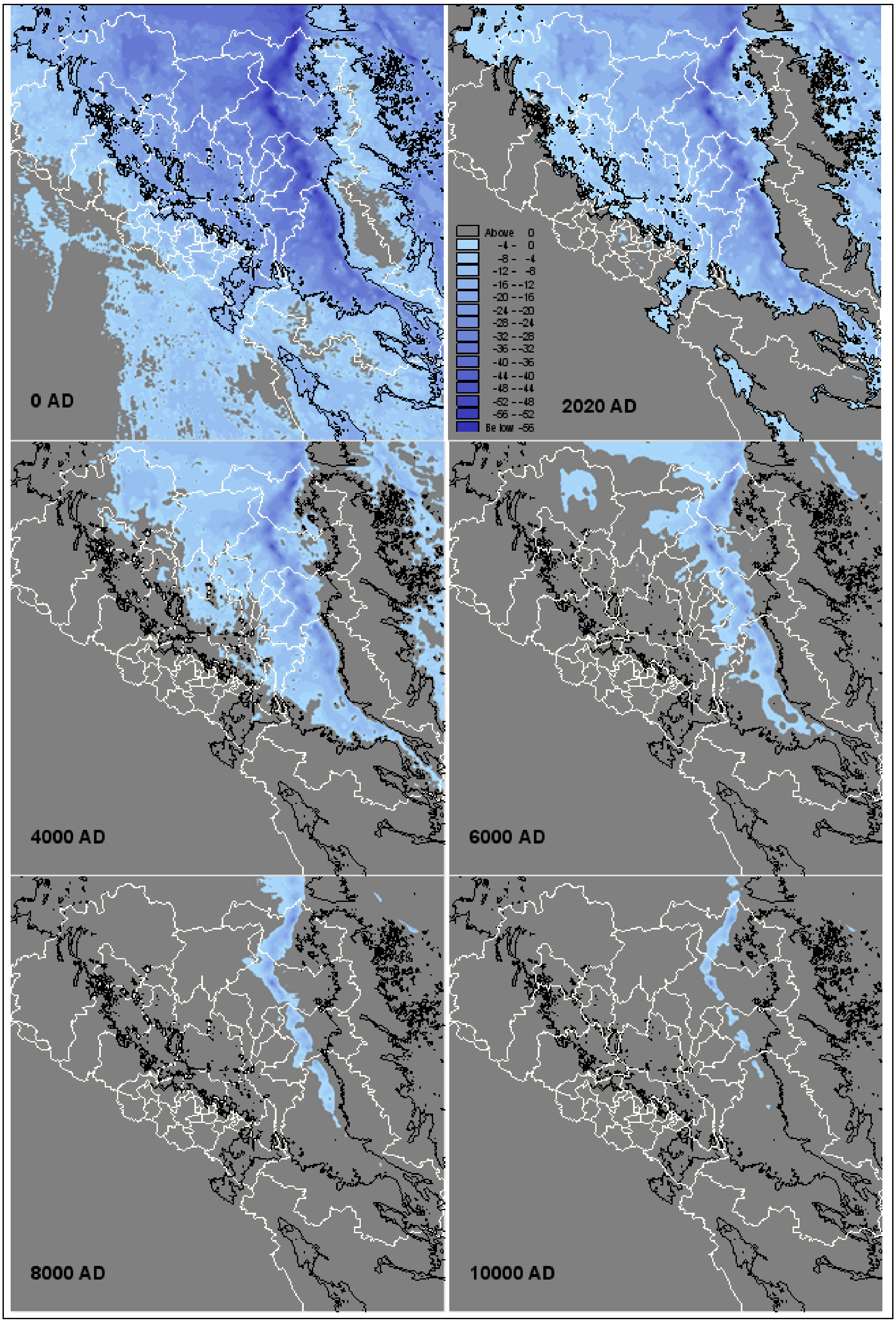

Figure 9-4. *Selected stages in the development of the Öregrundsgrepen from 0 AD to 10,000 AD. The present-day shoreline is shown by a black line and the basins by a white line. By the year 10,000 AD only lakes exists.*

9.2.3 Input data

The input data for the hydrodynamic Baltic Sea model is based on observations and to some degree – for the BC years – other models. The input data for the local MIKE 3 FM-model comes from the Baltic Sea model as well as observations. As very little is known about the past and future climate, the present-day climate has been used as input for all years. For the BC years, some modifications of the river runoff, initial salinity and temperature fields have been made based on the literature.

Bathymetric data

The bathymetry, shoreline and mean sea level for the different years have been determined from two DEM /Strömgren and Brydsten 2008/. One covers the Forsmark area with a 20 m resolution (see Figure 9-4) while the other covers the entire Baltic Sea with a 500 m resolution.

Meteorological forcing

The most important meteorological forcing of the water exchange in Öregrundsgrepen is the wind. Air temperature, humidity and cloudiness are required input data to determine the heat exchange with the atmosphere. The Baltic Sea model uses databases of analyzed fields of meteorological observations, while the local model uses observations from the Örskär station. In both cases, time series for the year 2004 are used.

Land runoff

The Baltic Sea model for 2020 AD is forced by calculated monthly values for 29 river discharges during 2004. For the BC years, these values have been adjusted using a relative change compared with 2000 AD /Gustafsson and Westman 2002/. Moreover, the source points have been moved to match the altered shoreline. The local model for 2020 AD uses the daily flows in Forsmarksån and Olandsån for 2004 as input for land runoff to Öregrundsgrepen. For all AD years, the drainage basins for Forsmarksån and Olandsån are more or less unchanged (Brydsten, pers. comm.), so the present-day flows in Forsmarksån and Olandsån have been used. The source points for future years have been determined from the landscape modelling in which the evolution of the mouths of these two rivers can be traced.

Hydrographical forcing

The Baltic Sea model is forced on its western boundary (Kattegat) by observed sea levels in Göteborg and Fredrikshavn for 2004. The salinity and temperature profiles are climatic averages. The local model is forced by the Baltic Sea model for 2004, i.e. sea levels as well as salinity and temperature profiles have been extracted from positions in the Baltic Sea model that match the boundaries of the local model and used as boundary forcing in the local model. The same forcing – for 2004 – has been used for all AD years.

The observed cooling water discharge for 2004 from the Forsmark power plant is included as a source in the 2020 AD local model simulation, but not in any other year.

Ice

Gridded ice cover data is available for 2004. However, for past and future years no such data is available. Even neglecting climatic variations, the ice cover will differ greatly depending on geometry, i.e. a small, shallow area will ice over more easily than open sea. Thus, it is hardly relevant to use ice cover data from 2004 for other years, particularly not those when the Öregrundsgrepen area looks much different from today. Alternatively, ice formation could be modelled using a separate ice model. As a first approximation, and considering other approximations that must be made, ice has been neglected for all years in the hydrodynamic simulations.

9.2.4 Results

Short-term relative sea level variations are dominated by wind and pressure fields over Scandinavia. Over the long term, land uplift and changes in oceanic mean sea level determine the local mean sea level. The sea temperature is dominated by meteorological forcing, both in the short and long term. Short-term salinity variations are dependent on short-term variations in runoff and wind conditions over the Baltic Sea (and to some degree over the Skagerrak, the Kattegat and the North Sea as well). Long term salinity is dependent on long term variations in runoff and the mean sea level, as water exchange with the Kattegat and the Skagerrak varies with the depth of the Baltic Sea sill.

Basin flow

The basin flows calculated for 2020 AD are shown in Tables 9-2 and 9-3. The calculated flows are rounded off to give a better idea of the order of magnitude of the flows. The basin flows for all the remaining years between 6500 BC and 9000 AD have also been calculated but are not shown here /Karlsson et al. 2010/.

The magnitude of the flow is primarily determined by the areas of the cross sections between basins. When the cross section between two basins is small, the flow is small and vice versa. For example, Basin 105 has large cross-sectional areas (wide and/or deep) to basins 100, 101, 110 and 114. This permits large annual mean flows through these sections, suggesting a net throughflow in the area.

Between basins 120 and 121 the flow is in one direction only. This is due to the cooling water intake located in basin 120.

Comparison of the basin flows in Table 9-2 calculated by the present model for 2020 AD with those presented earlier in Chapter 5 shows large differences. This is primarily due to the flows in Chapter 5 have been calculated for 1988. However, in general the two studies produce flows of the same order of magnitude.

Furthermore, all basin connections in the study from 1988 are not present in this study, and vice versa, mainly because the two studies use different kinds of grids and resolutions. Some of the connections were considered too small to be included in this study. The grid resolution does not resolve the smallest connections where flows between basins are in the order of 1 m^3/s.

Average Age

Dividing the basin volume by the net inflow to a basin yields the hydraulic residence time. However, this is a rather crude measure of the water exchange. Firstly, it considers all inflowing water as exogenous, i.e. it does not take into account recirculation between basins. Secondly, it does not resolve variations within a basin. The flow from a neighbouring basin may only ventilate parts of the basin, leaving other parts almost unaffected. Thirdly, it only considers advective exchange, not diffusive processes.

Hence, calculating the AvA for each computational cell in the model domain, producing a spatial variation within each basin, yields a better estimate of the water exchange. For the BC years, however, the box model used to calculate the AvA does not resolve spatial variations within basins, nor does it include diffusive processes. Thus, only the advantage of the AvA concept in terms of including the effect of recirculation within Öregrundsgrepen is retained.

The AvA is shortest for the three BC years. This is not surprising, as the Öregrundsgrepen area is located in the open sea without any physical boundaries restricting water exchange. There is no significant difference in the water exchange, as indicated by the AvA values, between these three BC years. The value for the entire Öregrundsgrepen area is between five and seven days, and the basin values lie in the same range, with extremes of two and ten days. However, the AvA appears to have a weak minimum for the year 3000 BC.

As the land rises, Öregrundsgrepen becomes more enclosed and the importance of open sea forcing (sea level and density variations) for the water exchange decreases compared with local effects (wind and land runoff). During the period 0–3000 AD, when the area is open at both ends (north and south), the water exchange is relatively high as water can pass through Öregrundsgrepen. As the land continues to rise and the narrow strait of Öregrund closes in the south, shallow embayments are formed and the water exchange is reduced.

Table 9-2. Annual mean flows between basins in Öregrundsgrepen for 2020 AD. Positive values signify flow from the first basin 'to' the second basin, and negative flow is thus in the opposite direction.

Basin ID	Pos. flow [m3/s]	Neg. Flow [m3/s]	Net flow [m3/s]
100 to Baltic	1341	-3085	-1743
101 to 100	751	-106	644
101 to 102	477	-299	177
101 to Baltic	1818	-392	1426
102 to Baltic	1326	-1244	82
103 to 102	395	-476	-80
104 to 101	165	-94	70
104 to 102	294	-278	16
104 to 103	43	-67	-25
105 to 100	675	-3063	-2388
105 to 101	2386	-398	1988
106 to 103	38	-82	-44
106 to 104	117	-103	15
106 to 107	166	-127	39
107 to 104	213	-196	17
108 to 101	462	-525	-63
108 to 107	396	-420	-24
108 to 110	191	-341	-150
109 to 105	148	-441	-293
110 to 101	481	-227	254
110 to 105	981	-1135	-154
111 to 103	54	-66	-12
111 to 106	30	-21	9
111 to 107	66	-83	-17
111 to 117	45	-29	17
112 to 110	273	-168	105
113 to 105	431	-457	-26
113 to 109	119	-154	-35
113 to 110	185	-273	-88
114 to 105	1001	-929	73
114 to 109	45	-303	-258
114 to 115	640	-908	-268
114 to 123	666	-287	379
114 to 151	753	-651	102
115 to 110	112	-192	-80
115 to 113	580	-729	-149
115 to 123	191	-230	-39
116 to 108	361	-688	-328
116 to 110	357	-204	153
116 to 112	338	-233	105
117 to 107	26	-10	16
118 to 117	2	-3	0
121 to 116	178	-214	-36
121 to 120	122	0	122
123 to 110	53	-38	14
126 to 110	15	-7	8
126 to 116	185	-108	76
126 to 121	247	-159	88
126 to 123	144	-105	39
134 to 121	3	-5	-2
134 to 126	5	-3	3
146 to 123	430	-626	-196
146 to 126	576	-373	204
150 to 146	32	-24	8
151 to 123	710	-879	-169
151 to Baltic	807	-593	214
152 to 150	14	-7	8

Table 9-3. Annual mean flow in and out of each basin for 2020 AD.

Basin ID	In flow [m3/s]	Out flow [m3/s]	Diff flow
Basin 100	4511	-4511	0 %
Basin 101	4292	-4290	0 %
Basin 102	2410	-2379	1 %
Basin 103	611	-611	0 %
Basin 104	769	-800	4 %
Basin 105	6023	-6023	0 %
Basin 106	342	-342	0 %
Basin 107	850	-853	0 %
Basin 108	1769	-1738	2 %
Basin 109	605	-605	0 %
Basin 110	2549	-2686	5 %
Basin 111	199	-196	2 %
Basin 112	506	-506	0 %
Basin 113	1464	-1464	0 %
Basin 114	3078	-3106	1 %
Basin 115	1791	-1791	0 %
Basin 116	1488	-1378	7 %
Basin 117	58	-57	1 %
Basin 118	3	-2	7 %
Basin 120	122	-122	0 %
Basin 121	464	-464	0 %
Basin 123	2180	-2180	0 %
Basin 126	961	-967	1 %
Basin 134	8	-8	0 %
Basin 146	1030	-1030	0 %
Basin 150	38	-38	0 %
Basin 151	2225	-2168	3 %

Figure 9-5 shows the average age of the water for each year simulated after the open sea phase, the AD years. The plots show the development of Öregrundsgrepen and how the water exchange in the inner parts decreases from 4000 AD (increasing AvA). Where the small rivers Olandån and Forsmarksån discharge into Öregrundsgrepen, the AvA is somewhat lower. This means that as Öregrundsgrepen shallows, the freshwater discharges become more important locally compared with other driving forces (wind and sea level variations). The effect of these small rivers is visible at 6000 AD.

Overall, the AvA increases with time as the individual basins become more secluded (Figures 9-5 and 9-6). Furthermore, during the BC years the AvA in Öregrundsgrepen is relatively homogeneous, as might be expected during the open sea phase. As Öregrundsgrepen shallows and is gradually closed off, the AvA increases to an average of 40 days. However, there are variations along the way due to different factors. One such factor is the basin volume relative the cross-sectional area over which water can pass in and out of the basin. From the year 1000 AD to 3000 AD the AvA decreases even though Öregrundsgrepen becomes more isolated from the open sea. This is probably an effect of a greater decrease in basin volume compared with the decrease in the cross-sectional area of the inter-basin connections. This means that the volume flow required to ventilate a basin completely decreases faster than the decrease in the water exchange rate due to shrinking cross-sections.

When Öregrundsgrepen is considered at the basin level (Figure 9-6), there are other interesting variations. It may seem strange that in 6000 AD the water exchange rate in basin 123 is much higher than it was in 5000 AD, even though the basin is more enclosed in 6000 AD. As mentioned earlier, fresh water input can have a significant effect on water exchange locally. In 5000 AD, the small rivers of Olandsån and Forsmarksån have a common discharge in basin 151. In 6000 AD, this discharge has moved to basin 123. At the same time, basin 123 is relatively small in volume – compared with basin 151 – and the fresh water thus has a greater local effect on the AvA than for the whole of Öregrundsgrepen. The same phenomenon, though not as pronounced, occurs when a basin has a small volume but relatively high water exchange (large cross-sectional area of inter-basin connections) with other basins. The opposite state of affairs, when the water exchange with other basins decreases but the volume in relation to the cross-sectional area of the connections increases, leads to rapidly increasing AvA. This is the case for basin 151 from 3000 AD to 7000 AD before it turns into a lake.

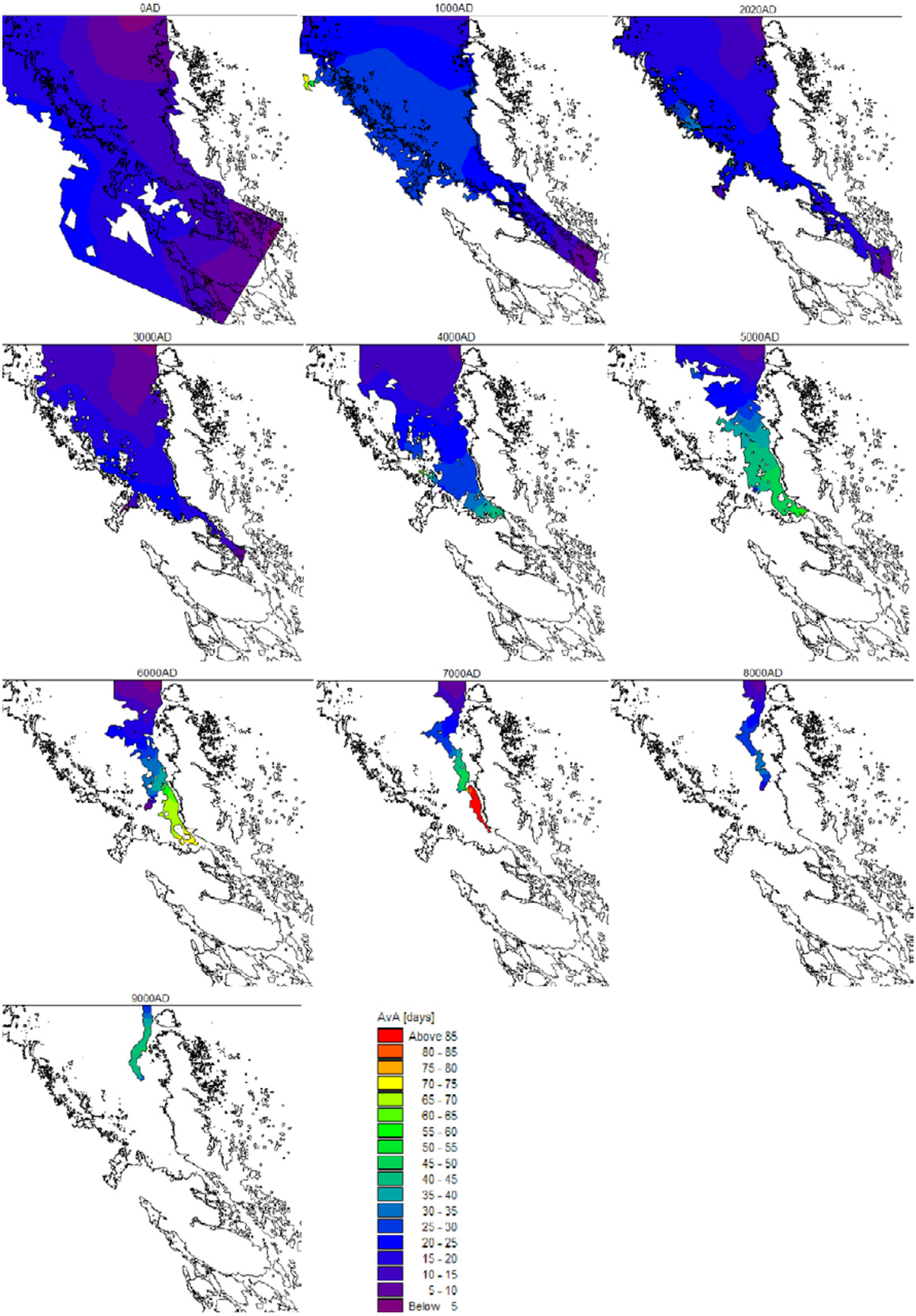

Figure 9-5. *Vertical average of the average age for each simulated AD year. In Öregrundsgrepen in Forsmark area.*

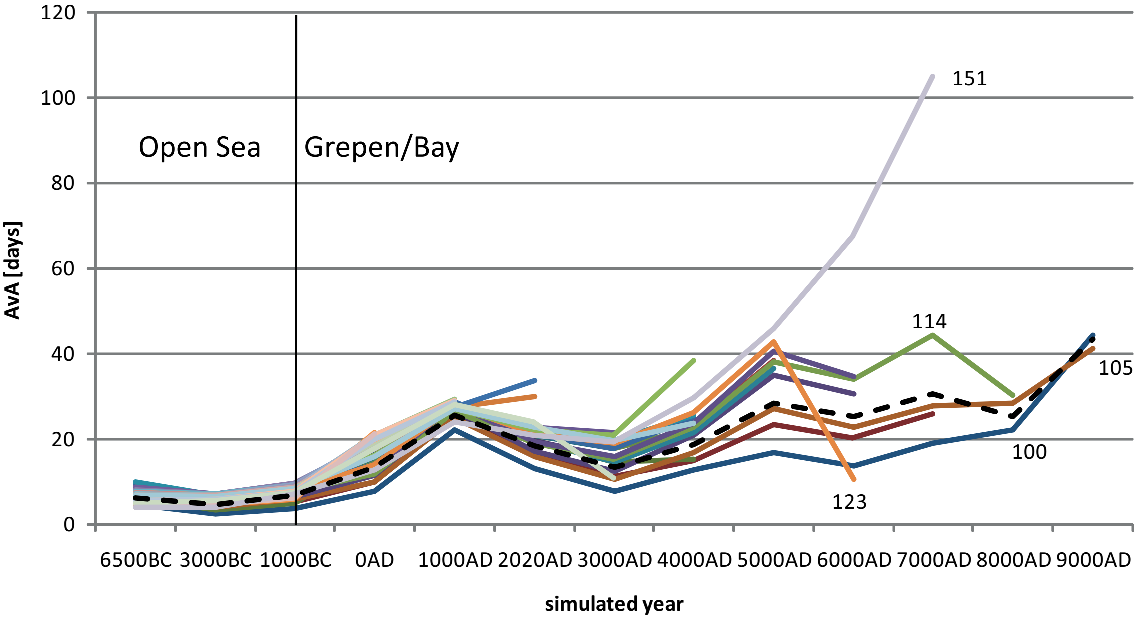

Figure 9-6. *Temporal evolution of AvA in each basin. Some of the curves are marked with basin number. The black dotted line is the mean AvA for all basins. For basin locations, see Figure 9-1.*

Finally, it might be reasonable to expect a comparison between the present model results for 2020 AD and those presented earlier in Chapter 5. However, there are several discrepancies that make such a comparison difficult. Firstly, as mentioned above, the year simulated in Chapter 5 is 1988. Secondly, the "individual" AvA is tabulated in Chapter 5, i.e. the AvA for each basin considering all water outside the basin as exogenous, whereas in this study only water outside of Öregrundsgrepen is considered exogenous. The closest comparison in the current study is the hydraulic residence time. The hydraulic residence times in this study have a median of about 0.6 days, with a maximum of about 12 days and a minimum of about 0.03 days. The corresponding statistics for the individual AvAs in the previous study are 0.26 days, 4.5 days and 0.02 days. So even though they are of the same order of magnitude, they differ noticeably. This is due not only to the choice of measure (hydraulic residence time and individual AvA, respectively), but also to the differences in computed basin flows, as discussed above.

Table 9-4. AvA in days for each basin, volume averaged. These values have been computed considering only water outside Öregrundsgrepen as exogenous.

Basin	6500 BC	3000 BC	1000 BC	0 AD	1000 AD	2020 AD	3000 AD	4000 AD	5000 AD	6000 AD	7000 AD	8000 AD	9000 AD
100	5	2	3	8	22	13	8	13	17	14	19	22	44
101	7	4	5	10	25	17	11	15	24	20	26		
102	6	3	5	16	25	19	14	15					
103	8	4	6	17	26	20	16						
104	8	4	6	15	27	21	18						
105	7	4	6	10	25	16	11	17	27	23	28	28	41
106	9	5	7	16	27	21	19						
107	9	6	8	16	27	22	19						
108	9	6	8	14	28	21	18	22					
109	7	5	7	11	27	17	12	21	35	31			
110	9	6	8	13	28	19	15	22	36				
111	8	5	8	19	27	24							
112	9	6	8	14	29	21	18	25					
113	8	5	8	13	28	19	16	23	39				
114	6	5	8	12	26	19	15	23	38	34	44	30	
115	8	6	8	13	28	19	16	23	40	35			
116	10	7	9	16	28	22	20	25					
117	8	6	10	19	27	30							
118	9	7	10	19	27	34							
119	7	7	9	20	29								
120	8	7	9	20	28	23							
121	9	7	9	18	27	23	22						
122	7	6	8	21	29								
123	7	6	8	14	28	21	19	26	43	10			
124	8	7	9	19	28								
125	8	7	9	19	28								
126	8	7	9	16	27	22	21	38					
127	9	7	10	19	28								
128	7	7	9	20	29								
129	4	4	6	21									
130	7	6	8	19	28								
131	7	7	9	20	29								
132	5	6	8	21	29								
133	8	7	9	19	28								
134	8	7	9	18	28	24							
135	7	7	9	18	28								
136	7	7	9	20	29								
137	7	7	9	18	28								
138	7	7	9	18	28								
139	7	7	9	19	28								
140	7	7	9	18	28								
141	7	7	8	20	28								
142	5	5	8	21	29								
143	7	7	9	18	28								
144	7	7	9	19	28								
145	6	6	8	18	28								
146	7	6	8	16	27	23	20	23					
147	5	6	8	21	29								
148	6	6	7	20	29								
149	4	5	6	21									
150	5	6	7	18	28	24	11						
151	4	4	7	13	24	21	19	29	46	67	105		
All basins	6	5	7	13	25	19	14	20	31	30	39	26	43

9.2.5 Validation

The quality of the Baltic Sea model has been investigated previously /Engqvist and Andrejev 2003/. The dominant factor when it comes to uncertainties for the BC year simulations is the meteorological forcing. Very little data is available on the detailed climate in Scandinavia thousands of years ago. The process of interpolating the model results to the basin connections may introduce errors, but these are unlikely to influence the order of magnitude of the calculated water exchange flows.

The model used for the AD years has been validated for the year 2004. Measurements of sea level, salinity and temperature have been used to compare with model results.

In Figure 9-7 a comparison is made between observations by SMHI and modelled sea level. The time series are closely correlated, but in general the modelled sea level is somewhat lower than the observed. When the modelled sea levels are compared with the sea levels from the Baltic model used as forcing, it becomes clear that the forcing data produces the offset. Öregrundsgrepen responds quickly to sea level variations at the northern boundary, and the modelled levels at Forsmark are a direct reflection of the forcing data. Overall there is a reasonable correspondence between modelled and measured data, indicating that water circulation due to sea level variations is modelled realistically.

Figures 9-8 and 9-9 compares modelled and measured data, forcing data and data from the Water Forecast model (DHI's operational model for the Baltic Sea). The correspondence between measured and modelled temperature data is fairly good, but the model does not capture the upwelling of cold water in July nor does it show the high maximum surface temperatures in August. Since the upwelling is not an effect due to local factors in Öregrundsgrepen, the lack of response in the local model is due to the forcing data. The temperatures from the Water Forecast model seem to match the measured temperatures slightly better.

The correspondence between measured and modelled salinity in Öregrundsgrepen is poor. The modelled variability seems good, but there is an offset in the data of more than 0.5 psu. This is due to the forcing data. The modelled data correlate well with the forcing, which is to be expected, but the forcing differs significantly from the measured data on the northern boundary. Again, there appears to be a somewhat better match between the measured salinity and the salinity modelled by the Water Forecast model.

There are questions about the quality of both measurements and model forcing data at the boundaries. This makes it difficult to determine the quality of the local model. Based on previous experience, the local model is nonetheless expected to yield reasonable estimates of the annual mean circulation in Öregrundsgrepen for 2004.

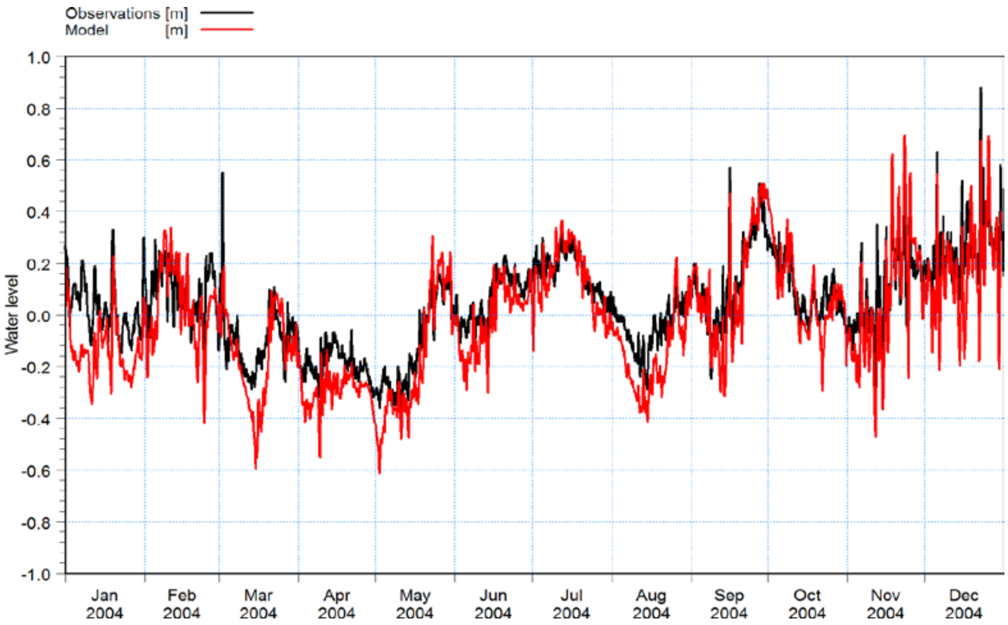

Figure 9-7. *Observed (SMHI) and modelled sea level at Forsmark 2004.*

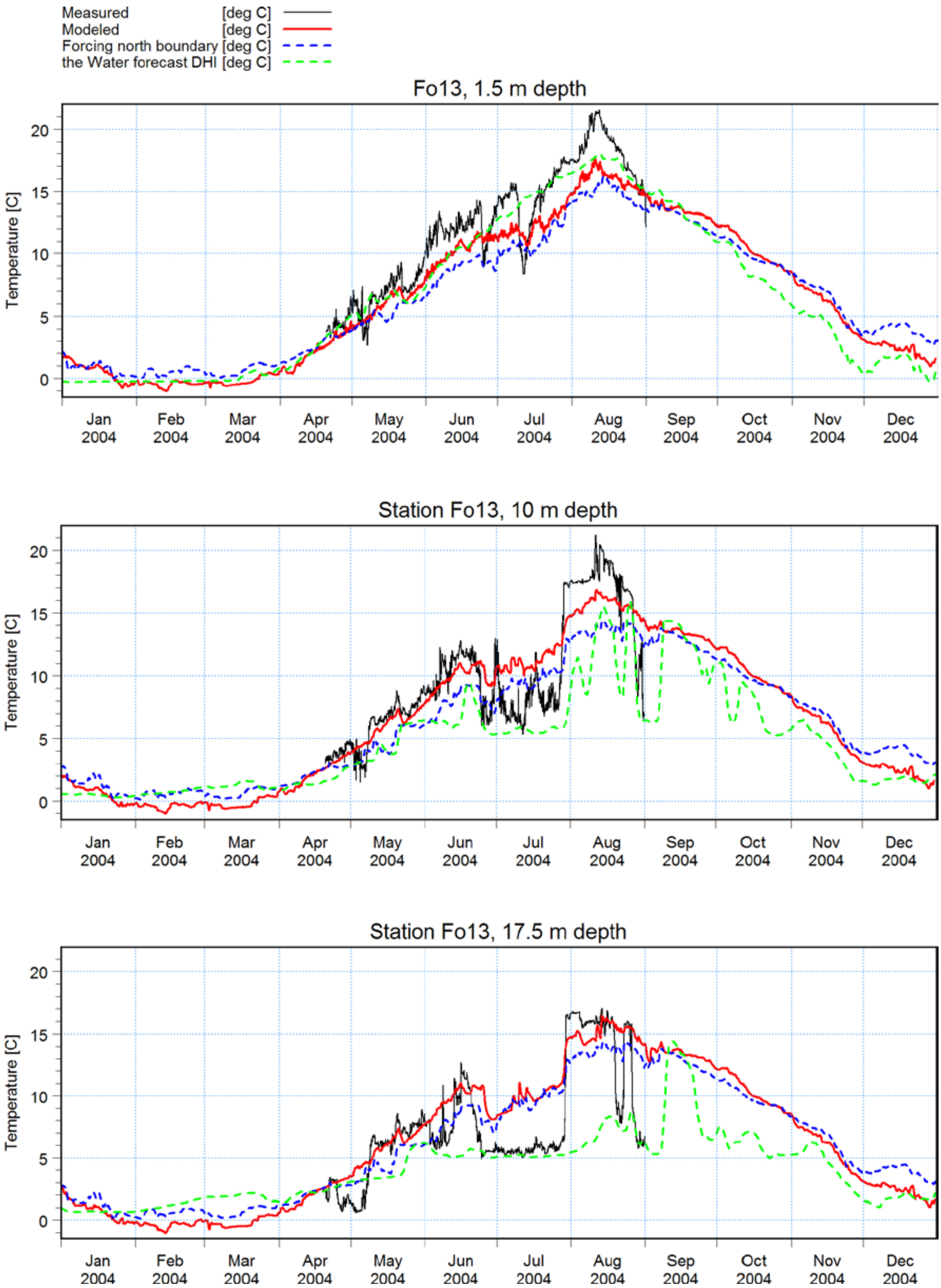

Figure 9-8. *Observed and modelled temperature at station Fo13 compared with the forcing temperature at the northern boundary as well as corresponding temperatures produced by the Water Forecast model.*

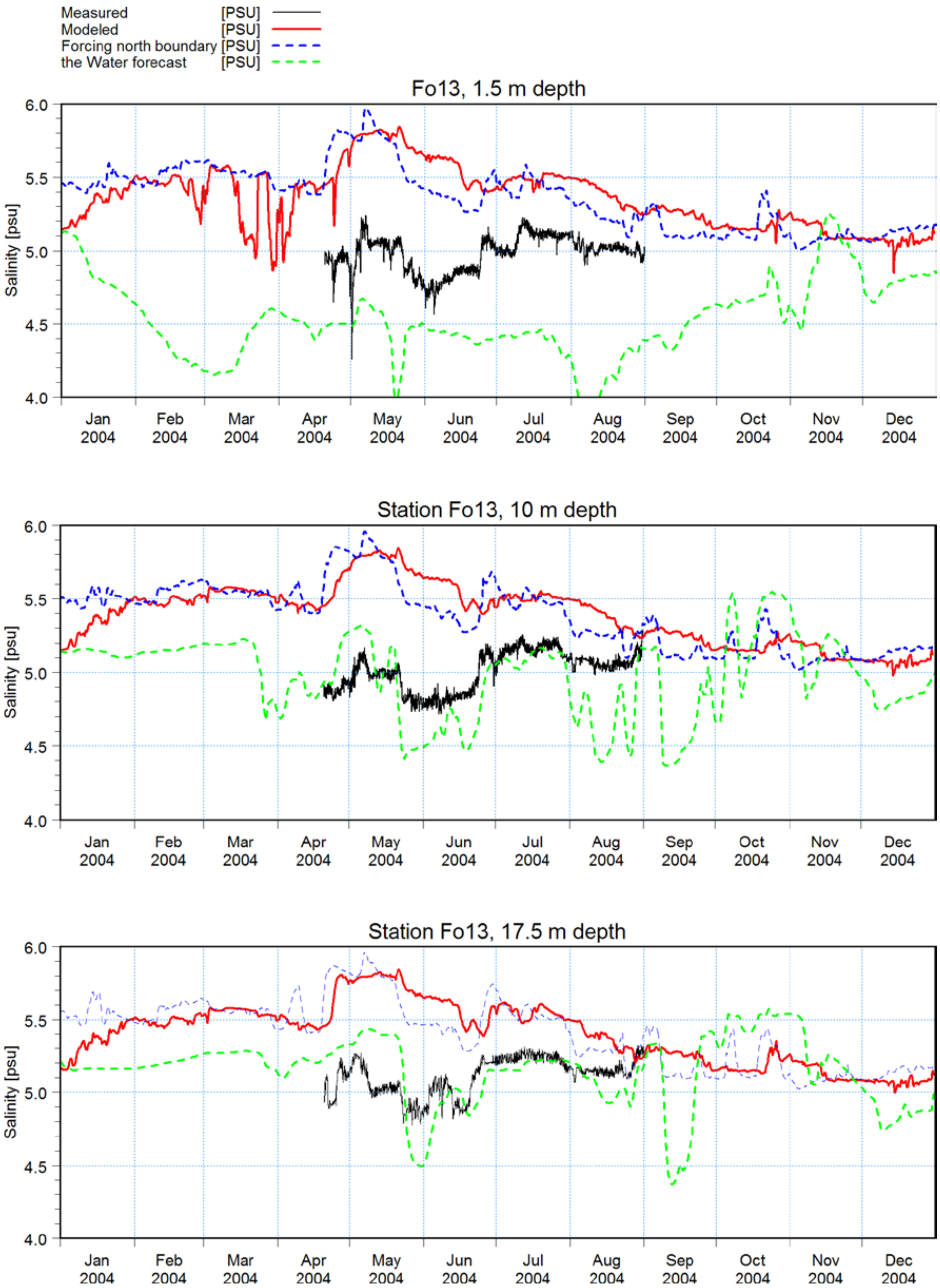

Figure 9-9. *Observed and modelled salinity at station Fo13 compared with the forcing salinity at the northern boundary as well as corresponding salinities produced by the Water Forecast model.*

9.2.6 Conclusions

Water circulation in the Forsmark marine area has been modelled for 13 different years spanning from 6500 BC to 9000 AD. Two different modelling approaches have been used for the BC and AD years, but both are based on three-dimensional hydrodynamic numerical models forced on their boundaries by exchange with the atmosphere, fresh water discharge, water level variations and changes in the stratification of salinity and temperature. The model outputs consist of hourly values for all hydrodynamic parameters for all computational cells (in three dimensions) for one year.

The yearly average flows between interconnected basins have been calculated from the computed hydrodynamic flow fields, along with an estimate of the mean residence time for each basin (using the average age concept, AvA). Note that the AvA considers only Baltic water as exogenous, i.e. it includes the effect of recirculation between basins.

The results for the average basin flows lie in the range from a few m^3/s to several thousand m^3/s. The magnitudes of the flows are to a large extent a result of the magnitudes of the cross-sectional areas through which the flows are defined as well as the size of the interconnected basins. Hence, the flows vary between the different years as the depths and coastline, and thus the existence of and volumes of the basins, change due to land uplift. A comparison with the results presented in Chapter 5, using another year and another model, indicates the same order of magnitude overall but great differences for specific basins.

The results for the AvA show an estimated residence time ranging from about two to ten days for the BC years (when the Forsmark area is located in open sea), and increasing to over a month for the later AD years as basins become increasingly isolated and their exchange with the Baltic Sea increasingly restricted. There is a local peak in the average age at around 1000 AD. This is probably due to the fact that Öregrundsgrepen is gradually closing in the south, decreasing the through-flow. Between 1000 and 3000 AD it seems that the basin volumes decrease faster than the cross-sectional areas of the inter-basin connections, resulting in a small increase in water exchange. For specific basins, the relocation of local river input due to changes in the coastline can have a marked effect on the AvA.

A preliminary validation shows that the model for 2020 AD is highly dependent on the quality of the boundary conditions. Both in water level and salinity there is an offset in the modelled data compared with measurements due to offsets in the forcing data. This suggests that the model for 2020 AD is controlled by the state of the Baltic Sea and not by local processes, which makes it difficult to determine the quality of the model.

A sensitivity analysis where different forcing factors have been removed one by one yields the following overall picture. For the year 2020 AD, removing wind or sea level variations has the greatest effect on the AvA. For the year 5000 AD, when Öregrundsgrepen has become an estuary with only one boundary with the Baltic Sea, removing sea level variations no longer has any noticeable effect on the AvA. Instead, removing vertical salinity variations or land runoff now has a more pronounced impact on the calculated AvA. Note that wind is still an important factor for 5000 AD. In conclusion, Öregrundsgrepen changes as the southern strait closes from a coastal area with a through-flow forced by sea level variations to an estuary with a density-driven estuarine circulation. In both cases, however, local wind plays an important role in the water exchange between basins, particularly in shallow areas near the shoreline. In general, completely removing a particular forcing results in relative changes in the AvA of less than 50%, though in some cases local variations of between 100 and 200% are found.

9.3 Ecological processes in the marine environment – ecosystem model for present conditions (2020 AD)

9.3.1 Methodology

The ecosystem model describing the most important ecological processes in the Öregrundsgrepen area was developed based on present-day conditions. The purpose was to:

- To present a dynamic C:N:P-based ecosystem model that is validated for present-day conditions (2020 AD) and can be coupled to the radionuclide model.

- To present complementary results, e.g. larger spatial and temporal distribution of ecological processes, that can be compared with earlier ecosystem models (Chapters 4 and 6 this report) carried out on a basin scale.

The estimated hydrodynamic flow fields for 2020 AD were directly connected to relevant transport processes included in the ecosystem model. The ecological data and functional groups included in the model are described in more detail in /Erichsen et al. 2010/and in summary below. The model results were validated by comparison with data from the local monitoring programme.

Geographically, the model was developed for the same area as previous ecosystem models (see Chapters 4 and 6) and was built to describe the fluxes of matter (i.e. carbon) within and between delimited basins, as well as between functional groups in the ecosystem.

The ecosystem model was implemented in the ECO Lab equation solver. Recent peer-reviewed studies where ECO Lab was instrumental include /Arndt and Regnier 2007, Lessin and Raudsepp 2006, Vanderborgth et al. 2007/ and /Rasmussen et al. 2009/.

The ecosystem model was forced by the hydrodynamic outputs of the MIKE 3 FM model (see Section 9.2). After model calibration, the ECOLab model was run for 5 years using the same hydrodynamic outputs and using the results from one year's simulation as initial conditions for the next year's simulation. The model data presented in 9.2.4 represent the results of the 5th year's simulation.

9.3.2 Short description of ecosystem model

Description of pelagic state variables and processes

An extensive description of the pelagic state variables (pools of organisms and matter) and processes can be found in /Erichsen et al. 2010/. Previous modelling efforts suggest that pelagic production is much less important than benthic production in most of the Forsmark area. The pelagic state variables in the model are therefore the simplest possible including phytoplankton, zooplankton, planktivorous fish and detritus in addition to the nutrients nitrogen and phosphorus. All state variables are defined in terms of carbon (C), nitrogen (N) and phosphorus (P).

Description of benthic state variables and processes

In the present set-up for the ecosystem model, the epibenthic autotrophic module represents three functional groups of attached macrophytes: perennial macroalgae (brown algae such as *Fucus*), annual macroalgae (*Ulva*, *Pilayella*), both of which take up nutrients from the water column, and "seagrass" (eelgrass, e.g. *Zostera, Potamogeton, Vaucheria*) but also including the rooted algae *Chara*, which take up nutrients both from sediment pore water and from water in the lowest water layer above the seabed. Other autotrophic components are epibenthic microphytes and epiphytes growing on macrophytes. The heterotrophic sediment processes include traditional microbial sediment processes but also benthic filter feeders (e.g. *Cardium*), epibenthic grazers (snails), deposit feeders (e.g. *Macoma* and various amphipods) and a predator (*Saduria*) preying on all other epi- and infauna.

9.3.3 Input data

Pelagic state variables such as phytoplankton and dissolved nutrients in a 3-D model can be transported between model grid cells with currents and as such have the ability to occur over the entire model area without any restrictions. However, the realized distribution of biomass in the model is the effect of internal processes (growth, loss, grazing/predation) within a grid cell and physical exchange between grid cells and between water column and sediments. In contrast to pelagic state variables, benthic variables that are fixed on the bottom, such as fucoid algae that require a hard substrate for attachment can only occur in certain grid cells, while non-sessile benthic organisms, such as predators, can be found in several habitats and growth and loss processes determine if their biomass can be sustained in the individual grid cells. An extensive description of the data used can be found in /Erichsen et al. 2010/. An overview of the input data used for the state variables follows below.

9.3.4 Results – ecosystem model

Mass budget and biomass distribution in selected basins

In order to verify the modelled ecosystem results, an overall mass budget describing the carbon fluxes of the food web of basin 116 has been calculated. All ecological processes can, individually, be compared with similar mass budgets presented in Chapter 6. In this analysis the mass budget is illustrated for:

- The pelagic zone (Figure 9-10).
- The benthic zone (Figure 9-11).
- Secondary producers (Figure 9-12).
- An inorganic material mass budget (Figure 9-13).

Organism biomass and production are presented in Table 9-5 for each of the subsystems, and the same rates are compared with the earlier study. The present analysis focused on how the modelled mass budgets and fluxes compare with results from the previous model approaches (GIS modelling and Box models). Further, the biomass distributions in selected basins are presented in order to describe spatial characteristics and differences within the Öregrundsgrepen area.

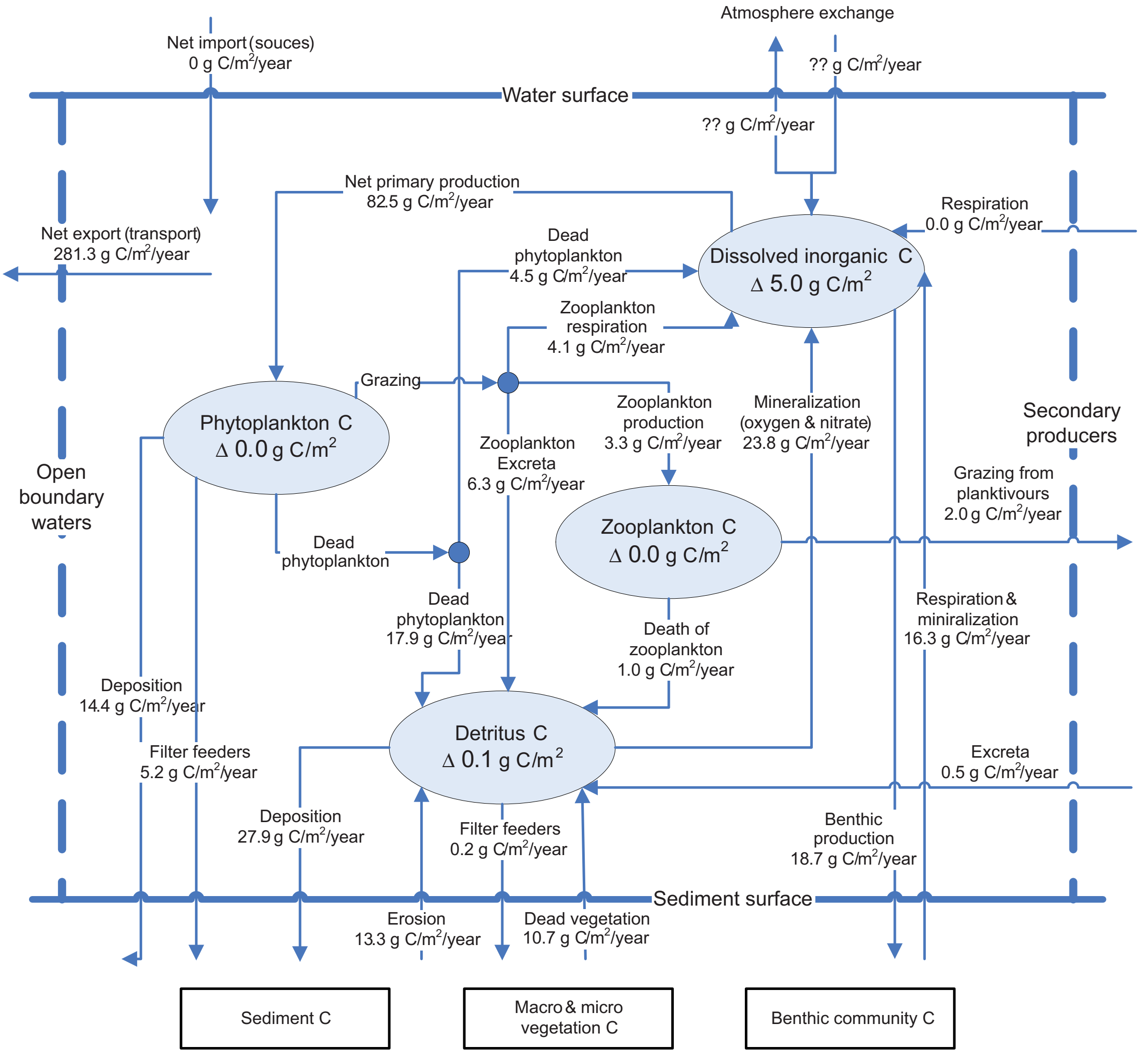

Figure 9-10. *Carbon mass budget results covering the pelagic zone in basin 116. As part of the model calibration, changes in pools/biomass from 1 Jan to 31 Dec (Δ g C/m^2) were kept to a minimum, preferably zero.*

Table 9-5. Comparison of primary production and biomass for basin 116 in Forsmark and earlier results (see Chapter 6).

State variables	Primary production gC/m^2 /year		Consumption by gC/m^2 /year		Biomass gC/m^2	
/Chap. 4/	*/Chap. 6/*	*this study*	*/Chap. 6/*	*this study*	*/Chap. 6/*	*this study*
Phytoplankton	11.7	82.5			0.12	1.43
Benthic microphytes	30.5	4.9			2.37	0.22
Benthic macrophytes	52.8	13.7			11.07	9.47
Bacterioplankton			61.4	46.2[1]	0.24	na
Zooplankton			8.6	13.7	0.04	0.06
Benthic bacteria			13.3	15[2]	0.82	na
Benthic herbivores			13.7	2.2[3]	1.31	1.56
Benthic filter feeders			16.3	5.4[4]	1.47	na
Benthic detrivores and meiofauna			47.7	17.9[5]	3.85	4.97
Benthic carnivores			3.3	0.4	0.33	0.16[6]
Benthic-feeding fish			1.3	0.4	0.19	
Planktivorous fish			0.7	2	0.10	1.36
Predatory fish			0.4	na	0.06	
Birds			1.5	na	0.01	
Seals			0.2	na	0.01	
Humans			0.0	na		
Sum primary production	95.0	101.1				

1. Calculated indirectly by summing degradation processes: dead phytoplankton → (dic + dead phyto till DetrC + mineralization).
2. Calculated indirectly by summing mineralization of Sed1 + Sed 2.
3. Production is assumed to be respired rather than be consumed by herbivores.
4. Filtration rate of phyt + detrC.
5. Includes assimilation only (ingestion rate c. 4 times higher).
6. Includes benthic-feeding fish.

Pelagic and benthic primary production in basin 116

The input of carbon to the pelagic system by pelagic primary production was estimated to be 82.5 g C m^{-2} year^{-1}, whereas the figures for *perennial macroalgae* and *rooted vegetation* (macrophytes) as well as *microalgae and epiphytes* were 13.7 and 4.9 g C m^{-2} year^{-1}, respectively (Table 9-5). Compared to data from the GIS model presented in Chapter 6, phytoplankton production was 7 times higher while macroalgae and microphytes production was 6 and 4 times lower, respectively, in this study. Accordingly, relative availability of primary production for consumers in the food web differs substantially in terms of the overall carbon flux in the pelagic and benthic subsystems. However, the total primary production averaged over basin 116 was comparable at 101 g C m^{-2} year^{-1} to an earlier estimate of 95 g C m^{-2} year^{-1} (see Chapter 6).

One third (32%) of the pelagic primary production was lost from the water column through advective processes and exported to nearby basins. Sedimentation of living and dead phytoplankton was the most important process fuelling the benthic food webs (33% of production), followed by filter-feeder grazing (6%) and zooplankton faeces production and sedimentation (5%). Total deposition from the pelagic production was approximately half of the annual primary production. Accordingly, the quality and quantity of the deposited material should be considered in the assessment of radionuclide flows. In terms of carbon, the deposition will fuel the benthic food web including detrivores and meiofauna as well as deposit feeders. Among benthic primary producers, only microphytes were grazed in significant amounts, totalling 43% of the annual production of 4.9 g C m^{-2} year^{-1}.The total annual grazing was comparable to the earlier estimate, with the notable exception that grazing by benthic herbivores was much lower in this modelling, also reflecting a much lower benthic production (Table 9-5).

Biomass

The annual average biomass for the different functional groups within basin 116 is shown in Table 9-5. The biomasses of zooplankton, macrophytes, deposit/detritus feeders, herbivores, as well as benthivorous fish are comparable and within the same range as previous estimates of biomasses (see Chapter 6, Table 6-8). However, the biomasses of phytoplankton, microalgae/epiphytes and planktivorous fish predators differ between these studies. In particular, the modelled biomass of planktivorous fish is much higher in this model compared with previous results.

The phytoplankton biomass differed significantly compared with the previous estimate of 0.12 g Cm^{-2} (see Chapter 6). The current estimate of 1.4 g C m^{-2} is much more reasonable considering the measurement of chlorophyll-a carried out in the area. Because of the low phytoplankton biomass in the previous ecosystem model, the model becomes relatively more dominated by benthic primary production. This may explain the relatively higher modelled microalgal and epiphytic biomasses, compared with this study.

The average concentration of planktivorous fish in basin 116 simulated in this study was about 10 times higher at 1.3 g C/m^2/y than previous estimates (Table 9-5). This is a consequence of the model approach where fish are stationary in a grid cell/basin and consumption is regulated solely by temperature-dependent physiological rates in addition to zooplankton production and horizontal transport into that grid cell. So even within basin 116, the average biomass of planktivorous fish differs markedly between model grid cells with the highest biomass, where advective fluxes are high. In other basins, the mean biomass approaches zero because currents (i.e. zooplankton fluxes) are low, while in the narrow strait the steady-state biomass is much higher.

Sediment budget

Averaged over the entire area, basin 116 acts as a sedimentation area for both organic and inorganic solids with accumulation rates of 12.6 g C m^{-2} y^{-1} and 56.1 g iSS m^{-2} y^{-1}, respectively (Figures 9-11, 9-12 and 9-13). In comparison, the GIS modelling study calculated a much lower burial rate of 0.07 g C m^{-2} y^{-1} (Chapter 6). The accumulation of suspended solids in the present model is roughly equivalent to an increase in sediment deposition of 0.06 mm y^{-1}.

Spatial biomass distribution

The spatial variation in biomass within and between basins as described by the ecosystem model is presented in Figure 9-14. For the sake of simplicity, only data from 8 basins are presented. In six of these (116, 117, 118, 120, 121 and 134), radionuclides are introduced with groundwater, while two basins of the eight did not receive radionuclides via groundwater. The pelagic biomass (per m^{-3}) of phyto- and zooplankton and planktivorous fish varied by almost a factor of 2 across the basins, while the within-basin variation, was generally on the same level or higher. The median biomass of phytoplankton and pelagic planktivorous fish was comparable in level and co-varied across basins. In contrast, the biomass of zooplankton was much lower and showed no relation to either phytoplankton or planktivorous fish (Figure 9-14).

In contrast to the pelagic biomasses, most benthic organism groups showed much higher variation. Rooted vegetation and macroalgae varied by 1–2 orders of magnitude across the eight basins, with higher biomasses in the smaller and shallow basins 117–118, 120–121 and 134 and lowest biomass in the deep 123 basin (Figure 9-15). The biomass of carnivores (i.e. *Saduria* and benthic-feeding fish) was consistently low across the basins, while the biomass of deposit feeders was consistently high with limited variation across the basins.

The biomass of rooted macrophytes and macroalgae showed a strong inverse correlation to the average depth of the basins, underlining the fact that light availability was the primary limiting factor for these autotrophs (see details in /Erichsen et al. 2010/).

The biomass of deposit feeders (*Macoma baltica*, amphipods) showed a weak but significant decrease ($r = 0.49$, $p = 0.03$) with depth, which was somewhat unexpected. But a closer examination of model data shows that the highest rates of detritus production actually occur in shallow waters caused by decaying macrophyte leaves and tissue from macroalgae, along with depositions from benthic filter feeders. Over time, the detritus will be advected to greater depth, but during this process the quality of the detritus will gradually decrease, making it less valuable for detritus feeders[1].

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[1] Growth formulation in detritus feeders includes a quality term for detritus and organic material in surface sediments, i.e. growth efficiency decreases with decreasing concentration of nitrogen in organic matter.

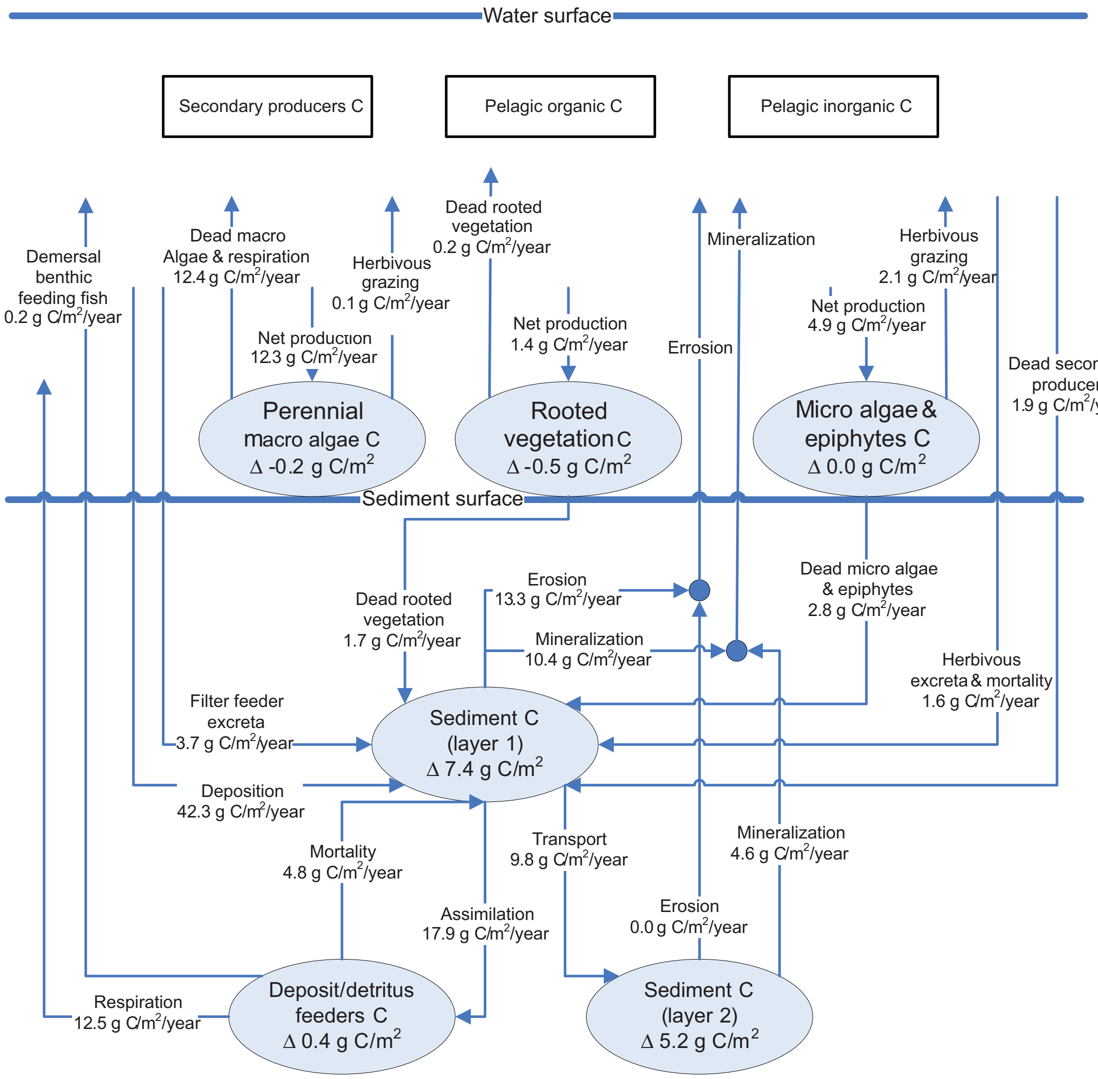


Figure 9-11. *Carbon mass budget results covering the benthic zone in Forsmark.*

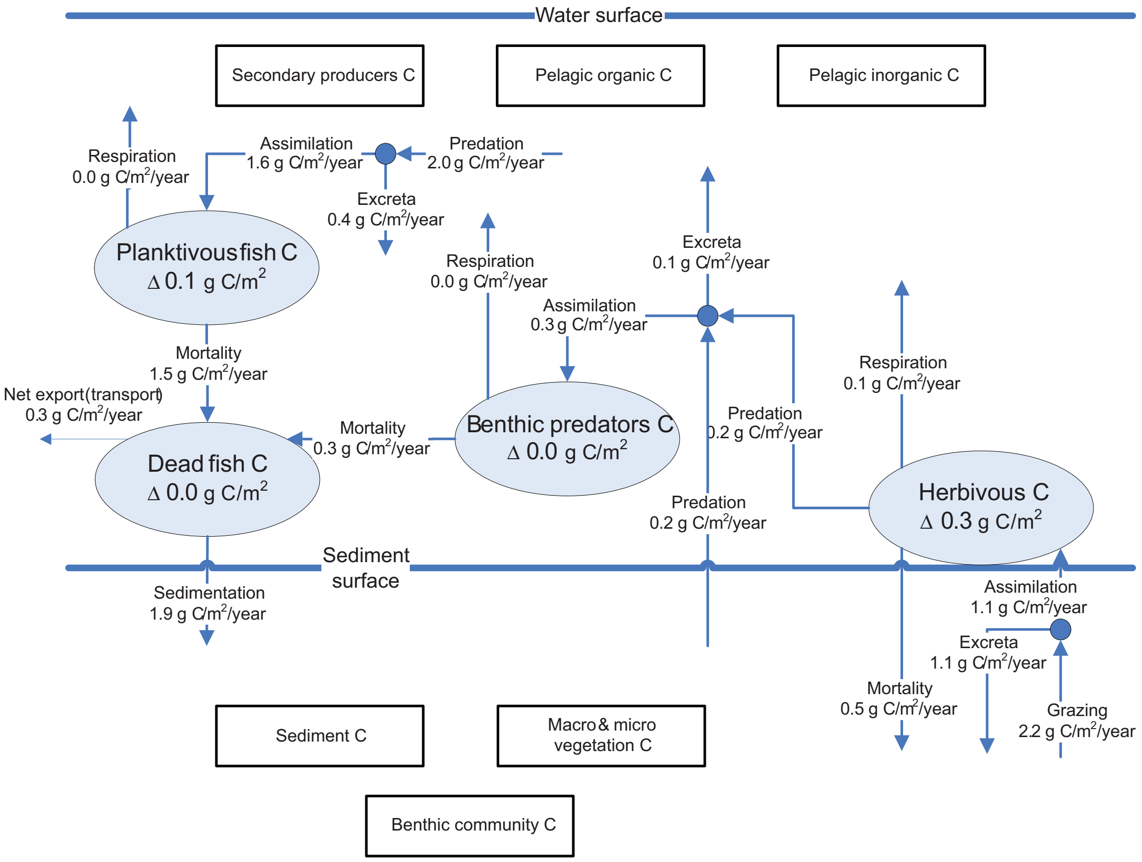


Figure 9-12. Carbon mass budget results covering secondary producers in Forsmark.

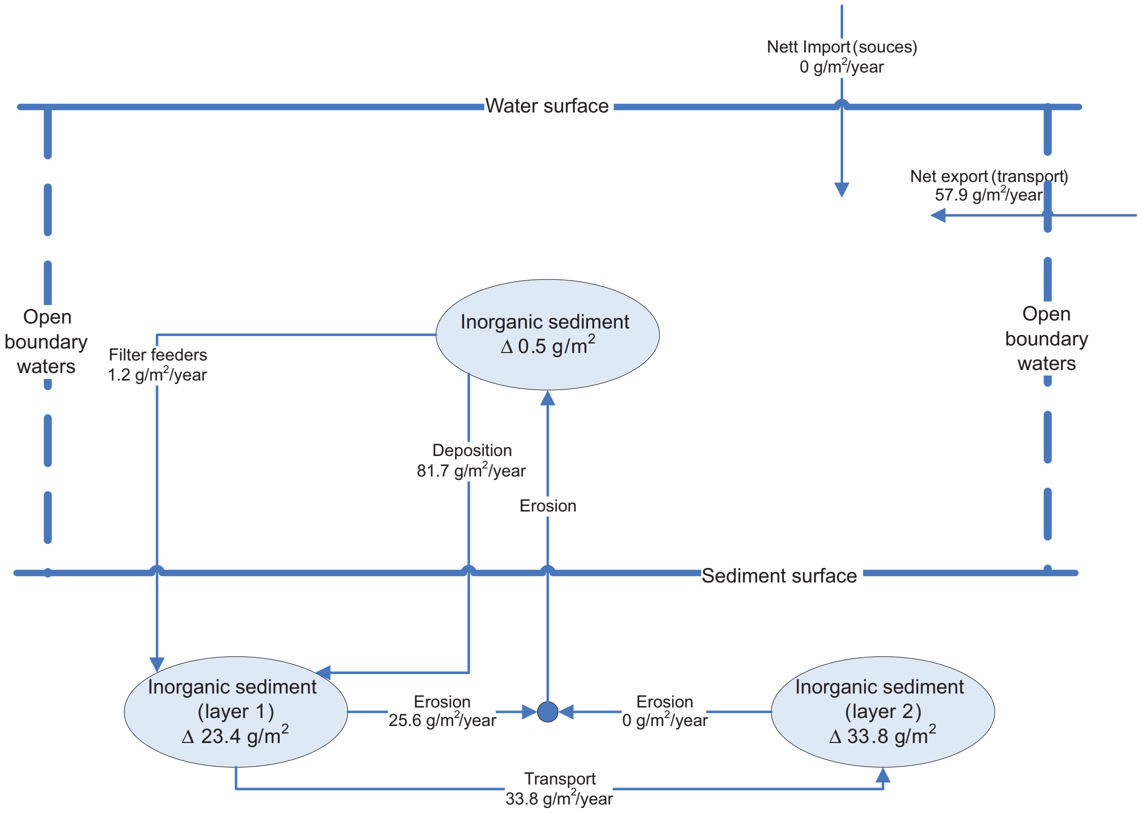


Figure 9-13. Mass budget of the inorganic material including the fluxes between the pelagic and benthic compartments and between the two sediment compartments.

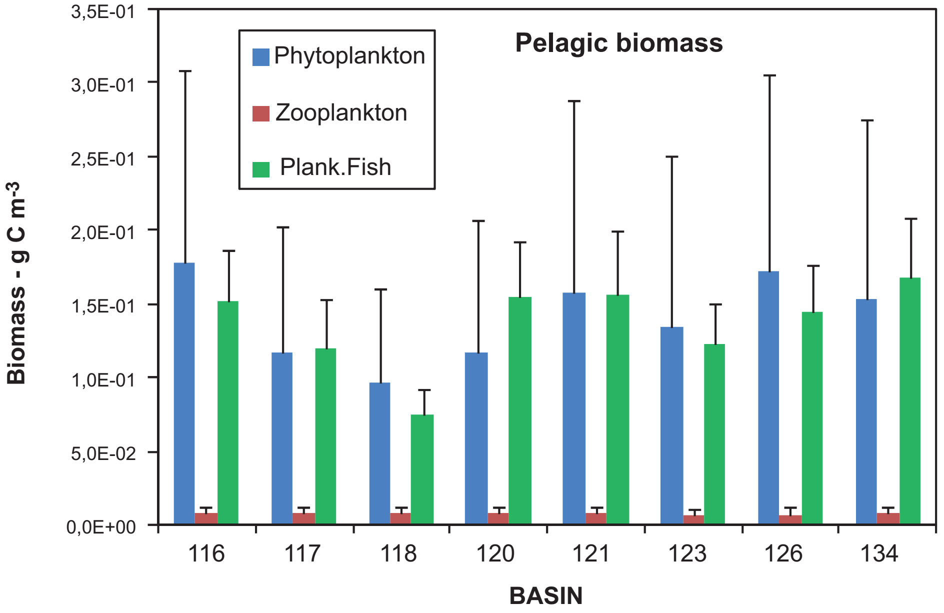


Figure 9-14. Biomass of pelagic (g C m^{-3}) auto- and heterotrophes across 8 basins in the Forsmark area. Median values calculated based on temporally averaged biomasses from individual model grid cells. Error bars denote +1 SD and reflect variation within individual basins.

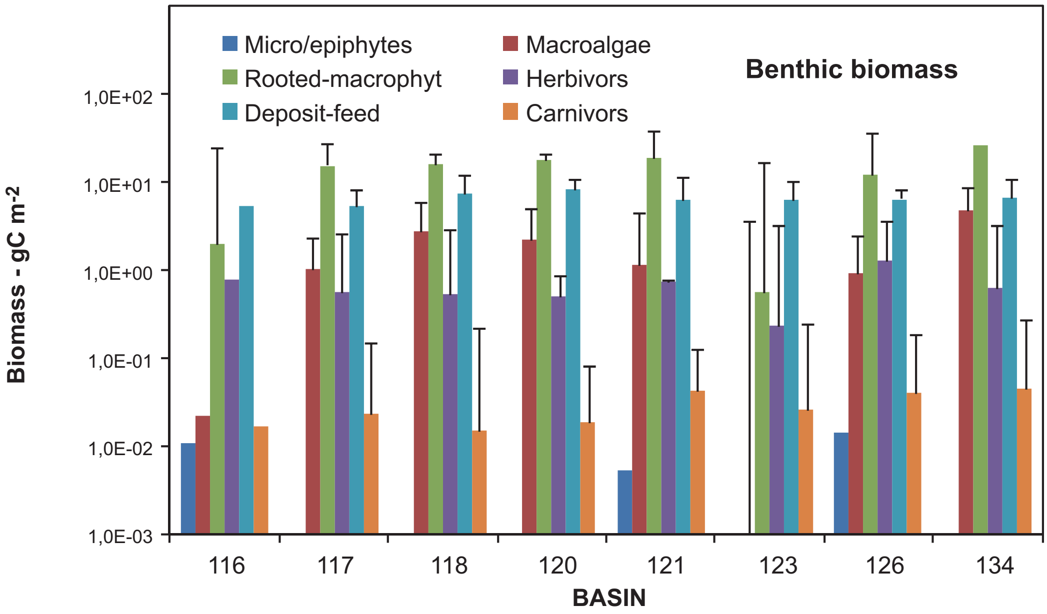


Figure 9-15. Biomass (g C m^{-2}) of benthic auto- and heterotrophs across 8 basins in the Forsmark area. Median values calculated based on temporally averaged biomasses from individual model grid cells. Error bars denote +1 SD and reflect variation within basins. Notice the log scale on the y-axis.

9.4 Radionuclide model in the marine environment – present conditions (2020 AD)

9.4.1 Methodology

The radionuclide model was developed in order to:

- Present a dynamic high-resolution radionuclide model that can be used to evaluate the distribution of 6 selected radionuclides in the marine environment.
- Evaluate how the modelled bioconcentration factors (BCFs) for the different elements are dependent on the spatial and temporal variation of abiotic and biotic variables in the Forsmark area. Such information can be used to evaluate to what extent BCF estimates that are based on spot measurements can be considered to be representative for larger areas and seasons.

The estimated hydrodynamic flow fields and ecological processes (Sections 9.2 and 9.3 above) for 2020 AD were directly connected to the relevant transport and radionuclide processes in the radionuclide model. Geographically, the model was developed for the same area as previously described hydrodynamic and ecosystem models (Figure 4-1) and was built to describe the fluxes of radionuclides within and between delimited basins, as well as between functional groups in the ecosystem. The radionuclide model is described in detail in /Erichsen et al. 2010/ and in summary below. The radionuclide model was run for 8 years using the same annual outputs from the hydrodynamic and ecosystem model and using the results from one year's simulation as initial conditions for the next year's simulation. The model data presented in 9.3.4 represents the results of the 8th year's simulation.

9.4.2 Short description of the radionuclide model

Processes

Radionuclides are found in the environment in various forms, such as dissolved in water or in sediment pore water, adsorbed to surfaces (inorganic and organic), assimilated within organisms or precipitated in sediments. The distribution of radionuclides between these states depends on the nature of the radionuclide and the composition of inorganic and organic matter and organisms in the ecosystem. In the radionuclide model (i.e. an ECOLab template), the flux of radionuclides (RN) is assumed to be proportional to the flux of carbon in the ecosystem model for the following processes:

- Diffusion.
- Sedimentation and resuspension.
- Consolidation of the sediment (transport from sediment Layer 1 to Layer 2).
- Mixing between sediment layers due to deposit feeders' burrowing and feeding activity.
- Uptake and accumulation internally in microalgae and micro-/epiphytes, macroalgae, macrophytes and plants.
- Assimilation of radionuclides from food by herbivorous invertebrates, deposit feeders, planktivorous fish and benthic feeding fish/benthic predatory invertebrates.
- Death of plants and animals.
- Mineralization (i.e. release of radionuclides from dead organic matter scaled to the degradation rate).

In the set-up used, the radionuclide model differs in one important aspect from the ecosystem model – the loss of assimilated carbon through catabolism/respiration in plants and in animals is not followed by loss of assimilated radionuclides. The implication is that radionuclides are accumulated continuously and scaled to primary production (in plants) and to carbon assimilation in animals.

The process rates involving radionuclides and the variation of state variables were not modelled explicitly; instead, relevant carbon outputs from the ecosystem model were used as forcing values to drive processes and state variables in the radionuclide model.

In addition to processes following carbon flux, the following processes that are specific for radionuclides and unrelated to carbon fluxes are included in the model:

- Radionuclide decay (varies with the specific radionuclide).
- Adsorption and desorption of radionuclides (to/from detritus, phytoplankton, zooplankton, organic matter in sediments, microalgae and epiphytes, macroalgae, macrophytes, herbivorous

invertebrates, deposit feeders, planktivorous fish and benthic feeding fish/benthic predatory invertebrates).

- Precipitation (e.g. as sulphides under low redox conditions) and dissolution of radionuclides in the sediment.

A simplified conceptual diagram of the radionuclide model is shown in Figure 9-16.

Radionuclides are introduced to the pore water of the lower sediment layer (Layer 2) via groundwater inflow. From the pore water in sediment Layer 2, the dissolved radionuclide is either adsorbed to inorganic sediment (particles) or organic sediment, precipitates or is transported to the pore water in the upper sediment layer (Layer 1), driven by the groundwater inflow or due to diffusion. Analogous to processes in Layer 2 sorption, precipitation and transport to the near-bed water due to diffusion or groundwater inflow takes place in sediment Layer 1. Besides the transport of dissolved radionuclides from sediment Layer 1 to the near-bed water, radionuclides are introduced to the near-bed water via erosion of sediments and in dissolved form (from pore water), or adsorbed to inorganic and organic suspended sediments.

Model assumptions

The biomass of organisms is estimated as a concentration per volume (g Carbon (N and P) m^{-3} for pelagic organisms) or per area (g C, N, P m^{-2} for benthic organisms), but adsorption is related to the surface of an organism. Adsorption to organisms larger than phytoplankton was therefore multiplied by a volume-to-area factor, which is specific for each organism state variable and related to the typical size of organisms present in the ecosystem.

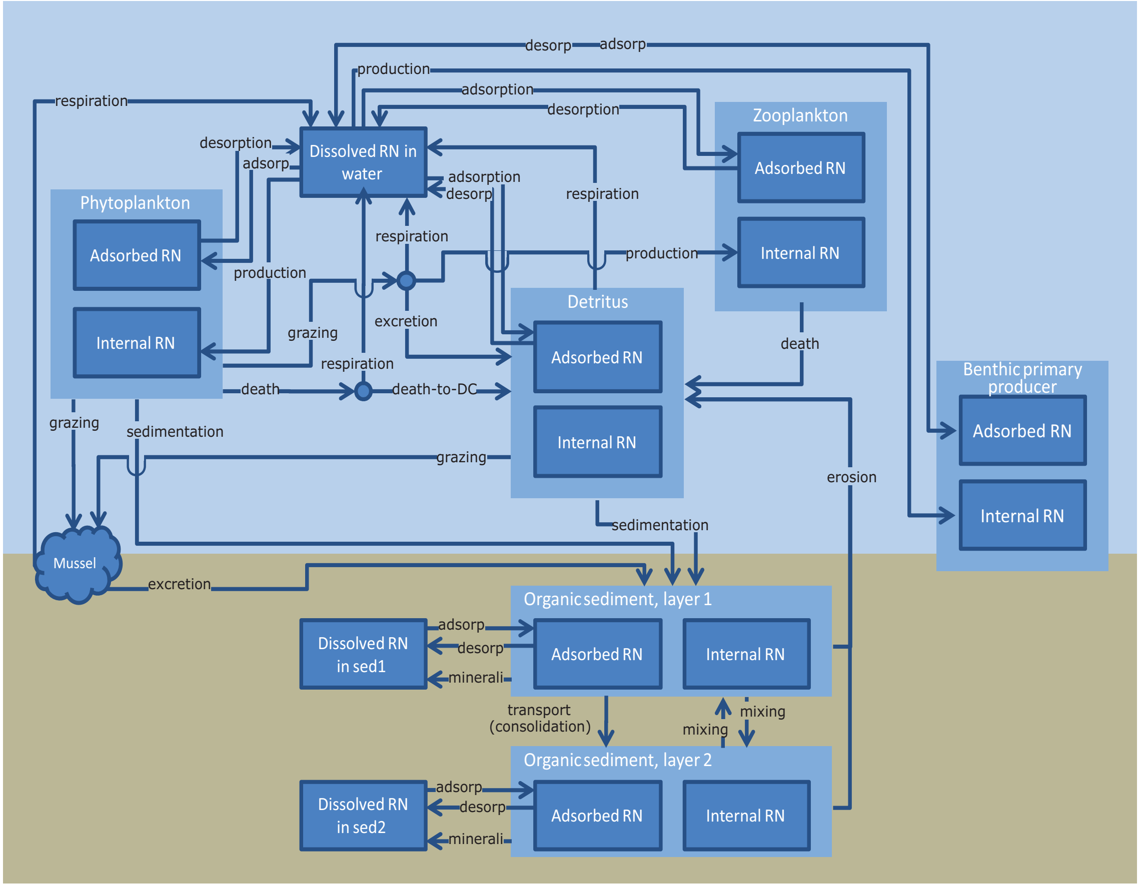


Figure 9-16. *Simplified conceptual radionuclide model showing 1) flows of radionuclides between inorganic state variables in the water column, in sediment layer 1 and layer 2, and between state variables across compartments, 2) flows between plankton state variables, detritus in the water column, organic matter in sediment layer 1 and layer 2, and 3) benthic primary producers and grazers (mussels).*

The adsorption of radionuclides to surfaces was differentiated between the organic and inorganic fractions by a partitioning coefficient relating to organic surfaces and another relating to inorganic surfaces. Besides adsorption and desorption, the flow of radionuclides related to primary producers is controlled by primary production, respiration and death. The uptake of radionuclides due to primary production incorporates the radionuclides internally in the primary producer as shown below for macroalgae:

$$\frac{RN_{dis} \cdot BP_{pr}}{BPC}$$

where RN_{dis} is dissolved radionuclides in the water (g m^{-3}), BP_{pr} is the production of perennial macroalgae (g C m^{-2} d^{-1}) and BC the biomass of macroalgae (g C m^{-2}).

9.4.3 Input data

Since the radionuclide model is an ECOLab template, all input data for the abiotic and biotic state variables and parameters of the ecosystem are the same as for the ECOLab ecosystem model, described in the former section (9.2).

Radionuclides selected for modelling

Various radionuclides may potentially be released to the aquatic environment from a deep repository of spent nuclear fuel. Six radionuclides were chosen to be included in the radionuclide model. In addition, C-14 was included for comparison, as this element can be regarded as a tracer for organic carbon (C-12), being subject to accumulation, metabolism to $^{14}CO_2$ and excretion. The radionuclides were chosen because in earlier studies they appeared to be of interest in the safety assessment /Nordén et al. 2010/ and because they represent a wide range of partitioning coefficients (K_d). Table 9-6 shows the radionuclides selected and the values of partition coefficients chosen for modelling in comparison with K_d values recommended by the IAEA, K_d values from a previous study and site specific K_d values used by SKB in the safety assessment (SR-Site) /IAEA 2004, Kumblad and Kautsky 2004, Nordén et al. 2010/.

Release scenario

The radionuclides were introduced to the model by groundwater inflow at a rate of 1 Bq/year, total for all basins. Individual radionuclides were introduced to the groundwater at a flow-proportional rate, and groundwater was then introduced to sediment Layer 2. The location of release areas is depicted in Figure 9-17.

Table 9-6. Values used in the model scenarios of radionuclide half-life, organic carbon partitioning coefficient (Kd_c) and inorganic partitioning coefficient (Kd_{in}). For comparison, Kd values recommended by the International Atomic Energy Agency /IAEA 2004/, Kd values used in an earlier study (a) /Kumblad and Kautsky 2004/ and Kd values for particulate matter (b) and for sediment layer 1 (c) in the landscape dose model /Nordén et al. 2010/ are also shown.

RN	Half-life (y)	Kdoc (m3/kg C)	Kdin (m3/kg DW)	kd-IAEA (m3/kg DW)	Kd a) (m3/kg DW)	Kd b) (m3/kg DW)	Kd c) (m3/kg DW)
C-14	5.73E+03	0	0	1	0	0	0
Cl-36	3.01E+05	6.0E-05	2.0E-05	3.0E-05	3.00E-02	0.001	0.01
Cs-135	2.30E+04	20	0.13	4	1	11	22
Nb-94	2.03E+04	4	0.50	800	500	196	85
Ni-59	7.60E+04	2.13	0.015	20	100	14	8.2
Ra-226	1.60E+03	10	0.05	2	5	4	2.5
Th-230	7.54E+04	417	1.67	3.0E+03	2.0E+03	995	97

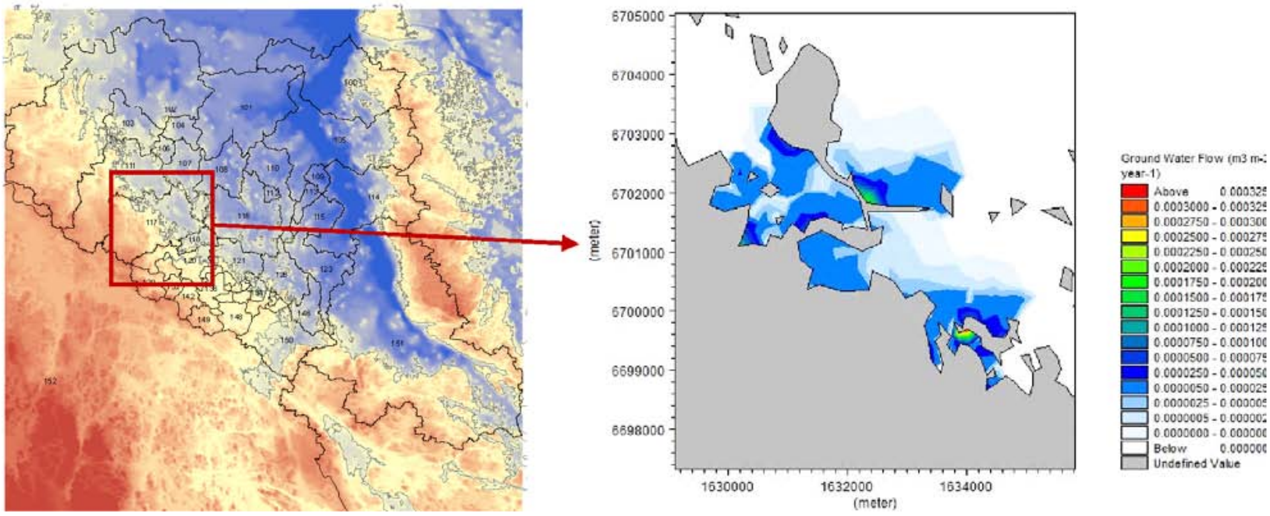


***Figure 9-17.** Locations of groundwater inflow and input of radionuclides into the model area in Forsmark.*

Groundwater flow and radionuclide release

Annual groundwater flow, A_{gwf} (m^3 $year^{-1}$ *or L* $year^{-1}$), was calculated from daily groundwater flow, D_{gwf} (m^3 $year^{-1}$ *or L* Day^{-1}), based on data from the numerous groundwater sources (*mm* d^{-1}) in the model area assuming mm d^{-1} is equal to L m^{-2}. The daily groundwater flow was calculated based on MIKE SHE modelling /Gustafsson et al. 2008/ The total annual groundwater flow in the Forsmark area was calculated to be 92.3 m^3, resulting in an average daily groundwater flow of 0.253 m^3, and an average radionuclide concentration in groundwater of 0.0108 Bq m^{-3}. The distribution of total groundwater flow and radionuclide release between basins is shown in Table 9-7.

9.4.4 Results – Radionuclide model

The fate of the modelled radionuclides in water and in organisms invariable will be a result of the assumptions and definitions made as well as how the hydrodynamic, ecosystem and radionuclide models have been linked. In the following we focus on presenting the results from the following perspectives:

- Relative distribution of radionuclides in abiotic fractions (sediment and water column).
- Spatial variation of radionuclides in water, sediment and biota.
- Temporal and spatial variation of bioconcentration factors (BCFs), using Ra-226 as an example.
- BCF per functional group and radionuclide.
- BCF per functional group and basin.
- Comparative analysis for basin 116.

Table 9-7. Groundwater flow into and radionuclide input to 6 model basins in Forsmark, from /Gustafsson et al. 2008/.

Basin	Groundwater flow (m3 year-1)	RN release Bq year-1
116	22.5	0.24
117	14.4	0.16
118	16.0	0.17
120	5.2	0.06
121	23.5	0.25
134	10.7	0.12
Total	*92.3*	*1.00*

A more thorough analysis and data presentations are available in /Erichsen et al. 2010/. It should be pointed out that uneven distribution of radionuclides in water and matter, especially occurrences of very low concentrations, can bias comparisons between basins if based on average values. Accordingly, in the following presentation of results, median values of radionuclide distribution and concentration have been used in all cases except the temporal analysis of BCF (see below).

Concentration of radionuclides in abiotic compartments of sediment and water

Modelled concentrations of radionuclides in water and sediment (Bq m^{-3}) are shown in Table 9-8 for Basin 116. Basically, the resulting concentrations are a result of the amount of radionuclide released, the characteristics of the receiving water and sediment, and the model assumptions concerning partition coefficients between sediments and water.

By applying a dimensionless approach, the inherent physico-chemical properties of the different radionuclides can be illustrated (Figure 9-17). Cl-35, which is characterized by a very low affinity to inorganic and organic surfaces and low partition coefficients (0.06 and 0.02, see Table 9-7), primarily occurs in the water column (76%), while the sediment-associated fractions add up to 12% in Layers 1 and 2. At the other end of the spectrum, only 2% of Th-230, with the highest partition coefficients among the selected radionuclides, occurs in the water column, while sediment fractions account for 51% and 47% of the "abiotic activity" in Layer 2 and Layer 1. The low mobility of radionuclides with high partition coefficients is illustrated by the difference in concentrations in Layer 2 and Layer 1, i.e. a higher enrichment in Layer 2 – where the radionuclide is released – compared with Layer 1. In contrast, the concentration of Cl-35 was similar in the two sediment layers due to the high mobility of chloride.

The analysis was repeated for several basins in the Forsmark area, and except for absolute concentrations, the distribution between the inorganic compartments was comparable to the results for basin 116. This leads to the conclusion that the main driver that affects the relative distribution of radionuclides between abiotic components such as water and sediment is the partition coefficients, rather than differences in the characteristics of the different basins.

Spatial variation of radionuclides in water, sediment and biota – comparison of Cs-135 and Ra-226

Due to high partition coefficients, K$_d$s, most radionuclides are associated with sediments, and their spread from release areas primarily occurs through resuspension events and subsequent sedimentation, especially for those radionuclides with high K$_d$s such as Cs-135. Figure 9-24 shows the spatial distribution of Cs-135 and Ra-226 in the upper sediment layer in terms of activity (Bq/m^2) after 8 years of modelling in the whole model area.

Table 9-8. Modelled concentration (Bq m^{-3}) of 6 radionuclides in abiotic fractions in Basin 116 following release of 0.24 Bq y^{-1} of each radionuclide. Data after 8 years of simulation. Values represent median values of all grid cells in the basin.

Compartment	Cl-36	Cs-135	Nb-94	Ni-59	Ra-226	Th-230
Water: dissolved	1.92E-08	1.31E-08	1.76E-08	1.87E-08	1.72E-08	6.01E-09
Water:particle bound	6.10E-11	2.98E-10	1.94E-09	7.38E-10	5.86E-10	1.28E-09
Sed layer 1: pore water	7.32E-11	8.78E-11	2.08E-10	1.98E-10	2.20E-10	2.06E-11
Sed layer 1: adsorb to inorganic	2.84E-09	2.23E-08	1.76E-07	5.25E-08	4.61E-08	3.90E-08
Sed layer 1: absorb to organic	1.71E-11	1.75E-08	1.80E-08	4.37E-08	7.43E-08	1.02E-07
Sed layer 1: absorb into organic	-	7.50E-09	5.06E-09	1.43E-08	2.23E-08	2.78E-08
Sed layer 2: pore water	4.39E-10	5.15E-09	2.12E-08	1.46E-08	1.98E-08	2.01E-08
Sed layer 2: adsorb to inorganic	2.50E-09	2.13E-08	1.70E-07	4.99E-08	4.39E-08	3.73E-08
Sed layer 2: absorb to organic	1.46E-11	1.65E-08	1.70E-08	4.22E-08	7.36E-08	9.69E-08
Sed layer 2: absorb into organic	3.66E-12	7.16E-09	4.85E-09	1.36E-08	2.12E-08	2.62E-08

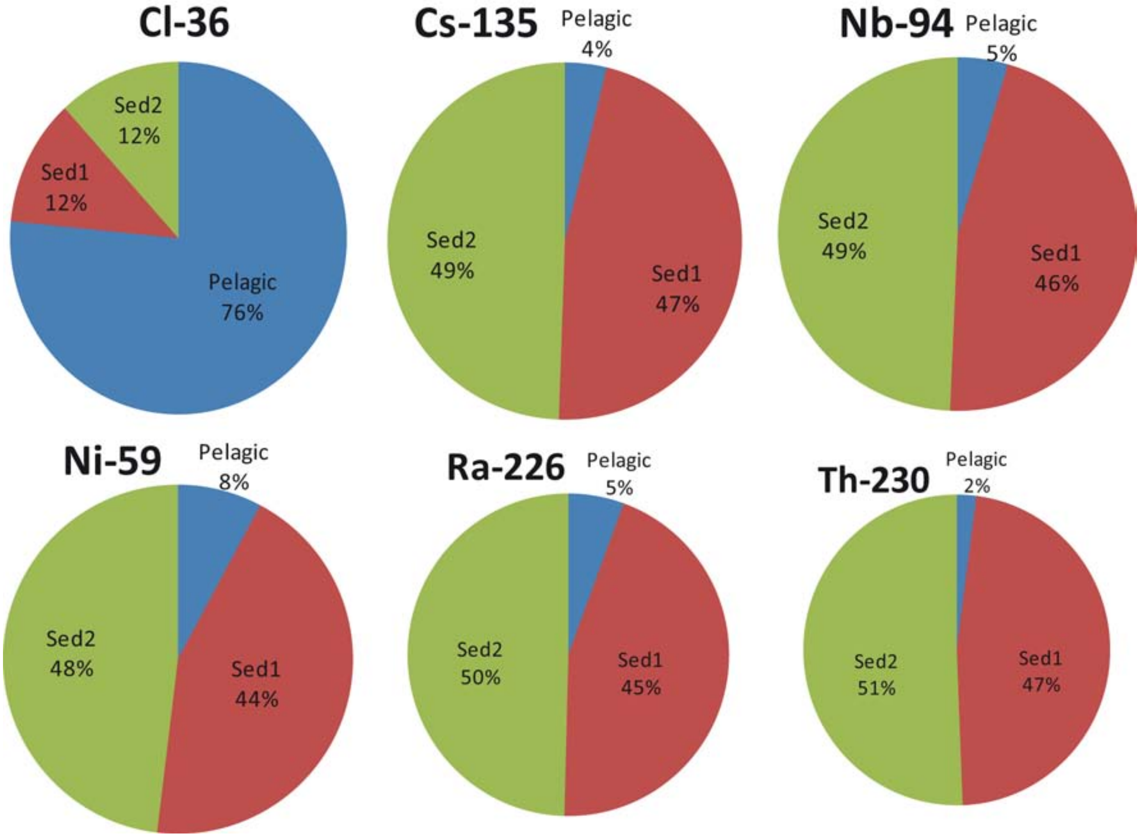


Figure 9-18. Relative distribution of 6 radionuclides, in basin 116 in Forsmark, between non-biotic components in the ecosystem model. Sediment compartments include radionuclides adsorbed to inorganic and organic surfaces, absorbed into organic matter and dissolved in pore water. Radionuclides in the pelagic compartment include radionuclides in solution and radionuclides adsorbed to non-living particles.

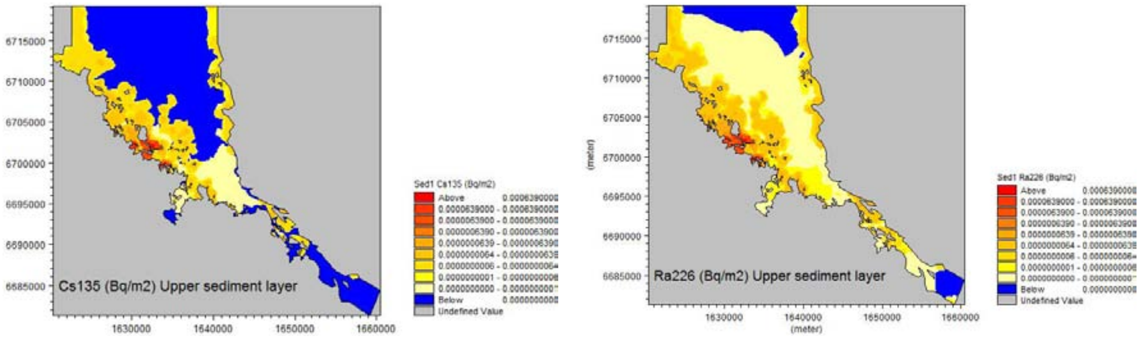


Figure 9-19. Modelled concentration of Cs-135 and Ra-226 in upper sediment layer; concentrations given in activity (Bq/m^2). The source strength was identical for both radionuclides at 1 Bq/y for the whole model area. Results after 8 years' modelling.

The activity of Ra-226 in surface sediments is predicted to occur almost over all of Öregrundsgrepen, due to a relatively low partition coefficient and a higher fraction occurring in the water column. In contrast, the physical spread of Cs-135 from release areas (see Figure 9-19) is less extensive due to a higher partition coefficient.

Due to lower partition coefficients, a larger fraction of Ra-226 is released from sediments compared with Cs-135. The higher rate of release from sediments results in a higher level of activity in phytoplankton, see Figure 9-20.

The modelled radium activity in sediments is also reflected in deposit feeders, which exhibit a larger area with Ra-226 activity compared with Cs-135, and the difference in activity is cascaded to benthic predators, which also exhibit a wider spread of Ra-226 compared with Cs-135 (Figures 9-21 and 9-22).

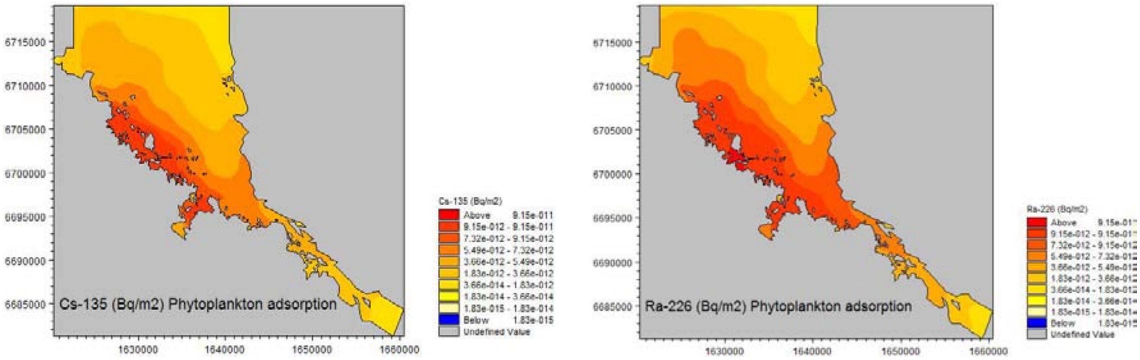


Figure 9-20. *Modelled activity of Cs-135 and Ra-226 adsorbed to phytoplankton. Results after 8 years' modelling.*

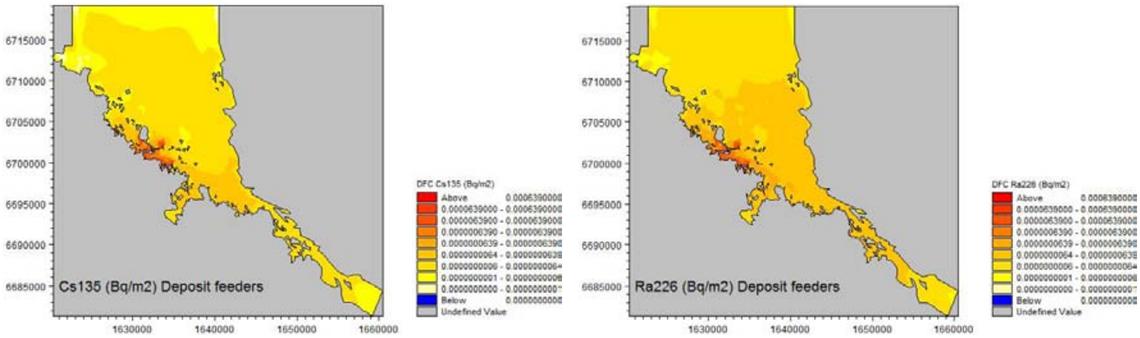


Figure 9-21. *Modelled activity of Cs-135 and Ra-226 accumulated in deposit feeders in Forsmark. Results after 8 years' modelling.*

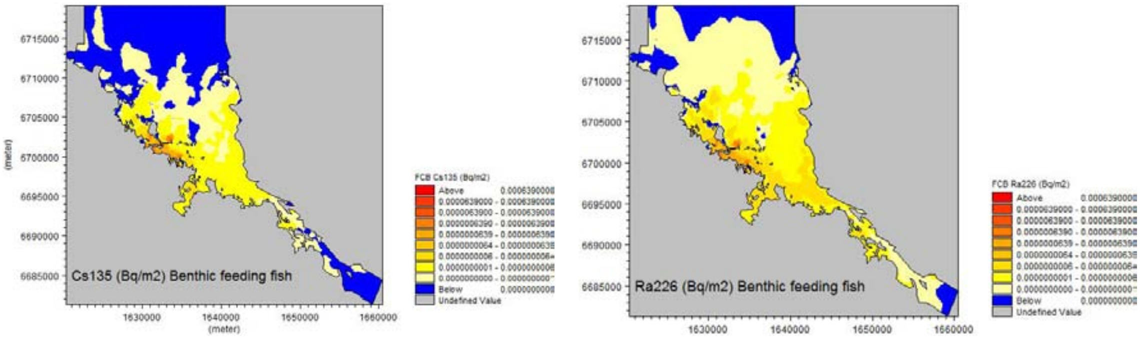


Figure 9-22. *Modelled activity of Cs-135 and Ra-226 accumulated in benthic predators. Results after 8 years' modelling.*

Temporal and spatial variation in BCF

Temporal characteristics – Ra-226

To illustrate the variation in BCF, a time series for Ra-226 was sampled (from model results covering the 8th year of modelling from 1 January to 31 December) in 4 grid cells (Figure 9-23; Points 1–4). Almost independently of the distance from release point of Ra-226 (see also Figure 9-17, where the area of groundwater release of radionuclides is presented), the temporal variation in BCF for phytoplankton shows similar patterns for all positions, i.e. a peak in January, stable values from April through September followed by a gradual increase through the autumn (Figure 9-24). The temporal variation in BCF is dependent on both variations in water concentration (especially near release from sediments, e.g. Point 1) and variations in algal biomass, with a dominance of the latter influence at increasing distance from radionuclide release.

Using a log-normal function, 75% of the variation in BCF could be explained by variation in algal biomass at Point 4 (Figure 9-25). The function indicates that radionuclide adsorption to phytoplankton is an important process in regulating the proportion between dissolved and particle-bound radionuclides, but also calls into question the concept of applying a fixed BFC value of a particular radionuclide to any environment.

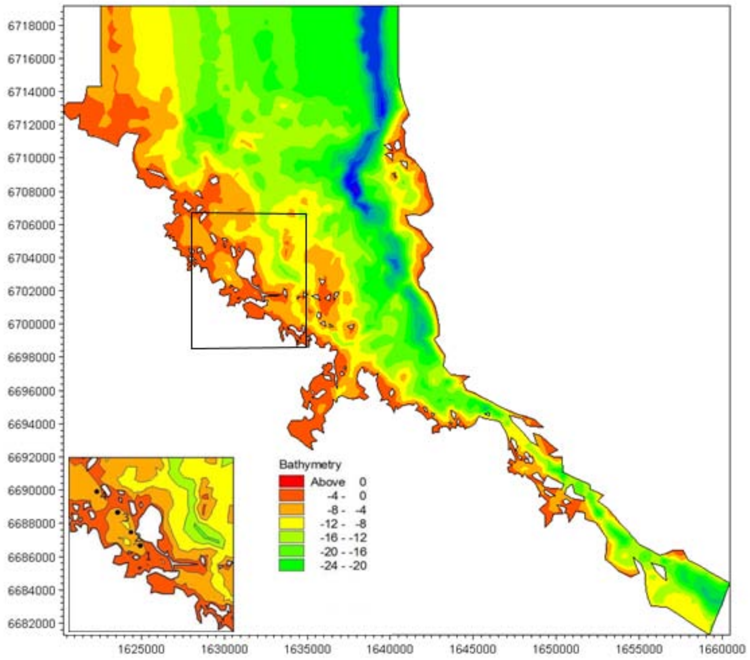


Figure 9-23. *Location of model sampling points (1–4) where temporal data on BCF in phytoplankton were sampled in model results. Point 1 represents a grid cell where radionuclides are released into sediment Layer 2.*

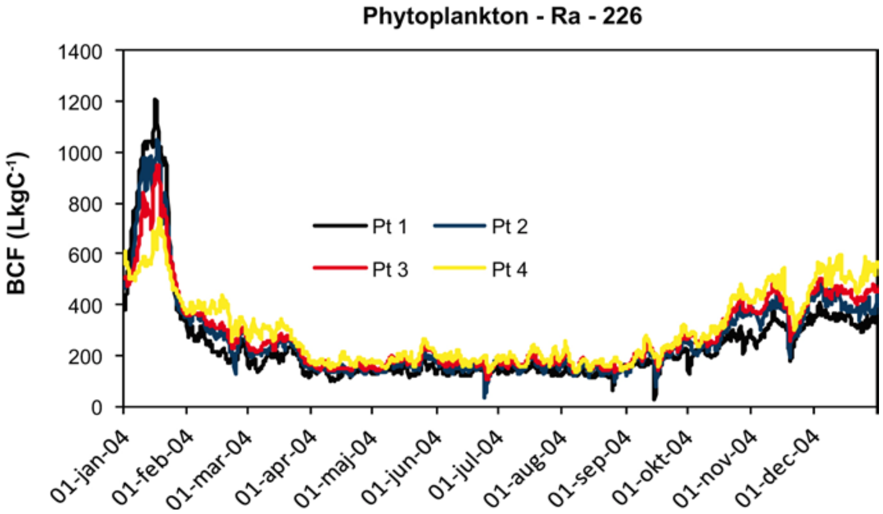


Figure 9-24. *Modelled BCF (biological concentration factor) for Ra-226 during a year. Points 1 to 4 represent sites with an increasing distance from a radionuclide release point (Point 1). BCF values from each grid cell represent the average BCF over the water column.*

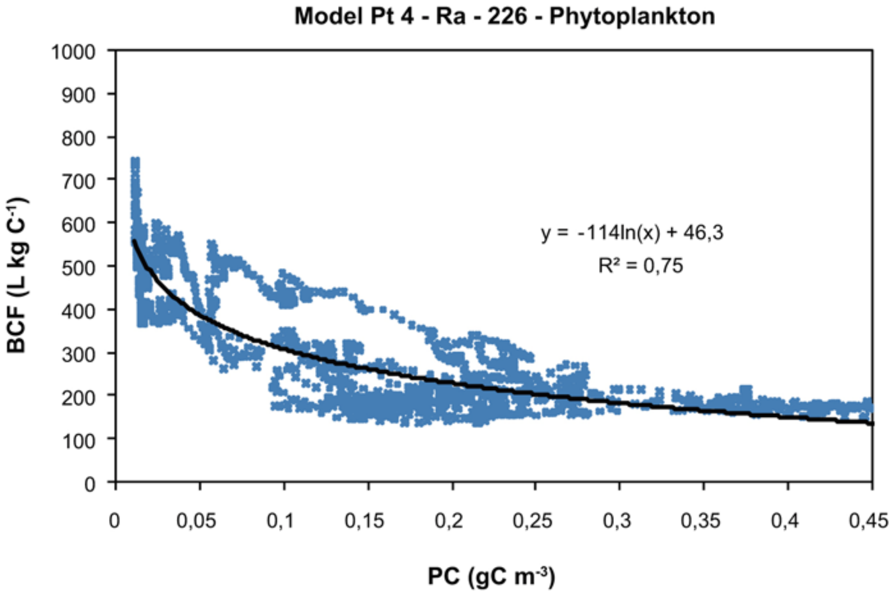


Figure 9-25. *Scatter plot between phytoplankton concentration and bioconcentration factor (BCF) for Ra-226 in phytoplankton. Individual value points represent 6 hourly values averaged over the entire water column. A log-normal function applied to data explains 75% of the observed variation.*

BCF in grazers and predators

For zooplankton and fish, the variation in BCF is unrelated to the biomass of the different biological components, but is related to the BCF in the next lower trophic level, underlining the fact that food-chain transfer of radionuclides is of greater importance than adsorption from water directly (see Figure 9-26). Correlations based on time series of BCFs (phytoplankton – zooplankton) from one grid point were most significant at the greatest distance from the release point (Point 1), underlining the fact that short-term variation in water concentration, which is most pronounced at the release point, does influence BCF through adsorption-desorption processes but food-chain transfer is the most important factor. If plots are based on temporally and spatially averaged BCF values, highly significant relationships that are best described by a power function indicate that "biomagnification" becomes more pronounced at higher BCFs in food (Figure 9-26 lower panel).

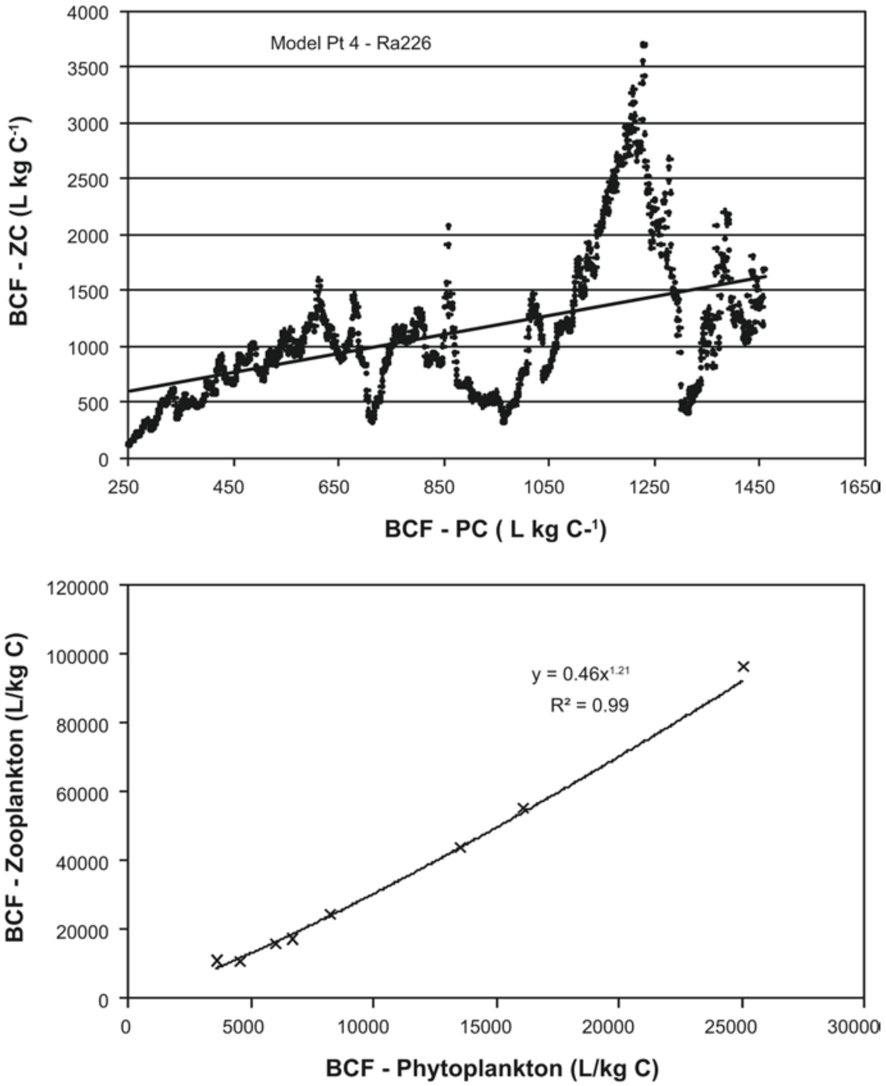


Figure 9-26. *Upper panel: Scatter plot between bioconcentration factor for phytoplankton (BCF-PC) and bioconcentration factor for zooplankton (BCF-ZC) for Ra-226. Individual value points represent depth-averaged 6-hourly values in model Point 4. Lower panel: Scatter plot between BCF for phyto- and zooplankton based on temporally (one year) and spatially (all depth and grid points) averaged values from 8 basins.*

The mechanism behind "biomagnification" is a result of the model assumption that once assimilated, radionuclides are not lost by excretion or respiration as is carbon. Hence, concentrations of radionuclides in grazers and predators will continue to increase and attain higher values than in their prey because about 50–60% of assimilated carbon is lost to cover maintenance costs, while all radionuclide mass is retained in the predator. The increase in grazer BCF with increasing radionuclide concentration in phytoplankton is probably related to a varying distribution between adsorbed and absorbed radionuclides in phytoplankton, and the fact that only adsorbed radionuclides are completely assimilated.

Variation in BCFs between basins and functional groups in the pelagic system

The spatial variations in BCFs for six radionuclides are presented in Figure 9-27, encompassing pelagic functional groups in the model (phytoplankton, zooplankton and planktivorous fish). A striking feature is an almost identical pattern in BCF variation across basins, although absolute values vary by almost 7 orders of magnitude depending on the particular radionuclide, i.e. the partition coefficient. The highest BCFs were modelled in the deepest basins, i.e. 116, 123 and 126,

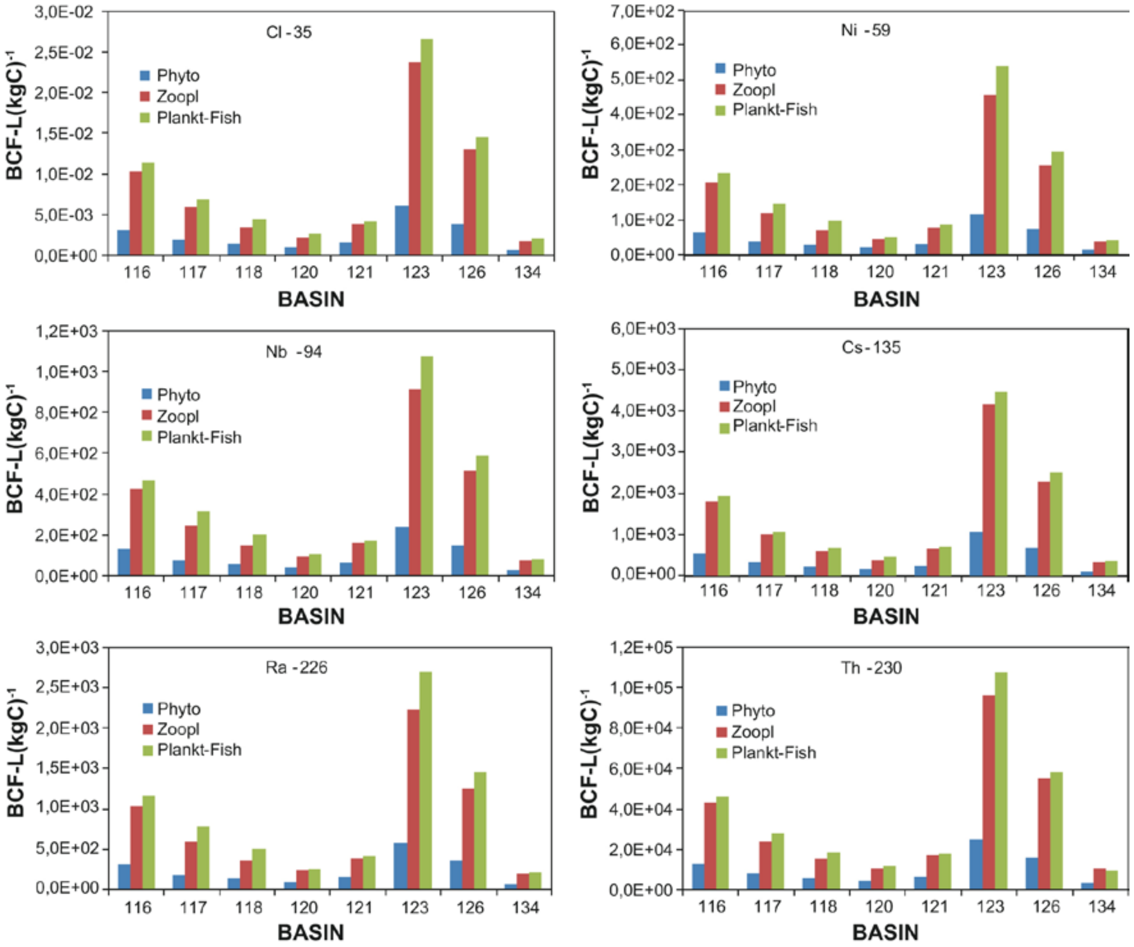


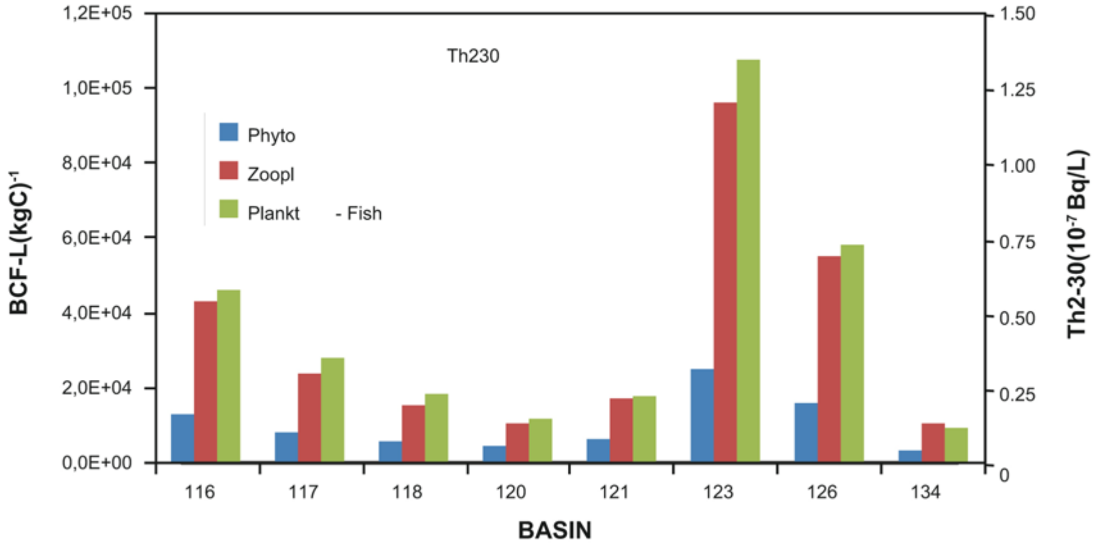
Figure 9-27. *Bioconcentration factors (BCFs) for 6 radionuclides in 3 pelagic functional groups across 8 selected basins in Öregrundsgrepen. Values denote median values encompassing the entire basin volume and representing the whole (8th) model year.*

while the lowest BCFs were modelled for the shallow basins, which received radionuclides through groundwater inflow. Depending on functional group and radionuclide, the relative range of BCFs (max/min) varied from 6.9 to 13.1.

A less prominent but consistent feature for all basins and radionuclides was the increase in BCFs from phytoplankton through zooplankton to planktivorous fish.

The reason for the large variation in BCFs across basins was examined by comparing dissolved radionuclide concentrations in the water column (Figure 9-28). For Th-230, the dissolved concentration varied from a low 0.08×10^{-7} Bq/l (basin 123, no groundwater input) to 1.3×10^{-7} Bq/l (basin 120, with groundwater input of radionuclide). The relative range (≈ 65) was comparable to that of the other radionuclides. Hence, a large part of the variation in BCFs for phytoplankton can be explained by differences in concentrations of dissolved radionuclides. The plot showed that the BCF was more or less constant at concentrations greater than 10^{-8} Bq/l, followed a dramatic increase at lower concentrations when water concentrations approached zero (Figure 9-28 lower panel).

In summary, phytoplankton that constitutes the entry of radionuclides into the pelagic food chain accumulates radionuclides by adsorption (primarily); bioconcentration factors representing the ratio of the radionuclide concentration in phytoplankton to the radionuclide concentration in water show substantial variation driven primarily by the variation in phytoplankton concentration (i.e. the total surface area of potential binding sites) and water concentration. Based on the modelling exercises we may expect a variation by a factor of 10 in BCFs in plankton organisms for a specific radionuclide due to seasonal variation in biomass and spatial variation in radionuclide concentration.



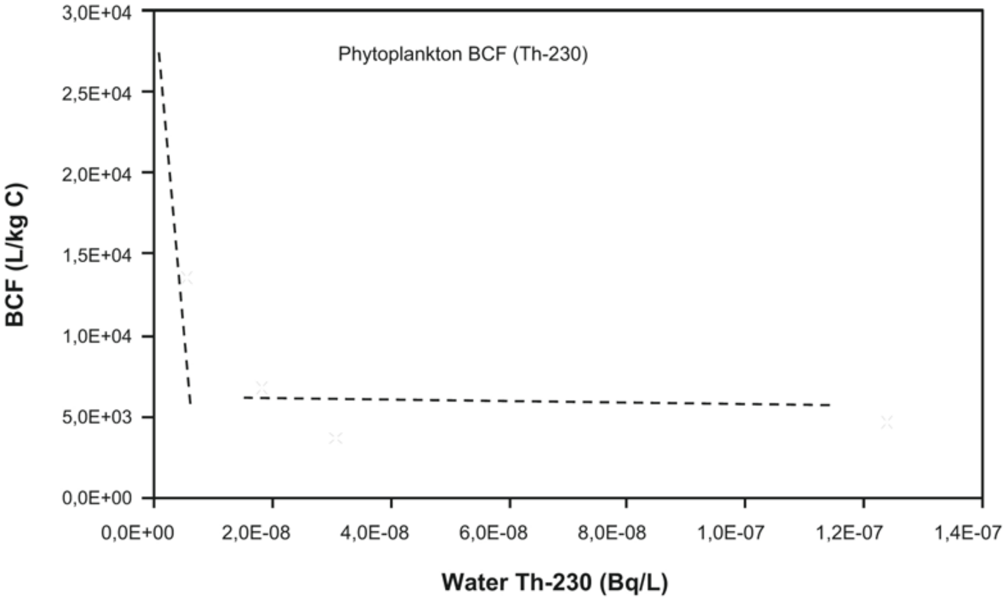


***Figure 9-28.** Bioconcentration factor for Th-230 in phytoplankton, zooplankton and planktivorous fish, and concentration of Th-230 in water across 8 Basins (upper). Bioconcentration factor for Th-230 in phytoplankton as a function of water concentration. All values represent median values for the 8 basins (across season, including spatial variation).*

The transfer of radionuclides to higher trophic levels in the pelagic food chain is mediated by adsorption and by intake of food containing radionuclides and effects of varying dissolved concentrations on BCFs in phytoplankton may also be reflected in higher trophic levels.

Variation in BCFs between basins and functional groups in the benthic system

The spatial variations in BCFs for benthic autotrophs and heterotrophs are shown in Figure 9-29. As in plankton and planktivorous fish, BCFs varied by 7–8 orders of magnitude between radionuclides, lowest for Cl-35 and highest for Th-230. This variation can be explained by the variation in partition coefficients.

In benthic autotrophs, where adsorption constitutes the most import accumulation process, the highest BCFs were predicted in the deep basins, e.g. basin 123 (without a release point for the radionuclide in the groundwater) and the lowest BCFs in the shallow basins. As for plankton, this pattern is a

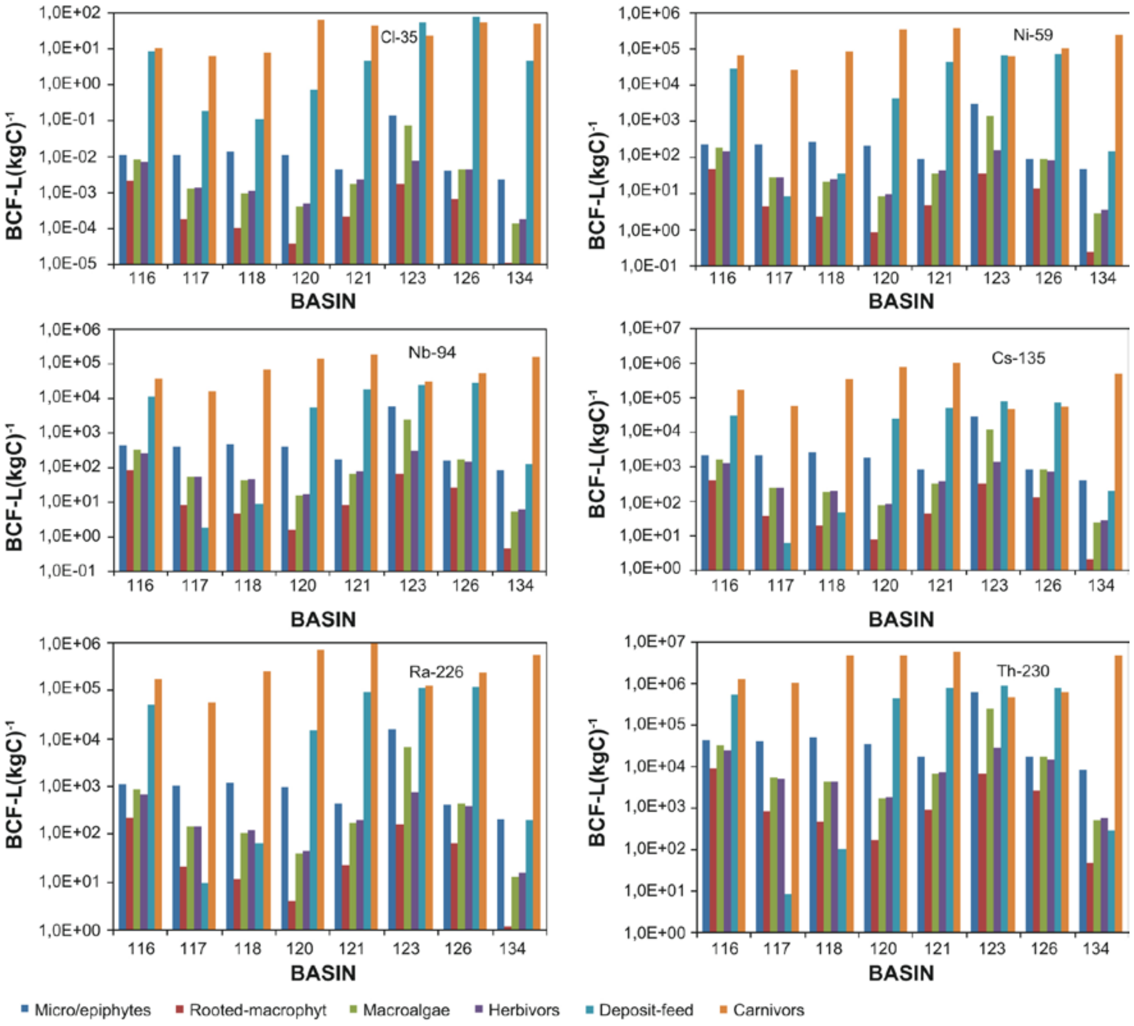


Figure 9-29. *Bioconcentration factors for 6 radionuclides in 6 benthic functional groups across 8 selected basins in Öregrundsgrepen. Values denote median values encompassing the entire basin seabed area and representing the whole model year.*

combination of low biomass in the deep basins caused by light limitation and a lower concentration of radionuclide than in the more shallow basins. In shallow basins higher growth rates and biomass in benthic plants, leads to "biomass dilution" of radionuclides. In contrast, the spatial pattern of BCFs in benthic deposit feeders and carnivores was unrelated to depth. Instead, the BCF was scaled positively to accumulated positive growth in deposit feeders and carnivores over the season. Deposit feeders ingest detritus and inorganic material containing a mixture of adsorbed (inorganic and organic dead matter, sedimented algae) radionuclides. Hence, in areas with high organic content in sediments, deposit feeders will have higher rates of radionuclide ingestion than deposit feeders in low-organic sediments, because partition coefficients for organics are approximately one order of magnitude higher than for inorganic particles. And as radionuclides are not excreted in the RN model, deposit feeders will accumulate radionuclides continuously until part of the biomass is consumed by predators. In that way, basins with high detritus production will give rise to high BCFs in detritus feeders and, as detritus feeders constitute the main food for predators, this distribution of BCFs will also be reflected in the BCFs in predators.

9.4.5 Comparison with other studies

Given the important role of partition coefficients in distributing radionuclides between water, sediments and organisms, the actual choice of partition coefficients will have a profound influence on results, including in situations where modelling approaches differ. In Table 9-9, modelled BCF results for phytoplankton, zooplankton, planktivorous fish and benthic deposit feeders are presented for this study and from the previous Kumblad modelling study, along with generic BCFs developed by the IAEA and site-specific BCFs for Forsmark /Nordén et al. 2010/.

Table 9-9. Bioconcentration factors (m^3 $(kgC)^{-1}$) for phytoplankton, zooplankton, planktivorous fish and molluscs/benthos calculated for basin 116. BCF values from this study represent median values (over time and space) to facilitate comparison with the studies by /Kumblad and Kautsky 2004/ and /Nordén (ed) 2010/ on basin 116. BCF data for fish for the Nordén study represent planktivorous and predatory fish. The benthos group was in this study exemplified by deposit feeders. Generic values from /IAEA 2004/ are also included for reference.

	Phytoplankton				Zooplankton			Plank. Fish				Benthos			
	IAEA	Kumblad & Kautsky	Nordén (ed) 2010	This study	IAEA	Kumblad & Kautsky	This study	IAEA	Kumblad & Kautsky	Nordén (ed) 2010	This study	IAEA	Kumblad & Kautsky	Nordén (ed) 2010	This study
Cl-35	0.0125	0.000048	0.13	0.003	0.013	0.000007	0.00001	0.0005	0.0003	0.001	0.00001	0.0006	0.0001	0.01	0.009
Cs-135	0.250	0.113	64	0.64	0.375	0.025	2.02	0.952	0.105	2.1	2.16	0.33	0.066	2.1	31.8
Nb-94	12.5	17.5	33	0.131	**250**	4	0.426	0.286	7.43	0.17	0.47	11.1	7.4	8.2	11.4
Ni-59	37.5	3.88	35	0.069	12.5	0.875	0.225	9.52	4.38	0.12	0.25	22.2	2.4	9.2	28.9
Ra-226	25	0.263	29	0.326	1.25	0.051	1.06	4.76	0.552	2.8	1.2	11.1	0.233	1.1	51.8
Th-230	250	65	2895	13.51	125	15	43.7	5.71	14.29	1.1	46.6	11.1	24.4	70	54.7

For every radionuclide and organism group considered there was a substantial variation among the four sets of data, partly driven by the use of different partition coefficients, but also caused by different importance of food-chain transport of radionuclides. In the Nordén study BCF generally decreased from phytoplankton, through zooplankton to fish, while BCF consistently increased from phytoplankton, through zooplankton and fish to deposit-feeders in this study underlining the importance of food-chain transport of radionuclides (Table 9-9).

In this study and the previous study by /Kumblad et al. 2006/, the BCF for each radionuclide was linearly correlated with the K_d/Kd_c for phytoplankton with identical slopes, because adsorption was the primary route of uptake and because the assumed surface-to-volume/biomass ratio in phytoplankton cells was identical in the two studies /Erichsen et al. 2010/. By comparison, the slope 'BCF/K_d' in the Nordén study /Nordén et al. 2010/ was 10–50 times higher.

At higher trophic levels in the food chain, the slopes in linear regressions between K_d-K_c and BCF for fish (planktivorous) were again comparable between this study and the Kumblad study, while the K_d and BCF values were unrelated in the Nordén study.

For benthos (e.g. deposit feeders), the ratio BCF:K_d was much higher in this model study compared with the Nordén study and the previous Kumblad study. This result stems from the model assumption that absorbed radionuclides from food were not excreted in the present radionuclide model. Consumers will therefore accumulate radionuclides as long as they ingest radionuclides in food until they die or are consumed by predators (see details and correlations in /Erichsen et al. 2010/). By comparison, in the Kumblad model adsorption of radionuclides is the dominant uptake process, including in consumers and predators, because ingested radionuclides are excreted at a rate scaled to respiration. For deposit feeders there was some scatter in the K_c-BCF relationship, compared with an almost perfect linear regression for BCFs for other organism groups. This scatter is apparently caused by a varying ratio (3–250) between Kd_c and Kd_{iss} for the different radionuclides. Hence, assuming a composition of 50% organics and 50% inorganics in ingested material for a deposit feeder, the accumulated radionuclide intake will vary according to the Kd_c: Kd_{iss} ratios of the different radionuclides.

9.5 General summary

The aim of this study was to provide supplementary input to the risk assessment of a planned final repository at Forsmark. The main deliverable was the hydrodynamic modelling, generating a computed water exchange between basins in the Forsmark marine area for the period 6500 BC to 9000 AD to be used as input to the landscape dose model. In addition, a second deliverable was high-resolution models for the marine ecosystem and radionuclide processes. The purpose of the main deliverable was to generate data on water exchange as input to the landscape dose model. The purpose of the second deliverable was to illustrate the spatial and temporal variation in important processes and parameters, while constituting a complement to previous modelling approaches and providing supporting information to discussions of the marine ecosystem, parameters and variation (see Chapter 6 and 10).To this end, a hydrodynamic model of high temporal and spatial resolution was constructed and calibrated for the Forsmark area. An ecosystem model was then developed and coupled to the hydrodynamic model. In turn, a detailed radionuclide model was coupled to the ecosystem model to provide detailed predictions of radionuclide transport and accumulation in the coastal ecosystem.

Circulation in the Forsmark marine area was simulated for 13 different years between 6500 BC and 9000 AD. Two different modelling approaches were used for the BC and AD years, but both are based on three-dimensional hydrodynamic numerical models.

The annual average flows between interconnected basins have been calculated from the computed hydrodynamic flow fields, an estimate also being made of the mean residence time for each basin (using the average age concept; AvA). The latter constitutes the direct input to the landscape dose model.

A validation against observations for the year 2020 AD shows that the model is highly dependent on the quality of the boundary conditions. Simulated water level and temperature show satisfactory agreement with observations, whereas salinity does not.

The results for the average basin flows lie in the range from a few m^3/s to several thousand m^3/s. The magnitudes of the flows are to a large extent a result of the magnitudes of the cross-sectional areas through which the flows are defined as well as the size of the interconnected basins, and are thus strongly influenced by the changes in shoreline and depths due to land rise. Comparison with results presented in Chapter 5, using another year and another model, indicates the same order of magnitude overall but large differences for specific basins.

The results for the AvA show an estimated residence time ranging from about two to ten days for the BC years (when the Forsmark area was located in open sea), and increasing to over a month for the later AD years as basins became increasingly isolated and their exchange with the Baltic Sea increasingly restricted.

A sensitivity analysis has been performed for the AD years where different forcing factors have been removed one by one. The results indicate Öregrundsgrepen changes as the southern strait closes, from a coastal area with a through-flow forced by sea level variations to an estuary with a density-driven estuarine circulation. In both cases, however, local wind plays an important role in the water exchange between basins, particularly in shallow areas near the shoreline. In general, completely eliminating a particular forcing factor results in relative changes in the AvA of less than 50%, although in some cases local variations between 100 and 200% are found.

The coupled ecosystem and radionuclide models were used to simulate present conditions, i.e. 2020 AD. Six radionuclides were modelled explicitly in addition to C-14. They represent a wide range of accumulation potentials and partition coefficients (K_d, distribution of radionuclides between water, sediment and biota). The spread and accumulation of other radionuclides with different partition coefficients can thus be inferred by comparison with relevant model results. As in every modelling study, the overall assumptions dictate the outcome of the modelling. In agreement with SKB it was decided that radionuclides accumulated through feeding in zooplankton, fish and benthic invertebrates were not excreted. Hence, in the model these organisms would continue to accumulate radionuclides throughout their life, and as a consequence the concentration of radionuclides will increase through the food chain. Based on this assumption the modelled accumulation of radionuclides in benthos and fish will constitute the theoretical maximum, i.e. a worst-case scenario.

With the exception of radionuclides with very low particle affinity, such as Cl-35, the majority of radionuclides released in basins where they were introduced via groundwater flow remained in the sediments even after a simulation period of eight years.

The most significant result of the modelling was the quantification of the seasonal and spatial variation in radionuclide accumulation and in bioconcentration factors (BCFs). In phytoplankton, BCFs varied temporally within a range of 3–4 over the seasons, primarily driven by natural variation in phytoplankton biomass. In contrast, spatial variation of BCFs was much higher with a maximum variation by a factor of 100 to 1000. This variation was totally dominated by spatial differences in concentrations of radionuclides in water. In basins where radionuclides were introduced by groundwater flow, BCFs were typically 2–3 orders of magnitude lower than in deep basins without radionuclide release in the groundwater.

In the lower parts of the food web, i.e. phytoplankton and grazers, bioconcentration factors (BCFs) scaled linearly to partition coefficients (K_d), underlining the fact that adsorption is an important process for radionuclide accumulation and also underlining the important role of K_d in the model. In contrast, BCFs were much higher in benthic fauna such as detritus feeders, and although K_d and BCF did correlate, the scatter was substantial.

The results for one of the basins in Öregrundsgrepen were compared with two other model studies, /Kumblad and Kautsky 2004/ and /Nordén et al. 2010/. Modelled bioconcentration factors (BCFs) differed substantially between the three studies, but for phytoplankton and grazers the differences in BCF could largely be explained by different values for partition coefficients (K_ds) used in the models. For detritus feeders and benthic predators, BCFs were consistently higher in this model study compared with the /Kumblad and Kautsky 2004/ and /Nordén et al. 2010/ studies, despite the fact that K_d values were lower. The higher modelled BCFs are a result of the model assumption that radionuclides are not excreted along with respired carbon. Hence, concentrations of radionuclides continue to increase as long as the organisms ingest and assimilate food containing radionuclides.

10 Radionuclide model parameterization for the marine ecosystems in Forsmark and Laxemar-Simpevarp

The radionuclide model for the biosphere is presented in chapter 10 in /Andersson 2010/, and rely 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 parameters in the marine part of the radionuclide model are populated, with background data, calculations and the resulting input data.

10.1 Guide to parameterization

The parameters used in the radionuclide model to model transport and accumulation of radionuclides in the biosphere have been divided into a number of categories presented in Table 10-1. The radionuclide model is hydrologically driven and the scenario is based on a below-ground release of radionuclides entering the biosphere. The radionuclide model is divided into three more or less distinct landscape stages, sea, lake and wetland (see Chapter 10 in /Andersson 2010/ and a conceptual description of the radionuclide model in Figure 8-4 in Chapter 8). The general modelling approach, the identification of release points in the biosphere and the configuration of the landscape perspective, is 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 discharge 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, the biosphere objects are located in the marine ecosystems but will follow a successional path from a marine stage into a terrestrial stage, due to the shoreline displacement. The criteria for this successional development is described in /Lindborg 2010/. The radionuclide model quantifies the accumulation of radionuclides in the biosphere object. The flux from one biosphere object into the next is calculated for each time-step during the whole modelling period of 120,000 years.

The parameters presented here are those describing marine biota, hydrology and regolith in Forsmark and Laxemar-Simpevarp. Other parameters e.g. biota in limnic and terrestrial systems are presented in /Andersson 2010/ and /Löfgren 2010/, element specific properties and universal constants in /Nordén et al. 2010/, the biosphere objects and their geometric properties in /Lindborg 2010 Brydsten and Strömgren 2010/ (Table 10-1). However, the definitions of the geometric parameters used for the objects in the radionuclide model are given a comprehensive presentation in the following text (10.4).

10.1.1 Dose calculations

Deterministic calculations with the radionuclide model have been based on the parameter values estimated for the temperate case (Chapter 7). Below follows a description of the parameter statistics and representation as well as a short discussion on parameter handling under alternative climate conditions.

Parameter statistics and their representation

Deterministic modelling in the radionuclide model 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, parameters in the radionuclide model have been estimated using raw data from the site or from models

Table 10-1. Parameters used in the radionuclide model. [a] each parameter estimated for 48 radionuclides, [b] each parameter estimated for 31 stable elements, [c] 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). Total number of parameters listed in parenthesis. The references are given in the footnote below the table.

Type of parameter	N	Example	Source	Reference
Radionuclide specific[a]	1	Radionuclide half life	Literature	TR-10-07
Landscape geometries[c]	13	Size of biosphere objects and catchment areas, sedimentation and resuspension rates	Site investigation, site modelling	TR-10-05
Regolith properties[c]	27	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	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-02, TR-10-03
Terrestrial ecosystem properties	34	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-01, TR-10-07
Surface hydrology and water exchange[c]	9	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	Element-specific solid/liquid distribution coefficients (K_d) for regolith and particulate matter	Site investigation, literature	TR-10-07
Concentration ratios	19	Element-specific ratios between environmental media and organisms (CR)	Site investigation, literature	TR-10-07
Human characteristics	5	Life span, energy and water consumption	Literature	TR-10-07
Dose coefficients[a]	4	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: /Andersson 2010/, TR-10-03: /Aquilonius 2010/, TR-10-05: /Lindborg 2010/, TR-10-07: /Nordén et al. 2010/.

populated with site data. In some cases when such data were lacking, data were obtained from other areas as similar to our sites as possible or generic data. The premises for parameter estimation are described below, along with statistical descriptions, such as means, medians, maximum and minimum values, and standard deviation. For some data, like for modelled or literature data, no statistical descriptions are available. For time dependent parameters the full set of input data is available in SKB´s document system, SKBdoc1263189. In the following parameter presentation the heading is the same as the parameter name used in the radionuclide model described in Chapter 10 in /Andersson 2010/.

The central value (arithmetic mean/median/geometric mean) for each parameter is representative for the property at the site at a certain depth. For example the central value describing the biomass of the macro benthic primary producers is a mean built upon the biomass for a specific depth interval, and the minimum and maximum represents the parameter range at this depth interval.

Standard deviation, and minimum and maximum values, were used in a sensitivity analysis describing the relative importance of different parameters for the model result /Avila et al. 2010/. In addition a parameter value distribution for each parameter, where mainly normal and lognormal distributions fit to the actual data. In some cases no distribution is suggested, due to lack of data and/or no apriori anticipation as to the likely shape of the distribution. However, some of the field estimates have neither the spatial nor the temporal extension 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 records extending more than 30 (often more than 50) years, and change in climate are typically defined relative to a baseline estimate obtained from a 30 years reference period. This implies that the described variation for some site parameters does not include the potential variation range, even though the estimated mean may be close to the true mean even for a longer time period. Most of the parameters describing the regolith have a rather short span both reflecting few samples in some cases but also a low variation.

Future conditions

The modelled time-period covering 120,000 years includes, beside successional changes, also climate changes during an interglacial. Three different climate domains are distinguished in the modelling; temperate, permafrost and glacial. There is also a time stage, were all objects are below sea level, a submerged stage (see Chapter 7). In addition to a reference case of an interglacial, a global warming case is also acknowledged by extending the length of the temperate stage. These aspects are more specifically addressed and discussed in Chapter 7. For the marine ecosystem it is assumed that the effect of different climate conditions on the marine ecosystem parameters will be within in the variation range for parameter estimate of the present conditions, i.e. temperate climate domain.

One major factor affecting the long term development of parameters in the marine ecosystem during the time period used in the radionuclide model is the varying depth caused by to the shore-line displacement. The model area develops from deep offshore areas to shallower less exposed marine basins. In order to predict the parameter values, using present conditions as a proxy, parameters were (when possible) correlated to the depth in each marine object to achieve a depth function. This function was then used to predict the parameter for an object at a specific time during the interglacial simulated in the radionuclide model.

10.2 Radionuclide model parameterisation

This section contains the descriptions of the site-specific marine parameters for Forsmark and Laxemar-Simpevarp and in the following sections, calculations and definitions of the marine parameters divided into; 1) geometric parameters, 2) regolith parameters, 3) hydrological parameters 4) chemical parameters, 5) biotic parameters and 6) human food parameters.

The parameters for Forsmark and Laxemar-Simpevarp are generally calculated the same way, although with site specific input data. Definitions and calculations are given along with description in the Forsmark section (Section 10.3–10.8). In the Laxemar-Simpevarp section (10.9–10.15), only the differences (if any), in comparison to Forsmark, and the site specific input data is described. All parameters for the marine biosphere objects in Forsmark and Laxemar-Simpevarp are stored in SKBdoc1263189[2], in addition, the non-time dependent parameters are presented with values below. For the marine parameters, the property that the parameter describes is assumed to be unchanged during permafrost and global warming.

The radionuclide model is focused on the transport and accumulation of radionuclides. Therefore some parameters, e.g. biomass and production are not always defined in the same way as in previous chapters of this report. Hence, only production and biomass where radionuclides are incorporated is of interest for the radionuclide model whereas in an ecosystem description all biomass and production in an ecosystem are of interest.

10.3 The marine Biosphere objects in Forsmark

The marine biosphere objects, the marine basins in Forsmark today represents shallow secluded bays and more exposed archipelago (see Chapter 3). In the initial marine interglacial stage, following upon a deglaciation, the areas will be submerged by sea water with a maximum depth around 200 m /Lindborg 2010/. Due to shore-line displacement the marine basins will gradually become shallower and the drainage from land areas will have more and more influence on the water volume and salinity. Finally bays will be cut off and form wetlands, lakes and streams.

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[2] SKBdoc1263189, access might be given upon request.

10.4 Geometric parameters

The geometric parameters describe geometric extensions (i.e. areas and depths), physical sediment parameters as well as transition times for different ecosystem stages, e.g. the time of transition between marine and limnic stages. Geometric parameters are connected to the bathymetry of the marine basin, filling of the marine basin with sediment or connected to the catchment geometry. The calculations of geometric parameters are described in a coupled model for regolith-lake development (RLDM) /Brydsten and Strömgren 2010/, constructed for the Forsmark area and applied to the Laxemar area in Chapter 10 in /Andersson 2010/ and /Lindborg 2010/. Nevertheless, the definitions of the geometric parameters are given here as they are often important for the marine part of the radionuclide model. Climate change, such as a global warming, may alter sea levels and thereby the time when basins become isolated from the sea. However, as this model describes one possible future, the timing of isolation is not of importance and no alternative values for the geometric parameters are presented for the global warming cases.

10.4.1 Aqu_area_obj (m^2)

This parameter represents the surface area of an aquatic object. This parameter is calculated for each time-step used in the radionuclide model. In the radionuclide model the marine basins have the same area for most of the time, although, when the marine basins gets shallower and closer to being a lake the aquatic area of the object decreases due to that parts of the basins becomes land. Maximum and minimum areas of the marine biosphere objects are 35,580,100 m^2 and 243,809 m^2, respectively.

10.4.2 Area_wshed (m^2)

This parameter represents the surface area of the watershed. Watershed is an extent of land where water from rain or snow melt drains downhill into a body of water, such as a river, lake, reservoir, estuary, wetland, sea or ocean. The drainage basin includes both the streams and rivers that convey the water as well as the land surfaces from which water drains into those channels, and is separated from adjacent basins by a drainage divide (also called water divide). When marine basins are located adjacent to the coast or land they exhibit watersheds areas larger than zero, whereas when they are located in open sea the contribution from the watershed goes via the coastal basins and the parameter is zero.

10.4.3 depth_aver (m)

This parameter represents the average depth in a biosphere object, the marine basin, and is calculated for each time-step used in the radionuclide model.

10.4.4 growth_rego (m/y)

This parameter represents the growth (in height) of the regolith layer. This parameter is calculated for each time-step used the in radionuclide model. Growth_rego is a mean value for sediment growth in the entire basin area. In marine basins growth_rego occurs only in the areas with accumulation bottoms whereas in erosion and transport bottoms the growth of the regolith layer may be negative. As a result, growth_rego can be negative due to large export of material from erosion and transport bottoms, i.e. there is a net export of material out of the basin.

10.4.5 Res_rate (kg dw m^{-2} y^{-1})

This parameter represents an estimate of resuspension and is calculated for each time-steps used the in radionuclide model. Resuspension is the process by which abiotic and biotic material that has been deposited on the bottom sediment is reconveyed into the overlaying water column. A resuspended particle may be resuspended c 60 times y^{-1} in lakes /Valeur et al. 1995/ and more than 100 times y^{-1} in sea basins before it is permanently buried or transported out of the system. Here, resuspension is defined as the amount of material that is subjected to resuspension in a year and is expressed as kg dw m^{-2} y^{-1}. In the model a radionuclide is connected to a particle as soon as the particle reaches the sediment and therefore it is not of importance to measure the rate of resuspension as the same particle may be counted many times. Instead it is of importance to estimate the amount of particles that is resuspended in a year. Resuspension is calculated for each time-step in the radionuclide model.

10.4.6 Sed_rate (kg dw m^{-2} y^{-1})

This parameter represents the amount of particles that is deposited on lake and sea bottoms in a year and is expressed in kg dw m^{-2} y^{-1}. Some of this material will permanently accumulate and some will be resuspended and return to the water column. This is parameter calculated for each time-step used in the radionuclide model.

10.4.7 threshold_start (y AD) and threshold_stop(yAD)

Lakes are formed due to land-rise which isolates marine basins from the adjacent marine areas. In order to illustrate the gradual process when a sea bay becomes a lake, with occasional salt water intrusion, three occasions is identified for each biosphere object, threshold start, tershold-stop and isolation year. Start year represent the year when the marine basins becomes a lake basin isolated for at least parts of the year and stop represent when there is no longer any salt water intrusion to the basin. The threshold start for each basin is presented in Table 10-2. Basin 124, is the first object that starts the isolation from sea to lake. Basin 105 is the last basin that starts isolation from sea to lake. Basin 124, is the first object that complete the isolation from sea to lake. Basin 105 is the last basin that completes isolation from sea to lake.

Table 10-2. Isolation year is the modelled isolation of a marine basin into a lake basin. Treshold_ start and threshold stop represent the start and stop of isolation period for each basin and isolation period represent the length of the isolation period in Forsmark.

	Isolation year (y AD)	Threshold _start (y AD)	Threshold_stop (y AD)	Isolation period (y)
Basin101	8015	7479	8376	897
Basin105	11,156	10,453	11,634	1,181
Basin107	3497	3157	3725	568
Basin108	5011	4610	5278	668
Basin114	8545	7983	8924	941
Basin116	4783	4393	5044	651
Basin117	2997	2675	3212	537
Basin118	2848	2531	3059	528
Basin120	2409	2106	2610	504
Basin121_1	4007	3648	4248	600
Basin123	6482	6019	6793	774
Basin124	1888	1603	2077	474
Basin125	1902	1616	2091	475
Basin126	4379	4005	4629	624
Basin136	1898	1613	2088	475

10.5 Regolith parameters

The regolith parameters describe properties of different generalized geological units as found in the occurring Biosphere objects. The regolith at each biosphere object is described according to the conceptual model of the spatial distribution of regolith in Forsmak (Figure 10-1) The main input for describing properties of the regolith is the surface map of Quaternary deposits (Figure 10-2), the depth and stratigraphy model of regolith, Regolith Depth Model (RDM) /Hedenström et al. 2008/, soiltype map /Lundin et al. 2004/ together with models of future distribution of quaternary deposits /Brydsten and Strömgren 2010, Lindborg 2010/.

The regolith below the marine basins in Forsmark is divided into four layers (with specific properties, e.g. density and porosity); 1) regoup, 2) regoMid_PG, 3) regoMid_Gl, and 4) regolow:

1) RegoUp is the upper regolith and is defined as the biologically active and generally oxygenated zone. The unit regoUp is divided into two sub-units: one representing accumulation bottoms and one representing transport and erosion bottoms.
2) RegoMid_PG represents the postglacial organic sediments, i.e. gyttja and clay gyttja and may also include postglacial sand and gravel.
3) RegoMid_GL represents the glacial clay.
4) Regolow is the lowest situated layer of regolith and is composed of glacial till.

In the Radionuclide model RegoMid_PG and regoMid_Gl is joined into one layer; regoMid (Chapter 10 in /Andersson 2010/). Calculations of all regolith parameters are described below and values of time dependent regolith parameters are stored and presented in SKBdoc1263189[3].

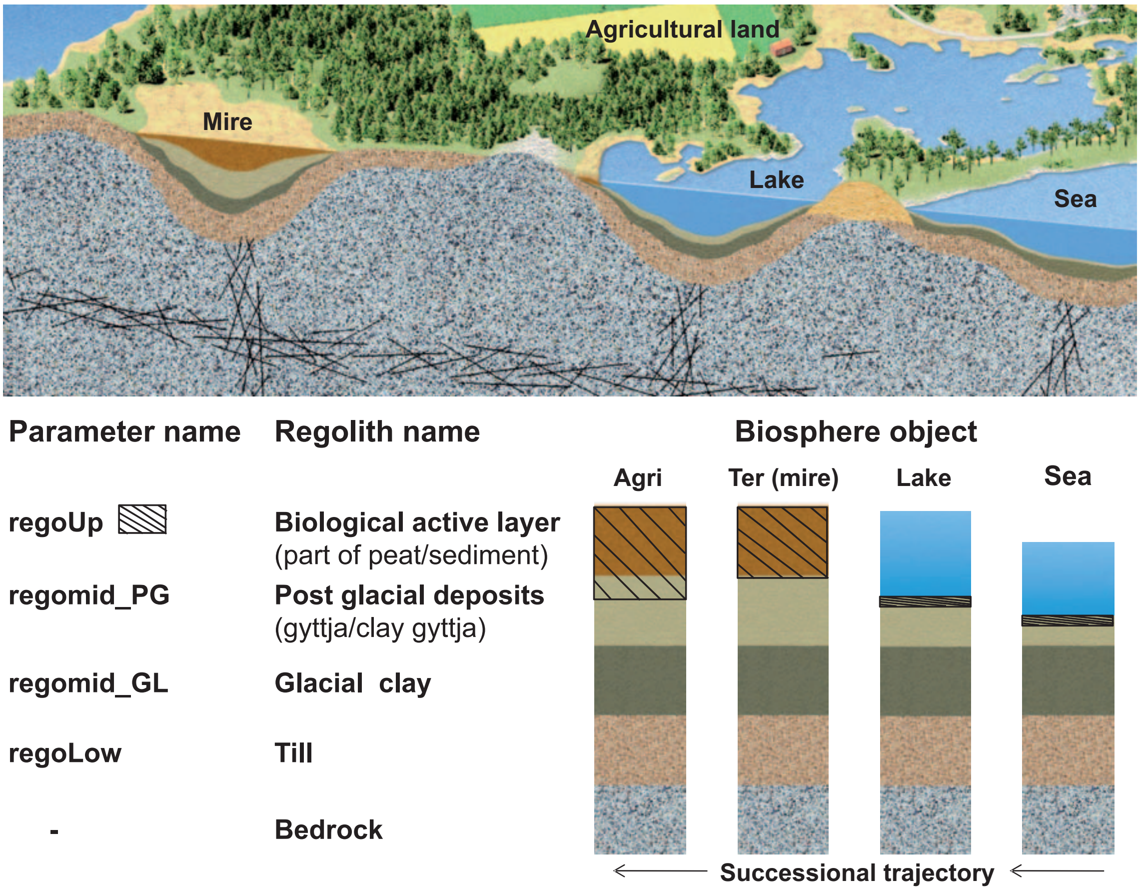

Figure 10-1. The conceptual model of the generalized distribution of the regolith for different types of biosphere objects at Forsmark and Laxemar-Simpevarp. In the radionuclide model (Chapter 10 in /Andersson 2010/), the postglacial and the glacial clay deposits are mixed together in regard to the radionuclide inventory.

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[3] SKBdoc 1263189, access might be given upon request.

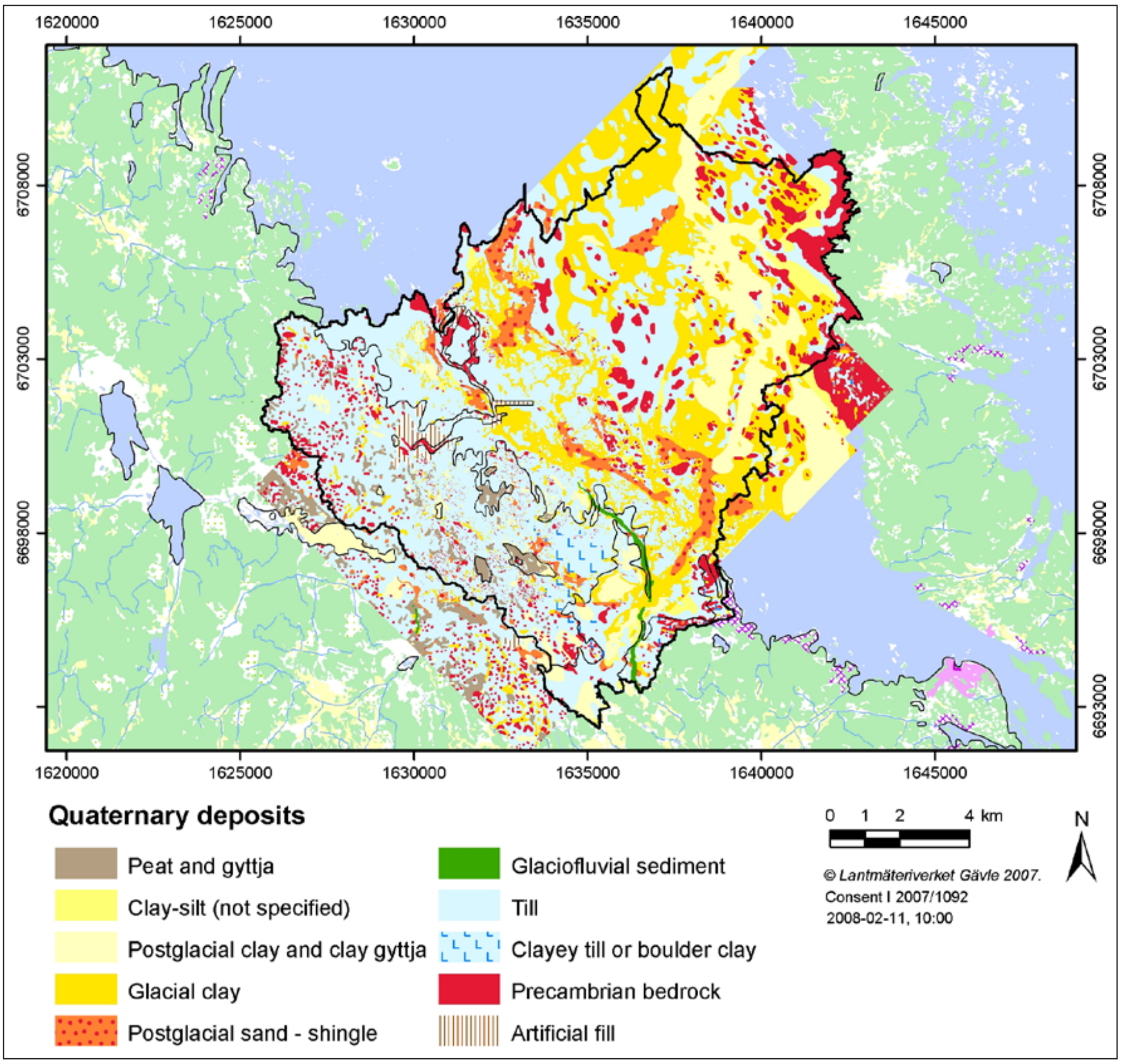

Figure 10-2. *The surface distribution of the Quaternary deposits (regolith) at Forsmark /Hedenström 2008/. Precambrian bedrock is not part of regolith but is sometimes the uppermost layer, i.e. there are no deposits on the bedrock. In the radionuclide model the quaternary deposits have been divided into three layers Regolow, regomid and regoup. Regolow includes a) Clayey till or boulder clay, and b) till. Regomid includes a) Glaciofluvial sediments, b) Postglacial sand-single, c) Glacial postglacial clay and clay gytta, d) Clay silt and part of e) peat and gyttja. Regoup includes the upper oxygenated layers sediment, Peat and gyttja.*

10.5.1 Sea_z_regoup (m)

This parameter represents the depth of the upper regolith layer in the marine basins, i.e. where bioturbation of marine organisms occur. The mean depth of the parameter was set to 0.1 m according to /Håkansson et al. 2004/ (minimum 0 and maximum 0.2 m) based on an average of data from the Baltic Sea.

10.5.2 Aqu_dens_regoUp _acc (kg m^{-3})

The parameter value represents the dry bulk density of accumulation bottoms in the limnic and marine areas, represented by soft organic sediment with very high water content. The proportions of accumulation/erosion bottom in each basin in the marine area are based on the sedimentation model (Landscape succession model) /Lindborg 2010/. For the isolated lake basins, the entire bottom area is regarded as accumulation bottom. The parameter values are based on measurements from the shallow marine area of the dry bulk density in the upper 10 cm (Table 10-3) of sediments. The parameter Aqu_dens_regoUp_acc is presented in Table 10-4.

Table 10-3. Measured dry bulk density /Sternbeck et al. 2006/ in Forsmark.

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 10-4. The parameter values for Aqua_dens_regoUp_acc in Forsmark, representing the dry bulk density of the surface sediments in accumulation bottoms in the aquatic system.

Dry bulk dens	kg m^{-3}
Mean	126
Max	220
Min	72
n	8

10.5.3 Aqu_dens_regoUp _ero (kg m^{-3})

The parameter value represents the dry bulk density of the upper sediment of erosion and transport bottoms in the marine area, represented by sand or gravel. The parameter values of Aqu_dens_regoUp_ero (Table 10-5) is based on two measurements of dry bulk density of sand from the surface of excavated trenches in the terrestrial area /Lundin et al. 2005/.

Table 10-5. The parameter values for Aqua_dens_regoUp_ero in Forsmark, representing the dry bulk density the surface sediment at transport and erosive bottoms in the marine areas.

Dry bulk dens	kg m^{-3}
Mean	1,800
Max	2,000
Min	1,600
n	2

10.5.4 Aqu_poro_regoup_acc (m^3 m^{-3})

This parameter represents the porosity of accumulation bottoms in the limnic and marine areas, mainly soft organic sediment with very high water content. The proportions of accumulation/erosion bottom at each site/basin are based on a sedimentation model (Landscape succession model) /Brydsten and Strömgren 2010, Lindborg 2010/. For the isolated lake basins (objects), the entire bottom area is regarded as accumulation bottom. The porosity values are based on measurements of water content in surface sediment from 7 lakes at Forsmark (Table 10-6) and measurements of water content and organic carbon content of lake sediments from the site investigations (Table 10-7). The formula for calculating porosity (n) is given below /Talme and Almén 1975/.

$n=V_p/V$

Were:

V_p represents the volume of water,

V represents the total volume.

1 g cm^{-3} used for the density of water and organic matter and 2.65 g cm^{-3} is used for density of the minerogenic fraction.

Mean, minimum and maximum values of the parameter for porosity in the upper regolith (Aqu_poro_regoup_acc) are presented in Table 10-8.

Table 10-6. Water content in the organic surface sediments from lakes at Forsmark, used for calculation of 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	0.00–0.05	96.9	0.97
Bolundsfjärden	0.05–0.10	96.2	0.96
Stocksjön	0.00–0.05	97.7	0.98
Stocksjön	0.09–0.14	95.6	0.96
Labboträsk	0.00–0.05	98.0	0.98
Hällefjärd*	0.00–0.05	98.1	0.98
Hällefjärd*	0.08–0.13	96.0	0.96
Eckarfjärden	0.00–0.05	98.3	0.98
Eckarfjärden	0.12–0.17	97.5	0.97
Landholmssjön*	0.00–0.05	98.1	0.98

Table 10-7. Organic carbon and water content in gyttja from lakes at Forsmark, used for calculation of 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	27	93	0.95	71.7
Fiskarfjärden	17	93	0.96	72.6
Stocksjön	27	86	0.92	149.5
Gällsboträsk	27	86	0.92	149.5
Bolundsfjärden	27	90	0.94	104.8
Puttan	20	89	0.94	116.4

Table 10-8. The 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

10.5.5 Aqu_poro_regoUp_ero ($m^3\ m^{-3}$)

This parameter represents the porosity of erosion bottoms in the marine area. The porosity values are based on two measurements of sand from the surface of excavated trenches in the terrestrial area /Lundin et al. 2005/ and one secondary calculation based on the grain size distribution curve from surface sediment offshore Forsmark /Risberg 2005/. The parameter values (Aqu_poro_regoUp_ero) are presented in Table 10-9.

Table 10-9. The parameter values for Aqu_poro_regoUp_ero in Forsmark, representing the porosity of the surface sediments at transport and erosion bottoms in the marine area.

Porosity	$m^3\ m^{-3}$
Mean	0.32
Max	0.38
Min	0.26
Std	0.6
n	3

10.5.6 z_regoMid_gl_basin (m)

The parameter value represents the depth of glacial clay. The depth and distribution of this layer is regarded as constant over time, covering the till and bedrock surface from the deglaciation onwards. The depth of this layer is specific for each object, based on the RDM /Hedenström et al. 2008/. The values presented in Table 10-10 are means for each marine basin prior to isolation.

Table 10-10. Mean, minimum and maximum depth, in m, of the lower regolith (z_regoMid_gl_basin) in the Forsmark objects.

Object	mean	minimum	maximum
10	0.58	0.00	9.01
101	0.58	0.00	9.01
105	1.34	0.00	18.3
107	0.58	0.00	9.01
108	0.83	0.00	14.1
114	2.00	0.00	25.4
116	0.68	0.00	13.6
117	0.06	0.00	5.36
118	0.36	0.00	5.70
120	0.03	0.00	2.67
121_01	0.79	0.00	10.1
121_02	0.44	0.00	2.78
121_03	1.17	0.00	5.16
123	2.29	0.00	12.8
124	0.00	0.00	0.35
125	0.01	0.00	0.35
126	0.87	0.00	18.2
136	0.02	0.00	0.35

10.5.7 Aqu_dens_regoMid_PG ($kg\ m^{-3}$)

The parameter values represent the dry bulk density of regoMid_PG, found in the aquatic systems, i.e. both the limnic and marine areas as well as under mires. The values are based on measurements of water content and organic content in the sediments from 7 lakes at the Forsmark site /Brunberg unpublished data (Table 10-6), Hedenström 2004/. Measurements of sediments from coastal bays were also used (Table 10-11). The mean, maximum and minimum values of the parameter (Aqu_dens_regoMid_PG) are presented in Table 10-12.

Table 10-11. Measured dry bulk density in Forsmark of coastal sediments /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 10-12. 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

10.5.8 Aqu_dens_regoMid_GL (kg m^{-3})

This parameter represents the dry bulk density of the glacial clay, found in both 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 of the parameter (Aqu_dens_regMid_GL) are presented in Table 10-13.

Table 10-13. The parameter values for Aqua_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

10.5.9 Aqu_poro_regoMid_PG ($m^3\ m^{-3}$)

This parameter represents porosity of the organic postglacial sediments, i.e. gyttja and clay gyttja, found in limnic and marine areas as well as under peat and mires. The values are based on measurements of water content and organic content of gyttja and clay gyttja from the Forsmark site (Table 10-14). The mean, maximum and minimum values of the parameter (Aqu_poro_regoMid_PG) are presented in Table 10-15.

Table 10-14. The input data used for calculations of porosity of the postglacial sediments. * /Hedenström 2004/, site specific, ** Eckarfjärden /Hedenström and Risberg 2003/, * /Karlsson and Nilsson 2007/ and values from Frisksjön, Oskarshamn (bold figures).**

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 10-15. Parameter values for Aqua_poro_regoMid_PG in Forsmark, representing the porosity of postglacial gyttja and clay gyttja.

Porosity	$m^3\ m^{-3}$
Mean	0.93
Max	0.96
Min	0.90
Std	0.02
n	7

10.5.10 Aqu_poro_regoMid_GL ($m^3\ m^{-3}$)

This parameter represents porosity of the glacial clay, found in limnic and marine areas. The porosity values for glacial clay are based secondary calculations from grain size distribution curves of clay collected offshore 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 10-16.

Table 10-16. Parameter values for Aqua_poro_regoMid_GL and Ter_poro_regoMid_GL, in Forsmark, representing the porosity of glacial clay.

Porosity	$m^3\ m^{-3}$
Mean	0.64
Max	0.75
Min	0.55
n	10

10.5.11 z_regolow (m)

This parameter represents the total depth of the glacial till. The depth and distribution of this layer is constant over time, covering the bedrock surface from the deglaciation onwards. The depth of this layer is based on the RDM /Hedenström et al. 2008/. The parameter (z_regolow) values presented are mean for each marine basin, prior to isolation, Table 10-17.

Table 10-17. Mean, minimum and maximum depth (m) of the lower regolith (z_regolow) in the Forsmark objects.

Object	Mean	minimum	maximum
10	3.62	0.00	17.3
101	3.62	0.00	17.3
105	4.59	0.00	22.5
107	3.62	0.00	17.3
108	4.27	0.00	27.5
114	4.68	0.00	12.1
116	3.91	0.00	23.1
117	2.89	0.00	14.6
118	3.26	0.00	13.1
120	2.39	0.00	9.7
121_01	4.53	0.00	19.3
121_02	3.21	0.00	9.5
121_03	5.78	0.00	19.6
123	6.50	0.00	28.5
124	2.67	0.00	7.1
125	3.12	0.00	14.6
126	5.32	0.00	23.2
136	2.39	0.00	15.4

10.5.12 dens_regoLow ($kg\ m^{-3}$)

This parameter represents the dry bulk density of the deeper parts of glacial till. The dry bulk density value 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/. The parameter (dens_regolow) values presented in Table 10-18, are mean for each marine basin, prior to isolation.

Table 10-18. The parameter values for dens_regoLow, representing the dry bulk density of till in Forsmark.

Dry bulk dens	(kg m^{-3})
Mean	2,132
Max	2,200
Min	1,980
Std	87
N	5

10.5.13 poro_regoLow (m^3 m^{-3})

This parameter represents the porosity of 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/. The parameter (poro_regolow) values presented in Table 10-19, are mean for each marine basin, prior to isolation.

Table 10-19. The 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

10.6 Hydrology parameters

This section includes hydrological parameters used in the radionuclide model to describe water fluxes in the sea in Forsmark and Laxemar-Simpevarp: The parameters are; Sea_adv_low_mid, Sea_Aqu_adv_mid_up_norm, Runoff and Wat_ret (Figure 10-3).

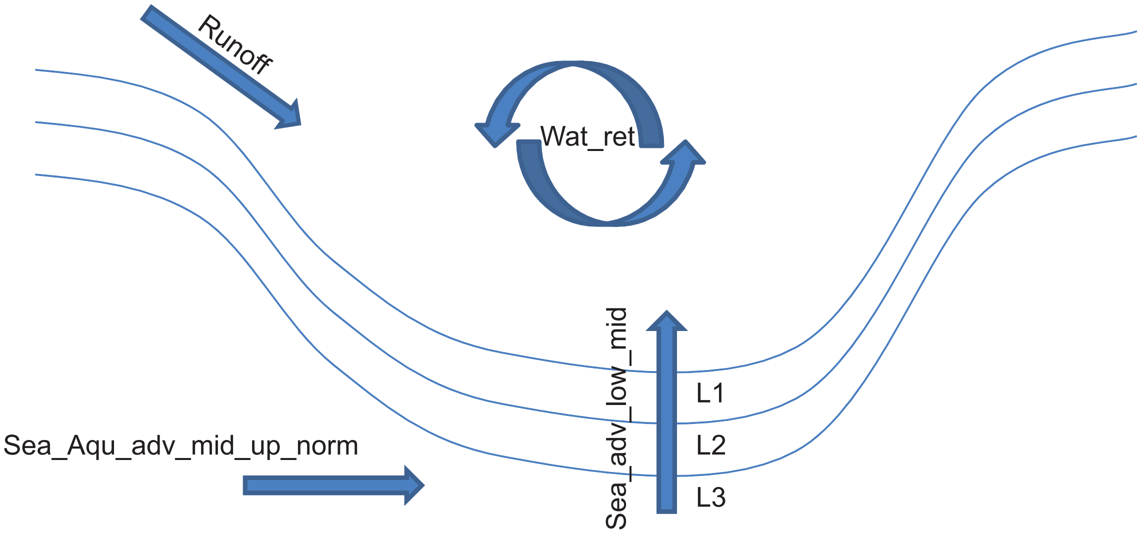

Figure 10-3. *Schematic figure showing parameters calculated by water balances for Forsmark and Laxemar-Simpevarp. L1 consists of marine sediments (corresponding to regoUp, regoMid_Gl and regomid PG in Section 9.1.5). L2 consist of till (corresponds to regoLow in Section 9.1.5) and L3 is the bedrock.*

10.6.1 Sea_adv_low_mid (m y^{-1}) (tidigare Adv_low_mid)

This parameter represents the total advective flux of ground water from the geosphere to the regoLow, to the postglacial and the glacial deposits (regoMid) to the regoUp and finally to water /Bosson et al. 2010/.

To estimate the water fluxes below the sea, a water balance for the area was calculated, based on the MIKE SHE model representing the shore line at 2000 AD. The reason to use the 2000 AD MIKE SHE model is that a large part of the model area is covered by sea at 2000 AD, thus data for the majority of the sea basins could be extracted. It is assumed that there is a net upward flux through the regolith layers, equal to the flux from the geosphere to the lowest regolith layer. This flux is assumed constant through the regoLow, regoMid and regoUp, because there is no influence of lateral surface fluxes as in lake and terrestrial periods /Bosson et al. 2010/. The maximum net up flux in the marine basins model at 2000 AD was assumed to be the best estimate of the parameter in order to have a conservative approach. The maximum net value, 0.008 m y^{-1}, was used for all marine biosphere objects during all time steps.

10.6.2 Sea_Aqu_adv_mid_up_norm (unitless)

This parameter represents a factor used to relate the lateral ground water flux to sub catchment area in the radionuclide model. In the landscape radionuclide model it is assumed that there is no influence of lateral advective fluxes in the marine biosphere object (see Chapter 10 in /Andersson 2010/), therefore this parameter is set to zero for the biosphere objects during the marine stages.

10.6.3 Runoff (m y^{-1})

The Runoff parameter describes the total mean annual runoff for the SDM-site model areas calculated in MIKE SHE. From the total mean annual runoff of 0.186 m $y^{-1,}$ 0.144 m y^{-1} is runoff from surface streams and 0.042 m y^{-1} 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/. Mean for the parameter (Runoff) is 0.186 m y^{-1}.

10.6.4 Wat_ret (y)

This parameter represents the hydraulic residence time, during the time period. The residence time is defined as the average age of the water (AvA) within each basin. The calculation of the parameter is extensively described in Chapter 9.1, this report and in /Karlsson et al. 2010/. AvA describes the average time that a water parcels have spent within a given water volume. Using the shoreline displacement equation /Brydsten 2006/ as input, /Karlsson et al. 2010/ conducted detailed hydrodynamic modelling of marine basins in the Forsmark area. The hydrodynamic model gives outputs on annual mean flows between adjacent basins and a measure of the water retention time for each basin and for the whole area. For the open sea stage, when the regional model area is submerged, the circulation was simulated using a model for the entire Baltic Sea. For the other two stages, an open-ended bay as today and a estuarine closed bay, a high-resolution local model was set up for the near-coastal basin Öregrundsgrepen. The present water retention time in the sub-basins varies between 13 and 34 AvA days (22 in average), with a more rapid water turnover in the deeper areas close to the open Baltic Sea and the longest retention in the shallow sub-basins 117 and 118, secluded from the other basins by the Biotest basin (see Chapter 9 in this report and /Karlsson et al. 2010/)

The parameter (wat_ret) values used in the radionuclide model are presented in Table 10-20. In the radionuclide model some of the marine objects (basins 105, 114 and 125) are given a larger area than earlier and therefore a mean value comprising the larger area, for wat_ret has been calculated. For intermediate time steps where no values were calculated by DHI, the wat_ret value has been interpolated. Empty grey cells in Table 10-20 indicate that the basin is above sea level.

Table 10-20. Calculated average age of water (y) whitin each marine basin in Forsmark for the various timesteps. *mean value for basin 109,113,114 and 115, **mean value for basin 105 and 112, ***mean value for basin 125 and 128. Empty grey cells indicate that the basin is above sea level.

Basin	6500 BC	3000 BC	1000 BC	0 AD	1000 AD	2020 AD	3000 AD	4000 AD	5000 AD	6000 AD	7000 AD	8000 AD	9000 AD	30,000 AD
100	0.013	0.006	0.009	0.021	0.060	0.036	0.021	0.035	0.046	0.038	0.052	0.060	0.121	0.121
101	0.019	0.011	0.014	0.027	0.069	0.046	0.031	0.041	0.064	0.056	0.071			
105**	0.022	0.015	0.020	0.033	0.074	0.051	0.039	0.058	0.087	0.062	0.076	0.078	0.113	0.113
107	0.025	0.016	0.022	0.044	0.075	0.060	0.052							
108	0.026	0.015	0.021	0.039	0.076	0.058	0.048	0.061						
114*	0.019	0.014	0.020	0.033	0.075	0.051	0.040	0.062	0.104	0.091	0.121	0.083		
116	0.027	0.018	0.024	0.043	0.076	0.061	0.053	0.070						
117	0.023	0.017	0.026	0.052	0.075	0.082								
118	0.023	0.018	0.026	0.051	0.075	0.092								
120	0.021	0.018	0.025	0.054	0.077	0.064								
121_01	0.024	0.019	0.025	0.049	0.074	0.062	0.059							
121_02	0.024	0.019	0.025	0.049	0.074	0.062	0.059							
121_02	0.024	0.019	0.025	0.049	0.074	0.062	0.059							
123	0.018	0.016	0.022	0.038	0.076	0.058	0.052	0.071	0.117	0.028				
124	0.021	0.019	0.025	0.052	0.077									
125***	0.021	0.019	0.025	0.054	0.078									
126	0.022	0.019	0.024	0.044	0.074	0.061	0.057	0.105						
136	0.019	0.018	0.025	0.054	0.078									
146	0.018	0.018	0.023	0.044	0.074	0.062	0.054	0.064						
All basins (Öregrundsgrepen)	0.017	0.012	0.018	0.036	0.070	0.050	0.037	0.051	0.078	0.070	0.084	0.069	0.119	0.119

10.7 Chemical and biological parameters

This section describes both chemical and biological parameters they are often closely connected in the marine ecosystem. Chemical parameters considered for the distribution of radionuclides in the radionuclide model are the concentrations of particulate matter (Sea_conc_PM) and concentrations of dissolved inorganic carbon (Sea_conc_DIC). Other parameters connected to chemistry are the gas-flux of carbon dioxide across the air-water interface (Aqu_degass_C and gasUptake_C). These fluxes are mainly driven by production and respiration of biota and thus the parameters can also be considered biological and may be an important transport pathway for the radionuclide C-14. Concentration of radionuclides in biota are calculated with bio-concentration factors, which are further described in /Nordén et al. 2010/.

Biotic parameters that are important for the transfer and accumulation of radionuclides are biomasses (Aqu_biom_pp) and production (Aqu_prod_pp). Biota incorporate radionuclides during production and consumption and the excess of production (i.e. the amount not respired) settle on the sea floor as sediment or is transported to downstream objects. The flux to the sediment in the marine basins is in the radionuclide model estimated by identifying the biomass and net productivity of the biota.

In the radionuclide model biota in the marine ecosystem is divided according to habitat; 1) pelagic community, 2) benthic macro community and 3) benthic micro community.

1) The pelagic community comprises: phytoplankton, bacterioplankton, zooplankton, benthivorous-, zooplanktivorous- and piscivorous fish

2) The benthic macro community comprises: macrophytes and benthic macro fauna

3) The benthic micro community comprises: microphytobenthos and benthic bacteria

In order to describe the transfer and accumulation of radionuclides released within each biosphere object, two variants of primary production and respiration have been used. One for calculations of gas flux across air-water interface (Aqu_degass_C and gasUptake_C) and one for net productivity (Aqu_prod_pp). Marine areas can be influenced by allochtonous material from land or from adjacent marine areas (especially in the pelagic community), the respiration can be larger than primary production, i.e. the ecosystem production is negative (net heterothropic). The large respiration leads to a flux of carbon dioxide from the sea water to atmosphere. However, respiration of allochtonous material does not influence the flux of radionuclides accumulated by the marine primary producers, to the sediment, since the allochtonous material is assumed to be uncontaminated. The net productivity (i.e. primary production minus respiration) in the modelling of the flux to the sediment cannot be negative as this would indicate a flux of radionuclides out of the sediment although in reality it is allochtonous material that is respired. Therefore, it is important to estimate the respiration that is connected to autochthonous material, i.e. primary production within the marine basin, since that contains radionuclides, in contrast to respiration of allochtonous material, from uncontaminated up stream sources. Hence, when calculating the community production in the radionuclide model the net productivity is set to zero when negative. For the carbon flux across the air/interface on the other hand all respiration is important to include since the model only estimates the transfer across air-water interface for carbon-14, and the carbon-14 part of the total carbon transfer is estimated by a concentration ration. Therefore there is no need to adjust the negative net production to zero. The calculations are thoroughly described in the section below (10.7.5).

The biological parameters have been assembled in a GIS database and the abundance of biota and productivity in current basins have been extrapolated from observed point estimates combined with modeled relationships based on substrate, depth, radiation and other abiotic factors (see Chapter 4). These GIS based estimates provide no estimate of in between year variations for individual objects. Nor have they been applied to basins of the past or the future. Instead predictions of future states are based on the relationship between model parameters and average depth, based on regressions from present date states. The deviation from the GIS estimates and the regression slope (i.e. the residual variation) has been used to derive a measure of between object variation as a function of object average depth.The time-dependent input parameters, mean and standard deviation used in the radionuclide model, are stored in SKBdoc1263189[4].

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[4] SKBdoc1263189, access might be given upon request.

10.7.1 Sea_conc_PM (kg dw m^{-3})

This parameter represents the concentration of particulate matter in the water column. The particulate matters in sea water were measured at four sites (PFM 000062, PFM000066, PFM007401 and PFM007402) during 2007 and 2008 in Forsmark. Based on these measurements an annual average value for the whole area was estimated to be used in the radionuclide model calculations. The parameter values (Sea_conc_PM) are presented in Table 10-21.

Table 10-21. Mean, minimum and maximum of Sea_conc_PM in Forsmark.

Unit	Mean	Std. Dev.	Min	Max
kg dw m^{-3}	0.002913	0.0012	0.0015	0.0054

10.7.2 Sea_conc_DIC (kg C m^{-3})

This parameter represents the concentration of dissolved inorganic carbon in the water column. The concentration of dissolved inorganic carbon were sampled and analyzed during the site investigations in Forsmark. The annual average value at five sites (PFM00062, PFM00063, PFM00064, PFM00065 and PFM00082) during the years 2002 to 2006 have been used in the radionuclide model calculations. The parameter values (Sea_conc_DIC) are presented in Table 10-22.

Table 10-22. Mean, minimum and maximum of Sea_conc_DIC in Forsmark.

Unit	Mean	Std. Dev.	Min	Max
kg dw m^{-3}	0.011	0.005	0.0003	0.027

10.7.3 Aqu_biom_pp

This parameter represents the biomass of the three communities in the marine ecosystem; the pelgic community (Aqu_biom_pp_plank), the benthic macro community (Aqu_biom_pp_macro) and the benthic micro community (Aqu_biom_pp_ubent).

The biomasses in these communities, the pelagic (phyto-, zooplankton, and fish), the benthic (macrophytes and benthic macrofauna) and the benthic micro (microphytobenthos and benthic bacteria), have been interpolated over the marine model area in GIS-models, based on site specific field studies, literature values and assumptions and predictors described more in detail in Chapter 4 this report. This modelling resulted in grids (20×20 m) with estimates of biomass for each grid cell in the marine model area.

In order to generate the parameter values for the various time steps used in the radionuclide model, the annual mean values in the separate basins were correlated with depth, and the parameter functions vs. depth are presented in Figure 10-4, 10-5 and 10-6. Primary producers occur down to depths were 1% of incoming light remains. Although, theoretically the photic depths for the three communities are identical (1% of incoming light reach the same depth regardless of which community we consider), the photic depth based on mean values from measured abundances of primary producers indicates a small difference between the communities (19 vs. 20 m). Even though the difference is small the different photic depths for the communities have been used, since the data does not supply enough information to decide which photic depth that is most correct.

Aqu_biom_pp_plank (kg C m^{-2})

This parameter represents the biomass of the pelagic community (phytoplankton, zooplankton, fish and pelagic bacteria). In areas shallower than 20 m (photic depth) biomass were calculated according to the pelagic biomass correlation with depth. In deeper areas, the biomass were assumed to be the calculated mean biomass for 20 m depth together with additional 10% to compensate for pelagic heterothropic biomass in the deeper waters. In Figure 10-4 the mean parameter value vs. mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) is plotted together with the depth function of the parameter.

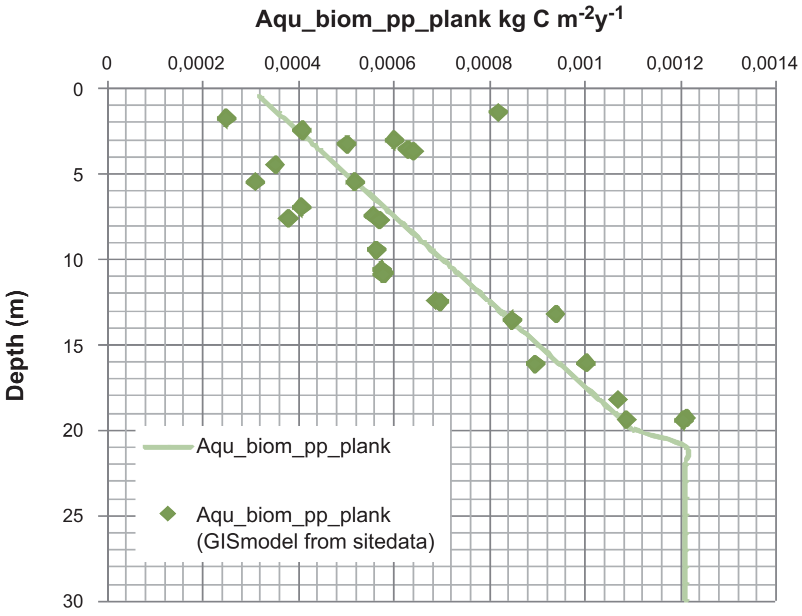

Figure 10-4. Pelagic biomass (Aqu_biom_pp_plank) vs. depth in the marine model area in Forsmark.

Aqu_biom_pp_macro (kg C m^{-2})

This parameter represents the biomass of the macrobenthic community (macrophytes and benthic macrofauna). In areas shallower than 19 m (photic area) biomass was calculated according to the macrobenthic biomass correlation with depth. Below 19 m depth the macrobenthic biomas consists only of macrofauna and was calculated according to the correlation of benthic macrofauna biomass and depth. The macrobenthic biomasses calculated with this depth function were in accordance with reported biomasses of benthic macro fauna and their depth distribution /Olenin 1997/. In Figure 10-5 the mean parameter value vs. mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) is plotted together with the depth function of the parameter.

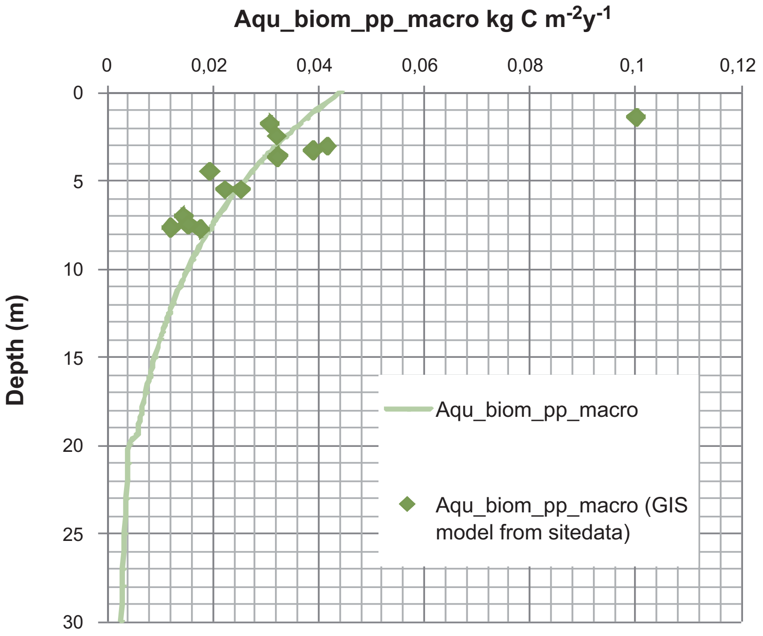

Figure 10-5. Macro benthic biomass (Aqu_biom_pp_macro), primary producers and consumers, vs. depth in the marine model area in Forsmark.

Aqu_biom_pp_ubent (kg C m^{-2})

This parameter represents the biomass of the microbenthic community, i.e. the microphytobenthos and the benthic bacteria. In the micro benthic community (Aqu_biom_pp_ubent) the biomass for the various time steps, and thereby depths, were calculated according to the micro benthic biomass correlation with depth down to 19 m. The biomass below 19 m depth was assumed to be the average benthic bacteria biomass for the whole area. In Figure 10-6 the mean parameter value vs. mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) is plotted together with the depth function of the parameter.

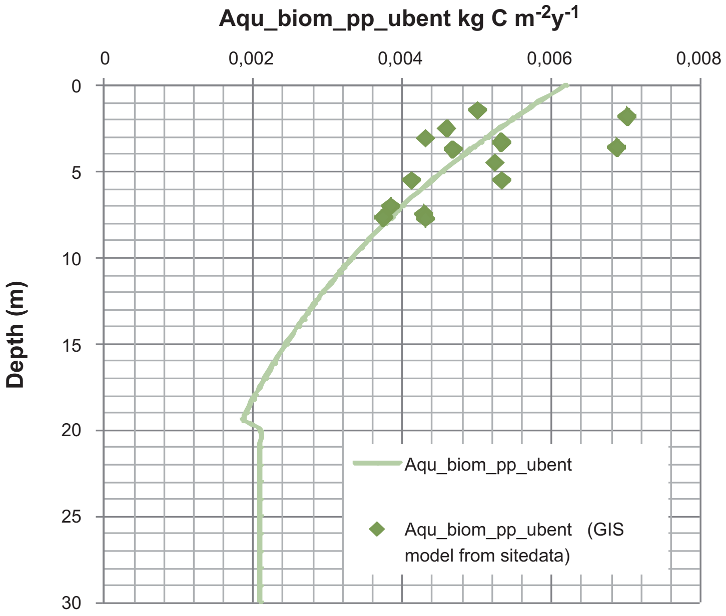

Figure 10-6. *Micro benthic biomass (Aqu_biom_pp_ubent) vs. depth in the marine model area in Forsmark.*

10.7.4 Aqu_prod_pp

This parameter represents the net ecosystem production (NEP) ratio per marine community, i.e. the community turn over, for the pelgic community (Aqu_prod_pp_plank), the benthic macro community (Aqu_prod_pp_macro) and the benthic micro community (Aqu_prod_pp_ubent).

The NEP ratio parameters were derived by dividing the annual community production (i.e. primary production minus respiration of the community), with respectively community biomasses (see previous section).

In order to generate the parameter values for the various time steps used in the landscape radionuclide model, the annual mean values in the separate basins were correlated with depth.

Aqu_prod_pp_plank (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the pelgic community (Aqu_prod_pp_plank) in the marine ecosystem.

Based on the phytoplankton biomass interpolated over the marine model area in a GIS model, the annual average phytoplankton production (NPP_plank) was obtained by multiplying areal biomass by an overall production-biomass (P/B) ratio set at 101 year^{-1} in Forsmark, see Chapter 4 and 6 /Harvey et al. 2003, Sandberg et al. 2000, Elmgren 1984, Wulff and Ulanowicz 1989/. The mean NPP per basin were correlated to the mean depth of the basins (r=0.8).

The pelagic respiration (Pel_resp) was calculated using grids for the annual average temperature and biomass together with specific values (for each functional group) describing specific respiration in relation to biomass (see Chapter 4 this report). The pelagic respiration (comprising respiration by pelagic bacteria, zooplankton and fish) correlates very well with depth (r=0.9).

The parameter, Aqu_prod_pp_plank, was calculated for the various basin depths occurring in the time span modelled in the radionuclide model, by using the depth functions for NPP, pelagic respiration and pelagic biomass (see above), according to:

Aqu_prod_pp_plank (kgC kgC^{-1} y^{-1}) = Pel_NPP (kgCm^{-2} y^{-1}) – pel_resp (kgC m^{-2} y^{-1}))/
Aqu_biom_pp_plank (kgC m^{-2} y^{-1})(equation 10-1)

The parameter is negative for all depths considered; i.e. the pelagic community is dependent on carbon from external sources (carbon from surrounding terrestrial areas, marine basins or from the benthic community). In coastal areas there is a large contribution of organic matter from land /Rolf 1998/. In order to only consider the respiration of autochthon material (see discussion Section 9.7 above) the parameter is set to zero in the radionuclide model.

Aqu_prod_pp_mac (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the macro benthic community in the marine ecosystem.

The net primary production of macrophytes (NPP_macro) has been modelled in GIS as dependent on irradiance and possible substrates in the model area (see Chapter 4 and 6 this report). The NPP_macro correlates well with depth (r=0.9). The respiration in the macrophytobenthic community (macro_resp), comprising respiration by benthic macro fauna, were modelled in GIS based on biomass, average annual benthic temperature and conversion factors from /Kautsky 1995/. Also the macro benthic respiration correlates well with depth (r=0.9).

The parameter, Aqu_prod_pp_macro, were calculated for the various basin depths occurring in the time span modelled in the radionuclide model, by using the depth functions for NPP, macro benthic respiration and macro benthic biomass (see above), according to:

Aqu_prod_pp_macro (kgC kgC^{-1} y^{-1}) =(macro_NPP (kgC m^{-2} y^{-1}) – macro_resp (kgCm^{-2} y^{-1}))/
Aqu_biom_pp_macro (kgC m^{-2} y^{-1})(equation 10-2)

The macro benthic productivity parameter is positive down to 19 m, which is the maximum depth in the area were macrophytic production is measured. Below this depth the community production is negative and dependent on lateral and vertical carbon flows from the surroundings. In order to only consider the respiration of autochthon material (see discussion Section 10.7 above) the negative production is set to zero in the radionuclide model. In Figure 10-7 the mean parameter value vs. mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) are plotted together with the depth function of the parameter.

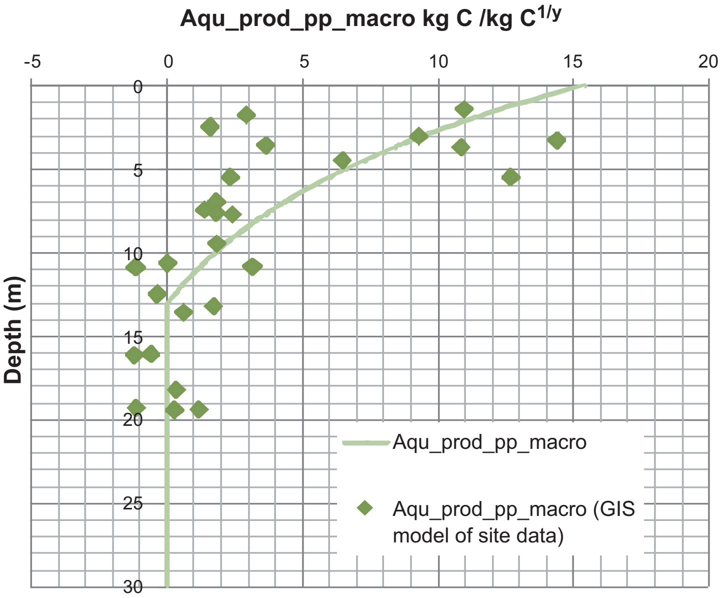

Figure 10-7. The parameter for the production ratio of the macro benthic community (Aqu_prod_pp_macro) vs. depths, representing the time span modelled in the radionuclide model in Forsmark.

Aqu_prod_pp_ubent (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the micro benthic community in the marine ecosystem.

The net primary production of microphytes (NPP_micro) has been modelled in GIS as dependent of irradiance and possible substrates in the model area (see Chapter 4 and 6 this report).The respiration in the microphytobenthic community (ubent_resp), comprising respiration by benthic bacteria, has also been modelled in GIS by using biomass, average annual benthic temperature and conversion factors (see also Chapter 4 and 6 this report and /Kautsky 1995/). Together with these parameters and the micro benthic biomass (Aqu_biom_ubent) the parameter Aqu_prod_pp_ubent,were calculated according to:

Aqu_prod_pp_ubent (kgC kgC^{-1} y^{-1}) = (ubent_NPP (kgC m^{-2} y^{-1}) – ubent_resp (kgCm^{-2} y^{-1}))/ Aqu_biom_pp_ubent (kgC m^{-2} y^{-1})(equation 10-3)

The micro benthic NEP ratio parameter is positive down to 19 m, which is the maximum depth in the area were primary production is measured. Below this depth the community production is negative and dependent on lateral and vertical carbon flows from the surroundings. In order only to only consider the respiration of autochthon material (see discussion Section 10.7 above) the negative production is set to zero in the radionuclide model. In Figure 10-8 the mean parameter value vs. mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) are plotted together with the depth function of the parameter.

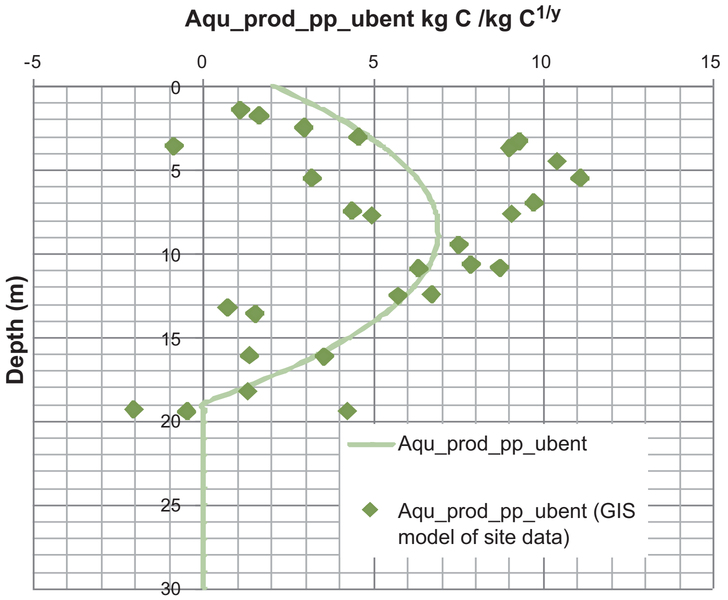

Figure 10-8. *The parameter for the production ratio of the micro benthic community (Aqu_prod_pp_ubent) vs. depths, representing the time span modelled in the radionuclide model in Forsmark.*

10.7.5 Gas uptake/release

In order to estimate carbon-14 flux across the air-water/interface in the marine ecosystem the parameters, gasUptake_C and Aqu_degass_C, was calculated. These parameters represent the flux of carbon dioxide from the water to the atmosphere. Some elements, e.g. carbon, are transported over the air-water interface at the sea surface. Data to estimate the flux of carbon is available, whereas for other radionuclides and their analogues this flux is considered to be small or insignificant.

There is equilibrium of CO_2 between air and surface waters as a response to partial pressure of the gas within the sea water and the atmosphere resulting in a flux of carbon dioxide across the air-water interface. This flux is mainly driven by primary production and respiration processes that consume or release carbon dioxide. Although primary producers have a fast uptake of CO_2 , not all CO_2 needed for primary production is taken up from the air, nor is all CO_2 from respiration released to the air but circulated within the water.

Literature concerning carbon dioxide in European coastal waters, reveals the continental shelves as significant carbon sinks while the analyzed estuaries generally acts as sources of atmospheric carbon (CO_2) /Omstedt et al. 2009/.

gasUptake_C (kg C m^{-2} y^{-1})

/Kumblad and Kautsky 2004/ estimates the uptake of carbon over the water-air interface to be 9% of the net primary production (NPP). Using this relation and the calculated NPP (see Section 4 and 6) to calculate the gas uptake in the marine model area in Forsmark, the carbon uptake lies within the range of literature values from for example /Schneider and Kuss 2004/ estimating the uptake of carbon from 0.006 to 0.02 kg C m^{-2} year^{-1} . The parameter was calculated for today's situation and assuming 9% of primary production in the marine area in Forsmark. In Figure 10-9 the mean parameter value versus mean depth in the separate marine basins is plotted together with the depth function of the parameter.

However, since the major process (photosynthesis) contributing to gas uptake from the atmosphere occur in the surface layer, the depth function is considered valid only down to around 20 m were the maximum depth for photosynthesis is.

Aqu_degass_C (kg C m^{-2} y^{-1})

The release of carbon from sea to atmosphere is a result of the biological processes respiration and mineralisation as well as chemical and physical processes like diffusion etc. Since these processes have not been measured, a theoretical estimate was made to calculate the aquatic gas release based on the assumption that there is a mass balance for carbon i.e. total influx of carbon should be equal to total outflux of carbon (Equation 10-4–10-5):

Advective influx + gasUptake_C + deposition = advective outflux + sedimentation + Aqu_degass_C (Equation 10-4)

By assuming that the influx and outflux of gas is mainly driven by primary production and respiration the equation can also be written:

Advective influx + NPP + Deposition = advective outflux + respiration + sedimentation (equation 10-5)

Where: Advective influx and advective outflux is the inflow and outflow of carbon via water, Deposition is the carbon deposition with precipitation, Sedimentation is the permanent carbon accumulation in sediment, NPP is net primary production and respiration is respiration.

The future inflow and outflow of carbon to marine basins is unknown. However, Equations 10-4 and 10-5 can be combined to give Equation 10-6:

Aqu_degass_C = respiration –NPP + gasUptake_C (equation 10-6)

In Equation 10-6, The net primary production (NPP) has been modelled in GIS as dependent of irradiance and possible substrates in the model area (see Chapter 4 and 6 this report).The respiration, have also been modelled in GIS from biomass, average annual benthic temperature and conversion factors from /Kautsky 1995/, see also Chapter 4 and 6 this report.

However, in very shallow marine areas where primary production is much larger than respiration, equation 10-6 gives a negative gas outflux. This can be caused by the fact that more than 7% of primary production is taken up of the water/air interface but also by an underestimated respiration or by underestimated influx of carbon from adjacent basins or from land. Therefore a minimum gas outflux (Aqu_degass_C) is set to 10% of gas influx (gasUptake). Thus, Aqu_degass_C is calculated from primary production, respiration and gasUptake_C when the parameter Aqu_degass_C is larger than 10% of gasUptake_C otherwise, Aqu_degass_C is estimated to be 10% of gasUptake_C. In Figure 10-9 the mean parameter values for gasUptake_C and Aqu_degass_C, versus mean depth in the separate marine basins (from the site specific GIS model of the area, see Chapter 6 this report) is plotted together with the depth function of the parameter.

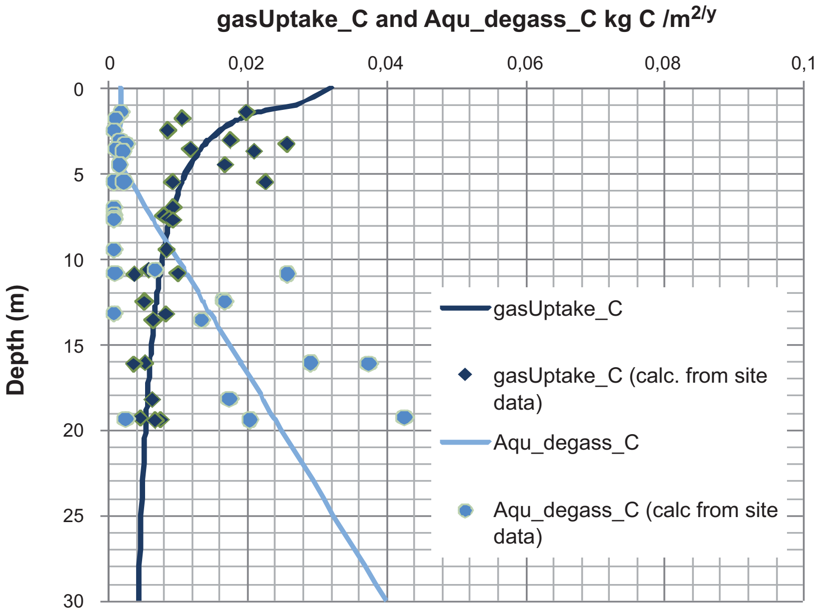

***Figure 10-9.** The flux of CO_2 from water to atmosphere (Aqu_degass_C) and the uptake of CO_2 from atmposphere to sea surface (gas_uptake_C) versus depth in Forsmark.*

Aqu_df_degass and Aqu_df_gasUptake

Aqu_df_degass and Aqu_df_gasUptake represent 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 the parameter is set to 1.

10.8 Human food parameters

The food production was categorised as food normally consumed and edible products /SKB 2006a/. Food normally consumed e.g. for a marine ecosystem fish, while edible products are everything that has some potential to be consumed by humans. Potentially it is possible to eat almost any organism above a certain size that can be handled. However, the effort to collect the food in comparison with the energy it supplies is often too large to be efficient. The benthic fauna in Forsmark is small and not easily caught. The macrophytes in the Baltic are generally not very tasty and not used as food today. Benthic fauna and algae may potentially serve as fertilizers in farming. Seals can potentially serve as food but is not used at present. Today, only fish and birds can be considered as normally eaten. However the production by the nesting birds in the marine model area /Löfgren 2010/ gave an almost insignificant contribution in relation to the fish production and is therefore not included in the radionuclide model.

Filter feeders and crayfish may be consumed by humans in marine ecosystems, although, in the area today, these food items are not consumed in any significant volumes and in addition the conditions with relatively low salinity (now and in the future) will not likely generate filter feeders and crayfish more favourable to be consumed by humans.

10.8.1 prod_edib_cray_Sea (kgC/m^2/y)

This parameter describs the productivity of crayfish normally consumed. As no crayfish exist in the marine model area today and is not likely to be present in the future, mainly due to the low salinity in the Baltic Sea. Therefore, this parameter was set to zero in the radionuclide model.

10.8.2 prod_edib_ff_Sea

This parameter describes the productivity of filter feeders normally consumed. Filter feeders possible to be consumed, like for example *Macoma baltica,* are present in the marine ecosystem in Forsmark. They are not caught today and likely neither in the future, hence they are small, not very tasteful or easily collected. In addition, due to salinity, it is not likely that the area will be inhabited by other filter feeders in the future. Therefore this parameter was set to zero in the radionuclide model.

10.8.3 prod_edib_fish_Sea

This parameter represents the productivity of fish normally consumed. The production of fish (prod_edib_fish_Sea) was initially estimated by using a size dependent ration for fish and production from a study of Canadian freshwater fish /Randall and Minns 2000/. In this study the P/B ratios are dependent on fish size (weight and length) and an allometric relationship were established from studies of 79 freshwater species. Several of the fish species were similar to the Scandinavian species and P/B is well correlated to size for most animals. /Randall and Minns 2000/. The site specific proportion of each size range of marine fish in the marine area in Forsmark /Heibo and Kårås 2005/, were compared were compared with the data from /Randall and Minns 2000/ and for each species a mean P/B was estimated for this range. This resulted in a very low parameter value for fish production in the sea, considerably lower than in the lake. Thus, these results were probably due to the different methods for test-fishing used in sea and in lake. The method in the sea /Heibo and Karås 2005/ will probably under estimate the smallest size fraction of fish in the sea. Instead, it was assumed that the P/B relationship in the lake (0.51, /Andersson 2010/) were more likely to be valid also for the sea. Thus this P/B ratio were used together with the estimated fish biomass in the area (see Chapter 6 this report). Mean value for fish production in the area is; 0.000022 kg C m^{-2} (min=0.000064 kg C m^{-2} and max=0.00071 kg C m^{-2}).

10.9 The marine Biosphere objects in Laxemar-Simpevarp

The marine biosphere objects in Laxemar-Simpevarp today, represent shallow secluded bays and more exposed archipelago (see Chapter 3). In the initial marine interglacial stage, following upon a deglaciation, the areas will be submerged by sea water with a maximum depth around 200 m /Brydsten and Strömgren 2005/. Due to shore-line displacement the marine basins will gradually become shallower and the drainage from land areas will have more and more influence on the water volume and salinity. Finally bays will be cut off and form wetlands, lakes and streams. For definitions and calculations of parameters, see Section 10.3 above. Site specific input data for Laxemar-Simpevarp and differences in comparison to the parameterisation in Forsmark is presented below. Parameter values are presented, although time dependent parameter values are presented in SKBdoc1263189[5].

10.10 Geometric parameters

The definition of geometric parameters is given in the former Section 10.4. Geometric parameters in Laxemar-Simpevarp and the time dependent parameter values are presented in SKBdoc1263189[4], but parameter values for threshold_start and threshold_stop for the biosphere objects in Laxemar-Simpevarp are presented in the following text.

10.10.1 threshold_start (y AD) and threshold_stop(yAD)

The threshold start and threshold stop for each basin is presented in Table 10-23. Basin 210, is the first object starting the isolation from sea to lake. Basin 215 is the last basin that starts isolation from sea to lake.

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[5] SKBdoc1263189, access might be given upon request.

Table 10-23. Isolation year is the modelled isolation of a marine basin into a lake basin in Laxemar-Simpevarp /Brydsten and Strömgren 2010/. Treshold_start and threshold stop represent the start and stop of isolation period for each basin and isolation period represent the length of the isolation period.

	Isolation year (y AD)	Threshold _start (y AD)	Threshold_stop (y AD)	Isolation period (y)
Basin 201	4700	3610	6225	2,615
Basin 202	0	–700	550	1,250
Basin 203	–1000	–1700	–450	1,250
Basin 204	–3000	–3700	–2450	1,250
Basin 205	–1000	–1700	–450	1,250
Basin 206	–3500	–3800	–2950	850
Basin 207	0	–4200	170	4,370
Basin 208	2500	1450	3340	1,890
Basin 209	2000	1300	2550	1,250
Basin 210	–4000	–4700	–3450	1,250
Basin 211	2000	1300	2550	1,250
Basin 212	500	–200	1050	1,250
Basin 213	–2000	–2700	–1450	1,250
Basin 214	–2500	–3200	–1950	1,250
Basin 215	9500	8800	10,050	1,250
Basin 216	2500	1800	3050	1,250

10.11 Regolith parameters

Definition of regolith parameters is given in Section 10.5. The regolith at each biosphere object is described according to the conceptual model of the spatial distribution of regolith in Forsmark and Laxemar-Simpevarp (Figure 10-1).The main input for describing properties of the regolith in Laxemar-Simpevarp is the surface map of Quaternary deposits (Figure 10-10), the depth and stratigraphy model of regolith, Regolith Depth Model (RDM), /Sohlenius and Hedenström 2008/, soiltype map /Nyman et al. 2008/ together with models of future distribution of quaternary deposits /Brydsten and Strömgren 2010/.

As mentioned above (in Section 10.5) the regolith can be divided into different compartments, specified according to their characteristics and location in; 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, whereas the definitions of density, porosity and layers are presented in the former Section 10.5.

10.11.1 Sea_z_regoup (m)

The mean depth of the parameter was set to 0.1 m according to /Håkansson et al. 2004/ (minimum 0 and maximum 0.2 m) based on an average of data from the Baltic Sea.

10.11.2 Aqu_dens_regoUp _acc (kg m^{-3})

The parameter value represents the dry bulk density of the uppermost sediments 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 erosion bottoms was calculated based on results from analyses of clay gyttja sampled by /Fredriksson 2004/ at the floor of Borholmsfjärden. The calculations are based on results from analyses 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 material 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 at accumulation bottoms (Aqu_den_regoup_acc) are presented in Table 10-24.

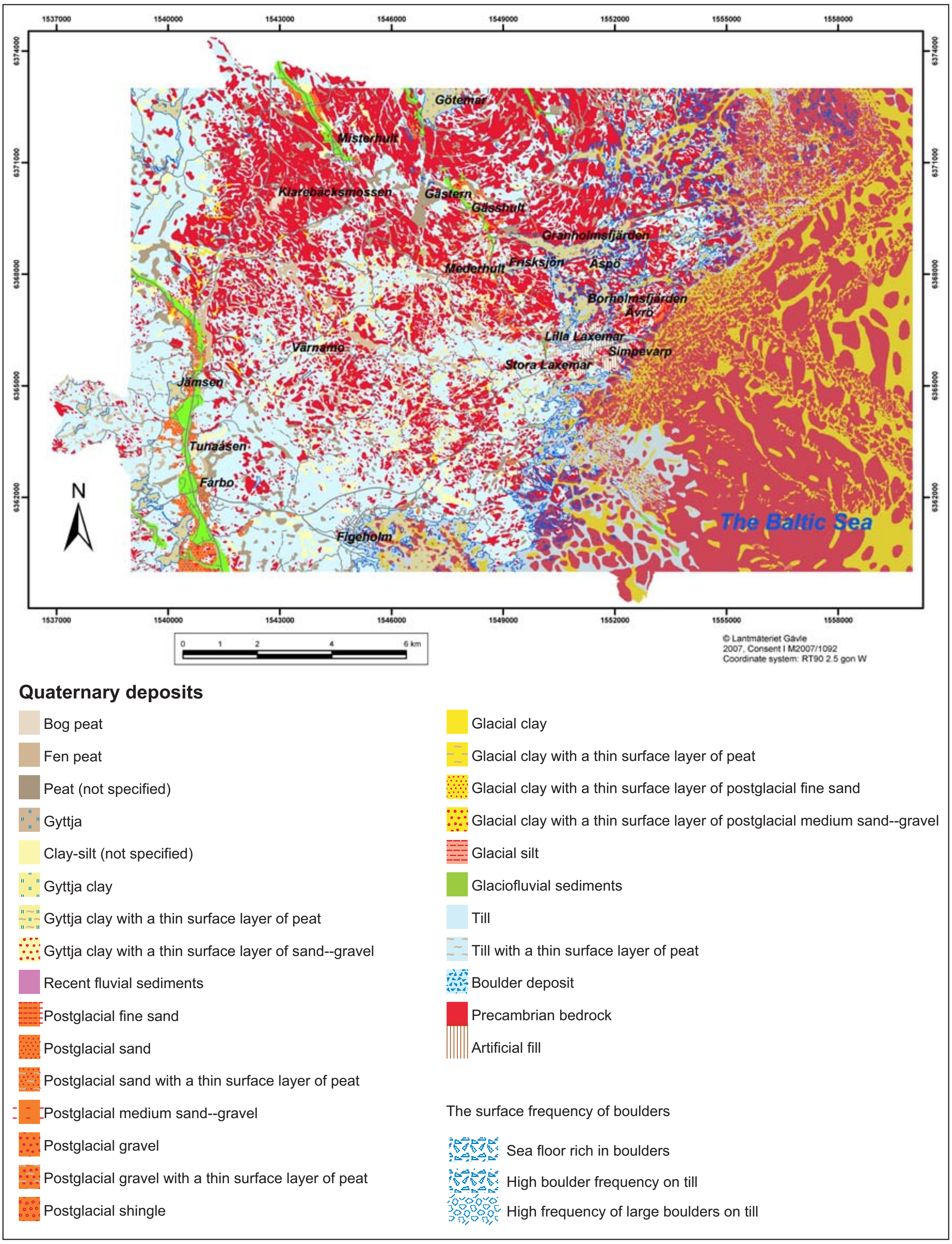

Figure 10-10. *The surface distribution of the Quaternary deposits (regolith) at Laxemar-Simpevarp /Sohlenius and Hedenström 2008/.Precambrian bedrock is not part of regolith but is sometimes the uppermost layer, i.e. there are no deposits on the bedrock. In the radionuclide model the quaternary deposits have been divided into three layers: Regolow, regomid and regoup. Regolow includes a) till. Regomid includes a) Glaciofluvial sediments, b) Postglacial sand-single, c) Glacial postglacial clay and clay gytta, d) Clay silt and part of e) peat and gyttja. Regoup includes the upper parts of the marine sediment peat and gyttja.*

Table 10-24. The parameter values for Aqua_dens_regoUp_acc in Laxemar-Simpevarp, representing the dry bulk density of the surface sediments in accumulation bottoms in the aquatic system.

Dry bulk dens	kg m^{-3}
Mean	96.1
Max	153.5
Min	66.0
Std	17.8
n	58

10.11.3 Aqu_dens_regoUp _ero (kg m^{-3})

The parameter value represents the dry bulk density of the upper sediment at erosion and transport bottoms in the marine area. The dry bulk density of regolith at erosion and transport bottoms was calculated based on results from analyses of sand sampled by /Fredriksson 2004/ at the floor of Borholmsfjärden. The calculations are based on results from analyses 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 material 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 at erosive and transport bottoms (Aqu_den_regoup_ero) are presented in Table 10-25.

Table 10-25. The parameter values for Aqua_dens_regoUp_ero in Laxemar-Simpevarp, representing the dry bulk density the surface sediment at transport and erosive bottoms in the marine areas.

Dry bulk dens	kg m^{-3}
Mean	1,480
Max	2,350
Min	560
Std	290
n	17

10.11.4 Aqu_poro_regoup_acc (m^3 m^{-3})

This parameter 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 calculations are made by the use of results from analyses 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 material 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 at accumulation bottoms (Aqu_poro_regoup_acc) are presented in Table 10-26.

Table 10-26. The parameter values for porosity of the top sediment in accumulation bottoms in the aquatic systems in Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.95
Max	0.96
Min	0.92
Std	0.01
n	58

10.11.5 Aqu_poro_regoUp_ero (m^3 m^{-3})

This parameter represents the porosity of the uppermost sediments at erosion and transport bottoms in the marine area. The porosity of regolith at erosion and transport bottoms was calculated based on results from analyses of sand sampled by /Fredriksson 2004/ at the floor of Borholmsfjärden. The calculations are made by the use of results from analyses 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 material have densities of 1 and 2.65 g/cm^3 respectively. The parameter values (Aqu_poro_regoUp_ero) are presented in Table 10-27.

Table 10-27. The parameter values for Aqu_poro_regoUp_ero in Laxemar-Simpevarp, representing the porosity of the surface sediments at transport and erosion bottoms in the marine area.

Porosity	m^3 m^{-3}
Mean	0.43
Max	0.77
Min	0.11
Std	0.17
n	22

10.11.6 z_regoMid_gl_basin (m)

The depth and distribution of this layer is regarded as constant over time, covering the till and bedrock surface from the deglaciation onwards. The depth of this layer is specific for each object, based on the RLDM /Brydsten and Strömgren 2010/. The values presented in Table 10-28 are means for each marine basin prior to isolation.

Table 10-28. Mean, minimum and maximum depth, in m, of the lower regolith (z_regoMid_gl_basin) in the Laxemar-Simpevarp objects.

Object	mean	minimum	maximum
Basin 201	0.31	0.08	0.43
Basin 202	0.16	0.08	0.43
Basin 203	0.19	0.08	0.43
Basin 204	0.23	0.08	0.43
Basin 205	0.16	0.08	0.43
Basin 206	0.18	0.08	0.43
Basin 207	0.17	0.08	0.43
Basin 208	0.43	0.08	0.43
Basin 209	0.14	0.08	0.43
Basin 210	0.16	0.08	0.43
Basin 211	0.08	0.08	0.43
Basin 212	0.08	0.08	0.43
Basin 213	0.09	0.08	0.43
Basin 214	0.16	0.08	0.43
Basin 215	0.20	0.08	0.43
Basin 216	0.11	0.08	0.43

10.11.7 Aqu_dens_regoMid_PG (kg m^{-3})

The postglacial clay in the Laxemar 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 material 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 10-29.

Table 10-29. The parameter values of Aqu_dens_regoMid_PG in Laxemar-Simpevarp, representing the dry bulk density of postglacial clay gyttja.

Dry bulk dens	kg m^{-3}
Mean	181
max	394
min	76
Std	0.06
n	42

10.11.8 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 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 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 area. The mean, maximum and minimum values of the parameter (Aqu_dens_regMid_GL) are presented in Table 10-30.

Table 10-30. The parameter values for Aqua_dens_regoMid_GL in Laxemar-Simpevarp, representing the dry bulk density of glacial clay.

Dry bulk dens	kg m^{-3}
Mean	696
Max	1,053
Min	446
stdev	171
n	11

10.11.9 Aqu_poro_regoMid_PG (m^3 m^{-3})

The postglacial clay in the Laxemar 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 material 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 10-31.

Table 10-31. Parameter values for Aqua_poro_regoMid_PG in Laxemar-Simpevarp, representing the porosity of postglacial clay gyttja.

Porosity	m^3 m^{-3}
Mean	0.9
Max	0.94
Min	0.75
Std	0.03
N	42

10.11.10 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 area. The porosity values for glacial clay are based secondary calculations from grain size distribution curves of clay collected offshore 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 10-32.

Table 10-32. Parameter values for Aqua_poro_regoMid_GL and Ter_poro_regoMid_GL in Laxemar-Simpevarp, representing the porosity of glacial clay.

Porosity	$m^3 m^{-3}$
Mean	0.74
Max	0.83
Min	0.60
Stddev	0.07
N	11

10.11.11 Sea_z_regolow (m)

The parameter (Sea_z_regolow) values presented are mean for each marine basin, prior to isolation, Table 10-33.

Table 10-33. 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

10.11.12 dens_regoLow (kg m^{-3})

The till in the Laxemar 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 was 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 10-34, are mean for each marine basin, prior to isolation.

Table 10-34. The parameter values for dens_regoLow, representing the dry bulk density of till in Laxemar-Simpevarp.

Dry bulk dens	kg m^{-3}
Mean	2,075
Max	2,300
Min	1,850

10.11.13 poro_regoLow (m^3 m^{-3})

This parameter represents the porosity of glacial till. The till in the Laxemar 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 was 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 10-35. The parameter values for dens_regoLow, representing the porosity of till in Laxemar-Simpevarp.

Porosity	m^3 m^{-3}
Mean	0.18
Max	0.25
Min	0.10

10.12 Hydrology parameters

This section includes hydrological parameters used in the radionuclide model to describe water fluxes in the sea: The parameters are; Sea_adv_low_mid, Sea_Aqu_adv_mid_up_norm, Runoff and Wat_ret, schematically presented above in Figure 10-6, and the definitions of the parameters in Section 10-6.

10.12.1 Sea_adv_low_mid (m y^{-1})

The average net up flux for the marine basins model at 2000 AD was assumed to be the best estimate of the parameter in order to have a conservative approach. The maximum net value, 0.036 m y^{-1}, was used for all marine biosphere objects during all time steps /Bosson et al. 2010/.

10.12.2 Sea_Aqu_adv_mid_up_norm (unitless)

In the radionuclide model it is assumed that there is no influence of lateral advective fluxes in the marine biosphere object (see Chapter 10 in /Andersson 2010/), therefore this parameter is set to zero for the biosphere objects during the marine stages.

10.12.3 Runoff (m y^{-1})

The runoff parameter represents the total mean annual runoff for the SDM-site model area in MIKE SHE. For distribution data of minimum, maximum and the standard deviation of the runoff data from long time regional measurement at the station in Forshultesjön nedre (SMHI station 1619) was used. The annual mean values, based on daily mean discharge during the period 1955 to 2000, was used when calculating the statistics of the runoff in the area. Of the total mean annual runoff of 0.170 m y^{-1}, and the min and max 0.06–0.4 m y^{-1}. 0.145 m 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. 2008/.

10.12.4 Wat_ret (y)

The method for calculating the parameter in Laxemar-Simpevarp was basically the same as in Forsmark. Caculations were made for the time span 3000 BC to 9000 AD, for 13 representative years, using the same forcing of the model. Although, instead of a high-resolution three-dimensional model as in Forsmark, a numerical two-dimensional model, computing the AvA days for a set of discrete hydraulically coupled basins were used /Engqvist 2010/. Except for the higher spatial resolution, the three dimensional model calculates gradients within a basin, while the two-dimensional basin calculates gradients in between basins. For intermediate time steps where no values were calculated, the wat_ret value, have been interpolated. Empty grey cells indicate that the basin is above sea level. The parameter values for basin 206 and 210 have been given the same values as adjacent basins during the early time steps when they are in sea stage, since they have already become lakes when the model computation begins, i.e. 3000 BC.

Table 10-36. Calculated average age of water (y) within each marine basin for the various timesteps in Laxemar-Simpevarp. Empty grey cells indicate that the basin is above sea level.

Basin	3000 BC	2000 BC	1000 BC	0 BC/AD	1000 AD	2000 AD	3000 AD	4000 AD	5000 AD	6000 AD	7000 AD	8000 AD	9000 AD
20	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
201	0.011	0.011	0.011	0.018	0.107	0.078	0.184	0.301	Lake				
202	0.261	0.107	Lake	Lake									
203	0.261	0.109	Lake										
204	0.261												
205	0.011	0.043											
206													
207	0.011	0.016	0.031	0.325									
208	0.011	0.011	0.011	0.011	0.082	0.055	0.106						
209	0.011	0.011	0.011	0.016	Lake	0.066							
210													
211	0.011	0.011	0.012	0.015	0.051	0.052							
212	0.011	0.023	0.019	0.018									
213	0.042	0.120	Lake										
214	0.074												
215	0.011	0.011	0.011	0.011	0.011	0.012	0.011	0.011	0.021	0.033	0.027	0.075	0.140
216	0.011	0.011	0.011	0.022	0.175	0.121							

10.13 Chemical and biotic parameters

This section describes both chemical and biological parameters in Laxemar-Simpevarp background and definitions of the parameters are presented in Section 10-7 above. The time-dependent input parameters, mean and std av for the three communities, used in the radionuclide model, are presented in SKBdoc1263189[6].

10.13.1 Sea_conc_PM (kg dw m^{-3})

The particulate matter in sea water was measured at three sample sites (PSM 002064, PSM007090 and PSM007097) during 2007 to 2008 in Laxemar-Simpevarp. Based on these measurements an annual average value for the whole area was calculated to be used in the radionuclide model calculations. The parameter values (Sea_conc_PM) is presented in Table 10-37.

Table 10-37. Mean, minimum and maximum of Sea_conc_PM in Laxemar-Simpevarp.

Unit	Mean	Std. Dev.	Min	Max
kg dw m^{-3}	0.00376	0.00044	0.0032	0.0043

10.13.2 Sea_conc_DIC (kg C m^{-3})

The concentration of dissolved inorganic carbon, were sampled and analyzed during the site investigations in Laxemar-Simpevarp (Chapter 3 this report). The annual average value at five sites (PSM002060, PSM002061, PSM002062 and PSM002064) during the years 2002 to 2006 have been used in the radionuclide model calculations. The parameter values (Sea_conc_DIC) is presented in Table 10-38.

Table 10-38. Mean, minimum and maximum of Sea_conc_DIC in Laxemar-Simpevarp.

Unit	Mean	Std. Dev.	Min	Max
kg dw m^{-3}	0,015	0,003	0,004	0,022

10.13.3 Aqu_biom_pp

The function for the biomass parameters vs. depth is presented in Figure 10-11, 10-12, and 10-13. Primary producers occur down to depths were 1% of incoming light remains. Although, theoretically the photic depth for the three communities are identical (1% of incoming light reach the same depth regardless of which community we consider), the photic depth based on mean values from measured abundances of primary producers indicates a small difference between the communities (19 vs. 20 m). Even though the difference is small the different photic depths for the communities have been used, since the data does not supply enough information to decide which photic depth that is most correct.

Aqu_biom_pp_plank (kg C m^{-2})

This parameter represents the biomass of the pelagic community (phytoplankton, zooplankton, fish and pelagic bacteria). In areas shallower than 20 m (photic depth) biomass were calculated according to the pelagic biomass correlation with depth. In deeper areas, the biomass were assumed to be the calculated mean biomass for 20 m depth together with additional 10% to compensate for pelagic heterothropic biomass in the deeper waters.

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[6] SKBdoc1263189, access might be given upon request.

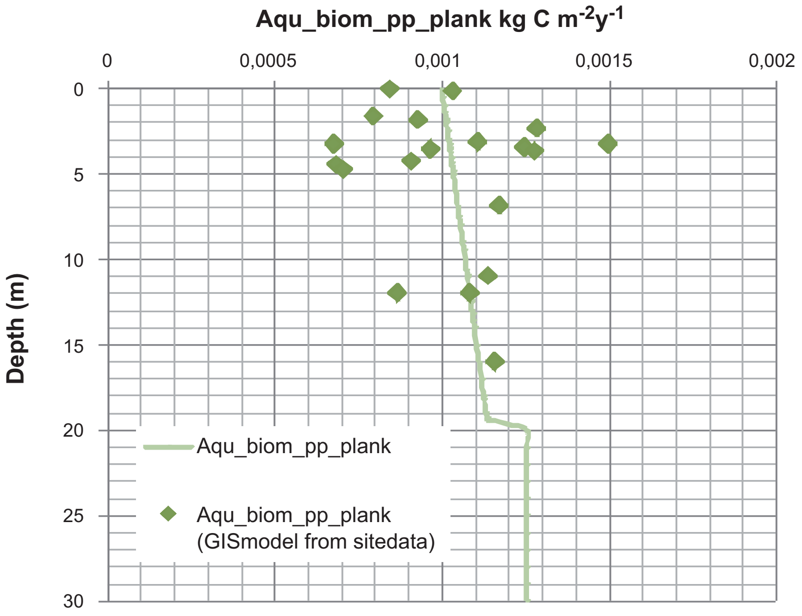

Figure 10-11. *Pelagic biomass in relation to depth in the marine model area in Laxemar-Simpevarp.*

Aqu_biom_pp_macro (kg C m^{-2})

This parameter represents the biomass of the macrobenthic community (macrophytes and benthic macrofauna). In areas shallower than 19 m (photic area) biomass was calculated according to the macrobenthic biomass correlation with depth, Figure 10-12. Below 19 m depth the macrobenthic biomass consists only of macrofauna and was calculated according to the correlation for biomass of benthic macro fauna biomass to depth. The macrobenthic biomasses calculated with this depth function were in accordance with reported biomasses of benthic macro fauna and their depth distribution /Olenin 1997/.

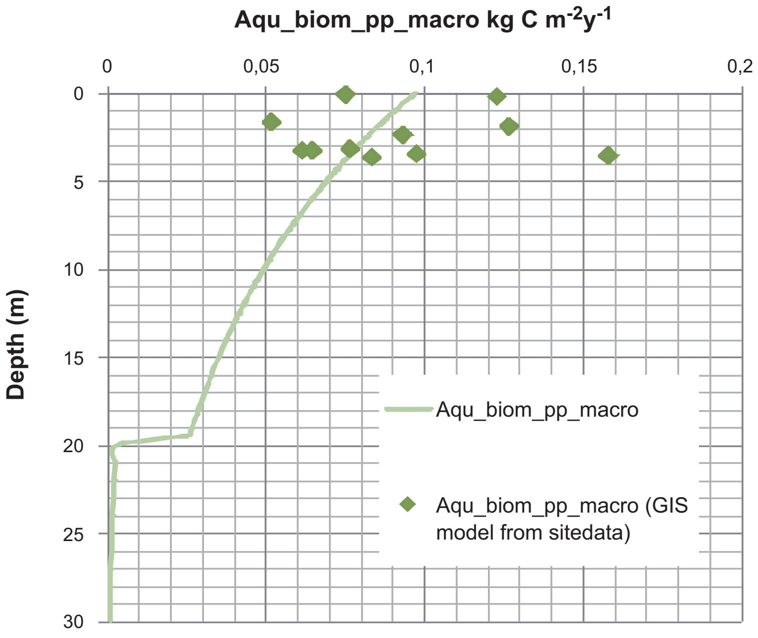

Figure 10-12. *Macro benthic biomass, primary producers and consumers, in relation to depth in the marine model area in Laxemar-Simpevarp.*

Aqu_biom_pp_ubent (kg C m^{-2})

This parameter represents the biomass of the microbenthic community, i.e. the microphytobenthos and the benthic bacteria. In the micro benthic community (Aqu_biom_pp_ubent) the biomass for the various time steps, and thereby depths, were calculated according to the micro benthic biomass correlation with depth down to 19 m. The biomass below 19 m depth was assumed to be the average benthic bacteria biomass for the whole area.

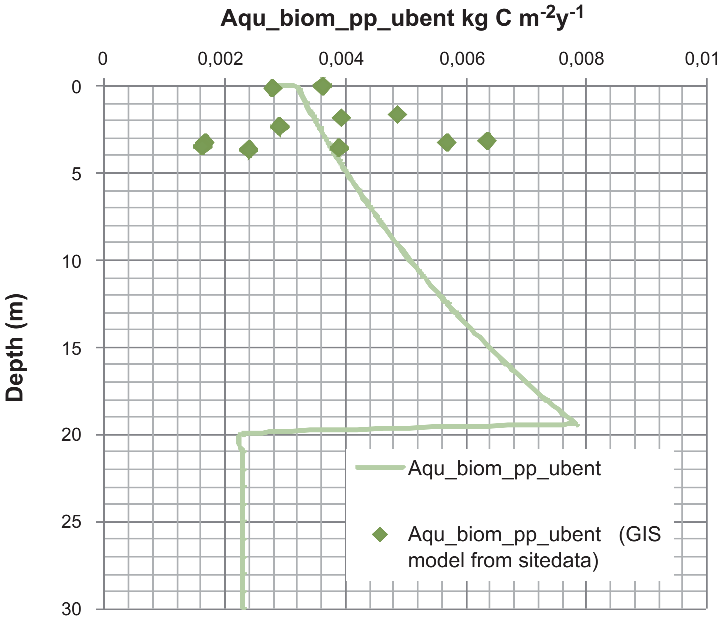

Figure 10-13. *Micro benthic biomass in relation to depth in the marine model area in Laxemar-Simpevarp.*

10.13.4 Aqu_prod_pp

This parameter represents the NEP ratio per marine community, i.e. the community turn over, for the pelgic community (Aqu_prod_pp_plank), the benthic macro community (Aqu_prod_pp_macro) and the benthic micro community (Aqu_prod_pp_ubent).

The NEP ratio parameters were derived by dividing the net annual community production (i.e. primary production minus respiration), with respectively community biomasses (see previous section).

In order to generate the parameter values for the various time steps used in the landscape radionuclide model, the annual mean values in the separate basins were correlated with depth, see Figure 10-14, 10-15 and 10-16.

Aqu_prod_pp_plank (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the pelgic community (Aqu_prod_pp_plank) in the marine ecosystem (see description in Section 10.7.4). In order to estimate only the respiration of autochthon material (see discussion Section 9.7 above) the parameter is set to zero in the radionuclide model.

Aqu_prod_pp_mac (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the macro benthic community in the marine ecosystem. Definition and explanation of the parameter is presented in Section 10.7.4. The macro benthic productivity parameter for all depths and all marine basins in Laxemar-Simpevarp is plotted in Figure 10-14. The parameter is positive down to 19 m, which is the maximum depth in the area were macrophytic production is measured. Below this depth the community production is negative and dependent on lateral and vertical carbon flows from the surroundings. In order to estimate only the respiration of autochthon material (see discussion Section 9.7 above) the parameter is set to zero when negative in the radionuclide model.

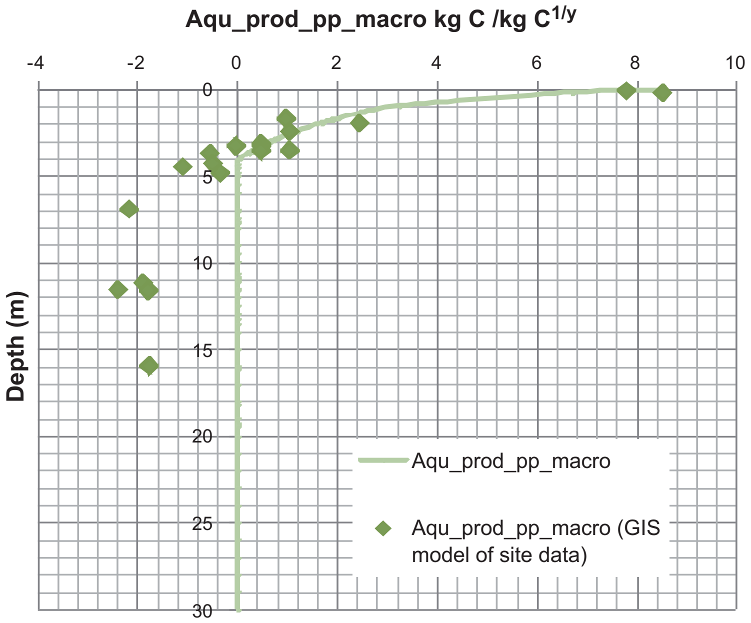

Figure 10-14. *Aqu_prod_pp_macro for all depths considered in the time span modelled in the landscape radionuclide model for Laxemar-Simpevarp.*

Aqu_prod_pp_ubent (kgC kgC^{-1} y^{-1})

This parameter represents the NEP ratio of the macro benthic community in the marine ecosystem. Definition and explanation of the parameter is presented in Section 10.7.4. The micro benthic productivity parameter for all depths and all marine basins in Laxemar-Simpevarp is plotted in Figure 10-15. The parameter will be negative at depths below 19 m. The size and actual origin of this external source of carbon is difficult to estimate with available data and therefore this term is unknown. In order to estimate only the respiration of autochthon material (see discussion Section 9.7 above) the parameter is set to zero when negative in the radionuclide model.

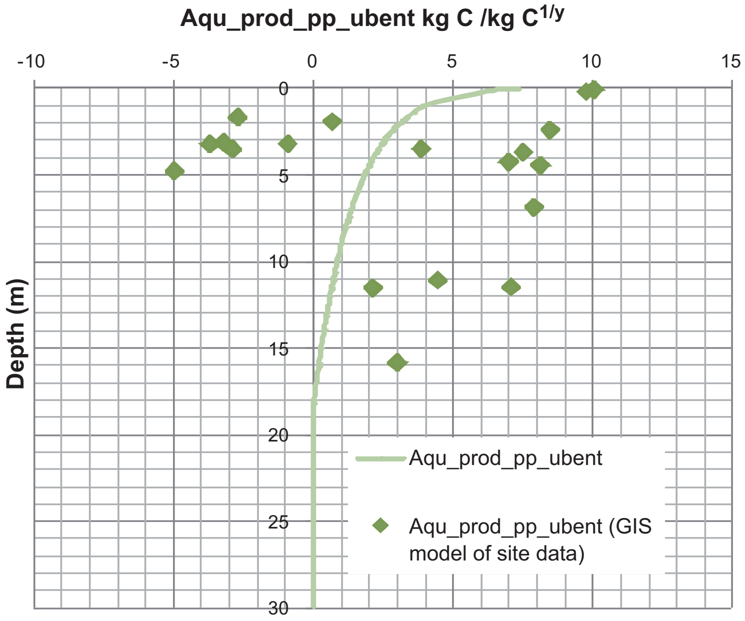

Figure 10-15. *Aqu_prod_pp_ubent for all depths considered in the time span modelled in the landscape radionuclide model in Laxemar-Simpevarp.*

10.13.5 Gas uptake/release

In the order to estimate the carbon-14 flux across the air-water interface in the marine ecosystem the parameters, gasUptake_C and Aqu_degass_C, were calculated. Definition and explanation of the parameter is presented in Section 10.7.4.

gasUptake_C (kg C m^{-2} y^{-1})

The parameter were calculated for today's situation and assuming 9% of primary production in the marine area in Laxemar-Simpevarp and plotted against depth. The Aquatic gas uptake was correlated with depth (see Figure 10-16) and the resulting function was used to estimate the parameter for the various time steps and depths used in the landscape radionuclide model calculations.

Aqu_degass_C (kg C m^{-2} y^{-1})

The gas release was correlated to the mean depth of the basins. The depth function along with the assumption that the gas release were always assumed to be at least 10% of the gas uptake, were then used for calculating the parameter for the time span used in the radionuclide model calculations (see Figure 10-16).

Aqu_df_degass and Aqu_df_gasUptake

Aqu_df_degass and Aqu_df_gasUptake represent 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 the parameter is set to 1.

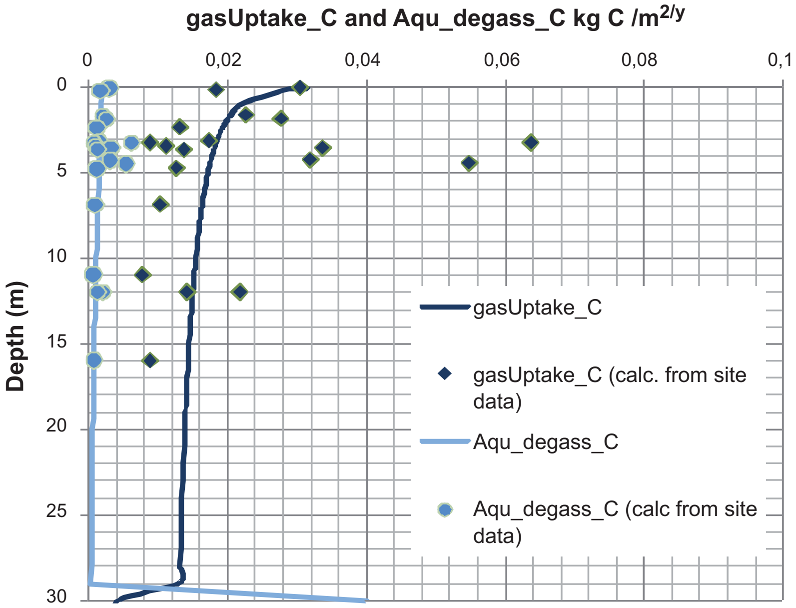

Figure 10-16. The calculated Aqu_gas_uptake_C as a function of depth, plotted for all basins based on the assumption that gas uptake is 9% of NPP in Laxemar-Simpevarp.

10.14 Human food parameters

See Section 10.8 for definition.

10.14.1 prod_edib_cray_Sea (kgC/m^2/y)

This parameter described the productivity of crayfish normally consumed. As no crayfish exist in the marine model area today and is not likely, due to the low salinity, to be present in the future. Therefore this parameter is set to zero in the radionuclide model.

10.14.2 prod_edib_ff_Sea

This parameter describes the productivity of filter feeders normally consumed. Filter feeders possible to be consumed, like for example *Macoma baltica,* are present in the marine ecosystem in Laxemar-Simpevarp, although, they are not eaten today. Hence, they are small, not very tasteful and not easily collected. In addition, due to the low salinity, it is not likely that the area will be inhabited by other filter feeders more likely as food source in the future either. Therefore this parameter is set to zero in the radionuclide model.

10.14.3 prod_edib_fish_Sea

This parameter represents the productivity of fish normally consumed. This parameter were derived as for Forsmark (see Section 10.8.3), thus by using the site specific estimates for fish biomass in Laxemar-Simpevarp (see Chapter 6 this report).Mean value for fish production in the area is; 0.000033 kg C m^{-2} (min=0 kg C m^{-2} and max=0.00054 kg C m^{-2}).

10.15 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.

10.15.1 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 emphasises 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 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 2010/.

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 /Näslund 2010/. In the radionuclide modelling, the temperate estimates are also used for periglacial and global warming conditions (see chapter 7). 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 porosity of peat in a mire or the density of soil used for agriculture purposes. In other cases, the estimates will be overestimates for permafrost conditions, such as tree net primary production. 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 /Biosphere synthesis report, Avila et al. 2010/.

11 Concluding description of the marine ecosystems in Forsmark and Laxemar-Simpevarp

This last chapter summarizes the previous chapters in order to give a comprehensive description of how the main objectives of the report were fulfilled and also to back the assumptions and conditions used for the marine ecosystems in the radionuclide model.

The main objectives of the report was 1) to give a comprehensive description of the marine ecosystems at the two sites including including major pools and fluxes of elements in Forsmark and Laxemar-Simpevarp today and during long-term development, 2) to describe the human impact on the ecosystems, 3) to identify and describe important processes in the marine ecosystems and how they are considered in the safety assessment and 4) to describe the derivation of the parameters used in the marine part of the radionuclide model (Chapter 10 in /Andersson 2010/). In order to meet these main objectives large amounts of data, (site specific and generic), descriptions, models and calculations have been presented in the previous chapters of this report.

11.1 Site descriptions

11.1.1 Abiotic characteristics

In comparison with the Gulf of Bothnia and the Baltic Proper, salinity is somewhat lower in Forsmark and Laxemar-Simpevarp, respectively, mainly due the influence of freshwater from land. Mean light penetration and depth are also lower at both sites than in the national monitoring, probably due to their location near the coast, with higher loads of organic material. The oxygen levels in Laxemar-Simpevarp are relatively high compared with the levels found in the national monitoring .

The nitrogen and phosphorus levels are low to moderately high at the two sites compared with the environmental monitoring data for the corresponding areas in the Baltic Sea. In Forsmark, nitrogen seems to be the limiting nutrient during the summer months. In Laxemar-Simpevarp, nitrogen seems to be the limiting nutrient in the outer areas and phosphorus in the inner bays. This coincides with general conditions in the Bothnian Sea (Forsmark) and the Baltic Proper (Laxemar-Simpevarp).

Forsmark is situated in an area with somewhat higher precipitation than Laxemar-Simpevarp. The annual mean water temperature is slightly above the mean for the Baltic Sea in Forsmark and slightly lower in Laxemar-Simpevarp. Runoff in the Forsmark area is higher (0.6 m^3 m^{-2} $year^{-1}$) than in Laxemar-Simpevarp (0.2 m^3 m^{-2} $year^{-1}$). Global irradiation is relatively evenly distributed throughout Sweden and the sites have similar daily values although slightly higher in Laxemar-Simpevarp than Forsmark.

Between 2003 and 2006, the sea level has fluctuated between 0.6 below and 1.3 m above the mean in Forsmark, and between 0.5 below and 0.7 m above mean in Laxemar-Simpevarp. Because the coastline in Forsmark has a gentler slope, the sea level fluctuation has a more marked effect on the landscape, than in Laxemar-Simpevarp. However, compared to other parts of the Swedish Baltic coastline the areas show low surface relief (< 25 m) associated with the subcambrian peneplains. Lineaments include bedrock fissures and in the Forsmark area, faultlines related to the Gräsö trough forming the deeper part of Öregrundsgrepen. Forsmark has a narrow shallow archipelago while Laxemar-Simpevarp is more clearly divided into the inner sheltered bays and the outer exposed coast.

Sediment conditions have been mapped in both areas using extensive seismic investigations, side-scan sonar, coring and probing. The sediment shows the characteristic sequence till, glacifluvial sediments along eskers, glacial and postglacial clay (redistributed by coastal processes during isostatic uplift). It is thickest along the lineaments, up to 10–20 m in both areas.

Both areas have also been relatively well exposed to coastal processes. Bedrock and till are typically exposed near shore, while glacial clay, usually covered with a thin sand layer, is exposed offshore. Postglacial clays and mud deposits (accumulation bottoms) are found only in either sheltered inshore settings, lagoonal areas (flads and gloes) in the Forsmark area and inner bays in Laxemar-Simpevarp, or in the deeper troughs.

The historic development of Accumulation bottoms areas has been studied through wave-ray modeling and the present organic carbon burial rates have been quantified as they constitute a potential sink of redistributed elements. Organic carbon burial rates are higher in the accumulation bottom locations in Laxemar-Simpevarp (74–95 gC $m^{-2}yr^{-1}$) than in Forsmark (~ 14 gC $m^{-2}yr^{-1}$). However, the burial is more rapid in the secluded bays in Laxemar-Simpevarp than in Forsmark although, the burial occurs over larger areas in Forsmark. The mean depth in the marine areas is somewhat higher in Forsmark than in Laxemar-Simpevarp and the extension of exposed hard bottoms is higher in Laxemar-Simpevarp.

The oceanographic models that quantify water exchange in the coastal area at the two sites indicate a more rapid water exchange in the whole marine model area in Forsmark than in Laxemar-Simpevarp, generally due to the more open character of the archipelago of Öregrundsgrepen in Forsmark. Hence, in Laxemar-Simpevarp enclosed basins with lower water turnover, like Borholmsfjärden and Granholmsfjärden is present.

11.1.2 Biotic characteristics

In Forsmark the macrophyte vegetation in the photic zone is dominated by red algae (e.g. Polysiphonia nigrescens) and brown filamentous algae (e.g. *Spacelaria arctica*) and the larger *Fucus vesiculosus*. In the sublittoral zone, green algae, e.g. *Cladophora glomerata*, are present as well as the moss *Fontinalis dalecarlica*. In secluded bays, soft bottom-dwelling phanerogams (e.g. *Potamogeton pectinatus* and *Charophyceae* (e.g. *Chara tomentosa*) dominate the macrophytes. In deeper areas in Tixelfjärden and Kallrigafjärden, the *Xanthophyceae* algae *Vaucheria dichotoma* is found in high densities.

In Laxemar-Simpevarp, the occuring macrophyte species are much the same as in Forsmark. Red algae community covers the largest area followed by *Potamogeton pectinatus* community, *Chara sp* and *Fucus vesiculosus*. The inner soft bottom parts of the archipelago north of Laxemar-Simpevarp (around the island of Äspö) are dominated by *Chara sp*. West of Ävrö, a large area is covered by *Xanthophyceae*. On inner soft bottoms in the southern area, the vegetation is dominated by vascular plant communities, mostly *P. pectinatus* and *Zostera marina*. Further out towards more exposed areas, *P. pectinatus* and *Z. marina* occur together in a patchy distribution. On hard substrates in shallow areas, the vegetation is dominated by *Fucus vesiculosus*, while in deeper areas red algae covers the hard substrate.

At both sites as generally in marine areas, the photic zone on the seabed is covered to a large extent with a layer of microalgae (microphytes), mainly diatoms.

Generally, phytoplankton in the Baltic Sea peak in a spring bloom and in an autumn maximum both dominated by diatoms. After the spring bloom of diatoms, dinoflagellates and other smaller flagellates become more important, later to be followed by maximum densities of the consumers cyanobacteria and zooplankton. Local conditions at the sites in Forsmark and Laxemar-Simpevarp cause somewhat different patterns. In Forsmark diatoms dominate only during the late winter growth period, while the autotrophic red-tide ciliate *Mesodinium rubrum* is the main constituent during the rest of the blooming period Laxemar-Simpevarp has a spring bloom dominated by the diatoms whereas the phytoplankton community late in summer is dominated by dinoflagellates and cyanobacteria. In comparison with data from the national environmental monitoring programme, the chlorophyll values in Forsmark are relatively low, whereas chlorophyll values in Laxemar-Simpevarp are high.

Benthic bacteria, i.e., all heterotrophic bacteria on the sea floor and in the sea bed, in Forsmark and Laxemar-Simpevarp show a higher abundance and biomass than generally found in Kattegat and the Baltic Sea. Bacterioplankton, i.e. free living bacteria in the pelagic habitat, in Forsmark and Laxemar-Simpevarp, show similar mean abundances as in the Gulf of Finland, the Baltic Sea and other temperate areas in the North Sea.

Species and abundances of benthic fauna in the Baltic and Bothnian Sea are clearly dependent on salinity, and the salinity levels in Forsmark are expected to harbour fewer species than Laxemar-Simpevarp. The site investigations at Laxemar-Simpevarp and Forsmark confirm this, and both taxa and mean biomass are much higher in Laxemar-Simpevarp than in Forsmark. The abundance and distribution of benthic fauna in Forsmark are similar to those in the geographical region. Since the start of the monitoring (1970), benthic biomass and species diversity has increased, probably due to the increased nutrient load. The biomass is dominated by the Baltic mussel (*Macoma baltica*) at the soft bottom sampling sites and by *Monoporeia affinis* in deeper areas. On hard bottoms the blue mussel (*Mytilus edulis*) also contributes to the benthic fauna. The highest biomass values in the Forsmark area are found in vegetation-associated soft bottom fauna. Also in soft bottoms in Laxemar-Simpevarp, the filter-feeding *M. baltica* clearly made the largest contribution to the total biomass in all areas. Although, the most abundant taxa in the samples from the archipelago north of Simpevarp were *Chironomidae* and *M. baltica*. The sessile macrofauna on hard bottoms is completely dominated by M. edulis (both in terms of biomass and abundance). Exposed hard bottoms in the area have the highest biomasses of benthic fauna in the area.

The zooplankton species in Forsmark and Laxemar-Simpevarp are generally the same species as in the rest of the Baltic. Winter and spring are dominated by copepods at both sites. However, in Laxemar-Simpevarp, a more diverse structure is found in the summer with cladocerans, rotifers and larvae of some benthic macroinvertebrates.

Test fishing in Forsmark and Laxemar-Simpevarp show similar development as in other nearby coastal areas and herring and sprat are the dominant species in offshore areas at both sites. In the inner bays at the sites, perch and pike are the most abundant species. The fish biomass was higher in Forsmark than in a reference area. Hence, probably an effect of the favourable temperature conditions for warm water species due to the slightly warmer water, caused by the release of cooling water.

Both sites harbour common bird species (as well as rarer ones), which feed in the marine habitat as piscivores or herbivores. Three species of seal live in the Baltic: grey seal, ringed seal and harbour seal. Grey seal live in the archipelago at the two sites, although not in high densities.

11.1.3 Human impact

The impact of industry and forestry was historically more direct in the Forsmark area through iron ore mining, than in Laxemar-Simpevarp, where emissions of heavy metals have been important mainly in a larger-scale regional context. The Forsmark area is influenced regionally also by pulp bleach industries along the Gulf of Bothnia coast to the north. Agricultural nutrient emissions are either local via rivers and streams, or part of the larger-scale eutrophication of the Baltic Sea.

Fishery represents mainly a larger-scale impact in both areas. This impact has been characterized by overfishing of Baltic herring, in particular by catches due to trawling, however ameliorated with recent legislation, and by hydropower regulation affecting migrating fish. The overall status of the Forsmark area is not markedly below average among Baltic Sea coastal areas. This is true also for the Laxemar-Simpevarp area, which shows better status than already the adjacent Västervik-Misterhult archipelago to the north.

The main human impact in general is the release of cooling water from the nuclear power plants at the sites. The release of heated cooling water creates a warm-water plume resulting locally in stratification and changed oxygen conditions. Its current impact in surface and bottom waters, and the slightly higher impact of planned elevated emissions, has been simulated using numeric hydrographic modeling. The area of elevated temperature is approximately 30 km^2 in the Forsmark area and 17–20 km^2 in Laxemar-Simpevarp.

11.2 Pools and fluxes

11.2.1 Carbon

Ecosystem models and mass balance calculations were used to visualize pools and fluxes within the marine ecosystems in Forsmark and Laxemar Simpevarp. A compilation of the major pools and fluxes of carbon at the sites is presented in Table 11-2. The mass balance calculations for the various elements are not all in balance probably due to the large impact on separate marine basins from adjacent marine areas, and/or by uncertainties in the calculations. For example will only small differences in water concentrations induce huge differences in the advective flows of elements, since the moving water volumes are so large.

The largest pools of carbon in all basins in the marine area in Forsmark are the abiotic pools; sediment, DIC and DOC, followed by the biotic pool, dominated by benthic primary producers and benthic fauna. In Laxemar-Simpevarp the DIC pool followed by the biota pool are larger than the sediment pool.

The biomass in both areas is distributed unevenly, focused mainly along the western coast and in more shallow areas. The biomass in Laxemar-Simpevarp is higher, which is in accordance with the general pattern in the Baltic were biomass and number of species increases from north to south. One major difference between the sites is the much higher abundance of blue mussels on exposed hard bottoms in Laxemar-Simpevarp. The blue mussels occur in vast amounts when the conditions are suitable (e.g. salinity and substrate) and may then influence the pools and fluxes of matter in the ecosystem to a great extent.

Both sites tend to be autothropic in the near shore and more secluded basins and heterothropic in the deeper more offshore basins. Although, in Forsmark the mean NEP for the whole area is autotrophic, while in Laxemar-Simpevarp the mean NEP is heterothropic. Probably due to the high abundances and thereby the higher respiration rate by the blue mussels resulting in negative NEP.

The major flux of carbon in Forsmark is the net advective flux, and in the whole area in average there is a net outflux of carbon. Although, it varies in between basins, and inner basins with high primary production tend to have a net outflux while in outer basin the opposite tends to be true. The largest biotic carbon flux is fixation of carbon by primary producers, while the second largest is consumption of DOC by bacterioplankton. In Laxemar-Simpevarp the area as a whole has a net influx of carbon, and respiration constitutes the major flux. At both sites transport from land, lakes and streams seem to only give minor contributions of organic matter to the marine ecosystems. Accumulation in sediments by burial is generally small, in relation to other fluxes, at both sites.

Table 11-1. Summary of pools and fluxes of carbon in average for the marine areas in Forsmark and Laxemar-Simpevarp. bPP, pPP, bF and pF denotes benthic primary producers, pelagic primary producers, benthic fauna and pelagic fauna respectively, sed denotes sediment, adv denotes net advective fluxes, PP denotes primary production and resp denotes respiration.

Pools and fluxes of carbon	Forsmark	Laxemar-Simpevarp
Total biomass, mean (min-max) (gC m2)	18 (5-160)	91 (2-450)
Pools per m2 (%)	Sed(57) > DIC(25) > DOC(12) > Biota (5) > POC (1)	DIC(43) > Biota(25) >sed(21) >DOC (11) > POC (1)
Biotic per m2 (%)	bPP(54) > bF(42) > pF(3) > pPP(1)	bF(65) > bPP(34) > pF(1) > pPP(0.2)
NPP mean (min-max) (gC m2)	100 (43-287)	170 (99-707)
NEP mean (min-max) (gC m2)	24 (-33-224)	-161(-282- 651)
Fluxes in (%)	Adv(58) > PP (22) > resp(16) > runoff (3) > burial (0.3) >deposition (0.3)	Resp(53) >PP(28) > adv(17) > runoff (1) > burial(0.4) > deposition (0.3)
Net flux whole area (gC m2 year-1)	-50	9

11.2.2 Abundance and distribution of elements

Pools and fluxes of totally 49 elements showed that the most abundant elements are the major constituents of sea water, such as Cl, Na, Mg, S. They are distributed to a large extent in the dissolved phase, and will therefore be very abundant due to the large water volume. Cl is the most abundant element in the marine ecosystem in both Forsmark and Laxemar-Simpevarp. On average, the total Cl content in all pools at the two sites is 31 kg m-2 and 32 kg m-2, respectively, followed by Na and Mg and in a slightly different order at the two sites Ca, K, S, Si and C. The rest of the elements are minor constituents contributing less than 1% of the total (by weight).

In Forsmark, the elements Mn, P, N, C, I, Co, Ni, Th, Cu, Fe and Ca have biotic pools larger than 1% (by weight), while 99% of all other elements is present in the abiotic pools considered (sediment, particulate matter and dissolved matter). In Laxemar-Simpevarp, more elements are distributed in the biotic pool, generally due to the higher biomass in the area. The major portion of all lanthanides and the majority of the metals are in the sediments. But nitrogen, phosphorus, carbon and selenium in particular have biotic pools of substantial magnitude, from 25 to 50%.

Mass balance calculations were performed for nitrogen, phosphorus, thorium, uranium and iodine. In Forsmark the major pool for nitrogen, phosphorus and thorium in the ecosystem is the sediment, while for uranium the sediment pool and the dissolved pool are almost equally large, and for iodine the dominant pool is the dissolved phase. The mass balance calculations showed a net outflux for the major part of the elements, except for phosphorus, which had a small net influx in the whole marine area.

Of the total inventory of nitrogen in the whole marine area in Laxemar-Simpevarp, consumers constitute the largest pool (49%), followed by sediment (40%) and macrophytes (6%). The consumer pool is totally dominated by filter feeders. Phosphorus is quite evenly distributed between the sediment and consumer pools, which are of the same order of magnitude (43% and 44%, respectively). The third largest pool, although much smaller than the former ones, is primary producers (7%). For thorium and uranium, sediment is the dominant pool in most basins, while for iodine it is generally the dissolved phase, although the producer pool is often quite large. Mass balance calculations for elements show a net outflux of nitrogen, thorium, and iodine. For uranium and phosphorus there is a net influx on average in the whole marine area. Burial is small for these elements.

11.3 Long term evolution of the marine ecosystem

11.3.1 Climate and shore displacements

The long term landscape development in marine ecosystems in the Baltic Sea is determined by two main and partly interdependent factors, climate variations and shoreline displacement. These two factors in combination strongly affect a number of processes (e.g. salinity and water turnover), which in turn determine the development of ecosystems. The shoreline displacement is mainly a secondary effect of climate variations. It is caused by the interaction between glacially induced isostatic variations on the one hand, and eustatic sea level variations on the other. Periodically, shoreline displacement has strongly affected the Forsmark and Laxemar-Simpevarp areas, both before and after the latest deglaciation, and it is likely that the areas repeatedly has been situated below the sea level for long periods (/Söderbäck 2008/).

In SR-Site a reconstruction of the last glacial cycle is used to describe possible future changes in climate and climate-related processes. This reconstruction, the reference case, is used as an example of a future evolution that, in a realistic way, covers all relevant climate-related changes that can be expected in a 120,000-year perspective. The reconstruction divides the period into distinct climate domains, temperate -, periglacial- and glacial climate domains. In addition a case with a prolonged temperate domain, a Global warming case, is evaluated.

The effects of a climate change, from the present temperate conditions, in the marine ecosystem are very complex and hard to predict. Here, the focus is on those climate-changing factors that may lead to differences in the transfer and accumulation of radionuclides in the marine ecosystem. During changes in climate conditions the main factors affecting the marine ecosystem, are the change in temperature and the presence or absence of sea ice. The changed conditions, during periglacial or global warming climate domain might result in lower biomasses and production as well as higher. In the colder and harsher climate during glacial conditions the marine ecosystems would be covered with a thick ice-cover and in addition the environment would probably not be suitable for humans to live in, but theoretically it can be hunting and fishing along the ice edge and on the open sea which could constitute a potential exposure pathway for radionuclides. The climate along the ice-edge will probably be similar to periglacial climate condition. Although many factors due to climate change may lead to increased primary production, other probable outcomes are that net ecosystem production remains the same or is included in the variation in present-day temperate conditions, regardless if the change is towards warmer or colder climate conditions. At present, with the current state of the art, it is assumed that data and parameters for present temperate conditions in the dose modeling in SR-site are less uncertain than potential predictions. The composition of the parameters may vary in the different climate domains, but the values are assumed to be in the same range. Based on the assumption that the variation due to the climate change mainly affects species composition and distribution, while the magnitude of material transfer between the functional groups and the abiotic components is similar.

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 marine ecosystems. The influence of the sea decreases with distance from the shoreline in coastal areas and results in a pronounced zonation of organisms in the marine ecosystem. Along slowly eroding rocky shorelines this zonation is essentially permanent but in areas where accretion is relatively rapid, such zonation represents successional change and is indicative of the dynamic character of the marine environment. Although conditions are less variable than on land, the limits of tolerance of most marine organisms are comparatively narrow and their distribution is determined primarily by the interrelated effects of water depth, latitude and distance from shore /Arcibold 1995/. As the sea bottom is elevated by the isostatic rebound, deeper offshore areas become shallow coastal areas. Water turnover becomes slower as a consequence of shallower water and a more secluded position. The deeper the marine ecosystem will during this development, transform from in general net heterotrophic and dominated by pelagic primary production towards a primarily benthic and in general autotrophic ecosystem.

11.3.2 Salinity

The future salinity the Baltic Sea is sensitive to changes in the freshwater supply, as well as to changes in the water exchange with the ocean. The postglacial isostatic rebound in southernmost Sweden today is negligible and it will therefore not affect the future salinity in the southern Baltic Sea /Gustafsson 2004a/. However, a possible range of future salinity in the southern Baltic Sea is between freshwater conditions and a salinity of 15 psu, depending on the combination of climate conditions and sea level. Accordingly, any long term forecast of the future salinity will be utterly uncertain, since information on the climate development is lacking. The isostatic recovery in central and northern Sweden is in contrast significant /Påsse 2001/. Due to the rising of the Southern Kvark sill, i.e. the most narrow part of the Baltic Sea between Åland and Sweden where the maximum depth today is c 40 m, we can anticipate large changes in the exchange of water between the Bothnian Sea and the Baltic Proper in the future. Accordingly, isostatic recovery will relatively soon dominate salinity variations north of Åland, regardless of prevailing climate conditions, and the uncertainty in the prediction of future salinity is therefore considerably lower for the Bothnian Sea than for the Baltic Proper. Extrapolation of the shoreline displacement models for sites situated both east and west of Åland /Påsse 2001/, suggests that it takes about 12,000 years to transfer the entire Forsmark area from fully submerged just before the first islet emerges above the sea surface (1000 BC), until the last marine embayment is turned into a lake (11,000 AD).

11.3.3 Coastal oceanography

The present water retention time in the sub-basins of Forsmark varies between 13 and 34 AvA days (18 in average in the whole area), with a more rapid water turnover in the deeper areas close to the open Baltic Sea and the longest retention in the shallow sub-basins, secluded from the other basins by the Biotest basin (Chapter 9 and 10). The direction of the flow through Öregrundsgrepen varies over time, but on an annual basis there is a net flow directed from north to south /Karlsson et al.

2010/.The present water retention time in Laxemar-Simpevarp range between 0.4 and 40 AvA days, with the higher values for the semi enclosed bays in the area /Engqvist 2010/.

The description of the long term development of coastal oceanography within SR-Site has focused on hydraulic residence time (water turnover), because of its importance for transfer and accumulation of radionuclides. According to /Brydsten 2006/, the local development in Forsmark can be divided into three stages; an open sea stage, an open-ended coastal area (as the present stage) and a bay stage with only one open boundary. These stages will appear in the above mentioned order following deglaciation and the subsequent roughly 15,000 years. Using the shoreline displacement equation /Brydsten 2006/ as input, /Karlsson et al. 2010 and Chapter 9 this report / detailed hydrodynamic modelling of marine basins was conducted for the Forsmark area. The hydrodynamic model gives outputs on annual mean flows between adjacent basins and a measure of the water retention time for each basin and for the whole area. For the open sea stage, the circulation was simulated using a model for the entire Baltic Sea. For the other two stages, a high-resolution local model was set up for the near-coastal basin Öregrundsgrepen. During an open sea stage the water turnover will be rapid and similar in the whole model area and in the open Baltic Sea. Oceanographic conditions will be fairly homogenous and the water exchange is at its maximum. In the open-ended second stage a net through-flow of the area is still possible, although the water retention time increases as a result of a complex interplay between a narrower southern boundary, decreasing volumes of the marine basins and decreasing the cross-sectional areas between adjacent basins. The water turnover during this stage is primarily determined by the wind and fluctuating sea levels, and water retention times will be longest in the shallow basins located far from the boundaries to the Baltic Sea. During the bay stage, the southern entrance has closed and Öregrundsgrepen has been transformed into a bay, whereby the water retention time for the whole area increases. The oceanographic conditions will be typical for estuarine circulation in an enclosed bay. The basins are there after gradually becoming more enclosed and are one by one transformed into lakes. Runoff from land becomes more important for water turnover during this stage and wind still plays an important role.

The long-term development water retention time in Laxemar-Simpevarp, expressed as AvA for the coastal basins, were estimated for 13 time periods from 3000 BC to 9000 AD equally interspersed 1,000 years apart in time /Engqvist 2010/. The hypsographic data and catchment areas estimates have been extracted from an enhanced DEM subjected to a sedimentation model /Brydsten and Strömgren 2004, Strömgren and Brydsten 2008/. The long-term development of the water retention time in Laxemar-Simpevarp shows a similar development as in Forsmark, i. e. the water retention time increases at the rate of the land rise. There are also temporary recessions caused by the transition of different sub-basins being connected or disconnected to the coastal zone of the Baltic Sea.

11.4 Marine ecosystem processes of importance and parameterization

The identification and handling of features, events and processes that are important for transport and accumulation of radionuclides in the environment is of central importance in the assessment of human health and the safety of the environment. Ecosystems are complex systems with a large number of structures and functions, and the number of interactions within an ecosystem is immense. The interaction matrix (IM), described in Chapter 8, is a practical tool to display identified components and pathways that may potentially affect radionuclide accumulation and exposure. The systematic approach of using an interaction matrix (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 8 stretches over subjects that are only partly or not treated in this report. For example hydrological fluxes (on land) have only been briefly handled in this report and are described elsewhere e.g. /Johansson 2008, Werner et al. 2008, Bosson et al. 2010/, and sorption and desorption processes is handled by /Nordén et al. 2010/. 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). In total 15 components and 51 processes have been identified and described in the biosphere IM for SR-Site Figure (Chapter 8), of them 34 processes were considered to be relevant and sufficient for assessing the safety of human health and the environment (Chapter 8). Primary production, growth, death, consumption, uptake, excretion and particle release/trapping are the major biotic processes which may affect the transfer and accumulation of radionuclides in marine ecosystems. Although, advective fluxes (i.e. water turnover) is in general the overall dominating factor affecting the transfer and accumulation of radionuclides, and in comparison the biotic processes is of minor importance. However, in general the abiotic processes sedimentation, resuspension and sorption/desorption of radionuclides to particles and sediments are crucial for the accumulation of radionuclides in aquatic ecosystem. I Figure 11-1 a compilation of the most important process that was identified from the IM for a marine ecosystem is presented at a given point in time.

In order to make a safety assessment, the processes identified to be important from a radionuclide point of view were parameterized. In Chapter 10 the parameters considered for the marine basins in the radionuclide modeling are presented for the five categories: Geometric parameters, Regolith parameters, Hydrology parameters, Chemical and biotic parameters and parameters for human utilization of the ecosystem. The estimation of parameter values is presented using relevant site data and /or literature data. In many cases are the correspondence between processes in figure 11-1 and the parameters not evident, and the reader is referred to Chapter 8 this report and /SKB 2010b/ for a comprehensive description of how different parameters are used to illustrate different processes. An alternative marine ecological model is also briefly presented in order to underpin and support assumptions made during the derivation of parameters used in the radionuclide model.

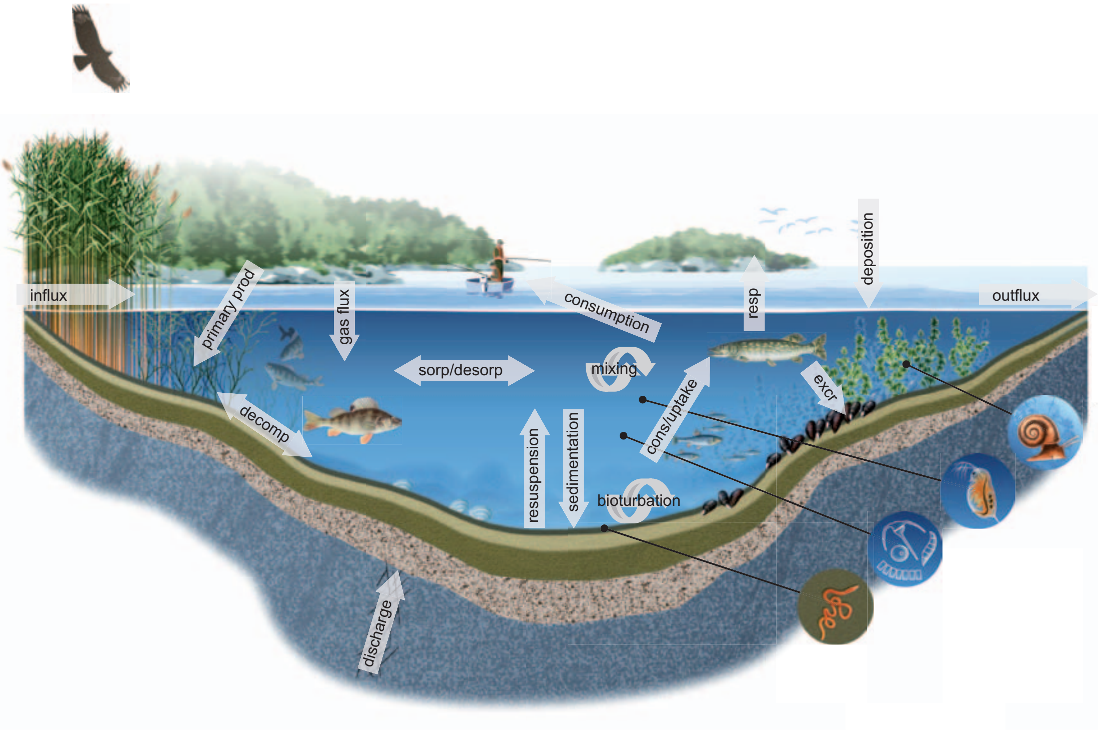

Figure 11-1. *A conceptual model with important processes affecting transport and accumulation of radionuclides in a marine ecosystem, where the exposure of radionuclides to humans is in focus.*

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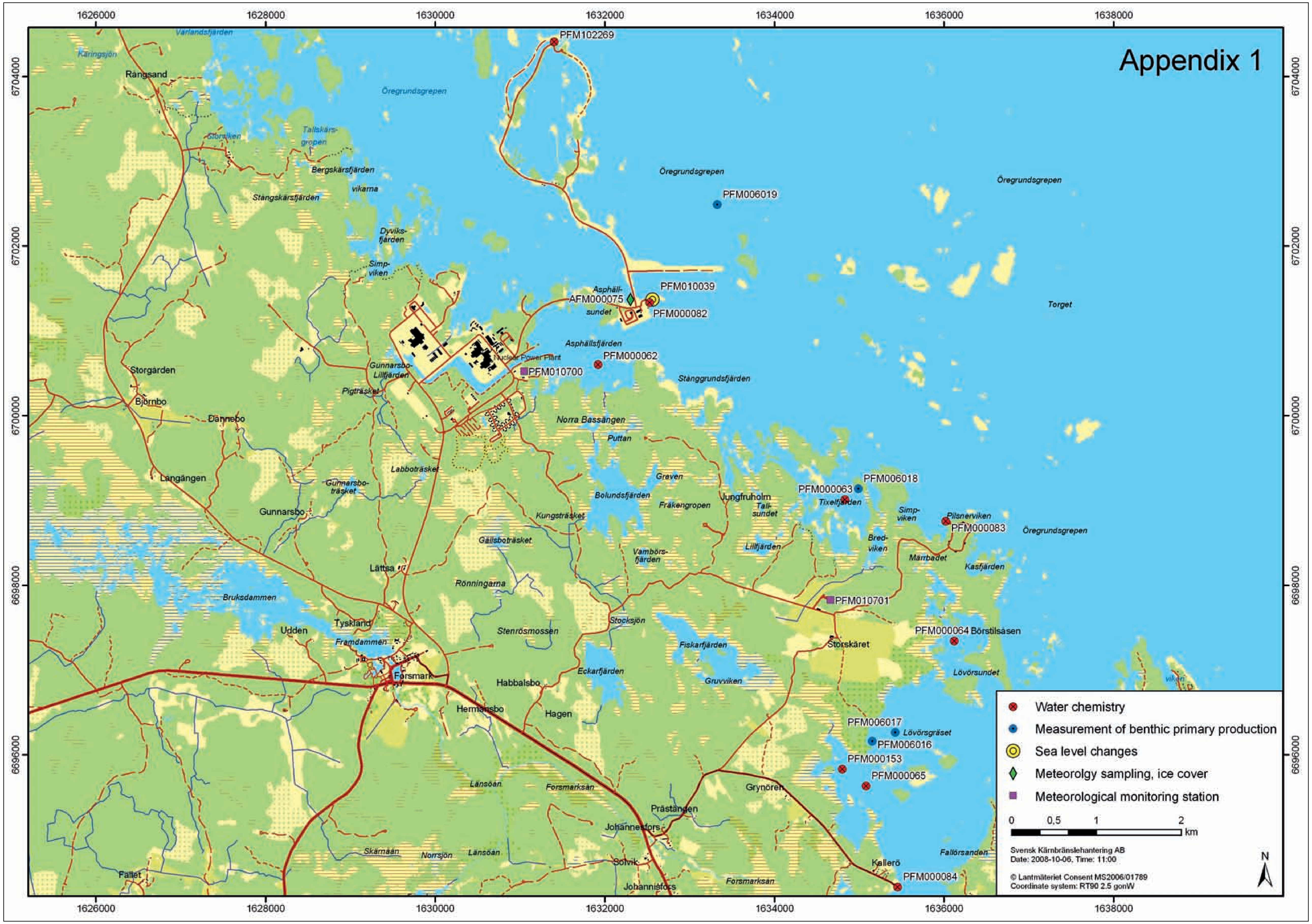
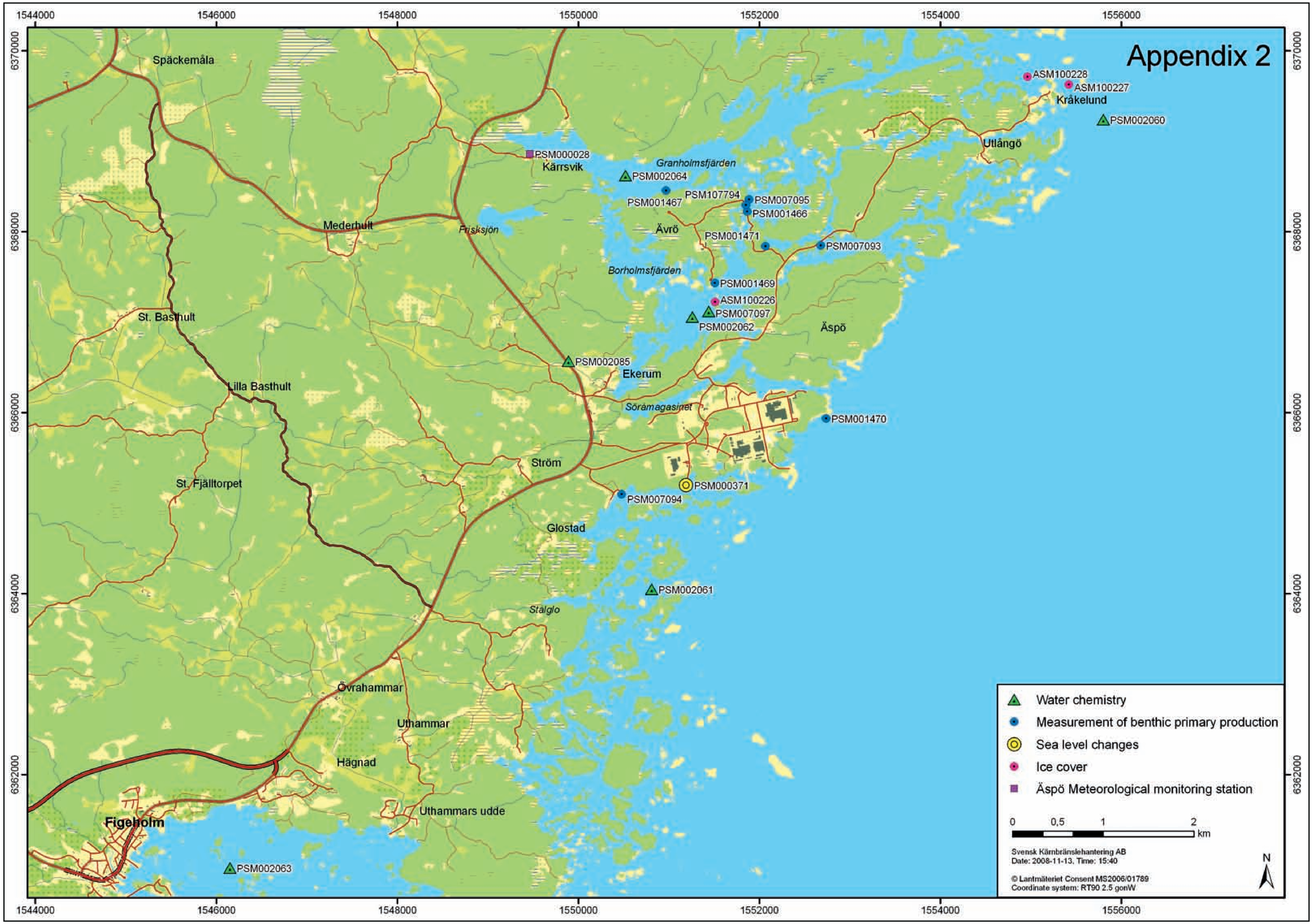
Map over Forsmark



Map over Laxemar-Simpevarp



Site specific input data table

In this table, SKB-reports used in the description and modelling of the marine ecosystems are listed. In addition, site data from the database SICADA and marine data in literature have been used in some of the models in Chapter 4, 5 and 6. For these references, see descriptions in the chapters.

Available data	Reference	Usage in the report	Section
Human population and activities	SKB R-04-10	Description	3
Human population and activities	SKB R-04-11	Description	3
Meteorological monitoring at	SKB P-06-322		3
Meteorological, hydrological and hydrogeological monitoring data	SKB R-08-73		3
Identification of catchments	SKB P-04-25	Description and modelling	3
Sensitivity analysis	SKB TR-00-01	Description and modelling	5
Coastal oceanographic models	SKB TR-08-01	Description and modelling	5
Biomass of benthic and planktonic bacteria	SKB P-06-232	Description and modelling	3 and 4
Benthic macro invertebrates	SKB P-04-252	Description and modelling	3 and 4
Soft-bottom macrozoobenthos community	SKB P-04-17	Description and modelling	3 and 4
Marine fauna attached to hard substrates	SKB P-05-45	Description and modelling	3 and 4
Bird monitoring	SKB P-05-73	Description	3 and 4
Bird monitoring	SKB P-06-46	Description	3 and 4
Test fishing	SKB P-05-116	Description and modelling	3 and 4
Fish community biomass	SKB P-06-10	Description and modelling	3 and 4
Pelagic fish	SKB P-05-57	Description and modelling	3 and 4
The coastal fish community	SKB P-05-148	Description and modelling	3 and 4
Snow depth, frost in ground and ice cove	SKB P-03-117	Description	3 and 4
Snow depth, snow water content and ice cover during	SKB P-04-137	Description	3 and 4
Snow depth, snow water content and ice cover during	SKB P-05-134	Description	3 and 4
Snow depth, snow water content and ice cover during	SKB P-06-97,.	Description	3 and 4
Snow depth, snow water content and ice cover during	SKB P-07-81	Description	3 and 4
Meteorological, hydrological and hydrogeological monitoring data	SKB R-08-10	Description and modelling	3 and 4
Meteorological and oceanographic information and data	SKB TR-02-02	Description and modelling	3 and 4
Meteorological and oceanographic information and data	SKB TR-02-03	Description and modelling	3 and 4
Late Holocene distribution of lake sediment and peat	SKB R-01-12	Description	3 and 4
Surface sediment	SKB P-04-05	Description and modelling	3 and 4
Investigation of marine and lacustrine sediment	SKB P-03-24	Description and modelling	3 and 4
Investigation of marine and lacustrine sediment	SKB P-04-86	Description and modelling	3 and 4
Description of the regolith	SKB R-08-04	Description and modelling	3 and 4
Depth and stratigraphies of regolith	SKB R-08-07	Description and modelling	3 and 4
Bathymetric and geophysical	SKB P-04-254	Description and modelling	3 and 4
Mapping of Quaternary deposits	SKB P-06-88	Description and modelling	3 and 4
Vegetation mapping	SKB P-03-83	Description	3 and 4
Benthic vegetation, plant associated macrofauna	SKB P-05-135	Description and modelling	3 and 4
Phytobenthic production	SKB P-06-252	Description and modelling	3 and 4
Element composition of biota,	SKB TR-08-09	Description and modelling	3 and 4
Modelling of marine organisms	SKB R-07-50	Description and modelling	3 and 4
Phytobentic plant and animal communities	SKB P-04-82	Description and modelling	3 and 4
Sampling and analyses of surface waters	SKB P-07-95	Description and modelling	3 and 4
Surface hydrology and near-surface hydrogeology	SKB R-08-08	Description and modelling	3 and 4
Salinity change in the Baltic Sea during the last 8,500 years	SKB TR 99-38		8
Digital elevation models	SKB R-05-38	Description and modelling	4, 5 and 6
Digital elevation models	SKB R-04-70	Description and modelling	4, 5 and 6
Geological survey of the sea bottom	SKB P-03-101	Description and modelling	4, 5 and 6
Geological survey of the sea bottom	SKB P-05-35	Description and modelling	4, 5 and 6

Available data	**Reference**	**Usage in the report**	**Section**
Isostatci land up-lift	SKB R-01-41	modelling	4,5 and 6
Shore displacement	SKB TR-03-17	Description and modelling	4, 5 and 6
Mathematical model of past, present and future shore level displacement in	SKB TR 9 -28	Understanding and modelling	4, 5 and 6
Change in coastal sedimentation conditions	SKB TR-99-37	Description and modelling	3, 4 and 6
Shoreline displacement, sediment dynamics,	SKB TR-06-40	Description and modelling	3, 4 and 6
Chemical composition of suspended material, sediment	SKB P-08-81	Description and modelling	3, 4 and 6
Holocene sedimentary environmental changes at sites	SKB P-06-250	Description and modelling	3, 4 and 6
Investigation of sediments, peat lands and wetlands	SKB P-04-273	Description and modelling	3, 4 and 6
Depth and stratigraphy of regolith	SKB R-08-06	Description and modelling	3, 4 and 6
Depth and stratigraphy of Quaternary deposits	SKB R-05-54	Description and modelling	3, 4 and 6
Holocene sediment accumulation	SKB R-02-47	Understanding and modelling	3, 4 and 6
Bio- and lithostratigraphy	SKB P-05-139	Understanding and modelling	3, 4 and 6
Quaternary deposits	SKB P-05-49	Description and modelling	3, 4 and 6
Geological evolution, palaeoclimate	SKB R-08-19	Description	3, 4 and 6
Soils, Quaternary deposits and bedrock	SKB P-06-120	Description and modelling	3, 4 and 6
Description of regolith	SKB R-08-05	Description and modelling	3, 4 and 6
Quaternary deposits	SKB R-04-39	Description and modelling	3, 4 and 6
Dating of sediments and peat	SKB P-06-301	Description and modelling	3, 4 and 6
Chemical characterisation of deposits and biota	SKB P-06-320	Description and modelling	3, 4 and 6
Analysis of radioisotopes	SKB P-07-32	Description and modelling	3, 4 and 6
Chemical characterisation of deposits and biota	SKB P-06-320	Description and modelling	3, 4 and 6
Macrophyte communities	SKB R-05-47	Description and modelling	3, 4 and 6
Macrophyte communities	SKB P-05-47	Description and modelling	3, 4 and 6
Macrophyte communities	SKB P-03-69	Description and modelling	3, 4 and 6
Sampling of phyto- and zooplankton	SKB P-05-72	Description and modelling	3, 4 and 6
Distribution of aquatic plant and animal communities in the Forsmark area	SKB R-99-69	Description and modelling	3, 4 and 6
Phytoplankton and zooplankton.	SKB P-04-253	Description and modelling	3, 4 and 6
Vegetation communities	SKB P-03-68	Description and modelling	3, 4 and 6
Chemical characteristics of surface systems in the Simpevarp area	SKB R-06-18		3, 4 and 6
Chemical characteristics of surface systems in the Forsmark area.	SKB R-06-19		3, 4 and 6
Primary production and respiration in shallow phyto-benthic communities.	SKB P-06-303		3, 4 and 6
Surface water sampling	SKB P-04-13	Description and modelling	3, 4 and 6
Surface water sampling	SKB P-04-75	Description and modelling	3, 4 and 6
Surface water sampling	SKB P-05-118	Description and modelling	3, 4 and 6
Surface water sampling	SKB P-06-155	Description and modelling	3, 4 and 6
Monitoring of brook levels, water	SKB P-07-135	Description and modelling	3, 4 and 6
Sampling and analyses of surface waters.	SKB P-03-27	Description and modelling	3, 4 and 6
Sampling and analyses of surface waters	SKB P-04-146	Description and modelling	3, 4 and 6
Sampling and analyses of surface waters.	SKB P-05-274	Description and modelling	3, 4 and 6
Sampling and analyses of surface waters.	SKB P-07-95	Description and modelling	3, 4 and 6

Appendix 4

List of species mentioned in the report

In the following table, species mentioned in the report in Forsmark and Laxemar-Simpevarp is listed. In addition, marine species included in the Swedish Redlist by /The Swedish Species Information Center 2010-05-24/, found at the sites or in the regions (County of Uppsala and County of Kalmar) is presented. X denotes that the species is found within the model area, and XX denotes that the species is found within the region. Data are gathered from SKB-reports.

Latin name	English name	Swedish name	Functional group	Included in the Swedish Redlist X found at the site XX found in the marine environment in the county (i.e County of Uppsala and Kalmar)
Mammals				
Halichoerus grypus	Grey seal	Grå säl	Mammal	
Lutra Lutra	Otter	Utter	Mammal	XX Forsmark
Phoca vitulina	Harbour seal	Knubbsäl	Mammal	XX Laxemar-Simpevarp
Pusa hispida	Ringed seal	Vikare	Mammal	XX Forsmark
Birds				
Alcidae sp.	Auks	Alkor	Bird	
Arenaria interpres	Ruddy turnstone	Roskarl	Bird	XX Forsmark, Laxemar-Simpevarp
Aythya fuligula	Tufted duck	Vitkindad gås	Bird	
Aythya marila	Scaup	Bergand	Bird	XX Forsmark, Laxemar-Simpevarp
Cepphus grylle	Black guillemont	Tobisgrissla	Bird	XX Forsmark, Laxemar-Simpevarp
Clangula hyamalis	Long-tailed duck	Alfågel	Bird	XX Laxemar-Simpevarp
Cygnus olor	Mute swan	Knölsvan	Bird	
Gavia arctica	Black-throathed diver	Storlom	Bird	
Haliaeetus albicilla	White tailed eagle	Havsörn	Bird	X Forsmark, Laxemar-Simpevarp
Hydroprogne caspia	Caspian tern	Skräntärna	Bird	XX Laxemar-Simpevarp
Laridae sp.	Gulls	Måsar	Bird	
Larus argentatus	Herrring gull	Gråtrut	Bird	XX Forsmark, Laxemar-Simpevarp
Larus fuscus	Lesser black-backed gull	Silltrut	Bird	XX Laxemar-Simpevarp
Melanitta fusca	Velvet scoter	Svärta	Bird	XX Forsmark, Laxemar-Simpevarp
Mergus albellus	Smew	Salskrake	Bird	
Mergus merganser	Goosander	Storskrake	Bird	
Pandion haliaetus	Osprey	Fiskgjuse	Bird	
Phalacrocorax carbo	Cormorants	Storskarv	Bird	
Podiceps auritius	Horned grebe	Svarthakedopping	Bird	XX Forsmark, Laxemar-Simpevarp
Polysticta stelleri	Stellers Eider	Alförrädare	Bird	
Somateria mollissima	Eider duck	Ejder	Bird	X Forsmark, Laxemar-Simpevarp
Sterna caspia	Caspian tern	Skräntärna	Bird	
Sterna hirundo	Common tern	Fisktärna	Bird	
Sterna sandviciens	Sandwich tern	Kents tärna	Bird	XX Laxemar-Simpevarp
Sternula albifrons	Little tern	Småtärna	Bird	XX Laxemar-Simpevarp
Macrophytes				
Alisma wahlenbergii		Småsvalting	Macrophytes/ Phanerogam	XX Forsmark
Chara horrida		Raggsträfse	Macrophytes/ Kransalger	X Forsmark, Laxemar-Simpevarp
Chara sp.	Stonewort	Sträfse	Macrophytes/ Kransalger	
Chara tomentosa	Coral stonewort	Rödsträfse	Macrophytes/ Kransalger	
Cladophora glomerata	Blanket weed	Grönslick	Macrophytes/ Green algae	
Cladophora rupestris	”	Bergsborsting	Macrophytes/ Green algae	

Latin name	English name	Swedish name	Functional group	Included in the Swedish Redlist X found at the site XX found in the marine environment in the county (i.e County of Uppsala and Kalmar)
Cladophora sp.	”	(Grönslick)	Macrophytes/ Green algae	
Dictyosiphon foeniculaceus	filamentous brown alga/golden sea hair	Smalskägg	Macrophytes/ Brown alga	
Elatine orthosperma		Nordskamkrypa	Macrophytes/ Phanerogam	XX Forsmark
Enteromorpha sp.	Hollow green weed	Tarmtång	Macrophytes/ Brown algae	
Fontanilis dalecarlica	Fontinalis moss	Smal snäckmossa	Macrophytes/ Moss	
Fucus vesiculosus	Bladderrack	Blåstång	Macrophytes/ Brown algae	
Limosella aquatica		Ävjebrodd	Macrophytes/ Phanerogam	XX Forsmark
Myriophyllum spicatum	Water milfoil	Axslinga	Macrophytes/ Green algae	
Najas marina	Holly-leafed najad	Havsnajas	Macrophytes/ Phanerogam	
Phragmites australis	Reed	Bladvass	Macrophytes/ Phanerogam	
Phyllophora sp.		Rödblad	Macrophytes/ Red algae	
Pilayella littoralis	Sea felt	Brunslick	Macrophytes/ Brown algae	
Polysiphonia fibrillosa		Violettslick	Macrophytes/ Red algae	
Polysiphonia fucoides		Fjäderslick	Macrophytes/ Red algae	
Polysiphonia nigrescens		Fjäderslick	Macrophytes/ Red algae	
Potamogeteon compressus		Bandnate	Macrophytes/ Phanerogam	XX Forsmark
Potamogeton friesii		Uddnate	Macrophytes/ Phanerogam	XX Forsmark
Potamogeton pectinatus	Sago pondweed	Borstnate	Macrophytes/ Phanerogam	
Potamogeton perfoliatus	Clasping leaf pondweed	Ålnate	Macrophytes/ Phanerogam	
Sphacelaria arctica		ishavstofs	Macrophytes/ Brown algae	
Stypocaulon scoparium		Taggtofs	Macrophytes/ Brown algae	XX Forsmark
Tillaea aquatica		Fyrling	Macrophytes/ Phanerogam	XX Forsmark
Ulothrix sp.	Hair alage	Armbandsalger	Macrophytes/ Green algae	
vaucheria dichotoma	Water felt	Sjalgräs	Macrophytes/Yellow/green algae	
Vaucheria sp.	Water felt	”	Macrophytes/Yellow/green algae	
Zanichellia sp.	Horned pondweed	Särv	Macrophytes/ Phanerogam	
Zostera marina	Eelgrass	Ålgräs/Bandtång	Macrophytes/ Phanerogam	
Phytoplankton				
Mesodinium rubrum	Red-tide ciliate	Röd ciliat	Phytoplankton	
	Diatoms	Diatomeer (Kiselalger)	Phytoplankton	
Zooplankton				
Acarttia bifilosa	Copepod	Hoppkräfta	Zooplankton	
Bosmina coregoni	Water flea	Hinnkräfta	Zooplankton	

Latin name	English name	Swedish name	Functional group	Included in the Swedish Redlist X found at the site XX found in the marine environment in the county (i.e County of Uppsala and Kalmar)
Benthic fauna				
Hydrobia sp.	Laver spire shell	Tusensnäcka	Benthic herbivore	
Idotea baltica	Isopod	Havsvatten-gråsugga	Benthic herbivore	
Idotea chelipes	Isopod	Tånggråsugga	Benthic herbivore	
Macoma baltica	Baltic clam	Östersjömussla	Benthic filter feeder	
Marenzelleria viridis	Spionid polychaeta	Havsborstmask	Benthic carnivore	
Monoporeia affinis	Amphipod	Vitmärla		
Mya arenaria	Soft shell clam	Sandmussla	Benthic filter feeder	
Mysis sp.	Shrimp	Räka		
Mytilus edulis	Blue/Common mussel	Blåmussla	Benthic filter feeder	
Nereis diversicolor	Ragworm	Rovborstmask	Benthic carnivore	
Oligochaeta sp	worm	Glattmaskar/ Daggmaskar	Benthic detrivore	
Prostoma obscurum		Småmaskar	Benthic detrivore	
Pygospio elegans		Havsborstmask	Benthic detrivore	
Saduria (Mesidothea) entomon	Isopod	Skorv	Benthic carnivore/	
Sphaeroma hookeri		Vattengråsugga	Benthic detrivore	
Theodoxus fluviatilis		Båtsnäcka/ Schackmönstrad båtsnäcka	Benthic herbivore	
Fish				
Abramis brama	Common bream	Braxen	Benthivorous fish	
Abramis vimba	Vimba	Vimma	Benthivorous fish	X Forsmark, Laxemar-Simpevarp
Acerina cernua	Ruffe	Gers	Benthivorous fish	
Anguilla anguilla	Eel	Ål	Benthivorous fish/	X Forsmark, Laxemar-Simpevarp
Blicca bjoerkna	White silver bream	Björkna	Benthivorous fish	
Clupea harengus	Herring	Strömming	Zooplanktivorous fish	
Coregonus albula	Bleak	Siklöja	Zooplanktivorous fish	
Coregonus sp.	Baltic white fish	Sik	Zooplanktivorous fish	
Cottus gobio	Bullhead	Stensimpa	Benthivorous fish	
Cottus quadricornis	Fourhorned sculpin	Hornsimpa	Benthivorous fish	
Cuprinidae	Carps	Karp	Benthivorous fish	
Cyclopterus lumpus	Stenbider	Sjurygg	Pelagic feeding fish	XX Forsmark, Laxemar-Simpevarp
Enchelyopus cimbrius	Fourbearded rockling	Fyrtömmad skärlånga	Benthivorous fish	XX Laxemar-Simpevarp
Esox lucius	Pike	Gädda	Piscivorous fish	
Gadus morhua	Cod	Torsk	Piscivorous fish	
Gasterosteus aculeatus	Stickleback	Storspigg		
Leuciscus erytrophthalmus	Rudd	Sarv	Benthivorous fish	
Leuciscus idus	Ide	Id	Piscivorous fish	
Limanda limanda	Dab	Sandskädda	Benthivorous fish	
Lota lota	Burbot	Lake	Piscivorous fish	X Forsmark, Laxemar-Simpevarp
Lucioperca sandra	European pike-perch	Gös	Piscivorous fish	
Myoxocephalus scorpius	Bull routs	Rötsimpa		

Latin name	**English name**	**Swedish name**	**Functional group**	**Included in the Swedish Redlist X found at the site XX found in the marine environment in the county (i.e County of Uppsala and Kalmar)**
Osmerus eperlanus	Smelt	Nors	Zooplanktivorous fish	
Perca fluviatilis	Perch	Aborre	Piscivorous fish	
Peuronectes flesus	Flounder	Flundra, Skrubbskädda	Benthivorous fish	
Pungitius pungitius	Nine-spined stickleback	Småspigg	Benthivorous fish	
Rutilus rutilus	Roach	Mört	Benthivorous fish	
Sprattus sprattus	sprat	Skarpsill	Zooplanktivorous fish	
Syngnathus typhle	Deep snouted pipefish	Tångsnälla	Benthivorous fish	
Tinca vulgaris	Tench	Sutare	Benthivorous fish/ piscivoros fish	
Zoarces viviparus	Eelpout	Tånglake	Benthivorous fish	X Forsmark, Laxemar-Simpevarp

Chemical analyzes of biota and sediment – Forsmark

A large number of elements have been analyzed in samples from most of the biotic pools and in the sediment. Concentrations of elements in water used in the model calculations are from the database SICADA and is not presented here. Values marked with an * were reported below detection limit and has therefore been divedid by two (best estimate).

mg/kg ts Element	N=3 Phyto-plankton	std dev	N=2 Micrphyto-benthos	std dev	N=9 Macro- phytes	std dev
C	1.74E+05	4.51E+03	1.44E+05	2.97E+04	3.40E+05	4.32E+04
N	2.11E+04	1.21E+03	1.67E+04	2.97E+03	2.18E+04	3.48E+03
P	1.31E+03	1.62E+02	2.66E+03	4.03E+02	2.18E+03	8.10E+02
Al	5.19E+00	1.19E+00	2.71E+01	4.17E+00	2.55E+00	2.10E+00
As	1.26E+01	3.16E+00	5.48E+01	3.76E+01	1.91E+01	1.28E+01
Ba	4.15E–02	7.16E–03	4.86E–01	1.85E–01	1.23E+02	9.21E+01
Br	1.31E+03	1.27E+02	1.04E+03	2.26E+02	2.71E+02	6.34E+01
Ca	3.40E+00	1.99E–01	2.92E+01	9.69E+00	1.63E+04	8.38E+03
Cd	2.50E–01	4.94E–02	2.81E+00	1.70E+00	2.05E+00	2.27E+00
Ce	9.54E–03	2.58E–03	4.83E–01	3.11E–02	6.83E–02	4.28E–02
Cl	6.35E+04	2.12E+03	4.15E+04	9.19E+03	2.57E+04	1.89E+04
Co	1.67E+00	3.86E–01	3.75E+01	2.30E+01	1.75E+00	9.11E–01
Cr	6.31E+00	1.21E+00	2.50E+01	1.13E+00	2.90E+00	2.39E+00
Cs	5.14E–01	1.26E–01	2.46E+00	1.41E–01	3.13E–01	2.66E–01
Cu	2.26E+01	5.46E+00	4.51E+01	1.58E+01	5.57E+00	1.98E+00
Dy	5.27E–04	1.59E–04	2.85E–02	9.90E–04	5.54E–03	4.16E–03
Er	2.97E–04	9.45E–05	1.60E–02	2.69E–03	3.31E–03	2.60E–03
Eu	2.00E–04*	0.00E+00	5.35E–03	8.34E–04	9.26E–04	6.33E–04
F	9.65E+02	4.95E+01	1.10E+02*	9.83E+01	3.14E+02*	4.12E+02
Fe	3.87E+03	9.25E+02	4.26E+04	1.42E+04	2.05E+03	1.63E+03
Gd	6.63E–04	2.02E–04	3.87E–02	1.63E–03	6.90E–03	5.18E–03
Hg	5.60E–02	6.67E–03	1.18E–01	1.41E–02	2.56E–02	6.60E–03
Ho	2.00E–04*	0.00E+00	5.47E–03	6.51E–04	1.14E–03	8.91E–04
I	1.52E+01	3.68E+00	3.05E+02	1.60E+02	7.38E+01	3.70E+01
K	9.02E+03	8.52E+02	1.30E+04	1.63E+03	2.01E+04	3.82E+03
Li	8.68E+00	2.16E+00	1.94E+01	2.19E+00	3.89E+00	2.29E+00
Lu	2.00E–04*	0.00E+00	2.20E–03	3.96E–04	5.22E–04*	3.85E–04
Mg	7.40E+03	2.25E+02	1.13E+04	1.06E+03	8.25E+03	1.46E+03
Mn	4.50E+02	6.15E+01	1.51E+04	9.24E+03	4.93E+02	2.76E+02
Mo	3.36E–01	2.55E–02	6.91E+00	5.37E+00	6.40E–01	5.36E–01
Na	4.80E+04	1.85E+03	3.16E+04	3.82E+03	2.06E+04	5.53E+03
Nd	4.05E–03	1.20E–03	2.27E–01	1.27E–02	3.65E–02	2.51E–02
Ni	6.10E+00	1.99E+00	1.34E+02	9.20E+01	9.96E+00	6.22E+00
Pb	1.13E+01	2.00E+00	8.92E+01	7.61E+01	2.87E+00	2.00E+00
Pr	1.09E–03	3.21E–04	6.17E–02	4.03E–03	9.77E–03	6.73E–03
Rb	1.28E+01	2.49E+00	5.63E+01	2.40E+00	1.35E+01	5.36E+00
S	7.20E+03	2.07E+02	9.34E+03	1.36E+03	1.65E+04	1.11E+04
Se	4.98E–01	5.78E–02	6.65E–01	9.90E–03	2.64E–01*	2.16E–01
Si	1.39E+05	1.39E+04	8.29E+04	2.33E+03	3.66E+04	2.73E+04
Sm	7.50E–04	2.25E–04	4.36E–02	4.17E–03	6.82E–03	4.72E–03
Tb	2.00E–04*	0.00E+00	5.33E–03	2.12E–05	9.82E–04	7.32E–04
Th	1.40E+00	2.45E–01	1.67E+01	6.01E+00	8.05E–01	6.69E–01
Ti	1.83E+02	3.89E+01	8.70E+02	8.77E+01	9.18E+01	7.67E+01
Tm	2.00E–04*	0.00E+00	2.25E–03	3.82E–04	4.90E–04*	3.38E–04
V	7.04E+00	1.55E+00	5.60E+01	1.56E+01	4.38E+00	3.39E+00
Yb	2.77E–04	8.39E–05	1.41E–02	2.26E–03	3.04E–03	2.45E–03
Zn	3.91E+02	1.49E+02	5.08E+02	2.18E+02	1.24E+02	8.84E+01
Zr	1.50E+01	1.42E+00	1.29E+02	1.27E+01	9.49E+00	6.97E+00

mg/kg ts N Element	N=1 Zoo- plankton	std dev	N=4 Benthic herbivores	std dev	N=2 Benthic filterfeeders	std dev
C	4.27E+05		2.63E+05	1.14E+05	1.54E+05	7.07E+02
N	9.71E+04		4.06E+04	3.06E+04	1.01E+04	7.78E+02
P	9.48E+03		4.48E+03	3.88E+03	1.06E+03	5.66E+01
Al	2.88E+03		7.13E–01	3.49E–02	2.72E–01	8.77E–02
As	2.34E+01		4.39E+00	2.73E+00	6.72E–01	5.59E–02
Ba	4.98E+01		4.69E+01	3.97E+01	3.11E+01	2.12E+00
Br	1.32E+04		1.13E+02	2.98E+01		
Ca	8.91E+04		2.23E+05	1.17E+05	3.16E+05	2.19E+04
Cd	3.57E+00		1.29E+00	6.71E–01	1.65E–01	2.76E–02
Ce	4.89E+00		1.16E–01	9.01E–02	1.38E–01	2.12E–03
Cl			2.90E+03	2.83E+02		
Co	1.68E+00		5.28E–01	2.81E–01	1.06E–01	1.37E–02
Cr	1.01E+01		6.94E–01	4.36E–01	2.58E–01	1.00E–01
Cs	3.24E–01		6.67E–02	3.38E–02	2.48E–02	1.27E–02
Cu	2.01E+02		3.41E+01	2.66E+01	1.73E+00	2.97E–01
Dy	2.76E–01		7.25E–03	5.44E–03	9.87E–03	6.15E–04
Er	1.56E–01		3.55E–03	2.49E–03	5.56E–03	2.33E–04
Eu	4.80E–02		1.37E–03	1.10E–03	2.15E–03	1.34E–04
F			2.05E+01*	7.07E–01		
Fe	2.09E+03		4.20E+02	1.93E+02	2.40E+02	1.05E+02
Gd	2.88E–01		9.59E–03	7.36E–03	1.52E–02	7.07E–05
Hg	6.01E–01		2.86E–02	4.80E–03	1.26E–02	2.62E–03
Ho	6.01E–02		1.34E–03	9.80E–04	2.01E–03	5.66E–05
I	7.09E+01		8.12E+00	3.25E–01		
K	6.45E+04		3.81E+03	3.14E+03	7.60E+02	1.44E+02
Li	9.99E+00		9.76E–01	6.23E–01	3.91E–01	1.08E–01
Lu	2.40E–02		4.93E–04*	3.27E–04	6.95E–04*	2.12E–05
Mg	2.69E+04		4.06E+03	3.81E+03	3.54E+02	4.81E+01
Mn	1.72E+02		1.23E+02	4.43E+01	2.29E+01	8.84E+00
Mo	2.58E+00		2.03E–01	5.31E–02	5.79E–02	5.37E–03
Na	1.93E+05		9.37E+03	5.22E+03	4.65E+03	5.23E+02
Nd	1.86E+00		5.34E–02	3.96E–02	7.46E–02	4.45E–03
Ni	1.23E+01		1.52E+00	6.09E–01	3.21E+00	4.24E–02
Pb	1.81E+01		6.65E–01	2.82E–01	2.38E–01	1.34E–02
Pr	4.80E–01		1.50E–02	1.14E–02	1.98E–02	8.49E–04
Rb	3.96E+01		2.55E+00	1.24E+00	9.25E–01	3.19E–01
S	4.72E+04		5.26E+03	4.45E+03	5.81E+02	4.10E+01
Se	1.04E+01		6.05E–01	4.23E–02	2.45E–01	8.56E–02
Si	9.80E+04		4.42E+03	1.50E+03	9.85E+02	1.48E+02
Sm	3.72E–01		1.02E–02	7.97E–03	1.40E–02	1.06E–03
Tb	4.80E–02		1.29E–03	9.63E–04	1.95E–03	1.84E–04
Th	5.41E–01		2.80E–01	5.52E–02	8.19E–02	3.41E–02
Ti	1.10E+02		2.04E+01	7.62E+00	8.13E+00	3.36E+00
Tm	2.40E–02		5.03E–04*	3.40E–04	7.20E–04*	4.24E–05
V	3.82E+00		9.35E–01	3.71E–01	3.86E–01	1.01E–01
Yb	1.44E–01		3.11E–03	2.18E–03	4.61E–03	7.07E–05
Zn	1.04E+03		3.69E+01	2.40E+01	7.32E+00	8.20E–01
Zr	4.90E+00		2.42E+00	3.29E–01	1.31E+00	1.13E+00

mg/kg ts N Element	N=3 Benthic detrivores and meiofauna	std dev	N=3 Benthivorous fish	std dev	N=3 Zooplanktivorous fish	std dev
C	1.71E+05	1.20E+04	4.28E+05	1.33E+04	4.82E+05	1.04E+04
N	1.36E+04	1.76E+03	1.15E+05	2.08E+03	1.16E+05	3.21E+03
P	1.52E+03	2.87E+02	2.96E+04	3.67E+03	1.98E+04	1.65E+03
Al	6.04E–01	6.70E–02	3.28E–03	3.73E–03	7.71E–04	6.34E–04
As	2.02E+00	4.54E–01	6.97E–01*	1.18E–01	7.76E–01*	5.58E–01
Ba	2.97E+01	4.24E+00	2.10E+00	1.33E+00	2.12E+00	7.85E–01
Br	3.18E+01	8.41E+00	1.90E+01	9.19E–01	1.50E+01	1.20E+00
Ca	2.68E+05	4.86E+04	5.80E+04	2.71E+04	3.42E+04	8.22E+03
Cd	1.63E–01	7.42E–02	1.00E–02	3.22E–03	3.53E–02	1.44E–02
Ce	3.20E–01	1.24E–02	2.90E–04	1.31E–04	2.00E–04	0.00E+00
Cl	1.85E+03	2.12E+02	1.55E+03	2.12E+02	9.30E+02	1.41E+01
Co	2.95E–01	6.72E–02	2.27E–02	8.70E–03	3.14E–02	4.23E–03
Cr	5.21E–01	4.35E–02	2.03E–02	5.20E–04	1.33E–02	5.77E–03
Cs	5.54E–02	3.08E–03	3.72E–02	7.72E–03	2.11E–02*	5.86E–04
Cu	2.28E+01	6.92E+00	1.75E+00	5.01E–01	1.94E+00	1.36E–01
Dy	1.83E–02	1.86E–03	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Er	9.49E–03	1.13E–03	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Eu	4.43E–03	4.92E–04	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
F	2.15E+01*	2.12E+00	2.00E+01	0.00E+00	2.00E+01	0.00E+00
Fe	8.06E+02	9.70E+01	2.24E+01	4.70E+00	3.84E+01	2.03E+01
Gd	2.92E–02	2.75E–03	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Hg	3.78E–02	7.35E–03	2.99E–01	7.04E–02	3.05E–01	1.50E–01
Ho	3.49E–03	3.01E–04	2.00E–04	0.00E+00	2.00E–04	0.00E+00
I	1.62E+00	3.54E–01	1.04E+00	2.26E–01	8.00E–01	0.00E+00
K	1.23E+03	1.29E+02	1.40E+04	9.54E+02	1.35E+04	1.15E+03
Li	4.77E–01	4.39E–02	3.80E–01	6.34E–02	2.81E–01	7.86E–02
Lu	1.26E–03*	7.51E–05	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Mg	4.43E+02	3.80E+01	1.73E+03	2.57E+02	1.62E+03	1.88E+02
Mn	2.47E+01	5.29E+00	4.79E+00	2.43E+00	7.94E+00	5.45E+00
Mo	1.87E–01	3.35E–02	2.53E–02	8.96E–03	3.76E–02	1.03E–02
Na	4.17E+03	5.27E+02	4.29E+03	4.72E+02	2.89E+03	4.37E+02
Nd	1.60E–01	5.03E–03	2.00E–04	0.00E+00	2.00E–04	0.00E+00
Ni	5.23E–01	1.18E–01	9.71E–02	4.59E–02	8.66E–02	2.99E–02
Pb	9.47E–01	3.81E–01	7.77E–02	1.91E–02	8.49E–02	3.64E–02
Pr	4.31E–02	1.68E–03	2.00E–04	0.00E+00	2.00E–04*	0.00E+00
Rb	1.70E+00	1.01E–01	8.00E+00	5.42E–01	5.94E+00	7.49E–01
S	1.27E+03	4.37E+02	9.86E+03	5.30E+02	9.41E+03	4.62E+02
Se	4.12E–01	1.13E–01	1.91E+00	2.91E–01	1.50E+00	8.96E–02
Si	1.97E+03	4.36E+02	3.73E+02	4.98E+02	7.05E+01	2.32E+01
Sm	2.96E–02	2.16E–03	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Tb	3.65E–03	2.90E–04	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Th	1.90E–01	3.58E–02	5.23E–03*	2.14E–03	3.67E–03*	1.15E–03
Ti	1.81E+01	2.91E+00	1.32E+00	7.19E–01	6.85E–01	3.25E–01
Tm	1.24E–03*	1.16E–04	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
V	7.94E–01	1.32E–01	2.34E–01	2.20E–01	2.26E–02	7.60E–03
Yb	7.83E–03	6.91E–04	2.00E–04*	0.00E+00	2.00E–04*	0.00E+00
Zn	3.94E+01	1.25E+01	6.42E+01	4.71E+00	1.62E+02	5.52E+01
Zr	2.78E+00	9.40E–01	1.32E–01	6.89E–02	2.05E–02	1.96E–03

mg/kg ts N Element	N=3 Pisci- vorous fish	std dev	N=1 Sediment	std dev
C	4.12E+05	1.14E+04	7.00E+04	
N	1.08E+05	4.51E+03	8.28E+03	
P	3.44E+04	2.73E+03	1.10E+03	
Al	7.88E–04	9.75E–05	5.20E+04	
As	2.43E+00*	4.17E–01	2.50E–02	
Ba	4.65E–01	1.61E–01	3.70E+02	
Br	2.48E+01	7.07E+00	1.70E+02	
Ca	1.30E+04	6.07E+03	7.40E+03	
Cd	1.09E–02	5.06E–03	3.10E+00	
Ce	1.67E–04	5.77E–05	8.10E+01	
Cl	1.50E+03	0.00E+00	6.78E+03	
Co	1.31E–02	6.93E–04	1.10E+01	
Cr	1.00E–02	0.00E+00	7.20E+01	
Cs	5.77E–02	2.65E–03	6.00E+00	
Cu	1.56E+00	3.99E–01	5.50E+01	
Dy	1.67E–04*	5.77E–05	4.40E+00	
Er	1.67E–04*	5.77E–05	2.80E+00	
Eu	1.67E–04*	5.77E–05	1.00E+00	
F	2.00E+01	0.00E+00	3.50E+01*	
Fe	1.57E+01	5.06E+00	3.70E+04	
Gd	1.67E–04*	5.77E–05	6.50E+00	
Hg	2.61E–01	6.95E–02	4.00E–01*	
Ho	1.67E–04*	5.77E–05	9.50E–01	
I	1.96E+00	6.36E–02	1.70E+01*	
K	1.68E+04	2.10E+03	2.20E+04	
Li	2.97E–01	2.81E–02	3.90E+01	
Lu	1.67E–04*	5.77E–05	4.00E–01*	
Mg	1.25E+03	1.65E+02	1.10E+04	
Mn	6.20E+00	8.34E–01	3.80E+02	
Mo	1.62E–02	4.99E–03	2.40E+00	
Na	3.47E+03	3.42E+02	1.40E+04	
Nd	1.67E–04	5.77E–05	3.40E+01	
Ni	8.52E–02	6.86E–03	3.30E+01	
Pb	5.87E–02	1.26E–02	6.30E+01	
Pr	1.67E–04	5.77E–05	9.30E+00	
Rb	5.77E+00	8.96E–01	1.20E+02	
S	8.07E+03	1.33E+02	1.60E+04	
Se	1.56E+00	6.08E–02	8.30E–01	
Si	2.11E+02	2.64E+02	2.50E+05	
Sm	1.67E–04*	5.77E–05	6.70E+00	
Tb	1.67E–04	5.77E–05	8.80E–01	
Th	3.33E–03	5.77E–04	1.10E+01	
Ti	2.95E–01	1.90E–01	2.90E+03	
Tm	1.67E–04*	5.77E–05	3.90E–01	
V	2.94E–02	9.51E–03	7.00E+01	
Yb	1.67E–04*	5.77E–05	2.50E+00	
Zn	6.85E+01	1.28E+01	2.90E+02	
Zr	2.65E–02	3.82E–03	2.30E+02	

Appendix 5b

Chemical analyzes of sediment and biota – Laxemar-Simpevarp

A large number of elements have been analyzed in samples from most of the biotic pools and in the sediment. Concentrations of elements in water used in the model calculations are from the database SICADA and is not presented here. Values marked with an * were reported below detection limit and has therefore been divided by two (best estiment).

mg/kg ts Element	N=12 Macro-phytes	std dev	N=2 Filter-feeders	std dev	N=3 Piscivorous fish	std dev
C	3.14E+05	4.69E+04	3.65E+05	7.07E+03	4.25E+05	4.25E+05
N (tot)	1.36E+04	6.71E+03	7.09E+04	2.11E+04	1.19E+05	1.19E+05
P	2.24E+03	8.40E+02	9.83E+03	3.89E+02	1.52E+04	1.52E+04
Ag	1.16E–02*	3.70E–03	2.70E–02	4.24E–03	8.33E–03*	8.33E–03
Al	1.10E+03	1.21E+03	4.32E+01	6.51E+00	2.80E–01	2.80E–01
As	4.58E+00	5.18E+00	6.26E+00	8.84E–01	2.47E+00	2.47E+00
B	2.47E+02	2.10E+02	1.80E+01	3.89E+00	9.20E–01	9.20E–01
Ba	6.41E+01	6.36E+01	3.20E+00	4.24E–01	0.00E+00	0.00E+00
Be	1.33E–01*	1.18E–01	3.75E–02*	3.54E–03	3.83E–02*	3.83E–02
Br	1.75E+02	5.67E+01	3.25E+02	4.24E+00	9.81E+00	9.81E+00
Ca	5.23E+04	6.72E+04	1.78E+04	2.97E+03	6.81E+02	6.81E+02
Cd	5.77E–01	5.45E–01	2.77E+00	2.40E–01	1.83E–03*	1.83E–03
Ce	6.92E+00	7.91E+00	2.50E–01	7.07E–02	0.00E+00	0.00E+00
Cl	3.58E+04	1.37E+04	7.81E+04	4.09E+04	1.44E+03	1.44E+03
Co	1.69E+00	1.86E+00	3.30E–01	7.78E–03	6.70E–03	6.70E–03
Cr	8.09E–01	7.50E–01	5.09E–01*	2.19E–02	1.00E–02*	1.00E–02
Cs	5.57E–02	3.85E–02	1.02E–02*	4.95E–04	8.56E–02	8.56E–02
Cu	3.80E+00	2.27E+00	1.10E+01	1.98E+00	5.03E–01	5.03E–01
Dy	3.56E–01	3.78E–01	1.79E–02	8.49E–04	1.50E–04*	1.50E–04
Er	2.13E–01	2.24E–01	1.07E–02	7.78E–04	1.50E–04*	1.50E–04
Eu	9.79E–02	9.77E–02	4.95E–03	2.12E–04	1.50E–04*	1.50E–04
Fe	1.60E+03	2.25E+03	1.27E+02	4.95E+00	1.00E+01*	1.00E+01
Ga	1.43E–01*	1.38E–01	1.05E–02*	6.36E–04	3.00E–03*	3.00E–03
Gd	4.12E–01	4.33E–01	2.38E–02	2.12E–04	1.50E–04*	1.50E–04
Hf	3.34E–02	2.63E–02	2.50E–03	1.41E–04	1.93E–03	1.93E–03
Hg	7.17E–03*	1.09E–02	8.00E–02*	1.13E–02	4.07E–01	4.07E–01
Ho	7.20E–02	7.66E–02	3.85E–03	2.12E–04	1.50E–04*	1.50E–04
I	5.53E+01	3.39E+01	1.97E+01	4.88E+00	8.77E–01	8.77E–01
K	2.63E+04	2.00E+04	9.28E+03	9.55E+02	2.19E+04	2.19E+04
La	3.85E+00	4.01E+00	2.45E–01	4.88E–02	3.67E–04	3.67E–04
Li	1.22E+00	9.52E–01	4.95E–01	1.20E–01	1.83E–02*	1.83E–02
Lu	3.03E–02	3.18E–02	1.40E–03	1.41E–04	1.50E–04*	1.50E–04
Mg	1.14E+04	4.58E+03	4.91E+03	7.00E+02	1.84E+03	1.84E+03
Mn	2.39E+02	1.93E+02	3.22E+01	1.09E+01	6.30E–01	6.30E–01
Mo	4.71E–01	4.79E–01	5.90E–01	9.90E–02	1.00E–02	1.00E–02
Na	2.25E+04	5.26E+03	3.39E+04	6.79E+03	1.99E+03	1.99E+03
Nb	1.13E–01	1.03E–01	8.95E–03	1.77E–03	1.50E–04*	1.50E–04
Nd	3.41E+00	3.58E+00	1.70E–01	2.47E–02	2.67E–04*	2.67E–04
Ni	5.45E+00	4.15E+00	2.69E+00	1.48E–01	1.50E–02*	1.50E–02
Pb	1.03E+00	7.05E–01	8.26E–01	4.16E–01	1.50E–02*	1.50E–02
Pr	8.98E–01	9.42E–01	4.24E–02	7.64E–03	1.50E–04*	1.50E–04
Rb	7.75E+00	4.38E+00	3.90E+00	4.24E–01	1.07E+01	1.07E+01
S	2.20E+04	1.32E+04	9.82E+03	5.44E+02	1.45E+04	1.45E+04

mg/kg ts **Element**	**N=12** **Macro-phytes**	**std dev**	**N=2** **Filter-feeders**	**std dev**	**N=3** **Piscivorous fish**	**std dev**
Sb	2.90E–02	1.20E–02	2.80E–02	0.00E+00	1.50E–03*	1.50E–03
Sc	1.83E–01	1.85E–01	4.45E–02	2.62E–03	7.33E–04	7.33E–04
Se	3.37E–01	8.66E–02	2.48E+00*	2.33E–01	9.76E–01	9.76E–01
Si	9.08E+03	7.45E+03	5.64E+02	1.80E+02	1.70E+02	1.70E+02
Sm	5.58E–01	5.88E–01	2.93E–02	4.10E–03	1.50E–04*	1.50E–04
Sn	8.08E–02	5.57E–02	3.50E–02*	7.07E–03	3.00E–02	3.00E–02
Sr	9.26E+02	9.24E+02	8.00E+01	7.57E+00	4.33E–01	4.33E–01
Ta	8.92E–03	6.02E–03	2.50E–03*	7.07E–04	1.17E–03*	1.17E–03
Tb	5.91E–02	6.39E–02	3.25E–03	7.07E–05	1.50E–04*	1.50E–04
Th	2.18E–01*	2.34E–01	2.47E–02*	1.23E–02	1.00E–02	1.00E–02
Ti	1.98E+01	1.92E+01	1.56E+00	1.41E–02	6.00E–02	6.00E–02
Tl	3.04E–02*	2.30E–02	7.50E–03*	3.54E–03	8.33E–03*	8.33E–03
Tm	3.02E–02	3.22E–02	1.25E–03	7.07E–05	1.50E–04*	1.50E–04
U	7.13E–01	7.63E+00	3.16E–01	2.83E–01	8.33E–05*	2.28E+01
V	1.77E+00	4.23E–01	2.02E–01	3.04E–02	8.33E–03*	8.33E–05
W	4.51E–02	1.93E+00	3.30E–02*	2.12E–02	8.00E–04	8.33E–03
Y	2.83E+00	3.20E–02	1.57E–01	8.49E–03	1.50E–04*	8.00E–04
Yb	1.99E–01	3.01E+00	8.45E–03	2.33E–02	1.50E–04*	1.50E–04
Zn	3.29E+01	2.12E–01	8.88E+01	1.06E–03	1.79E+01	1.50E–04
Zr	1.53E+00	2.18E+01	1.40E–01	2.83E–01	1.70E–01	1.79E+01

mg/kg ts Element	N=3 Zooplanktivorous fish	std dev	N=3 Benthi-vorous fish	std dev	N=6 Sediment	std dev
C	5.31E-05	2.02E+05	4.24E+05	1.19E+04	1.38E+05	1.07E+04
N (tot)	1.18E+05	1.65E+04	1.31E+05	1.61E+04	1.64E+04	1.34E+03
P	1.17E+04	3.06E+02	1.20E+04	7.57E+02	1.63E+03	2.84E+02
Ag	6.67E–03*	2.89E–03	5.00E–03*	0.00E+00	1.42E–02*	3.00E–03
Al	1.40E–01	6.08E–02	6.57E–01	3.61E–01	2.56E+04	1.61E+03
As	1.12E+00	1.96E–01	7.43E+00	1.94E+00	6.43E+00	1.00E+00
B	1.05E+00	8.02E–02	5.00E–01*	0.00E+00	7.50E–01*	3.00E–01
Ba	0.00E+00	0.00E+00	3.33E–02	5.77E–02	1.08E+02	2.10E+01
Be	3.67E–02*	2.89E–03	3.33E–02*	2.89E–03	2.52E+00	4.00E–01
Br	9.60E+00	4.22E–01	1.05E+01	9.35E–01	1.41E+02	2.50E+01
Ca	1.26E+03	4.59E+02	5.83E+02	2.91E+02	6.59E+03	7.00E+02
Cd	2.50E–03*	1.32E–03	4.00E–03*	2.00E–03	1.94E+00	1.00E+00
Ce	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.34E+02	8.00E+00
Cl	2.84E+03	1.01E+02	4.23E+03	1.03E+03	4.21E+04	1.03E+04
Co	1.40E–02	2.88E–03	7.83E–03	2.36E–03	1.01E+01	3.00E+00
Cr	1.00E–02*	0.00E+00	1.00E–02*	0.00E+00	2.77E+01	4.00E+00
Cs	2.91E–02	3.06E–03	7.59E–02	1.27E–03	1.93E+00	2.00E–01
Cu	1.51E+00	2.92E–01	7.77E–01	3.51E–02	5.93E+01	8.00E+00
Dy	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	7.40E+00	3.00E–01
Er	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	4.24E+00	3.00E–01
Eu	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	1.83E+00	2.00E–01
Fe	6.67E+00*	2.89E+00	5.00E+00*	0.00E+00	2.62E+04	4.28E+03
Ga	2.67E–03*	2.89E–04	2.83E–03*	2.89E–04	5.00E–01*	0.00E+00
Gd	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	9.18E+00	1.00E+00
Hf	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	7.19E–01	3.00E–01
Hg	1.59E–01	4.59E–02	3.88E–01	1.11E–01	6.52E–02*	0.00E+00
Ho	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	1.41E+00	1.00E–01
I	2.50E–01*	0.00E+00	2.50E–01*	0.00E+00	8.49E+00	1.00E+00
K	2.12E+04	1.62E+03	2.07E+04	1.47E+03	8.11E+03	1.02E+03
La	2.00E–04*	8.66E–05	4.00E–04	1.00E–04	7.04E+01	4.00E+00
Li	1.67E–02*	2.89E–03	1.83E–02*	2.89E–03	3.00E+01	7.00E+00
Lu	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	6.95E–01	1.00E–01
Mg	1.56E+03	1.27E+02	1.48E+03	1.00E+02	8.93E+03	1.84E+02
Mn	1.33E+00	3.11E–01	4.87E–01	1.03E–01	1.73E+02	1.10E+01
Mo	1.00E–02	0.00E+00	2.00E–02	0.00E+00	1.38E–01*	2.00E+00
Na	2.41E+03	5.00E+01	3.30E+03	3.37E+02	2.33E+04	3.10E+03
Nb	1.50E–04*	0.00E+00	3.00E–04	0.00E+00	3.00E+00*	0.00E+00
Nd	1.50E–04*	0.00E+00	2.67E–04*	2.02E–04	7.24E+01	2.00E+00
Ni	1.50E–02*	0.00E+00	7.37E–02*	1.02E–01	3.32E+01	4.00E+00
Pb	1.50E–02*	0.00E+00	2.50E–02*	1.73E–02	2.43E+01	3.00E+00
Pr	1.50E–04*	0.00E+00	8.83E–05*	6.83E–05	1.70E+01	1.00E+00
Rb	3.67E+00	2.52E–01	8.03E+00	6.03E–01	3.27E+01	9.00E+00
S	9.35E+03	3.41E+02	1.09E+04	6.24E+02	3.08E+04	3.53E+03
Sb	1.50E–03*	2.66E–19	3.33E–03*	3.18E–03	5.24E–01	1.00E–01
Sc	4.00E–04	1.00E–04	6.67E–04	2.08E–04	5.51E+00	1.00E+00
Se	9.60E–01	4.98E–02	9.04E–01	1.18E–01	1.00E+00*	0.00E+00*
Si	1.46E+02	5.70E+01	1.42E+02	1.19E+01	1.96E+05	8.81E+03
Sm	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	1.08E+01	1.00E+00

mg/kg ts Element	N=3 Zooplanktivorous fish	std dev	N=3 Benthi-vorous fish	std dev	N=6 Sediment	std dev
Sn	2.00E–02	0.00E+00	1.50E–02*	0.00E+00	1.00E+01*	0.00E+00
Sr	1.40E+00	5.29E–01	1.33E+00	9.24E–01	1.03E+02	9.00E+00
Ta	3.33E–03	1.53E–03	1.17E–03	7.64E–04	2.27E–01	1.00E–01
Tb	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	1.32E+00	1.00E–01
Th	2.83E–03*	2.89E–04	2.83E–03*	2.89E–04	7.11E+00	1.00E+00
Ti	5.27E–01	8.43E–01	1.40E–01	1.56E–01	9.49E+02	1.67E+02
Tl	6.67E–03*	2.89E–03	5.00E–03*	0.00E+00	4.59E–01	1.00E–01
Tm	1.50E–04*	0.00E+00	1.33E–04*	2.89E–05	6.43E–01	1.00E–01
U	5.67E–04	1.22E+00	6.67E–04	2.65E–01	6.21E+00	1.00E+00
V	6.67E–03*	5.77E–05	1.03E–02*	3.79E–04	3.41E+01	2.00E+00
W	4.33E–04	2.89E–03	1.30E–03	9.24E–03	3.00E+01*	0.00E+00
Y	2.00E–04*	1.15E–04	3.50E–04	2.00E–04	5.46E+01	4.00E+00
Yb	1.50E–04*	8.66E–05	1.33E–04*	1.80E–04	4.48E+00	4.00E–01
Zn	3.00E+01	0.00E+00	1.95E+01	2.89E–05	1.65E+02	5.00E+01
Zr	3.67E–03*	6.30E+00	4.93E–03*	1.42E+00	4.89E+01	1.00E+01

C:X ratios for the pools of the mass balances – Forsmark

Ratios between carbon (C) and a large number of elements (X) in various pools of the marine ecosystem in Forsmark. The ratios are based on analyzes in the same sample. For some elements the concentration have been bellow the detection limit, for these elements an estimated mean have been used. These values are marked in italic in the table.

	N=3 Particulate matter	N=3 Dissolved matter	N=4 Benthic herbivores (mean two species)	N=3×3 Macrophytes (mean 3 species)	N=3 Phytoplankton
Al	0.3	11,036	364	309	35
As	*5,791*	*2,163*	66,500	41,224	14,335
Ba	0.3	871	8,670	4,898	4,287
Br	*145*	*1*	1,496	1,274	132
C	1	1	1	1	1
Ca	0.1	0.2	2	26	51
Cd	687	810,971	210,867	588,926	714,619
Ce	986	1,463,333	5,205,619	7,781,578	19,398,659
Cl	26	0.01	57	23	3
Co	25,768	1,258,824	520,297	240,063	108,821
Cr	120	23,253	429,164	240,715	28,396
Cs	5,165	243,889	4,088,215	2,343,442	355,391
Cu	1,082	18,814	10,362	67,971	7,994
Dy	27,540	1,463,333	78,975,524	110,761,649	356,631,731
Er	5,103	1,463,333	145,218,002	192,986,048	640,290,530
Eu	*10,961*	*1,463,333*	480,379,871	578,838,117	868,333,333
F	380	49	8,038	5,292	178
Fe	11	5,938	633	345	47
Gd	25,367	1,463,333	61,465,184	86,305,801	284,565,693
Hg	*57,909*	*7,316,667*	9,028,090	14,032,549	3,134,448
Ho	139,547	1,463,333	412,965,207	558,569,061	*868,333,333*
I	290	624	20,249	5,074	11,594
K	0.4	0.2	99	18	19
Li	772	534	307,770	138,470	20,816
Lu	309,187	1,463,333	966,984,207	*945,827,455*	*868,333,333*
Mg	3	0.08	130	42	24
Mn	221	7,195	2,679	907	391
Mo	539	8,677	1,258,119	865,212	519,584
N	9	67	9	16	8
Na	0.1	0.01	30	18	4
Nd	3,594	1,186,633	10,449,433	15,352,101	46,358,557
Ni	2,752	15,581	172,419	46,114	30,693
P	53	2,867	86	183	85
P	59	2,663	92	185	134
Pb	185	13,023	394,299	229,095	15,791
Pr	13,749	1,463,333	38,947,386	57,771,175	172,108,404
Rb	110	787	105,266	29,160	14,024
S	7	0.11	78	29	24
Se	*2,895*	*572,662*	435,602	*4,371,999*	352,295
Si	0	38	58	29	1
Sm	16,085	1,463,333	57,299,866	82,437,961	251,050,982

	N=3 Particulate matter	**N=3 Dissolved matter**	**N=4 Benthic herbivores (mean two species)**	**N=3×3 Macrophytes (mean 3 species)**	**N=3 Phytoplankton**
Tb	166,314	146,333	443,213,976	609,664,715	868,333,333
Th	8,656	365,833	1,007,991	992,109	127,079
Ti	79	287,233	12,731	8,058	988
Tm	309,187	1,463,333	964,968,615	*970,135,158*	*868,333,333*
U					
V	4,621	115,638	278,074	136,517	25,710
Yb	50,003	1,463,333	166,145,571	216,988,878	681,586,700
Zn	0	10,425	8,175	4,133	488
Zr	213	243,889	107,033	60,662	11,665

	N=2 microphytobenthos	**N=3 Benthic detrtivore**	**N=2 Filter feeder**	**N=3 benthivorous fish**	**N=3 piscivorous fish**
Al	5	287	595	263,811	617,609
As	3,194	87,313	229,342	*602,399*	*201,511*
Ba	307	5,824	4,946	262,128	1,123,817
Br	139	5,570		21,918	20,445
C	1	1	1	1	1
Ca	5	1	0.49	8	43
Cd	59,011	1,167,413	946,064	43,942,179	50,526,532
Ce	300,741	534,651	1,116,536	1,597,608,696	3,201,666,667
Cl	3	94		271	323
Co	4,437	598,361	1,455,719	20,126,142	36,893,707
Cr	5,793	329,409	643,133	20,294,976	48,200,000
Cs	58,286	3,091,981	7,126,639	11,382,999	8,355,692
Cu	3,282	7,988	90,020	247,306	320,692
Dy	5,037,573	9,468,751	15,592,614	*2,060,000,000*	*3,201,666,667*
Er	8,970,641	18,266,385	27,659,840	*2,060,000,000*	*3,201,666,667*
Eu	26,809,057	39,028,173	71,692,073	*2,060,000,000*	*3,201,666,667*
F	*1,998*	*8,041*		*20,725*	*24,225*
Fe	3	214	709	18,893	32,696
Gd	3,745,226	5,906,983	10,132,015	2,060,000,000	3,201,666,667
Hg	1,213,976	4,614,950	12,496,755	1,434,921	1,921,717
Ho	26,187,759	49,380,465	76,403,368	2,060,000,000	3,201,666,667
I	518	110,447		406,629	248,069
K	11	141	206	30	29
Li	7,402	359,489	408,513	1,109,409	1,632,349
Lu	65,297,379	136,589,744	220,950,704	*2,060,000,000*	*3,201,666,667*
Mg	13	387	438	241	392
Mn	11	7,126	7,267	99,315	78,752
Mo	27,485	925,772	2,662,022	17,789,454	31,571,337
N	9	13	15	4	4
Na	5	41	33	97	140
Nd	639,034	1,074,392	2,062,987	2,060,000,000	3,201,666,667
Ni	1,307	334,413	47,825	5,147,513	5,688,628
P	47	104	229	14	36
P	54	115	145	12	24
Pb	2,314	196,413	647,436	5,528,756	8,506,021
Pr	2,356,550	3,972,507	7,760,417	*2,060,000,000*	*3,201,666,667*
Rb	2,549	101,180	176,399	51,703	85,210
S	15	146	265	42	60
Se	216,233	432,516	668,220	218,995	309,203
Si	2	90	158	3,406	5,885
Sm	3,354,600	5,817,950	11,037,415	*2,060,000,000*	*3,201,666,667*
Tb	27,053,577	47,184,318	79,086,538	*2,060,000,000*	*3,201,666,667*
Th	9,596	917,907	2,049,945	85,981,602	146,944,444
Ti	168	9,553	20,638	425,392	2,062,049
Tm	63,798,701	138,703,042	213,594,203	*2,060,000,000*	*3,201,666,667*
U					
V	2,598	218,313	412,121	2,889,979	18,056,238
Yb	10,174,777	22,005,659	33,299,921	*2,060,000,000*	*3,201,666,667*
Zn	299	4,656	21,108	6,443	7,215
Zr	1,110	65,906	185,037	3,618,224	18,408,550

	N=3 zooplnkativorous fish	N=1 Zooplankton	N=3×3 Sediment (top 10mean)
Al	2,169,376	148	1
As	791,269	18,230	1,727
Ba	225,158	8,566	29
Br	28,905	32	193
C	1	1	1
Ca	13	5	2
Cd	14,330,926	87,342	18,734
Ce	2,141,666,667	119,691	4,634
Cl	463	0	4
Co	13,876,028	253,916	1,286
Cr	35,883,333	42,370	298
Cs	20,288,112	1,316,604	2,550
Cu	221,183	2,129	605
Dy	*2,141,666,667*	1,545,578	41,100
Er	*2,141,666,667*	2,734,484	104,972
Eu	*2,141,666,667*	8,887,074	215,280
F	21,500	0	5,250
Fe	13,438	204	0
Gd	*2,141,666,667*	1,481,179	34,102
Hg	1,662,309	710,966	35,209
Ho	*2,141,666,667*	7,109,659	212,836
I	537,500	6,025	879
K	32	7	3
Li	1,603,936	42,726	415
Lu	*2,141,666,667*	17,774,147	549,994
Mg	268	16	2
Mn	79,103	2,486	23
Mo	11,953,200	165,341	16,902
N	4	4	9
Na	151	2	4
Nd	*2,141,666,667*	229,344	6,207
Ni	5,380,836	34,851	619
P	18	7	11
P	15	45	11
Pb	5,839,340	23,542	160
Pr	*2,141,666,667*	888,707	22,023
Rb	72,767	10,772	65
S	46	9	8
Se	286,909	41,192	73,197
Si	6,580	4	32
Sm	*2,141,666,667*	1,146,719	32,547
Tb	*2,141,666,667*	8,887,074	234,513
Th	*124,244,444*	789,962	5,508
Ti	710,311	3,872	6
Tm	*2,141,666,667*	17,774,147	592,246
U			71,333
V	20,448,179	111,787	194
Yb	*2,141,666,667*	2,962,358	91,171
Zn	2,945	410	90
Zr	21,098,521	87,128	23

Appendix 6b

C:X ratios for the pools of the mass balances – Laxemar-Simpevarp

Ratios between carbon (C) and a large number of elements (X) in the analyzed pools of the marine ecosystem in Laxemar-Simpevarp. The ratios are based on analyzes in the same sample. For some elements the concentration have been bellow the detection limit, for these elements an estimated mean have been used. These values are marked in italic in the table.

	N=12 Macrophytes	N=3 Filter feeders (Mytilus edulis)	N=3 Benthivorous fish (Flounder)	N=3 Piscivorous fish (Perch)
Ag	27,085,612	*13,518,519*	*84,700,000*	*51,028,000*
Al	286	8,449	644,924	1,518,690
As	68,440	58,353	56,999	172,392
B	1,271	20,334	847,000	462,043
Ba	4,893	114,063	12,705,000	
Be	2,367,862	*9,733,333*	*12,705,000*	*11,093,043*
Br	1,796	1,123	40,423	43,332
C	1	1	1	1
Ca	6	21	726	625
Cd	543,746	131,769	105,875,000	231,945,455
Ce	45,360	1,460,000		
Cl	9	5	100	296
Co	185,802	1,107,739	54,063,830	63,467,662
Cr	387,734	*717,797*	*42,350,000*	*42,523,333*
Cs	5,634,391	*35,960,591*	5,582,162	4,969,614
Cu	82,545	33,182	545,279	844,834
Dy	880,472	20,391,061	*3,176,250,000*	*2,834,888,889*
Er	1,471,124	34,272,300	*3,176,250,000*	*2,834,888,889*
Eu	3,204,716	73,737,374	*3,176,250,000*	*2,834,888,889*
F				
Fe	196	2,885	84,700	42,523
Ga	2,200,666	34,928,230	*149,470,588*	*141,744,444*
Gd	761,309	15,368,421	*3,176,250,000*	*2,834,888,889*
Hf	9,381,759	146,000,000	3,176,250,000	219,948,276
Hg	43,777,907	4,562,500	1,090,558	1,045,656
Ho	4,357,523	94,805,195	*3,176,250,000*	*2,834,888,889*
I	5,673	18,575	*1,694,000*	*484,688*
K	12	39	20	19
La	81,571	1,492,843	1,058,750,000	1,159,727,273
Li	258,047	737,374	*23,100,000*	*23,194,545*
Lu	10,371,625	260,714,286	*3,176,250,000*	*2,834,888,889*
Mg	28	74	286	231
Mn	1,313	11,335	870,205	674,974
Mo	666,354	618,644	21,175,000	42,523,333
N	23	5	3	4
Na	14	11	128	214
Nb	2,786,544	40,782,123	*1,411,666,667*	*2,834,888,889*
Nd	92,112	2,153,392	1,588,125,000	1,594,625,000
Ni	57,567	135,940	5,748,869	28,348,889
P	140	37	35	28
Pb	305,394	441,889	16,940,000	28,348,889
Pr	349,553	8,608,491	*4,794,339,623*	*2,834,888,889*
Rb	40,483	93,590	52,718	39,618
S	14	37	39	29
Sb	10,818,678	13,035,714	*127,050,000*	*283,488,889*

	N=12 Macrophytes	N=3 Filter feeders (Mytilus edulis)	N=3 Benthivorous fish (Flounder)	N=3 Piscivorous fish (Perch)
Sc	1,718,662	8,211,474	635,250,000	579,863,636
Se	*929,835*	147,475	468,301	435,839
Si	35	648	2,989	2,506
Sm	562,144	12,457,338	3,176,250,000	2,834,888,889
Sn	3,881,340	10,428,571	28,233,333	14,174,444
Sr	339	4,565	317,625	981,308
Ta	35,185,981	146,000,000	363,000,000	364,485,714
Tb	5,307,161	112,307,692	3,176,250,000	2,834,888,889
Th	1,439,347	14,777,328	149,470,588	42,523,333
Ti	15,816	233,974	3,025,000	7,087,222
Tl	10,314,795	48,666,667	84,700,000	51,028,000
Tm	10,385,931	292,000,000	3,176,250,000	2,834,888,889
U	440,283	1,156,894	635,250,000	5,102,800,000
V	176,955	1,806,931	40,983,871	51,028,000
W	6,960,436	11,060,606	325,769,231	531,541,667
Y	110,980	2,332,268	1,210,000,000	2,834,888,889
Yb	1,579,435	43,195,266	3,176,250,000	2,834,888,889
Zn	9,543	4,110	21,681	23,800
Zr	205,004	2,607,143	85,844,595	2,499,412

	N=3 Zooplanktivorous fish (Roach)	**N=2 Sediment (top 10 cm)**
Ag	*79,600,000*	9,764,706
Al	3,790,476	5
As	474,940	21,514
B	504,916	184,444
Ba		1,283
Be	*14,472,727*	54,894
Br	55,259	983
C	1	1
Ca	422	21
Cd	212,266,667	71,392
Ce		1,031
Cl	187	3
Co	37,904,762	13,724
Cr	53,066,667	5,003
Cs	18,235,968	71,613
Cu	352,212	2,333
Dy	*3,537,777,778*	18,706
Er	*3,537,777,778*	32,664
Eu	*3,537,777,778*	75,523
F		
Fe	*79,600*	5
Ga	*199,000,000*	276,667
Gd	*3,537,777,778*	15,066
Hf	*3,537,777,778*	192,308
Hg	3,337,526	2,122,762
Ho	*3,537,777,778*	98,341
I	*2,122,667*	16,287
K	25	17
La	2,653,333,333	1,965
Li	*31,840,000*	4,606
Lu	*3,537,777,778*	199,184
Mg	341	15
Mn	400,000	801
Mo	53,066,667	1,000,000
N	4	8
Na	220	6
Nb	3,537,777,778	46,111
Nd	3,537,777,778	1,911
Ni	*35,377,778*	4,173
P	45	85
Pb	*35,377,778*	5,704
Pr	*3,537,777,778*	8,137
Rb	144,727	4,230
S	57	4
Sb	353,777,778	264,079
Sc	1,326,666,667	25,121
Se	552,970	138,333
Si	3,646	1

	N=3 Zooplanktivorous,fish, (Roach)	**N=2 Sediment, (top,10,cm)**
Sm	*3,537,777,778*	12,862
Sn	*26,533,333*	13,833
Sr	379,048	1,346
Ta	*159,200,000*	608,504
Tb	*3,537,777,778*	104,666
Th	*187,294,118*	19,461
Ti	1,007,595	146
Tl	*79,600,000*	301,708
Tm	*3,537,777,778*	215,305
U	936,470,588	22,270
V	*79,600,000*	4,055
W	1,224,615,385	4,611
Y	*2,653,333,333*	2,533
Yb	3,537,777,778	30,855
Zn	17,689	836
Zr	*144,727,273*	2,832

Appendix 7a

Physical charactenstivs of the basins – Forsmark.

Physical characteristics of the marine basins in the marine Forsmark area.

IDKOD	Marine basin area (m^2)	Mean depth (m)	Max depth (m)	Volume (m^3)	Total drainage area to basin (m^2)	Runoff (m^3 $year^{-1}$)	Advective outflow (m^3)	Avdective inflow (m^3)	AvA days	Net advective flow (m3)
Basin 102	34,173,600	10.9	24.9	370,872,411	65,213,200	55,630,862	146,331,158,485	146,180,202,705	0.676	–150,955,780
Basin 100	18,455,600	19.4	55.9	357,667,682	22,922,000	53,650,152	274,020,917,607	273,937,775,954	0.345	–83,141,653
Basin 101	21,798,800	16.1	27.2	351,911,108	21,800,000	52,786,666	199,998,839,854	199,899,086,280	0.391	–99,753,574
Basin 105	22,664,000	18.2	58.8	412,799,830	27,716,000	61,919,974	235,063,186,637	234,961,476,492	0.487	–101,710,145
Basin 103	5,693,600	5.5	14.8	31,342,357	6,317,200	4,701,354	31,451,639,046	31,426,402,434	0.127	–25,236,613
Basin 104	2,698,000	7.6	11.3	20,631,606	2,746,400	3,094,741	23,632,530,445	23,620,181,956	0.067	–12,348,489
Basin 108	7,193,600	10.6	20.1	76,441,352	7,590,000	11,466,203	60,258,899,534	60,228,111,939	0.189	–30,787,595
Basin 106	1,385,600	4.5	9	6,227,718	1,434,000	934,158	8,657,076,489	8,650,805,994	0.137	–6,270,495
Basin 111	6,736,800	3.3	9.3	22,247,608	18,810,000	3,337,141	3,374,817,080	3,349,321,695	0.994	–25,495,385
Basin 107	4,627,600	7.0	13.2	32,359,557	4,840,000	4,853,934	21,819,748,293	21,798,822,449	0.217	–20,925,845
Basin 110	7,072,400	12.4	23.7	87,928,320	7,169,200	13,189,248	87,612,923,074	87,581,081,455	0.124	–31,841,618
Basin 114	14,030,800	19.4	45.2	272,614,235	18,974,800	40,892,135	154,336,567,378	154,273,543,695	0.444	–63,023,683
Basin 109	1,521,200	19.3	27.3	29,331,322	1,525,200	4,399,698	44,854,811,320	44,847,742,418	0.045	–7,068,902
Basin 116	**13,534,000**	**9.5**	**18.9**	**128,153,311**	**14,101,600**	**19,222,997**	**52,142,360,552**	**52,082,246,480**	**0.74**	**–60,114,072**
Basin 113	1,596,800	12.5	20.1	19,990,020	1,598,000	2,998,503	43,629,729,510	43,622,322,941	0.031	–7,406,569
Basin 117	5,762,800	3.7	10	21,379,066	16,125,200	3,206,860	1,769,974,267	1,746,034,672	1.411	–23,939,595
Basin 112	696,400	10.9	13.4	7,587,139	693,200	1,138,071	13,108,992,327	13,105,975,420	0.023	–3,016,907
Basin 115	4,211,200	16.1	25.9	67,701,357	4,214,800	10,155,204	74,020,809,137	74,002,038,677	0.119	–18,770,460
Basin 151	41,924,400	13.2	43.5	553,750,053	91,454,000	83,062,508	73,081,613,936	72,912,922,785	4.52	–168,691,151
Basin 118	1,446,400	3.1	8	4,429,817	2,001,200	664,473	227,782,757	221,954,068	0.666	–5,828,689
Basin 123	7,284,400	13.6	23.1	98,880,631	7,717,200	14,832,095	83,375,277,029	83,342,343,517	0.125	–32,933,511
Basin 152	2,134,800	1.4	4.7	3,066,448	1,277,480,000	459,967	402,539,278	84,448,138	0.524	–318,091,141
Basin 150	5,856,800	3.6	14.2	21,083,192	15,624,800	3,162,479	3,347,210,492	3,324,384,880	0.686	–22,825,612
Basin 146	3,404,000	7.7	16.2	26,299,440	3,823,200	3,944,916	23,179,435,891	23,164,029,471	0.091	–15,406,420
Basin 126	5,440,400	7.5	16.4	40,604,153	7,232,000	6,090,623	22,217,768,523	22,194,479,015	0.245	–23,289,509
Basin 134	586,400	1.8	5.8	1,052,611	1,957,600	157,892	1,017,417	862,217	0.024	–155,200
Basin 121	3,692,400	5.5	12.8	20,313,960	13,983,600	3,047,094	8,073,976,047	8,058,725,774	0.27	–15,250,273
Basin 120	729,200	2.5	12.3	1,815,453	10,336,400	272,318	26,125,590	24,685,617	0.329	–1,439,973
Allbasins	246,352,000	12.6	58.8	3,088,481,756	1,675,400,800	463,272,263	1,690,017,727,996	**1,688,642,009,137**		–1,375,718,859

Appendix 7b

Physical charactenstivs of the basins – Laxenar-Simpevarp.

Physical characteristics of the marine basins in the marine Laxemar-Simpevarp area.

IDKOD	Marine basin area (m^2)	Mean depth (m)	Max depth (m)	Volume (m^3)	Total drainage area to basin (m^2)	Runoff (m^3 $year^{-1}$)	Advective outflow (m^3)	Avdective inflow (m^3)	AvA days	Net advective flow (m3)
Basin 524	14,680,400	11.6	27.7	170,467,920	138,000	30,360	465,695,503,200	843,092,841,600	0.14	377,397,338,400
Basin 525	15,211,200	6.9	24.7	105,559,158	0	0	55,819,082,880	46,610,575,200	0.31	–9,208,507,680
Basin 522	13,567,200	15.9	35.8	216,473,156	0	0	267,987,139,200	469,577,088,000	0.19	201,589,948,800
Basin 523	13,933,600	11.5	25.8	160,983,466	0	0	201,933,926,640	337,281,317,280	0.27	135,347,390,640
Basin 521	**38,044,800**	**11.1**	**45.1**	**425,691,909**	**1,538,000**	**338,360**	**226,170,479,016**	**355,090,217,688**	**0.81**	**128,919,738,672**
Basin 501	334,800	3.2	10.4	1,066,472	12,214,000	2,698,112	27,770,688	27,770,688	15.8	0
Basin 500	2,906,000	2.0	9.1	5,757,570	13,300,000	2,938,013	0	911,067,912	4.26	911,067,912
Basin 504	**608,000**	**3.6**	**16.1**	**2,187,558**	**1,948,000**	**428,560**	**228,477,024**	**229,423,752**	**5.88**	**946,728**
Basin 502	**1,126,800**	**4.8**	**18.1**	**5,461,854**	**34,675,000**	**7,628,500**	**89,939,160**	**90,254,736**	**24.4**	**315,576**
Basin 506	**334,400**	**3.3**	**12.1**	**1,105,921**	**951,000**	**209,220**	**309,264,480**	**302,637,384**	**2.78**	**–6,627,096**
Basin 508	**1,374,800**	**1.7**	**8.1**	**2,387,159**	**46,517,000**	**10,233,880**	**60,906,168**	**55,225,800**	**10.3**	**–5,680,368**
Basin 513	4,062,800	4.3	16.1	17,556,328	7,356,000	1,618,320	8,429,034,960	8,410,100,400	0.29	–18,934,560
Basin 514	952,000	4.5	17.1	4,298,745	0	0	8,488,994,400	8,498,461,680	0.31	9,467,280
Basin 516	482,000	0.1	0.87	73,975	2,732,000	601,040	2,556,165,600	2,556,165,600	9.25	0
Basin 518	758,800	3.7	16.6	2,863,972	0	0	11,329,178,400	11,322,866,880	0.40	–6,311,520
Basin 515	869,600	3.3	8.2	2,872,032	11,552,000	2,541,440	716,041,944	716,041,944	6.86	0
Basin 517	6,686,000	3.5	18.4	23,713,485	22,719,000	4,998,180	6,065,370,720	6,060,952,656	1.03	–4,418,064
Basin 520	2,269,200	2.4	11.3	5,560,975	12,200,000	2,695,019	1,084,319,136	1,082,425,680	0.40	–1,893,456
Basin 519	590,400	0.2	2.7	138,681	139,057,000	30,718,136	12,307,464	12,307,464	7.98	0
Allbasins	**118,792,800**	**9.9**	**45.1**	**1,154,220,339**	**306,897,000**	**67,677,140**	**1,257,003,901,080**	**2,091,927,742,344**		**834,923,841,264**

Results generated in GIS-models for marine ecosystems, in gC m^{-2} $year^{-2}$, for functional groups, abiotic pools and fluxes – Forsmark.

Physical parameters in the marine Forsmark area, depths and areas in m and m^2 respectively.

IDKOD	AREA (m2)	secchi	Depth	Medel PAR	Burial (gC m^{-2} $year^{-1}$)
Basin 102	34173600	10.84	10.85	0.91	0.34
Basin 100	18455600	10.18	19.38	0.44	0.42
Basin 101	21798800	11.10	16.14	0.29	0.00
Basin 105	22664000	10.15	18.21	0.37	0.85
Basin 103	5693600	10.57	5.50	1.72	0.40
Basin 104	2698000	11.05	7.65	1.13	0.01
Basin 108	7193600	9.90	10.63	0.70	0.72
Basin 106	1385600	11.00	4.49	1.77	0.01
Basin 111	6736800	8.21	3.30	1.99	2.84
Basin 107	4627600	11.01	6.99	1.20	0.02
Basin 110	7072400	10.97	12.43	0.56	0.04
Basin 114	14030800	9.55	19.43	0.35	3.51
Basin 109	1521200	10.91	19.28	0.15	1.97
Basin 116	**13534000**	**10.71**	**9.47**	**0.88**	**0.06**
Basin 113	1596800	10.87	12.52	0.55	0.29
Basin 117	5762800	7.53	3.71	1.74	3.14
Basin 112	696400	11.09	10.89	0.60	0.00
Basin 115	4211200	10.75	16.08	0.34	3.72
Basin 151	41924400	7.20	13.21	0.51	0.74
Basin 118	1446400	4.46	3.06	1.31	11.51
Basin 123	7284400	10.24	13.57	0.50	0.25
Basin 152	2134800	2.88	1.44	1.58	24.37
Basin 150	5856800	4.34	3.60	1.14	9.35
Basin 146	3404000	9.18	7.73	0.99	0.32
Basin 126	**5440400**	**8.61**	**7.46**	**0.93**	**0.14**
Basin 134	**586400**	**3.35**	**1.80**	**1.35**	**7.47**
Basin 121	**3692400**	**7.48**	**5.50**	**1.09**	**3.13**
Basin 120	**729200**	**2.59**	**2.49**	**0.95**	**7.91**

Biomasses and masses in the marine Forsmark area, in g m^{-1} $year^{-1}$.

IDKOD	Phyto-plankton	Micro-phytes	Macro-phytes	Bacterio-plankton	Zoo-plank-ton	Benthic bacteria	Benthic herbi-vores	Benthic filterfeed-ers	Benthic detrivores	Benthic carni-vores	Benth-vorus fish	Zooplank-tivorus fish	Pis-civorus fish	Bird	Seal	DIC	DOC	POC	Sediment (top 10cm)
Basin 102	0.16	2.24	5.81	0.27	0.05	0.58	1.10	1.04	4.62	0.26	0.07	0.07	0.01	0.01	0.014	68.84	30.39	1.92	55.54
Basin 100	0.36	1.08	5.29	0.37	0.12	0.88	0.87	0.84	3.24	0.35	0.05	0.20	0.02	0.00	0.014	92.46	57.69	3.94	122.39
Basin 101	0.29	0.86	0.43	0.39	0.10	0.75	0.65	0.69	2.84	0.39	0.03	0.10	0.00	0.00	0.014	104.46	45.16	2.91	167.98
Basin 105	0.36	0.96	3.27	0.38	0.12	1.36	0.59	0.62	3.24	0.45	0.05	0.18	0.01	0.00	0.014	101.39	55.29	3.90	219.48
Basin 103	0.04	3.77	15.87	0.14	0.01	0.35	1.68	1.44	6.10	0.13	0.16	0.06	0.04	0.01	0.014	41.11	15.97	1.03	0.00
Basin 104	0.05	3.06	4.45	0.19	0.02	0.68	1.01	1.03	5.13	0.32	0.17	0.06	0.04	0.01	0.014	64.80	21.46	1.38	531.98
Basin 108	0.15	1.85	4.82	0.27	0.05	0.59	1.03	1.06	4.45	0.28	0.10	0.07	0.02	0.01	0.014	86.58	31.27	2.09	143.20
Basin 106	0.02	4.62	8.75	0.11	0.01	0.62	1.71	1.39	7.23	0.11	0.30	0.10	0.10	0.02	0.014	41.40	12.99	0.86	276.12
Basin 111	0.03	4.43	28.93	0.08	0.01	0.89	1.90	1.86	5.70	0.20	0.47	0.19	0.17	0.02	0.014	35.79	11.39	0.87	46.87
Basin 107	0.05	3.26	5.61	0.17	0.02	0.58	1.41	1.37	5.68	0.19	0.22	0.08	0.07	0.01	0.014	63.12	20.03	1.31	278.60
Basin 110	0.19	1.60	5.92	0.31	0.06	0.68	1.07	1.20	3.29	0.35	0.09	0.08	0.02	0.00	0.014	98.67	36.15	2.45	72.11
Basin 114	0.43	0.90	2.13	0.40	0.14	1.81	0.37	0.44	3.31	0.53	0.05	0.21	0.02	0.00	0.014	123.10	62.18	4.64	425.20
Basin 109	0.45	0.45	0.33	0.45	0.15	1.42	0.37	0.42	2.76	0.51	0.01	0.14	0.00	0.00	0.014	123.77	57.62	4.05	350.43
Basin 116	**0.12**	**2.37**	**11.07**	**0.24**	**0.04**	**0.82**	**1.31**	**1.47**	**3.85**	**0.33**	**0.19**	**0.10**	**0.06**	**0.01**	**0.014**	**83.73**	**28.35**	**1.97**	**126.91**
Basin 113	0.21	1.60	8.60	0.31	0.07	0.86	1.14	1.35	2.80	0.39	0.06	0.08	0.01	0.00	0.014	96.11	37.46	2.64	114.44
Basin 117	0.04	3.83	22.60	0.09	0.01	0.85	1.67	1.59	5.55	0.20	0.65	0.24	0.24	0.02	0.014	44.02	13.57	1.08	78.39
Basin 112	0.12	1.76	2.60	0.27	0.04	0.79	0.92	1.03	3.50	0.34	0.15	0.08	0.05	0.00	0.014	95.39	31.79	2.17	95.04
Basin 115	0.36	0.99	3.81	0.39	0.12	1.32	0.65	0.79	2.99	0.47	0.04	0.12	0.01	0.00	0.014	115.49	48.50	3.44	260.84
Basin 151	0.32	1.17	5.71	0.31	0.11	1.72	0.75	0.87	3.71	0.44	0.07	0.17	0.02	0.01	0.014	105.39	49.26	4.00	300.36
Basin 118	0.05	2.65	33.23	0.08	0.02	1.66	1.17	1.27	5.26	0.18	0.64	0.23	0.22	0.02	0.014	39.17	15.58	1.37	47.01
Basin 123	0.27	1.33	6.00	0.34	0.09	1.63	0.63	0.89	3.07	0.51	0.08	0.11	0.02	0.00	0.014	105.79	42.04	3.05	300.52
Basin 152	0.15	2.35	92.72	0.04	0.05	2.66	0.54	0.57	5.53	0.17	0.83	0.28	0.29	0.03	0.014	20.46	8.47	0.75	285.98
Basin 150	0.18	2.52	24.28	0.09	0.06	4.36	1.12	1.23	5.17	0.21	0.39	0.16	0.12	0.02	0.014	40.52	16.89	1.45	350.40
Basin 146	0.10	2.68	10.65	0.19	0.03	1.63	1.19	1.37	3.91	0.37	0.23	0.14	0.08	0.01	0.014	69.57	25.32	1.92	188.60
Basin 126	**0.10**	**2.56**	**8.21**	**0.19**	**0.03**	**1.74**	**1.14**	**1.27**	**4.26**	**0.34**	**0.21**	**0.15**	**0.08**	**0.01**	**0.014**	**68.23**	**25.71**	**2.01**	**186.01**
Basin 134	**0.03**	**3.28**	**22.28**	**0.05**	**0.01**	**3.74**	**0.81**	**0.72**	**6.89**	**0.15**	**0.09**	**0.11**	**0.03**	**0.02**	**0.014**	**19.33**	**11.04**	**0.95**	**313.91**
Basin 121	**0.06**	**2.91**	**15.21**	**0.14**	**0.02**	**2.43**	**1.00**	**1.17**	**4.38**	**0.33**	**0.31**	**0.16**	**0.11**	**0.01**	**0.014**	**55.31**	**20.05**	**1.59**	**165.01**
Basin 120	**0.05**	**2.50**	**23.48**	**0.06**	**0.02**	**2.09**	**1.08**	**1.04**	**5.93**	**0.17**	**0.49**	**0.14**	**0.13**	**0.02**	**0.014**	**31.92**	**17.24**	**1.46**	**52.68**

Net Primary production(NPP) and Net Ecosystem Production (NEP) in the marine Forsmark area, in g m^{-1} $year^{-1}$.

IDKOD	Benthic NPP	Macrophyte NPP	Microphyte NNP	Pelagic NPP	Total NPP	Total NEP	Benthic NEP	Pelagic NEP
Basin 102	96.85	68.02	28.83	16.63	113.48	45.84	65.66	–19.82
Basin 100	49.34	35.38	13.97	36.27	85.62	5.11	23.84	–18.74
Basin 101	13.60	2.60	11.01	29.67	43.28	–33.61	–9.29	–24.32
Basin 105	36.10	23.70	12.40	36.59	72.69	–10.92	7.89	–18.80
Basin 103	248.72	200.25	48.48	4.37	253.09	195.42	209.44	–14.02
Basin 104	93.78	54.37	39.41	5.48	99.26	38.84	57.67	–18.83
Basin 108	52.09	28.20	23.89	15.19	67.28	–0.68	19.83	–20.51
Basin 106	186.45	126.81	59.64	2.30	188.75	125.37	138.36	–12.99
Basin 111	284.76	227.58	57.18	2.88	287.64	224.47	235.31	–10.84
Basin 107	101.21	59.14	42.08	4.85	106.06	43.10	61.05	–17.95
Basin 110	40.29	19.69	20.60	19.62	59.91	–11.11	11.28	–22.39
Basin 114	34.13	22.47	11.65	43.03	77.16	–13.49	2.79	–16.28
Basin 109	7.00	1.17	5.83	46.11	53.11	–37.88	–17.98	–19.90
Basin 116	**83.32**	**52.77**	**30.54**	**11.72**	**95.04**	**27.95**	**48.12**	**–20.17**
Basin 113	38.41	17.88	20.53	21.31	59.72	–11.52	9.78	–21.30
Basin 117	230.97	181.46	49.51	4.01	234.98	170.21	182.40	–12.19
Basin 112	32.10	9.58	22.52	12.17	44.27	–21.84	1.75	–23.59
Basin 115	25.02	12.27	12.75	35.96	60.98	–23.65	–3.90	–19.75
Basin 151	61.92	46.65	15.27	32.24	94.17	11.17	24.91	–13.74
Basin 118	191.96	157.42	34.54	4.78	196.74	130.24	139.72	–9.48
Basin 123	46.28	29.16	17.12	27.65	73.93	–6.91	13.00	–19.91
Basin 152	207.81	177.18	30.63	14.72	222.53	147.92	147.01	0.91
Basin 150	115.04	82.32	32.72	17.97	133.01	41.28	41.56	–0.28
Basin 146	95.22	60.53	34.70	10.49	105.72	36.52	53.01	–16.49
Basin 126	**80.93**	**47.79**	**33.14**	**9.92**	**90.85**	**20.94**	**37.18**	**–16.23**
Basin 134	**117.64**	**74.73**	**42.91**	**2.95**	**120.59**	**45.33**	**49.80**	**–4.47**
Basin 121	**98.56**	**60.79**	**37.76**	**6.52**	**105.08**	**34.07**	**47.68**	**–13.61**
Basin 120	**92.15**	**59.57**	**32.58**	**4.77**	**96.92**	**28.42**	**34.70**	**–6.28**

Respiration in the marine Forsmark area, in g m^{-1} year^{-1}.

IDKOD	Benthic respiration	Pelagic respiration	Total respiration
Basin 102	31.20	36.45	67.65
Basin 100	25.50	55.01	80.51
Basin 101	22.89	53.99	76.88
Basin 105	28.21	55.39	83.60
Basin 103	39.28	18.39	57.67
Basin 104	36.11	24.32	60.43
Basin 108	32.25	35.71	67.96
Basin 106	48.09	15.29	63.38
Basin 111	49.44	13.73	63.17
Basin 107	40.16	22.80	62.96
Basin 110	29.01	42.01	71.02
Basin 114	31.34	59.31	90.65
Basin 109	24.98	66.01	90.99
Basin 116	**35.19**	**31.89**	**67.08**
Basin 113	28.63	42.61	71.24
Basin 117	48.57	16.20	64.77
Basin 112	30.35	35.76	66.11
Basin 115	28.92	55.71	84.63
Basin 151	37.01	45.98	82.99
Basin 118	52.25	14.26	66.50
Basin 123	33.28	47.56	80.84
Basin 152	60.80	13.81	74.61
Basin 150	73.48	18.25	91.73
Basin 146	42.21	26.98	69.19
Basin 126	**43.75**	**26.15**	**69.91**
Basin 134	**67.84**	**7.42**	**75.26**
Basin 121	**50.88**	**20.13**	**71.00**
Basin 120	**57.44**	**11.05**	**68.49**

Consumption in the marine Forsmark area, in g m^{-1} year^{-1}.

IDKOD	Cons. of phyto-plankton	Cons. of micro-phytes	Cons. of macro-phytes	Cons. Of bacterio-plankton	Cons. Of zoo-plank-ton	Cons. Of benthic bacteria	Cons. Of benthic herbi-vores	Cons. of benthic filter feeders	Cons. of benthic det-rivores and meiofauna	Cons. of benthic carnivores	Cons. of benthi-vorus fish	Cons. of zooplank-tivorous fish	Cons. of piscivo-rous fish	Cons. of burial (sedi-ment)	Cons. of DOC	Cons. of POC
Basin 102	5.51	5.44	5.55	8.42	0.55	0.42	0.33	0.43	2.18	0.01	1.63	0.31	0.06	36.74	66.54	13.27
Basin 100	13.67	4.22	4.15	14.16	1.37	0.34	0.41	0.42	2.49	0.01	2.25	0.43	0.05	27.18	91.60	13.18
Basin 101	10.08	4.35	1.73	12.86	0.77	0.07	0.31	0.49	2.77	0.01	0.87	0.27	0.00	26.18	94.74	11.55
Basin 105	13.68	2.74	3.04	14.06	1.21	0.27	0.27	0.42	3.41	0.02	1.45	0.40	0.04	26.30	92.11	11.75
Basin 103	1.20	6.02	11.63	4.17	0.51	1.07	0.56	0.50	1.79	0.02	2.58	0.50	0.18	40.27	35.17	15.76
Basin 104	1.21	5.21	5.45	4.42	0.50	0.41	0.26	0.65	3.55	0.08	1.71	0.38	0.13	38.98	46.34	12.78
Basin 108	4.73	4.78	5.90	8.07	0.66	0.50	0.35	0.56	2.62	0.04	1.66	0.45	0.07	40.01	64.68	13.78
Basin 106	0.61	8.58	10.07	3.17	0.79	0.85	0.61	0.52	2.85	0.03	3.64	0.78	0.30	49.31	27.48	15.54
Basin 111	1.15	4.61	17.02	3.63	1.61	1.35	1.18	1.25	3.67	0.10	5.13	1.39	0.27	33.24	21.81	20.96
Basin 107	1.19	7.56	7.41	4.49	0.70	0.45	0.46	0.61	2.60	0.06	2.11	0.55	0.16	46.03	42.60	15.99
Basin 110	6.39	4.37	6.55	9.87	0.72	0.34	0.49	0.77	2.72	0.04	1.08	0.39	0.05	31.34	74.99	15.88
Basin 114	16.78	1.61	2.12	15.37	1.43	0.29	0.16	0.40	4.35	0.03	3.32	0.42	0.04	25.70	95.47	10.90
Basin 109	17.42	1.99	1.30	17.03	0.99	0.12	0.18	0.35	3.71	0.01	2.50	0.28	0.00	23.12	108.95	10.79
Basin 116	**3.49**	**4.32**	**9.62**	**7.27**	**0.85**	**0.62**	**0.60**	**0.93**	**3.10**	**0.08**	**1.91**	**0.59**	**0.13**	**33.71**	**57.41**	**17.84**
Basin 113	7.13	3.41	7.98	10.46	0.69	0.34	0.52	0.84	2.68	0.02	0.97	0.34	0.04	26.46	75.28	17.31
Basin 117	1.42	5.53	14.20	3.54	1.95	1.39	1.33	1.39	4.78	0.17	6.08	1.71	0.30	37.47	22.88	18.21
Basin 112	3.22	5.29	4.14	7.32	0.72	0.18	0.44	0.77	3.18	0.09	1.15	0.46	0.08	32.79	65.82	13.85
Basin 115	13.36	2.43	4.01	14.19	0.89	0.30	0.27	0.57	3.61	0.02	1.20	0.32	0.02	26.12	93.51	13.47
Basin 151	12.69	1.93	6.29	12.03	1.26	0.75	0.32	0.60	3.84	0.02	3.69	0.53	0.06	30.04	74.37	14.09
Basin 118	1.78	3.39	11.31	2.95	1.86	1.99	1.04	1.17	5.20	0.12	6.35	1.63	0.35	36.77	18.67	15.00
Basin 123	9.79	1.70	4.84	11.75	0.88	0.44	0.25	0.79	4.11	0.05	1.42	0.42	0.05	24.11	81.22	13.81
Basin 152	9.62	0.19	8.25	2.42	2.54	2.91	0.70	0.75	7.30	0.17	8.43	2.14	0.46	31.98	8.77	5.71
Basin 150	10.24	3.49	10.09	4.92	1.63	1.74	0.71	0.87	4.11	0.11	5.47	1.19	0.26	21.64	22.09	12.83
Basin 146	3.31	3.60	9.34	6.20	1.15	0.66	0.60	1.01	3.85	0.11	2.45	0.86	0.16	26.70	46.63	16.52
Basin 126	**3.00**	**4.32**	**8.02**	**5.88**	**1.17**	**0.64**	**0.50**	**0.89**	**3.68**	**0.11**	**2.39**	**0.90**	**0.16**	**31.44**	**45.29**	**15.65**
Basin 134	**1.04**	**1.72**	**8.56**	**1.72**	**0.88**	**2.01**	**0.29**	**0.28**	**2.64**	**0.03**	**8.93**	**1.76**	**0.16**	**30.44**	**11.67**	**8.26**
Basin 121	**1.93**	**2.94**	**8.56**	**4.28**	**1.30**	**1.09**	**0.56**	**0.97**	**4.28**	**0.17**	**3.78**	**1.17**	**0.22**	**26.25**	**33.64**	**14.14**
Basin 120	**1.85**	**1.62**	**12.29**	**2.49**	**1.15**	**2.12**	**0.78**	**0.76**	**4.85**	**0.09**	**5.05**	**0.98**	**0.33**	**43.57**	**15.23**	**12.29**

Appendix 8b

Results generated in GIS-models for marine ecosystem, in gC m^{-2} year^{-1} for functional groups, abiotic pools and fluxes – Laxemar-Simpevarp.

Physical parameters in the marine Laxemar-Simpevarp area, depths and areas in m and m^2 respectively.

IDKOD	AREA (m2)	secchi	Depth	Medel PAR	Burial (gC m^{-2} year^{-1})
Basin 524	14680400	10 .9	11 .59	0 .810	0 .0
Basin 525	15211200	9 .8	6 .92	1 .413	0 .0
Basin 522	13567200	11 .1	15 .93	0 .382	0 .0
Basin 523	13933600	11 .1	11 .53	0 .697	0 .0
Basin 521	**38044800**	**9 .6**	**11 .15**	**0 .873**	**0 .6**
Basin 501	334800	1 .5	3 .17	0 .837	21 .6
Basin 500	2906000	1 .9	1 .95	1 .692	9 .8
Basin 504	**608000**	**1 .5**	**3 .55**	**1 .019**	**23 .9**
Basin 502	**1126800**	**1 .7**	**4 .83**	**0 .624**	**45 .7**
Basin 506	**334400**	**1 .6**	**3 .28**	**0 .744**	**7 .4**
Basin 508	**1374800**	**1 .6**	**1 .72**	**1 .078**	**34 .8**
Basin 513	4062800	7 .6	4 .28	1 .856	2 .1
Basin 514	952000	9 .2	4 .48	2 .053	0 .0
Basin 516	482000	1 .6	0 .10	3 .362	0 .0
Basin 518	758800	8 .4	3 .72	2 .185	0 .0
Basin 515	869600	2 .9	3 .25	1 .068	24 .0
Basin 517	6686000	4 .4	3 .53	1 .741	12 .1
Basin 520	2269200	4 .4	2 .44	2 .351	0 .0
Basin 519	590400	1 .6	0 .22	3 .383	0 .0

Biomasses and masses in the marine Laxemar-Simpevarp area, in g m^{-1} year^{-1}.

IDKOD	Phyto-plankton	Micro-phytes	Macro-phytes	Bacteri-oplank-ton	Zoo-plank-ton	Benthic bacteria	Benthic herbi-vores	Benthic filter-feeders	Benthic detriv-ores	Benthic carni-vores	Benth-vorus fish	Zoo-plank-tivorus fish	Pis-civorus fish	Bird	Seal	DIC	DOC	POC	Sediment (top 10cm)
Basin 524	0.25	1.25	25.88	0.29	0.083	1.700	4.20	52.16	10.87	0.28	0.22	0.422	0.016	0.002	0.0046	184.69	45.64	1.76	8.27
Basin 525	0.14	2.18	38.01	0.17	0.045	0.706	5.51	69.13	10.01	0.32	0.24	0.405	0.031	0.006	0.0046	111.52	27.93	1.12	3.26
Basin 522	0.36	0.59	14.72	0.38	0.121	1.089	2.79	36.73	7.24	0.16	0.20	0.424	0.014	0.000	0.0046	252.00	62.27	2.40	109.15
Basin 523	0.23	1.08	23.71	0.29	0.076	0.563	4.42	60.54	8.81	0.21	0.21	0.424	0.014	0.001	0.0046	182.54	45.11	1.74	22.13
Basin 521	**0.26**	**1.35**	**26.89**	**0.26**	**0.088**	**1.142**	**3.64**	**45.06**	**7.77**	**0.26**	**0.22**	**0.398**	**0.036**	**0.004**	**0.0046**	**179.19**	**45.15**	**1.83**	**91.08**
Basin 501	0.14	1.29	34.60	0.08	0.048	4.204	1.72	5.29	2.02	0.70	0.42	0.147	0.253	0.014	0.0046	49.30	23.01	1.94	257.92
Basin 500	0.09	2.61	32.37	0.05	0.029	3.138	2.08	4.97	2.23	0.68	0.31	0.147	0.253	0.016	0.0046	32.37	15.11	1.27	139.04
Basin 504	**0.18**	**1.57**	**37.26**	**0.09**	**0.060**	**4.271**	**1.69**	**3.64**	**2.30**	**0.71**	**0.33**	**0.147**	**0.253**	**0.014**	**0.0046**	**57.74**	**26.95**	**2.27**	**292.25**
Basin 502	**0.23**	**0.96**	**29.06**	**0.12**	**0.078**	**5.729**	**1.49**	**3.89**	**2.43**	**0.70**	**0.33**	**0.147**	**0.253**	**0.012**	**0.0046**	**74.61**	**34.83**	**2.93**	**496.70**
Basin 506	**0.16**	**1.15**	**33.46**	**0.08**	**0.054**	**4.615**	**1.69**	**4.94**	**2.17**	**0.69**	**0.37**	**0.148**	**0.252**	**0.015**	**0.0046**	**52.17**	**24.33**	**2.05**	**252.08**
Basin 508	**0.15**	**1.66**	**68.31**	**0.04**	**0.049**	**4.970**	**1.53**	**3.81**	**2.29**	**0.86**	**0.40**	**0.147**	**0.253**	**0.020**	**0.0046**	**27.05**	**12.62**	**1.06**	**396.07**
Basin 513	0.09	2.86	59.58	0.11	0.031	1.266	5.26	53.21	8.25	0.48	0.27	0.339	0.088	0.012	0.0046	72.01	19.10	0.86	72.42
Basin 514	0.09	3.17	76.68	0.11	0.030	0.874	6.42	64.68	9.78	0.47	0.28	0.405	0.030	0.012	0.0046	74.80	18.70	0.74	47.44
Basin 516	0.01	5.19	55.29	0.00	0.002	0.650	3.43	3.61	1.75	0.87	0.29	0.147	0.253	0.017	0.0046	2.72	1.27	0.11	0.00
Basin 518	0.07	3.37	64.27	0.09	0.024	1.068	6.25	63.30	10.46	0.49	0.27	0.384	0.048	0.012	0.0046	62.63	15.63	0.62	59.84
Basin 515	0.13	1.65	17.05	0.08	0.043	4.219	1.59	6.50	2.72	0.47	0.21	0.147	0.253	0.015	0.0046	49.86	23.28	1.96	279.39
Basin 517	0.12	2.69	27.94	0.09	0.041	2.436	2.64	17.58	3.39	0.46	0.23	0.201	0.206	0.012	0.0046	56.92	23.13	1.77	176.47
Basin 520	0.08	3.63	37.17	0.06	0.025	0.459	3.54	30.30	3.84	0.47	0.26	0.271	0.146	0.009	0.0046	44.65	13.72	0.79	0.00
Basin 519	0.01	5.22	45.54	0.01	0.003	0.650	3.32	4.07	1.84	0.86	0.31	0.147	0.253	0.011	0.0046	3.93	1.84	0.15	0.00

Net Primary production(NPP) and Net Ecosystem Production (NEP) in the marine Laxemar-Simpevarp area, in g m^{-1} year^{-1}.

IDKOD	Benthic NPP	Macrophyte NPP	Microphyte NNP	Pelagic NPP	Total NPP	Total NEP	Benthic NEP	Pelagic NEP
Basin 524	121 .63	106 .06	16 .12	24 .42	146 .2	–206 .28	–123 .65	–18 .33
Basin 525	191 .11	164 .33	28 .12	13 .24	204 .6	–282 .29	–130 .89	–13 .07
Basin 522	63 .49	55 .88	7 .61	35 .64	99 .1	–155 .29	–91 .22	–21 .04
Basin 523	102 .53	88 .68	13 .87	22 .29	124 .8	–274 .99	–151 .43	–19 .46
Basin 521	**126 .87**	**110 .67**	**17 .37**	**25 .91**	**153 .1**	**–179 .56**	**–82 .26**	**–15 .33**
Basin 501	100 .36	88 .11	16 .65	14 .16	115 .1	15 .36	13 .92	–2 .81
Basin 500	233 .26	205 .76	33 .67	8 .46	242 .5	153 .75	153 .36	–2 .79
Basin 504	**138 .72**	**124 .43**	**20 .27**	**17 .71**	**157 .5**	**58 .44**	**56 .61**	**–2 .17**
Basin 502	**75 .39**	**67 .06**	**12 .42**	**23 .00**	**99 .1**	**–16 .29**	**–18 .76**	**–2 .35**
Basin 506	**69 .93**	**60 .37**	**14 .81**	**15 .88**	**86 .6**	**–20 .01**	**–22 .06**	**–2 .42**
Basin 508	**177 .77**	**161 .00**	**21 .46**	**14 .35**	**192 .8**	**87 .11**	**81 .15**	**1 .34**
Basin 513	298 .92	264 .64	36 .94	8 .97	308 .3	–75 .96	22 .95	–9 .16
Basin 514	365 .91	326 .84	40 .85	8 .83	375 .1	–70 .90	34 .54	–9 .60
Basin 516	707 .17	641 .74	66 .91	0 .65	707 .9	651 .92	652 .30	–2 .12
Basin 518	347 .26	306 .12	43 .48	7 .03	354 .7	–80 .02	13 .36	–8 .60
Basin 515	128 .19	109 .82	21 .25	12 .60	141 .1	35 .28	35 .60	–3 .54
Basin 517	239 .01	208 .56	34 .65	12 .08	251 .8	82 .03	114 .93	–4 .83
Basin 520	329 .55	290 .21	46 .79	7 .47	338 .2	72 .38	170 .21	–5 .07
Basin 519	607 .44	543 .04	67 .32	0 .94	608 .5	550 .28	550 .75	–2 .19

Respiration in the marine Laxemar-Simpevarp area, in g m^{-1} year^{-1}.

IDKOD	Benthic respiration	Pelagic respiration	Total respiration
Basin 524	309 .58	42 .90	352 .48
Basin 525	460 .33	26 .53	486 .86
Basin 522	197 .74	56 .69	254 .42
Basin 523	358 .06	41 .76	399 .82
Basin 521	**291 .07**	**41 .55**	**332 .63**
Basin 501	82 .19	17 .50	99 .69
Basin 500	76 .72	12 .07	88 .79
Basin 504	**78 .11**	**20 .96**	**99 .07**
Basin 502	**89 .33**	**26 .03**	**115 .36**
Basin 506	**87 .53**	**19 .08**	**106 .60**
Basin 508	**92 .00**	**13 .65**	**105 .65**
Basin 513	365 .72	18 .55	384 .27
Basin 514	427 .21	18 .77	445 .98
Basin 516	53 .13	2 .88	56 .01
Basin 518	418 .69	16 .04	434 .73
Basin 515	89 .37	16 .45	105 .82
Basin 517	152 .15	17 .67	169 .82
Basin 520	252 .11	13 .75	265 .86
Basin 519	54 .96	3 .28	58 .25

Consumption in the marine Laxemar-Simpevarp area, in g m^{-1} $year^{-1}$.

IDKOD	Cons. of phyto-plankton	Cons. of micro-phytes	Cons. of macro-phytes	Cons. Of bacterio-plankton	Cons. Of zooplank-ton	Cons. Of benthic bacteria	Cons. Of benthic herbi-vores	Cons. of benthic filter feeders	Cons. of benthic detrivores and mei-ofauna	Cons. of benthic carni-vores	Cons. of benthi-vorus fish	Cons. of zooplank-tivorous fish	Cons. of piscivo-rous fish	Cons. of burial (sediment)	Cons. of DOC	Cons. of POC
Basin 524	701	2 .0	42	1,006	233	120	0 .3	3 .5	0 .9	0 .01	0 .4	0 .2	0 .00	32	70	1 .8
Basin 525	1,036	3 .3	60	1,451	346	124	0 .6	4 .8	1 .0	0 .02	1 .2	0 .4	0 .01	13	44	1 .2
Basin 522	489	1 .0	26	653	160	44	0 .2	2 .1	0 .6	0 .005	0 .1	0 .1	0 .003	47	91	2 .3
Basin 523	763	2 .0	43	1,151	254	88	0 .2	3 .1	0 .5	0 .004	0 .2	0 .2	0 .003	21	70	1 .8
Basin 521	**680**	**1 .9**	**39**	**881**	**225**	**66**	**0 .5**	**3 .5**	**0 .9**	**0 .02**	**0 .9**	**0 .3**	**0 .01**	**43**	**66**	**1 .7**
Basin 501	58	0 .8	22	34	18	13	2 .6	7 .2	3 .1	0 .29	3 .6	0 .8	0 .04	106	20	1 .4
Basin 500	52	2 .0	27	31	16	17	3 .3	6 .0	3 .3	0 .24	4 .4	1 .1	0 .05	87	14	1 .0
Basin 504	**48**	**0 .7**	**22**	**27**	**13**	**16**	**2 .8**	**5 .4**	**4 .0**	**0 .29**	**3 .5**	**1 .0**	**0 .05**	**107**	**24**	**1 .7**
Basin 502	**51**	**0 .4**	**19**	**29**	**13**	**9**	**2 .4**	**5 .4**	**3 .8**	**0 .28**	**3 .1**	**1 .0**	**0 .05**	**142**	**31**	**2 .2**
Basin 506	**61**	**0 .6**	**22**	**37**	**18**	**12**	**2 .6**	**6 .4**	**3 .5**	**0 .30**	**3 .7**	**1 .0**	**0 .05**	**122**	**22**	**1 .6**
Basin 508	**74**	**0 .7**	**21**	**25**	**22**	**13**	**3 .2**	**6 .5**	**5 .3**	**0 .46**	**4 .6**	**1 .0**	**0 .05**	**137**	**11**	**0 .7**
Basin 513	781	3 .1	62	1,116	262	84	1 .4	6 .4	1 .8	0 .07	2 .6	0 .7	0 .02	53	29	0 .8
Basin 514	1,011	3 .4	77	1,426	339	94	1 .0	7 .2	1 .5	0 .03	2 .2	0 .7	0 .01	55	29	0 .8
Basin 516	37	4 .2	45	22	13	27	6 .2	6 .3	3 .3	0 .30	4 .8	1 .2	0 .05	14	1	0 .1
Basin 518	992	4 .1	74	1,414	333	86	1 .4	6 .9	1 .7	0 .05	2 .2	0 .7	0 .01	80	25	0 .6
Basin 515	60	1 .6	20	40	18	13	1 .6	4 .9	2 .6	0 .11	4 .6	1 .3	0 .06	115	20	1 .5
Basin 517	302	2 .7	32	301	99	31	1 .9	5 .1	2 .0	0 .09	3 .6	1 .1	0 .05	66	25	1 .5
Basin 520	726	3 .6	43	697	242	54	2 .4	5 .6	1 .6	0 .11	2 .8	0 .8	0 .03	9	22	0 .8
Basin 519	42	4 .7	43	27	15	28	5 .9	6 .4	3 .3	0 .28	3 .7	1 .0	0 .05	14	3	0 .2

Appendix 9a

Results for mass balance calculations for carbon, nitrogen, phosphorus, thorium, uranium and iodine in all marine basins – Forsmark.

Pools and fluxes per basin and year for carbon (C) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_ drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_ upper	Particulate	Dissolved
Basin 102	8.23E+07	4.33E+11	3.88E+09	4.30E+07	4.36E+11	2.31E+09	1.15E+07	2.80E+08	2.76E+08	1.90E+09	6.57E+07	1.04E+09
Basin 100	1.17E+07	8.32E+11	1.58E+09	2.32E+07	8.71E+11	1.49E+09	7.82E+06	1.24E+08	1.28E+08	2.26E+09	7.28E+07	1.06E+09
Basin 101	0.00E+00	6.18E+11	9.43E+08	2.74E+07	5.95E+11	1.68E+09	0.00E+00	3.44E+07	1.29E+08	3.66E+09	6.34E+07	9.84E+08
Basin 105	1.33E+07	7.41E+11	1.65E+09	2.85E+07	7.64E+11	1.89E+09	1.93E+07	1.04E+08	1.59E+08	4.97E+09	8.83E+07	1.25E+09
Basin 103	1.66E+06	9.43E+10	1.44E+09	7.16E+06	9.72E+10	3.28E+08	2.26E+06	1.12E+08	5.76E+07	0.00E+00	5.88E+06	9.10E+07
Basin 104	1.23E+05	7.10E+10	2.68E+08	3.39E+06	7.06E+10	1.63E+08	3.99E+04	2.04E+07	2.34E+07	1.44E+09	3.73E+06	5.79E+07
Basin 108	1.06E+06	1.83E+11	4.84E+08	9.05E+06	1.89E+11	4.89E+08	5.17E+06	4.91E+07	5.69E+07	1.03E+09	1.50E+07	2.25E+08
Basin 106	1.17E+05	2.68E+10	2.62E+08	1.74E+06	2.67E+10	8.78E+07	1.00E+04	1.86E+07	1.62E+07	3.83E+08	1.19E+06	1.80E+07
Basin 111	3.20E+07	1.07E+10	1.94E+09	8.47E+06	1.25E+10	4.26E+08	1.92E+07	2.25E+08	7.75E+07	3.16E+08	5.84E+06	7.67E+07
Basin 107	5.57E+05	6.82E+10	4.91E+08	5.82E+06	6.66E+10	2.91E+08	1.10E+05	4.13E+07	4.54E+07	1.29E+09	6.08E+06	9.27E+07
Basin 110	2.63E+05	2.79E+11	4.24E+08	8.90E+06	2.72E+11	5.02E+08	2.72E+05	5.45E+07	5.07E+07	5.10E+08	1.73E+07	2.56E+08
Basin 114	1.32E+07	5.30E+11	1.08E+09	1.76E+07	5.31E+11	1.27E+09	4.93E+07	4.85E+07	1.02E+08	5.97E+09	6.51E+07	8.72E+08
Basin 109	1.38E+04	1.48E+11	8.08E+07	1.91E+06	1.43E+11	1.38E+08	3.00E+06	1.88E+06	9.48E+06	5.33E+08	6.16E+06	8.76E+07
Basin 116	**1.31E+06**	**1.66E+11**	**1.29E+09**	**1.70E+07**	**1.67E+11**	**9.08E+08**	**8.70E+05**	**1.83E+08**	**1.14E+08**	**1.72E+09**	**2.67E+07**	**3.84E+08**
Basin 113	0.00E+00	1.40E+11	9.54E+07	2.01E+06	1.40E+11	1.14E+08	4.68E+05	1.66E+07	1.13E+07	1.83E+08	4.21E+06	5.98E+07
Basin 117	2.75E+07	6.42E+09	1.35E+09	7.25E+06	6.99E+09	3.73E+08	1.81E+07	1.53E+08	6.40E+07	4.52E+08	6.24E+06	7.82E+07
Basin 112	0.00E+00	4.14E+10	3.08E+07	8.76E+05	4.09E+10	4.60E+07	0.00E+00	3.12E+06	5.00E+06	6.62E+07	1.51E+06	2.21E+07
Basin 115	1.27E+04	2.46E+11	2.57E+08	5.30E+06	2.39E+11	3.56E+08	1.57E+07	2.17E+07	2.91E+07	1.10E+09	1.45E+07	2.04E+08
Basin 151	1.31E+08	2.45E+11	3.95E+09	5.27E+07	2.95E+11	3.48E+09	3.12E+07	3.02E+08	3.42E+08	1.26E+10	1.68E+08	2.07E+09
Basin 118	1.46E+06	8.77E+08	2.85E+08	1.82E+06	1.26E+09	9.62E+07	1.66E+07	5.20E+07	1.55E+07	6.80E+07	1.99E+06	2.25E+07
Basin 123	1.16E+06	3.06E+11	5.39E+08	9.16E+06	2.77E+11	5.89E+08	1.84E+06	5.55E+07	5.37E+07	2.19E+09	2.22E+07	3.06E+08
Basin 152	3.38E+09	4.30E+08	4.75E+08	2.69E+06	2.58E+09	1.59E+08	5.20E+07	2.03E+08	2.34E+07	6.11E+08	1.59E+06	1.81E+07
Basin 150	2.97E+07	1.29E+10	7.79E+08	7.37E+06	1.70E+10	5.37E+08	5.48E+07	1.59E+08	7.58E+07	2.05E+09	8.49E+06	9.89E+07
Basin 146	1.00E+06	8.63E+10	3.60E+08	4.28E+06	8.17E+10	2.36E+08	1.07E+06	4.57E+07	3.12E+07	6.42E+08	6.53E+06	8.62E+07
Basin 126	**4.43E+06**	**7.54E+10**	**4.94E+08**	**6.84E+06**	**8.25E+10**	**3.80E+08**	**7.46E+05**	**5.91E+07**	**5.12E+07**	**1.01E+09**	**1.09E+07**	**1.40E+08**
Basin 134	**6.05E+06**	**3.13E+06**	**7.07E+07**	**7.38E+05**	**4.32E+06**	**4.41E+07**	**4.38E+06**	**1.53E+07**	**7.41E+06**	**1.84E+08**	**5.57E+05**	**6.47E+06**
Basin 121	**5.54E+07**	**2.71E+10**	**3.88E+08**	**4.64E+06**	**2.93E+10**	**2.62E+08**	**1.15E+07**	**6.73E+07**	**3.71E+07**	**6.09E+08**	**5.86E+06**	**7.40E+07**
Basin 120	**3.34E+07**	**8.95E+07**	**7.07E+07**	**9.17E+05**	**9.47E+07**	**4.99E+07**	**5.77E+06**	**1.90E+07**	**8.16E+06**	**3.84E+07**	**1.07E+06**	**1.26E+07**
Allbasins	**3.83E+09**	**5.39E+12**	**2.50E+10**	**3.10E+08**	**5.46E+12**	**1.87E+10**	**3.33E+08**	**2.47E+09**	**2.00E+09**	**4.78E+10**	**6.96E+08**	**9.70E+09**

Pools and fluxes per basin and year for nitrogen (N) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 102	3.44E+06	4.97E+10	6.83E+08	1.23E+07	6.90E+10	4.07E+08	1.32E+06	2.19E+07	2.76E+07	2.18E+08	8.90E+01	1.98E+02
Basin 100	0.00E+00	9.95E+10	2.78E+08	6.64E+06	1.29E+11	2.62E+08	8.97E+05	9.19E+06	1.47E+07	2.59E+08	2.24E+07	4.97E+07
Basin 101	9.80E+06	8.62E+10	1.66E+08	7.85E+06	9.44E+10	2.95E+08	0.00E+00	3.52E+06	1.47E+07	4.20E+08	2.16E+07	4.80E+07
Basin 105	9.49E+05	1.11E+11	2.90E+08	8.16E+06	1.11E+11	3.34E+08	2.22E+06	8.14E+06	1.92E+07	5.71E+08	2.11E+07	4.69E+07
Basin 103	4.13E+05	1.48E+10	2.54E+08	2.05E+06	1.48E+10	5.78E+07	2.59E+05	8.14E+06	5.42E+06	0.00E+00	2.49E+07	5.52E+07
Basin 104	4.16E+06	1.11E+10	4.72E+07	9.71E+05	1.11E+10	2.87E+07	4.58E+03	1.73E+06	2.38E+06	1.65E+08	1.91E+06	4.24E+06
Basin 108	2.15E+05	2.84E+10	8.52E+07	2.59E+06	2.84E+10	8.61E+07	5.93E+05	3.83E+06	5.78E+06	1.18E+08	1.24E+06	2.76E+06
Basin 106	7.27E+05	4.08E+09	4.61E+07	4.99E+05	4.08E+09	1.55E+07	1.15E+03	1.50E+06	1.59E+06	4.39E+07	4.62E+06	1.03E+07
Basin 111	1.14E+06	1.58E+09	3.41E+08	2.43E+06	1.59E+09	7.49E+07	2.20E+06	1.56E+07	8.24E+06	3.62E+07	3.76E+05	8.35E+05
Basin 107	2.29E+05	1.03E+10	8.64E+07	1.67E+06	1.03E+10	5.13E+07	1.26E+04	3.39E+06	4.50E+06	1.48E+08	1.38E+06	3.06E+06
Basin 110	1.08E+06	4.13E+10	7.46E+07	2.55E+06	4.13E+10	8.85E+07	3.12E+04	4.08E+06	5.44E+06	5.85E+07	1.95E+06	4.34E+06
Basin 114	2.83E+06	7.28E+10	1.91E+08	5.05E+06	7.28E+10	2.24E+08	5.66E+06	4.05E+06	1.30E+07	6.85E+08	5.29E+06	1.17E+07
Basin 109	0.00E+00	2.12E+10	1.42E+07	5.48E+05	2.12E+10	2.44E+07	3.44E+05	1.95E+05	1.20E+06	6.12E+07	1.64E+07	3.65E+07
Basin 116	**0.00E+00**	**2.36E+10**	**2.27E+08**	**4.87E+06**	**2.46E+10**	**1.60E+08**	**9.98E+04**	**1.32E+07**	**1.22E+07**	**1.97E+08**	**1.76E+06**	**3.91E+06**
Basin 113	2.85E+06	2.06E+10	1.68E+07	5.75E+05	2.06E+10	2.00E+07	5.37E+04	1.19E+06	1.24E+06	2.10E+07	7.73E+06	1.72E+07
Basin 117	6.33E+05	7.98E+08	2.38E+08	2.07E+06	8.35E+08	6.57E+07	2.08E+06	1.07E+07	7.13E+06	5.18E+07	1.20E+06	2.66E+06
Basin 112	2.12E+06	6.18E+09	5.43E+06	2.51E+05	6.18E+09	8.11E+06	0.00E+00	2.65E+05	5.47E+05	7.60E+06	1.31E+06	2.91E+06
Basin 115	2.42E+06	3.49E+10	4.52E+07	1.52E+06	3.49E+10	6.28E+07	1.80E+06	1.66E+06	3.47E+06	1.26E+08	4.55E+05	1.01E+06
Basin 151	3.01E+05	3.40E+10	6.95E+08	1.51E+07	3.45E+10	6.13E+08	3.58E+06	2.22E+07	4.08E+07	1.45E+09	4.06E+06	9.02E+06
Basin 118	1.55E+06	1.05E+08	5.01E+07	5.21E+05	8.20E+07	1.69E+07	1.91E+06	3.44E+06	1.83E+06	7.80E+06	3.37E+07	7.48E+07
Basin 123	2.10E+06	3.84E+10	9.48E+07	2.62E+06	3.93E+10	1.04E+08	2.12E+05	4.08E+06	6.51E+06	2.51E+08	1.79E+05	3.13E+05
Basin 152	1.16E+06	5.91E+07	8.37E+07	7.69E+05	1.90E+08	2.80E+07	5.97E+06	1.29E+07	3.04E+06	7.01E+07	5.96E+06	1.32E+07
Basin 150	1.09E+06	1.57E+09	1.37E+08	2.11E+06	2.34E+09	9.46E+07	6.28E+06	1.07E+07	9.65E+06	2.36E+08	1.89E+05	4.19E+05
Basin 146	2.94E+05	1.06E+10	6.34E+07	1.23E+06	1.09E+10	4.15E+07	1.23E+05	3.36E+06	3.60E+06	7.37E+07	1.88E+06	4.53E+06
Basin 126	**5.74E+05**	**9.53E+09**	**8.70E+07**	**1.96E+06**	**7.78E+09**	**6.70E+07**	**8.55E+04**	**4.46E+06**	**5.87E+06**	**1.16E+08**	**1.59E+06**	**3.54E+06**
Basin 134	**2.35E+06**	**2.33E+05**	**1.25E+07**	**2.11E+05**	**3.66E+05**	**7.77E+06**	**5.03E+05**	**1.04E+06**	**8.57E+05**	**2.11E+07**	**2.48E+06**	**2.48E+06**
Basin 121	**1.37E+07**	**3.50E+09**	**6.83E+07**	**1.33E+06**	**2.18E+09**	**4.62E+07**	**1.32E+06**	**4.77E+06**	**4.49E+06**	**6.99E+07**	**5.88E+04**	**7.05E+04**
Basin 120	**1.92E+08**	**6.67E+06**	**7.46E+07**	**2.63E+05**	**1.23E+07**	**8.80E+06**	**6.62E+05**	**1.28E+06**	**9.36E+05**	**4.41E+06**	**8.32E+05**	**4.16E+05**
Allbasins	**2.48E+08**	**7.36E+11**	**4.46E+09**	**8.87E+07**	**7.94E+11**	**3.29E+09**	**3.82E+07**	**1.81E+08**	**2.26E+08**	**5.48E+09**	**1.87E+08**	**4.10E+08**

Pools and fluxes per basin and year for phosphorus (P) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_ drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 102	1.01E+05	1.26E+10	9.45E+07	4.15E+05	2.51E+09	5.63E+07	2.25E+05	2.79E+06	4.32E+06	3.73E+07	1.47E+01	2.95E+00
Basin 100	1.44E+04	2.04E+10	3.85E+07	2.24E+05	4.71E+09	3.62E+07	1.54E+05	1.04E+06	2.73E+06	4.43E+07	3.69E+06	7.41E+05
Basin 101	0.00E+00	7.71E+09	2.30E+07	2.65E+05	3.44E+09	4.08E+07	0.00E+00	5.26E+05	2.71E+06	7.19E+07	3.56E+06	7.15E+05
Basin 105	1.63E+04	4.04E+09	4.01E+07	2.75E+05	4.04E+09	4.62E+07	3.80E+05	9.68E+05	3.87E+06	9.76E+07	3.48E+06	6.99E+05
Basin 103	2.04E+03	5.40E+08	3.51E+07	6.92E+04	5.40E+08	8.00E+06	4.44E+04	9.56E+05	7.39E+05	0.00E+00	4.10E+06	8.23E+05
Basin 104	1.51E+02	4.06E+08	6.53E+06	3.28E+04	4.06E+08	3.97E+06	7.83E+02	2.45E+05	3.70E+05	2.82E+07	3.15E+05	6.33E+04
Basin 108	1.30E+03	1.03E+09	1.18E+07	8.74E+04	1.04E+09	1.19E+07	1.01E+05	4.87E+05	9.13E+05	2.02E+07	2.05E+05	4.11E+04
Basin 106	1.43E+02	1.49E+08	6.37E+06	1.68E+04	1.49E+08	2.14E+06	1.97E+02	2.04E+05	2.33E+05	7.51E+06	7.62E+05	1.53E+05
Basin 111	3.93E+04	5.76E+07	4.72E+07	8.19E+04	5.80E+07	1.04E+07	3.76E+05	1.71E+06	1.30E+06	6.20E+06	6.20E+04	1.24E+04
Basin 107	6.83E+02	3.75E+08	1.20E+07	5.62E+04	3.75E+08	7.10E+06	2.16E+03	4.68E+05	6.73E+05	2.53E+07	2.28E+05	4.56E+04
Basin 110	3.23E+02	1.50E+09	1.03E+07	8.60E+04	1.51E+09	1.22E+07	5.33E+03	4.87E+05	9.04E+05	1.00E+07	3.22E+05	6.47E+04
Basin 114	1.62E+04	2.65E+09	2.64E+07	1.71E+05	2.65E+09	3.10E+07	9.68E+05	5.04E+05	2.81E+06	1.17E+08	8.73E+05	1.75E+05
Basin 109	1.69E+01	7.71E+08	1.97E+06	1.85E+04	7.71E+08	3.37E+06	5.89E+04	2.56E+04	2.57E+05	1.05E+07	2.71E+06	5.44E+05
Basin 116	**6.00E+02**	**8.65E+08**	**3.13E+07**	**1.64E+05**	**8.96E+08**	**2.21E+07**	**1.71E+04**	**1.52E+06**	**1.98E+06**	**3.37E+07**	**2.90E+05**	**5.82E+04**
Basin 113	0.00E+00	7.50E+08	2.32E+06	1.94E+04	7.50E+08	2.77E+06	9.19E+03	1.34E+05	2.12E+05	3.59E+06	1.28E+06	2.56E+05
Basin 117	3.37E+04	2.94E+07	3.30E+07	7.00E+04	3.04E+07	9.10E+06	3.55E+05	1.19E+06	1.17E+06	8.87E+06	1.98E+05	3.97E+04
Basin 112	0.00E+00	2.25E+08	7.51E+05	8.46E+03	2.25E+08	1.12E+06	0.00E+00	3.72E+04	9.28E+04	1.30E+06	2.16E+05	4.34E+04
Basin 115	1.56E+01	1.27E+09	6.26E+06	5.12E+04	1.27E+09	8.69E+06	3.08E+05	1.94E+05	6.91E+05	2.16E+07	7.52E+04	1.51E+04
Basin 151	1.61E+05	1.44E+09	9.62E+07	5.10E+05	1.26E+09	8.48E+07	6.13E+05	2.52E+06	8.16E+06	2.47E+08	6.71E+05	1.35E+05
Basin 118	1.79E+03	3.81E+06	6.94E+06	1.76E+04	3.28E+06	2.34E+06	3.27E+05	3.45E+05	3.42E+05	1.33E+06	5.56E+06	1.11E+06
Basin 123	1.42E+03	1.41E+09	1.31E+07	8.85E+04	1.43E+09	1.44E+07	3.62E+04	4.69E+05	1.31E+06	4.30E+07	2.76E+04	1.59E+04
Basin 152	4.15E+06	1.45E+06	1.16E+07	2.59E+04	6.92E+06	3.88E+06	1.02E+06	1.19E+06	6.52E+05	1.20E+07	9.83E+05	1.97E+05
Basin 150	5.55E+04	5.71E+07	1.90E+07	7.12E+04	7.96E+07	1.31E+07	1.08E+06	1.10E+06	2.15E+06	4.03E+07	3.12E+04	6.25E+03
Basin 146	3.39E+02	3.89E+08	8.77E+06	4.14E+04	3.98E+08	5.74E+06	2.11E+04	3.97E+05	6.64E+05	1.26E+07	3.34E+05	4.29E+04
Basin 126	**3.86E+03**	**3.52E+08**	**1.20E+07**	**6.61E+04**	**3.05E+08**	**9.27E+06**	**1.46E+04**	**5.48E+05**	**1.09E+06**	**1.99E+07**	**2.63E+05**	**5.27E+04**
Basin 134	**5.06E+03**	**9.38E+03**	**1.72E+06**	**7.13E+03**	**1.50E+04**	**1.08E+06**	**8.60E+04**	**1.13E+05**	**1.80E+05**	**3.61E+06**	**3.45E+05**	**3.96E+04**
Basin 121	**4.09E+04**	**1.30E+08**	**9.46E+06**	**4.49E+04**	**8.78E+07**	**6.39E+06**	**2.27E+05**	**5.40E+05**	**8.99E+05**	**1.20E+07**	**9.82E+03**	**2.01E+03**
Basin 120	**2.28E+04**	**2.69E+05**	**1.72E+06**	**8.86E+03**	**4.49E+05**	**1.22E+06**	**1.13E+05**	**1.33E+05**	**1.79E+05**	**7.54E+05**	**1.18E+05**	**2.89E+04**
Allbasins	**4.67E+06**	**5.92E+10**	**6.08E+08**	**2.99E+06**	**2.89E+10**	**4.56E+08**	**6.54E+06**	**2.08E+07**	**4.16E+07**	**9.38E+08**	**3.07E+07**	**6.13E+06**

Pools and fluxes per basin and year for thorium (Th) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_ drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 102	No data	1.12E+07	No data	1.71E+02	1.13E+07	No data	7.25E+02	8.20E+03	2.35E+02	1.20E+05	7.59E+03	1.14E–01
Basin 100	No data	2.11E+07	No data	9.23E+01	2.11E+07	No data	4.94E+02	2.23E+03	9.58E+01	1.43E+05	8.41E+03	2.87E+04
Basin 101	No data	1.54E+07	No data	1.09E+02	1.54E+07	No data	0.00E+00	2.00E+03	9.73E+01	2.31E+05	7.32E+03	2.77E+04
Basin 105	No data	1.81E+07	No data	1.13E+02	1.81E+07	No data	1.22E+03	2.41E+03	1.10E+02	3.14E+05	1.02E+04	2.71E+04
Basin 103	No data	2.42E+06	No data	2.85E+01	2.42E+06	No data	1.43E+02	2.33E+03	5.19E+01	0.00E+00	6.79E+02	3.19E+04
Basin 104	No data	1.82E+06	No data	1.35E+01	1.82E+06	No data	2.52E+00	8.75E+02	1.98E+01	9.07E+04	4.31E+02	2.45E+03
Basin 108	No data	4.63E+06	No data	3.60E+01	4.64E+06	No data	3.27E+02	1.43E+03	4.77E+01	6.51E+04	1.74E+03	1.59E+03
Basin 106	No data	6.66E+05	No data	6.93E+00	6.66E+05	No data	6.33E–01	6.79E+02	1.43E+01	2.42E+04	1.38E+02	5.93E+03
Basin 111	No data	2.58E+05	No data	3.37E+01	2.60E+05	No data	1.21E+03	3.31E+03	6.17E+01	2.00E+04	6.74E+02	4.82E+02
Basin 107	No data	1.68E+06	No data	2.31E+01	1.68E+06	No data	6.96E+00	1.60E+03	3.89E+01	8.15E+04	7.03E+02	1.77E+03
Basin 110	No data	6.74E+06	No data	3.54E+01	6.74E+06	No data	1.72E+01	1.23E+03	3.92E+01	3.22E+04	2.00E+03	2.51E+03
Basin 114	No data	1.19E+07	No data	7.02E+01	1.19E+07	No data	3.12E+03	1.40E+03	6.63E+01	3.77E+05	7.52E+03	6.78E+03
Basin 109	No data	3.45E+06	No data	7.61E+00	3.45E+06	No data	1.90E+02	7.78E+01	6.26E+00	3.37E+04	7.12E+02	2.11E+04
Basin 116	**No data**	**4.09E+06**	**No data**	**6.77E+01**	**4.01E+06**	**No data**	**5.50E+01**	**3.50E+03**	**8.77E+01**	**1.09E+05**	**3.08E+03**	**2.26E+03**
Basin 113	No data	3.36E+06	No data	7.98E+00	3.36E+06	No data	2.96E+01	2.83E+02	8.27E+00	1.15E+04	4.86E+02	9.92E+03
Basin 117	No data	1.34E+05	No data	2.88E+01	1.36E+05	No data	1.14E+03	2.43E+03	4.98E+01	2.85E+04	7.20E+02	1.54E+03
Basin 112	No data	1.01E+06	No data	3.48E+00	1.01E+06	No data	0.00E+00	1.30E+02	3.84E+00	4.18E+03	1.75E+02	1.68E+03
Basin 115	No data	5.69E+06	No data	2.11E+01	5.70E+06	No data	9.91E+02	4.61E+02	2.01E+01	6.94E+04	1.68E+03	5.84E+02
Basin 151	No data	5.61E+06	No data	2.10E+02	5.62E+06	No data	1.97E+03	5.45E+03	2.37E+02	7.96E+05	1.94E+04	5.21E+03
Basin 118	No data	1.71E+04	No data	7.23E+00	1.75E+04	No data	1.05E+03	4.49E+02	1.11E+01	4.30E+03	2.29E+02	4.32E+04
Basin 123	No data	6.41E+06	No data	3.64E+01	6.42E+06	No data	1.17E+02	1.07E+03	3.54E+01	1.38E+05	2.57E+03	1.34E+02
Basin 152	No data	7.18E+03	No data	1.07E+01	3.10E+04	No data	3.29E+03	7.25E+02	1.50E+01	3.86E+04	1.84E+02	7.64E+03
Basin 150	No data	2.56E+05	No data	2.93E+01	2.40E+05	No data	3.46E+03	1.69E+03	4.43E+01	1.30E+05	9.81E+02	2.42E+02
Basin 146	No data	1.76E+06	No data	1.70E+01	1.78E+06	No data	6.79E+01	9.89E+02	2.18E+01	4.06E+04	7.54E+02	1.54E+03
Basin 126	**No data**	**1.82E+06**	**No data**	**2.72E+01**	**1.71E+06**	**No data**	**4.71E+01**	**1.50E+03**	**3.63E+01**	**6.40E+04**	**1.26E+03**	**2.04E+03**
Basin 134	**No data**	**8.77E+01**	**No data**	**2.93E+00**	**6.95E+01**	**No data**	**2.77E+02**	**2.14E+02**	**5.15E+00**	**1.16E+04**	**6.43E+01**	**6.32E+02**
Basin 121	**No data**	**6.20E+05**	**No data**	**1.85E+01**	**8.21E+05**	**No data**	**7.29E+02**	**1.18E+03**	**2.43E+01**	**3.85E+04**	**6.77E+02**	**8.03E+01**
Basin 120	**No data**	**2.51E+03**	**No data**	**3.65E+00**	**2.01E+03**	**No data**	**3.65E+02**	**2.08E+02**	**5.97E+00**	**2.43E+03**	**1.23E+02**	**2.11E+03**
Allbasins	**No data**	**1.30E+08**	**No data**	**1.23E+03**	**1.30E+08**	**No data**	**2.11E+04**	**4.81E+04**	**1.49E+03**	**3.02E+06**	**8.05E+04**	**2.37E+05**

Pools and fluxes per basin and year for uranium (u) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 102	No data	1.48E+08	No data	6.83E+01	1.48E+08	No data	6.19E+02	5.11E+02	2.09E+02	1.02E+05	3.55E+03	1.50E+00
Basin 100	No data	2.77E+08	No data	3.69E+01	2.77E+08	No data	4.22E+02	2.26E+02	8.65E+01	1.22E+05	3.93E+03	3.78E+05
Basin 101	No data	2.02E+08	No data	4.36E+01	2.02E+08	No data	0.00E+00	6.25E+01	8.79E+01	1.98E+05	3.42E+03	3.64E+05
Basin 105	No data	2.38E+08	No data	4.53E+01	2.38E+08	No data	1.04E+03	1.90E+02	9.84E+01	2.69E+05	4.77E+03	3.56E+05
Basin 103	No data	3.18E+07	No data	1.14E+01	3.18E+07	No data	1.22E+02	2.04E+02	4.61E+01	0.00E+00	3.17E+02	4.19E+05
Basin 104	No data	2.39E+07	No data	5.40E+00	2.39E+07	No data	2.16E+00	3.72E+01	1.75E+01	7.75E+04	2.01E+02	3.22E+04
Basin 108	No data	6.09E+07	No data	1.44E+01	6.10E+07	No data	2.79E+02	8.93E+01	4.26E+01	5.56E+04	8.13E+02	2.09E+04
Basin 106	No data	8.75E+06	No data	2.77E+00	8.76E+06	No data	5.41E–01	3.38E+01	1.25E+01	2.07E+04	6.45E+01	7.79E+04
Basin 111	No data	3.39E+06	No data	1.35E+01	3.41E+06	No data	1.03E+03	4.09E+02	5.63E+01	1.71E+04	3.15E+02	6.34E+03
Basin 107	No data	2.21E+07	No data	9.26E+00	2.21E+07	No data	5.95E+00	7.51E+01	3.47E+01	6.96E+04	3.29E+02	2.33E+04
Basin 110	No data	8.86E+07	No data	1.41E+01	8.86E+07	No data	1.47E+01	9.92E+01	3.65E+01	2.75E+04	9.34E+02	3.29E+04
Basin 114	No data	1.56E+08	No data	2.81E+01	1.56E+08	No data	2.66E+03	8.82E+01	5.81E+01	3.22E+05	3.52E+03	8.92E+04
Basin 109	No data	4.54E+07	No data	3.04E+00	4.54E+07	No data	1.62E+02	3.42E+00	5.54E+00	2.88E+04	3.33E+02	2.77E+05
Basin 116	**No data**	**5.16E+07**	**No data**	**2.71E+01**	**5.28E+07**	**No data**	**4.70E+01**	**3.34E+02**	**8.18E+01**	**9.28E+04**	**1.44E+03**	**2.97E+04**
Basin 113	No data	4.41E+07	No data	3.19E+00	4.41E+07	No data	2.53E+01	3.03E+01	7.91E+00	9.87E+03	2.27E+02	1.30E+05
Basin 117	No data	1.77E+06	No data	1.15E+01	1.79E+06	No data	9.78E+02	2.78E+02	4.50E+01	2.44E+04	3.37E+02	2.02E+04
Basin 112	No data	1.33E+07	No data	1.39E+00	1.33E+07	No data	0.00E+00	5.68E+00	3.51E+00	3.57E+03	8.16E+01	2.21E+04
Basin 115	No data	7.49E+07	No data	8.42E+00	7.49E+07	No data	8.47E+02	3.95E+01	1.83E+01	5.93E+04	7.83E+02	7.68E+03
Basin 151	No data	7.38E+07	No data	8.38E+01	7.39E+07	No data	1.69E+03	5.50E+02	2.13E+02	6.80E+05	9.05E+03	6.85E+04
Basin 118	No data	2.25E+05	No data	2.89E+00	2.30E+05	No data	8.99E+02	9.46E+01	9.87E+00	3.67E+03	1.07E+02	5.68E+05
Basin 123	No data	8.43E+07	No data	1.46E+01	8.44E+07	No data	9.96E+01	1.01E+02	3.27E+01	1.18E+05	1.20E+03	3.70E+03
Basin 152	No data	1.20E+05	No data	4.27E+00	4.07E+05	No data	2.81E+03	3.70E+02	1.26E+01	3.30E+04	8.60E+01	1.01E+05
Basin 150	No data	3.36E+06	No data	1.17E+01	4.27E+06	No data	2.96E+03	2.88E+02	3.94E+01	1.11E+05	4.58E+02	3.18E+03
Basin 146	No data	2.43E+07	No data	6.81E+00	2.35E+07	No data	5.80E+01	8.32E+01	2.02E+01	3.47E+04	3.53E+02	2.74E+04
Basin 126	**No data**	**2.09E+07**	**No data**	**1.09E+01**	**2.25E+07**	**No data**	**4.03E+01**	**1.08E+02**	**3.31E+01**	**5.46E+04**	**5.90E+02**	**2.68E+04**
Basin 134	**No data**	**5.80E+02**	**No data**	**1.17E+00**	**7.42E+02**	**No data**	**2.36E+02**	**2.73E+01**	**4.35E+00**	**9.94E+03**	**3.01E+01**	**3.05E+04**
Basin 121	**No data**	**8.15E+06**	**No data**	**7.38E+00**	**5.43E+06**	**No data**	**6.23E+02**	**1.22E+02**	**2.20E+01**	**3.29E+04**	**3.16E+02**	**8.57E+02**
Basin 120	**No data**	**1.66E+04**	**No data**	**1.46E+00**	**2.64E+04**	**No data**	**3.12E+02**	**3.46E+01**	**5.20E+00**	**2.07E+03**	**5.76E+01**	**1.40E+04**
Allbasins	**No data**	**1.71E+09**	**No data**	**4.93E+02**	**1.71E+09**	**No data**	**1.80E+04**	**4.49E+03**	**1.34E+03**	**2.58E+06**	**3.76E+04**	**3.13E+06**

Pools and fluxes per basin and year for iodine (I) in the marine Forsmark area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 102	No data	1.43E+09	No data	9.57E+03	1.43E+09	No data	1.38E+03	1.87E+05	3.61E+03	2.28E+05	2.27E+05	1.45E+01
Basin 100	No data	2.67E+09	No data	5.17E+03	2.67E+09	No data	9.39E+02	5.84E+04	1.71E+03	2.71E+05	2.51E+05	3.64E+06
Basin 101	No data	1.95E+09	No data	6.10E+03	1.95E+09	No data	0.00E+00	3.84E+04	1.62E+03	4.39E+05	2.19E+05	3.51E+06
Basin 105	No data	2.29E+09	No data	6.35E+03	2.29E+09	No data	2.32E+03	5.74E+04	1.79E+03	5.97E+05	3.05E+05	3.43E+06
Basin 103	No data	3.07E+08	No data	1.59E+03	3.07E+08	No data	2.71E+02	5.93E+04	8.04E+02	0.00E+00	2.03E+04	4.05E+06
Basin 104	No data	2.31E+08	No data	7.55E+02	2.31E+08	No data	4.79E+00	1.83E+04	2.70E+02	1.72E+05	1.29E+04	3.11E+05
Basin 108	No data	5.88E+08	No data	2.01E+03	5.88E+08	No data	6.20E+02	3.26E+04	7.18E+02	1.24E+05	5.20E+04	2.02E+05
Basin 106	No data	8.44E+07	No data	3.88E+02	8.45E+07	No data	1.20E+00	1.47E+04	2.11E+02	4.59E+04	4.13E+03	7.52E+05
Basin 111	No data	3.27E+07	No data	1.89E+03	3.29E+07	No data	2.30E+03	9.61E+04	1.01E+03	3.79E+04	2.02E+04	6.12E+04
Basin 107	No data	2.13E+08	No data	1.30E+03	2.13E+08	No data	1.32E+01	3.43E+04	5.77E+02	1.55E+05	2.10E+04	2.24E+05
Basin 110	No data	8.55E+08	No data	1.98E+03	8.55E+08	No data	3.26E+01	3.02E+04	6.63E+02	6.12E+04	5.97E+04	3.18E+05
Basin 114	No data	1.51E+09	No data	3.93E+03	1.51E+09	No data	5.92E+03	3.08E+04	1.01E+03	7.16E+05	2.25E+05	8.61E+05
Basin 109	No data	4.38E+08	No data	4.26E+02	4.38E+08	No data	3.60E+02	1.49E+03	1.04E+02	6.40E+04	2.13E+04	2.68E+06
Basin 116	**No data**	**5.11E+08**	**No data**	**3.79E+03**	**5.09E+08**	**No data**	**1.04E+02**	**9.16E+04**	**1.45E+03**	**2.06E+05**	**9.22E+04**	**2.86E+05**
Basin 113	No data	4.26E+08	No data	4.47E+02	4.26E+08	No data	5.62E+01	7.67E+03	1.49E+02	2.19E+04	1.45E+04	1.26E+06
Basin 117	No data	1.70E+07	No data	1.61E+03	1.73E+07	No data	2.17E+03	6.83E+04	7.96E+02	5.42E+04	2.15E+04	1.95E+05
Basin 112	No data	1.28E+08	No data	1.95E+02	1.28E+08	No data	0.00E+00	2.74E+03	5.89E+01	7.94E+03	5.22E+03	2.13E+05
Basin 115	No data	7.22E+08	No data	1.18E+03	7.22E+08	No data	1.88E+03	1.13E+04	3.33E+02	1.32E+05	5.01E+04	7.41E+04
Basin 151	No data	7.12E+08	No data	1.17E+04	7.13E+08	No data	3.75E+03	1.43E+05	3.74E+03	1.51E+06	5.79E+05	6.61E+05
Basin 118	No data	2.17E+06	No data	4.05E+02	2.22E+06	No data	2.00E+03	1.69E+04	1.60E+02	8.16E+03	6.86E+03	5.48E+06
Basin 123	No data	8.13E+08	No data	2.04E+03	8.14E+08	No data	2.21E+02	2.75E+04	5.44E+02	2.63E+05	7.67E+04	3.33E+04
Basin 152	No data	8.07E+05	No data	5.98E+02	3.93E+06	No data	6.24E+03	4.87E+04	1.89E+02	7.33E+04	5.50E+03	9.70E+05
Basin 150	No data	3.24E+07	No data	1.64E+03	3.32E+07	No data	6.57E+03	5.66E+04	6.67E+02	2.46E+05	2.93E+04	3.07E+04
Basin 146	No data	2.27E+08	No data	9.53E+02	2.26E+08	No data	1.29E+02	2.48E+04	3.44E+02	7.70E+04	2.26E+04	2.14E+05
Basin 126	**No data**	**2.21E+08**	**No data**	**1.52E+03**	**2.17E+08**	**No data**	**8.95E+01**	**3.57E+04**	**5.52E+02**	**1.21E+05**	**3.78E+04**	**2.59E+05**
Basin 134	**No data**	**9.15E+03**	**No data**	**1.64E+02**	**9.63E+03**	**No data**	**5.26E+02**	**6.29E+03**	**6.13E+01**	**2.21E+04**	**1.92E+03**	**2.48E+05**
Basin 121	**No data**	**7.87E+07**	**No data**	**1.03E+03**	**8.56E+07**	**No data**	**1.38E+03**	**3.19E+04**	**3.48E+02**	**7.31E+04**	**2.02E+04**	**1.11E+04**
Basin 120	**No data**	**2.62E+05**	**No data**	**2.04E+02**	**2.55E+05**	**No data**	**6.92E+02**	**6.90E+03**	**8.15E+01**	**4.61E+03**	**3.68E+03**	**2.21E+05**
Allbasins	**No data**	**1.65E+10**	**No data**	**6.90E+04**	**1.65E+10**	**No data**	**4.00E+04**	**1.24E+06**	**2.36E+04**	**5.73E+06**	**2.41E+06**	**3.02E+07**

Appendix 9b

Results from massbalance calculations for carbon, nitrogen, phosphorus, thorium, uranium and iodine in all marine basin – Laxemar-Simpevarp.

Pools and fluxes per basin and year for carbon (C) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	5.66E+05	1.83E+12	2.15E+09	2.76E+07	1.85E+12	5.17E+09	0.00E+00	4.02E+08	1.03E+09	1.21E+08	2.59E+07	6.70E+08
Basin 525	0.00E+00	2.01E+11	3.11E+09	2.86E+07	2.27E+11	7.41E+09	0.00E+00	6.13E+08	1.32E+09	4.95E+07	1.70E+07	4.25E+08
Basin 522	0.00E+00	1.06E+12	1.34E+09	2.55E+07	1.06E+12	3.45E+09	0.00E+00	2.13E+08	6.67E+08	1.48E+09	3.26E+07	8.45E+08
Basin 523	0.00E+00	9.46E+11	1.74E+09	2.62E+07	7.96E+11	5.57E+09	0.00E+00	3.49E+08	1.05E+09	3.08E+08	2.43E+07	6.28E+08
Basin 521	**5.53E+06**	**8.97E+11**	**5.82E+09**	**7.15E+07**	**9.23E+11**	**1.27E+10**	**2.46E+07**	**1.08E+09**	**2.24E+09**	**3.47E+09**	**6.96E+07**	**1.72E+09**
Basin 501	5.47E+04	2.18E+08	3.85E+07	6.29E+05	2.04E+08	3.34E+07	7.24E+06	1.21E+07	4.99E+06	8.64E+07	6.49E+05	7.70E+06
Basin 500	5.96E+04	3.81E+09	7.05E+08	5.46E+06	0.00E+00	2.58E+08	2.85E+07	1.02E+08	4.04E+07	4.04E+08	3.70E+06	4.39E+07
Basin 504	**8.18E+06**	**1.18E+09**	**9.58E+07**	**1.14E+06**	**1.76E+09**	**6.02E+07**	**1.45E+07**	**2.37E+07**	**8.21E+06**	**1.78E+08**	**1.38E+06**	**1.64E+07**
Basin 502	**1.62E+08**	**6.89E+08**	**1.12E+08**	**2.12E+06**	**6.57E+08**	**1.30E+08**	**5.15E+07**	**3.41E+07**	**1.71E+07**	**5.60E+08**	**3.31E+06**	**3.92E+07**
Basin 506	**4.40E+06**	**1.39E+09**	**2.90E+07**	**6.29E+05**	**2.33E+09**	**3.56E+07**	**2.48E+06**	**1.16E+07**	**5.03E+06**	**8.43E+07**	**6.85E+05**	**8.14E+06**
Basin 508	**2.13E+08**	**4.11E+08**	**2.65E+08**	**2.58E+06**	**4.54E+08**	**1.45E+08**	**4.78E+07**	**9.64E+07**	**1.98E+07**	**5.45E+08**	**1.46E+06**	**1.74E+07**
Basin 513	3.38E+07	3.46E+10	1.25E+09	7.64E+06	3.80E+10	1.56E+09	8.60E+06	2.54E+08	2.82E+08	2.94E+08	3.51E+06	7.76E+07
Basin 514	0.00E+00	3.58E+10	3.57E+08	1.79E+06	3.57E+10	4.25E+08	0.00E+00	7.61E+07	7.91E+07	4.52E+07	7.07E+05	1.78E+07
Basin 516	1.28E+07	1.08E+10	3.41E+08	9.06E+05	3.14E+10	2.70E+07	0.00E+00	2.92E+07	5.31E+06	0.00E+00	5.15E+04	6.11E+05
Basin 518	0.00E+00	6.69E+10	2.69E+08	1.43E+06	4.80E+10	3.30E+08	0.00E+00	5.14E+07	6.25E+07	4.54E+07	4.69E+05	1.19E+07
Basin 515	5.34E+07	4.75E+09	1.23E+08	1.63E+06	5.19E+09	9.20E+07	2.09E+07	1.64E+07	1.41E+07	2.43E+08	1.71E+06	2.02E+07
Basin 517	1.04E+08	2.71E+10	1.68E+09	1.26E+07	4.02E+10	1.14E+09	8.07E+07	2.06E+08	1.82E+08	1.18E+09	1.19E+07	1.55E+08
Basin 520	5.47E+04	4.56E+09	7.68E+08	4.27E+06	6.15E+09	6.03E+08	0.00E+00	9.27E+07	8.94E+07	0.00E+00	1.79E+06	3.11E+07
Basin 519	6.23E+05	6.98E+07	3.59E+08	1.11E+06	1.02E+08	3.44E+07	0.00E+00	3.00E+07	6.77E+06	0.00E+00	9.13E+04	1.08E+06
Allbasins	**5.98E+08**	**5.12E+12**	**2.06E+10**	**2.23E+08**	**5.06E+12**	**3.91E+10**	**2.87E+08**	**3.70E+09**	**7.13E+09**	**9.09E+09**	**2.01E+08**	**4.73E+09**

Pools and fluxes per basin and year for nitrogen (N) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	4.97E+02	1.35E+10	5.23E+07	3.96E+05	1.35E+10	1.26E+08	0.00E+00	3.15E+06	2.64E+07	2.38E+06	2.22E+06	1.58E+06
Basin 525	0.00E+00	1.35E+09	7.58E+07	4.11E+05	1.62E+09	1.80E+08	0.00E+00	4.86E+06	3.33E+07	9.72E+05	1.37E+06	9.78E+05
Basin 522	0.00E+00	7.65E+09	3.28E+07	3.66E+05	7.77E+09	8.41E+07	0.00E+00	1.66E+06	1.72E+07	2.91E+07	2.81E+06	2.01E+06
Basin 523	0.00E+00	6.68E+09	4.24E+07	3.76E+05	5.86E+09	1.36E+08	0.00E+00	2.72E+06	2.68E+07	6.05E+06	2.09E+06	1.49E+06
Basin 521	**5.58E+03**	**6.56E+09**	**1.42E+08**	**1.03E+06**	**5.66E+09**	**3.08E+08**	**4.82E+05**	**8.52E+06**	**5.75E+07**	**6.80E+07**	**1.42E+06**	**6.97E+06**
Basin 501	8.63E+01	8.05E+05	9.39E+05	9.04E+03	8.05E+05	8.13E+05	1.42E+05	9.26E+04	1.60E+05	1.70E+06	1.39E+04	9.88E+03
Basin 500	9.39E+01	2.29E+07	1.72E+07	7.85E+04	0.00E+00	6.29E+06	5.59E+05	8.37E+05	1.19E+06	7.93E+06	7.48E+04	5.34E+04
Basin 504	**9.33E+03**	**6.27E+06**	**2.33E+06**	**1.64E+04**	**6.63E+06**	**1.47E+06**	**2.86E+05**	**1.84E+05**	**2.68E+05**	**3.49E+06**	**2.84E+04**	**2.03E+04**
Basin 502	**2.95E+05**	**7.45E+06**	**2.72E+06**	**3.04E+04**	**2.90E+06**	**3.17E+06**	**1.01E+06**	**2.60E+05**	**6.00E+05**	**1.10E+07**	**1.07E+05**	**4.27E+04**
Basin 506	**5.63E+03**	**1.71E+07**	**7.06E+05**	**9.03E+03**	**8.97E+06**	**8.69E+05**	**4.87E+04**	**8.88E+04**	**1.65E+05**	**1.65E+06**	**1.44E+04**	**1.03E+04**
Basin 508	**3.91E+05**	**1.67E+06**	**6.46E+06**	**3.71E+04**	**1.59E+07**	**3.54E+06**	**9.39E+05**	**7.22E+05**	**6.63E+05**	**1.07E+07**	**3.50E+04**	**7.68E+03**
Basin 513	5.68E+04	2.19E+08	3.05E+07	1.10E+05	2.46E+08	3.80E+07	1.69E+05	1.98E+06	7.13E+06	5.78E+06	8.85E+04	2.77E+05
Basin 514	0.00E+00	2.41E+08	8.70E+06	2.57E+04	2.46E+08	1.03E+07	0.00E+00	5.87E+05	1.98E+06	8.87E+05	5.59E+04	3.98E+04
Basin 516	2.02E+04	7.41E+07	8.32E+06	1.30E+04	7.41E+07	6.58E+05	0.00E+00	2.44E+05	1.14E+05	0.00E+00	9.61E+02	6.86E+02
Basin 518	0.00E+00	3.28E+08	6.56E+06	2.05E+04	3.29E+08	8.04E+06	0.00E+00	4.04E+05	1.57E+06	8.91E+05	3.72E+04	2.65E+04
Basin 515	9.92E+04	2.08E+07	2.99E+06	2.35E+04	2.08E+07	2.24E+06	4.10E+05	1.38E+05	4.46E+05	4.77E+06	3.73E+04	2.66E+04
Basin 517	2.20E+05	1.76E+08	4.10E+07	1.81E+05	1.76E+08	2.77E+07	1.58E+06	1.73E+06	4.93E+06	2.32E+07	3.08E+05	2.20E+05
Basin 520	8.62E+01	3.14E+07	1.87E+07	6.13E+04	3.14E+07	1.47E+07	0.00E+00	7.81E+05	2.24E+06	0.00E+00	7.23E+04	5.15E+04
Basin 519	9.82E+02	3.57E+05	8.76E+06	1.59E+04	3.57E+05	8.38E+05	0.00E+00	2.58E+05	1.48E+05	0.00E+00	1.80E+03	1.29E+03
Allbasins	**1.10E+06**	**3.69E+10**	**5.01E+08**	**3.21E+06**	**3.56E+10**	**9.54E+08**	**5.63E+06**	**2.92E+07**	**1.83E+08**	**1.78E+08**	**1.08E+07**	**1.38E+07**

Pools and fluxes per basin and year for phosphorus (P) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	2.38E+04	1.54E+11	3.78E+08	9.40E+06	2.27E+11	9.11E+08	0.00E+00	1.90E+07	1.93E+08	1.44E+07	1.08E+07	1.34E+07
Basin 525	0.00E+00	2.27E+10	5.48E+08	9.74E+06	2.72E+10	1.30E+09	0.00E+00	2.92E+07	2.47E+08	5.87E+06	6.68E+06	8.30E+06
Basin 522	0.00E+00	8.53E+10	2.37E+08	8.68E+06	1.31E+11	6.08E+08	0.00E+00	1.02E+07	1.25E+08	1.75E+08	1.37E+07	1.70E+07
Basin 523	0.00E+00	8.47E+10	3.06E+08	8.92E+06	9.83E+10	9.81E+08	0.00E+00	1.64E+07	1.98E+08	3.65E+07	1.02E+07	1.27E+07
Basin 521	**2.40E+05**	**8.41E+10**	**1.03E+09**	**2.43E+07**	**6.27E+10**	**2.23E+09**	**2.91E+06**	**5.15E+07**	**4.20E+08**	**4.10E+08**	**7.82E+06**	**9.03E+06**
Basin 501	3.13E+03	1.35E+07	6.78E+06	2.14E+05	1.35E+07	5.88E+06	8.57E+05	5.58E+05	8.91E+05	1.02E+07	6.75E+04	8.39E+04
Basin 500	3.41E+03	2.58E+08	1.24E+08	1.86E+06	0.00E+00	4.54E+07	3.37E+06	4.99E+06	7.10E+06	4.79E+07	3.64E+05	4.53E+05
Basin 504	**3.66E+05**	**8.28E+07**	**1.69E+07**	**3.89E+05**	**1.11E+08**	**1.06E+07**	**1.72E+06**	**1.11E+06**	**1.45E+06**	**2.10E+07**	**1.38E+05**	**1.72E+05**
Basin 502	**1.03E+07**	**4.72E+07**	**1.97E+07**	**7.21E+05**	**4.84E+07**	**2.29E+07**	**6.10E+06**	**1.58E+06**	**3.04E+06**	**6.63E+07**	**3.78E+05**	**5.62E+05**
Basin 506	**2.07E+05**	**9.99E+07**	**5.10E+06**	**2.14E+05**	**1.51E+08**	**6.28E+06**	**2.94E+05**	**5.36E+05**	**8.95E+05**	**9.98E+06**	**7.00E+04**	**8.70E+04**
Basin 508	**1.40E+07**	**2.80E+07**	**4.67E+07**	**8.80E+05**	**3.92E+07**	**2.56E+07**	**5.66E+06**	**4.36E+06**	**3.49E+06**	**6.45E+07**	**2.38E+05**	**2.83E+05**
Basin 513	2.09E+06	2.76E+09	2.21E+08	2.60E+06	2.61E+09	2.75E+08	1.02E+06	1.19E+07	5.25E+07	3.48E+07	5.39E+05	3.52E+05
Basin 514	0.00E+00	3.45E+09	6.29E+07	6.09E+05	4.13E+09	7.48E+07	0.00E+00	3.52E+06	1.47E+07	5.35E+06	2.72E+05	3.38E+05
Basin 516	7.17E+05	1.24E+09	6.01E+07	3.08E+05	1.24E+09	4.75E+06	0.00E+00	1.45E+06	8.66E+05	0.00E+00	4.68E+03	5.82E+03
Basin 518	0.00E+00	5.51E+09	4.74E+07	4.86E+05	5.52E+09	5.81E+07	0.00E+00	2.42E+06	1.17E+07	5.38E+06	1.81E+05	2.25E+05
Basin 515	3.45E+06	3.49E+08	2.16E+07	5.57E+05	3.49E+08	1.62E+07	2.48E+06	8.22E+05	2.55E+06	2.88E+07	1.82E+05	2.26E+05
Basin 517	7.64E+06	2.95E+09	2.97E+08	4.28E+06	2.95E+09	2.00E+08	9.56E+06	1.03E+07	3.35E+07	1.40E+08	1.50E+06	1.87E+06
Basin 520	3.13E+03	5.27E+08	1.35E+08	1.45E+06	5.28E+08	1.06E+08	0.00E+00	4.63E+06	1.66E+07	0.00E+00	3.52E+05	4.37E+05
Basin 519	3.56E+04	5.99E+06	6.33E+07	3.78E+05	5.99E+06	6.06E+06	0.00E+00	1.52E+06	1.12E+06	0.00E+00	8.77E+03	1.09E+04
Allbasins	**3.91E+07**	**4.48E+11**	**3.62E+09**	**7.60E+07**	**5.63E+11**	**6.89E+09**	**3.40E+07**	**1.76E+08**	**1.33E+09**	**1.08E+09**	**5.35E+07**	**6.55E+07**

Pools and fluxes per basin and year for thorium (Th) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	no data	6.36E+05	no data	7.34E+01	3.35E+06	no data	0.00E+00	6.27E+01	1.06E+04	6.24E+03	2.99E+03	1.23E+03
Basin 525	no data	3.35E+05	no data	7.61E+01	4.01E+05	no data	0.00E+00	8.40E+01	5.45E+03	2.55E+03	1.96E+03	7.59E+02
Basin 522	no data	3.44E+05	no data	6.78E+01	1.93E+06	no data	0.00E+00	3.96E+01	8.15E+04	7.61E+04	3.77E+03	1.56E+03
Basin 523	no data	7.44E+05	no data	6.97E+01	1.45E+06	no data	0.00E+00	6.25E+01	1.99E+04	1.58E+04	2.80E+03	1.16E+03
Basin 521	**no data**	**6.89E+05**	**no data**	**1.90E+02**	**6.22E+05**	**no data**	**1.26E+03**	**1.42E+02**	**1.88E+05**	**1.78E+05**	**8.04E+03**	**1.17E+03**
Basin 501	no data	2.00E+02	no data	1.67E+00	2.00E+02	no data	3.72E+02	5.92E–01	4.52E+03	4.44E+03	7.50E+01	7.67E+00
Basin 500	no data	2.63E+03	no data	1.45E+01	0.00E+00	no data	1.46E+03	6.11E+00	2.12E+04	2.08E+04	4.27E+02	4.14E+01
Basin 504	**no data**	**8.81E+02**	**no data**	**3.04E+00**	**1.64E+03**	**no data**	**7.48E+02**	**1.06E+00**	**9.31E+03**	**9.13E+03**	**1.60E+02**	**1.57E+01**
Basin 502	**no data**	**7.44E+02**	**no data**	**5.63E+00**	**5.40E+02**	**no data**	**2.65E+03**	**1.78E+00**	**2.92E+04**	**2.88E+04**	**3.82E+02**	**3.28E+01**
Basin 506	**no data**	**1.22E+03**	**no data**	**1.67E+00**	**2.22E+03**	**no data**	**1.27E+02**	**5.83E–01**	**4.42E+03**	**4.33E+03**	**7.91E+01**	**7.95E+00**
Basin 508	**no data**	**3.72E+02**	**no data**	**6.87E+00**	**7.16E+02**	**no data**	**2.46E+03**	**2.18E+00**	**2.82E+04**	**2.80E+04**	**1.69E+02**	**2.80E+01**
Basin 513	no data	3.22E+04	no data	2.03E+01	4.64E+04	no data	4.42E+02	2.14E+01	1.57E+04	1.51E+04	4.06E+02	9.66E+01
Basin 514	no data	5.02E+04	no data	4.76E+00	6.10E+04	no data	0.00E+00	6.10E+00	2.44E+03	2.32E+03	8.17E+01	3.09E+01
Basin 516	no data	1.84E+04	no data	2.41E+00	1.84E+04	no data	0.00E+00	1.64E+00	7.97E+00	0.00E+00	5.95E+00	5.32E–01
Basin 518	no data	8.14E+04	no data	3.79E+00	8.15E+04	no data	0.00E+00	4.73E+00	2.42E+03	2.33E+03	5.42E+01	2.06E+01
Basin 515	no data	5.15E+03	no data	4.35E+00	5.15E+03	no data	1.07E+03	1.42E+00	1.27E+04	1.25E+04	1.97E+02	2.07E+01
Basin 517	no data	4.36E+04	no data	3.34E+01	4.36E+04	no data	4.15E+03	1.79E+01	6.22E+04	6.06E+04	1.37E+03	1.71E+02
Basin 520	no data	7.78E+03	no data	1.13E+01	7.80E+03	no data	0.00E+00	8.04E+00	2.60E+02	0.00E+00	2.07E+02	4.00E+01
Basin 519	no data	8.85E+01	no data	2.95E+00	8.85E+01	no data	0.00E+00	1.95E+00	1.34E+01	0.00E+00	1.06E+01	9.97E–01
Allbasins	**no data**	**2.99E+06**	**no data**	**5.94E+02**	**8.02E+06**	**no data**	**1.47E+04**	**4.66E+02**	**4.98E+05**	**4.67E+05**	**2.32E+04**	**6.38E+03**

Pools and fluxes per basin and year for uranium (U) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	no data	3.58E+08	no data	2.94E+01	3.54E+08	no data	0.00E+00	5.33E+01	1.37E+05	5.45E+03	1.40E+03	1.30E+05
Basin 525	no data	3.55E+07	no data	3.04E+01	4.25E+07	no data	0.00E+00	7.25E+01	8.45E+04	2.22E+03	9.16E+02	8.04E+04
Basin 522	no data	2.06E+08	no data	2.71E+01	2.04E+08	no data	0.00E+00	3.27E+01	2.34E+05	6.65E+04	1.76E+03	1.65E+05
Basin 523	no data	1.83E+08	no data	2.79E+01	1.54E+08	no data	0.00E+00	5.33E+01	1.39E+05	1.38E+04	1.31E+03	1.23E+05
Basin 521	**no data**	**1.73E+08**	**no data**	**7.61E+01**	**1.75E+08**	**no data**	**1.10E+03**	**1.20E+02**	**4.90E+05**	**1.56E+05**	**3.76E+03**	**3.29E+05**
Basin 501	no data	2.11E+04	no data	6.70E–01	2.11E+04	no data	3.25E+02	4.98E–01	4.73E+03	3.88E+03	3.51E+01	8.12E+02
Basin 500	no data	7.03E+05	no data	5.81E+00	0.00E+00	no data	1.28E+03	5.23E+00	2.27E+04	1.81E+04	2.00E+02	4.38E+03
Basin 504	**no data**	**1.77E+05**	**no data**	**1.22E+00**	**1.74E+05**	**no data**	**6.53E+02**	**8.86E–01**	**9.72E+03**	**7.98E+03**	**7.46E+01**	**1.67E+03**
Basin 502	**no data**	**6.83E+04**	**no data**	**2.25E+00**	**6.90E+04**	**no data**	**2.31E+03**	**1.45E+00**	**2.95E+04**	**2.51E+04**	**1.79E+02**	**4.19E+03**
Basin 506	**no data**	**2.32E+05**	**no data**	**6.69E–01**	**2.35E+05**	**no data**	**1.11E+02**	**4.88E–01**	**4.67E+03**	**3.79E+03**	**3.70E+01**	**8.42E+02**
Basin 508	**no data**	**4.22E+04**	**no data**	**2.75E+00**	**4.51E+04**	**no data**	**2.15E+03**	**1.82E+00**	**2.63E+04**	**2.45E+04**	**7.90E+01**	**1.77E+03**
Basin 513	no data	6.47E+06	no data	8.13E+00	6.50E+06	no data	3.86E+02	1.85E+01	2.72E+04	1.32E+04	1.90E+02	1.35E+04
Basin 514	no data	6.51E+06	no data	1.90E+00	6.46E+06	no data	0.00E+00	5.29E+00	5.40E+03	2.03E+03	3.82E+01	3.27E+03
Basin 516	no data	1.95E+06	no data	9.64E–01	1.95E+06	no data	0.00E+00	1.43E+00	6.17E+01	0.00E+00	2.78E+00	5.63E+01
Basin 518	no data	8.62E+06	no data	1.52E+00	8.62E+06	no data	0.00E+00	4.10E+00	4.29E+03	2.04E+03	2.53E+01	2.18E+03
Basin 515	no data	5.45E+05	no data	1.74E+00	5.45E+05	no data	9.39E+02	1.19E+00	1.32E+04	1.09E+04	9.21E+01	2.19E+03
Basin 517	no data	4.61E+06	no data	1.34E+01	4.62E+06	no data	3.63E+03	1.53E+01	7.18E+04	5.30E+04	6.40E+02	1.81E+04
Basin 520	no data	8.24E+05	no data	4.54E+00	8.25E+05	no data	0.00E+00	6.95E+00	4.40E+03	0.00E+00	9.69E+01	4.23E+03
Basin 519	no data	9.37E+03	no data	1.18E+00	9.37E+03	no data	0.00E+00	1.69E+00	1.14E+02	0.00E+00	4.93E+00	1.06E+02
Allbasins	**no data**	**9.87E+08**	**no data**	**2.38E+02**	**9.59E+08**	**no data**	**1.29E+04**	**3.96E+02**	**1.31E+06**	**4.08E+05**	**1.08E+04**	**8.83E+05**

Pools and fluxes per basin and year for iodine (I) in the marine Laxemar-Simpevarp area, in g basin^{-1} year^{-1}.

IDKOD	Runoff (from basin_drainage_areas)	Advective flow	Net Primary Production	deposition	Advective flow	Respiration	Burial	Producers	Consumers	Regolith_upper	Particulate	Dissolved
Basin 524	no data	5.12E+09	no data	4.40E+03	7.12E+09	no data	0.00E+00	3.25E+03	2.75E+06	7.46E+03	8.94E+04	2.61E+06
Basin 525	no data	7.13E+08	no data	4.56E+03	8.54E+08	no data	0.00E+00	4.25E+03	1.74E+06	3.04E+03	5.86E+04	1.61E+06
Basin 522	no data	2.91E+09	no data	4.07E+03	4.10E+09	no data	0.00E+00	2.14E+03	3.54E+06	9.09E+04	1.13E+05	3.31E+06
Basin 523	no data	2.89E+09	no data	4.18E+03	3.09E+09	no data	0.00E+00	3.22E+03	2.61E+06	1.89E+04	8.38E+04	2.46E+06
Basin 521	**no data**	**2.75E+09**	**no data**	**1.14E+04**	**2.56E+09**	**no data**	**1.51E+03**	**7.40E+03**	**5.36E+06**	**2.13E+05**	**2.40E+05**	**4.81E+06**
Basin 501	no data	4.25E+05	no data	1.00E+02	4.25E+05	no data	4.44E+02	3.11E+01	2.40E+04	5.30E+03	2.24E+03	1.63E+04
Basin 500	no data	1.04E+07	no data	8.72E+02	0.00E+00	no data	1.75E+03	3.13E+02	1.27E+05	2.48E+04	1.28E+04	8.81E+04
Basin 504	**no data**	**3.13E+06**	**no data**	**1.82E+02**	**3.49E+06**	**no data**	**8.93E+02**	**5.67E+01**	**4.93E+04**	**1.09E+04**	**4.77E+03**	**3.35E+04**
Basin 502	**no data**	**1.34E+06**	**no data**	**3.38E+02**	**1.69E+06**	**no data**	**3.16E+03**	**9.75E+01**	**1.49E+05**	**3.44E+04**	**1.14E+04**	**1.03E+05**
Basin 506	**no data**	**3.52E+06**	**no data**	**1.00E+02**	**4.73E+06**	**no data**	**1.52E+02**	**3.09E+01**	**2.46E+04**	**5.18E+03**	**2.37E+03**	**1.69E+04**
Basin 508	**no data**	**9.17E+05**	**no data**	**4.12E+02**	**8.00E+05**	**no data**	**2.94E+03**	**1.15E+02**	**7.03E+04**	**3.34E+04**	**5.05E+03**	**3.14E+04**
Basin 513	no data	1.03E+08	no data	1.22E+03	9.62E+07	no data	5.28E+02	1.08E+03	2.43E+05	1.81E+04	1.21E+04	2.00E+05
Basin 514	no data	1.16E+08	no data	2.86E+02	1.30E+08	no data	0.00E+00	3.07E+02	7.45E+04	2.77E+03	2.44E+03	6.58E+04
Basin 516	no data	3.91E+07	no data	1.45E+02	3.91E+07	no data	0.00E+00	8.17E+01	1.46E+03	0.00E+00	1.78E+02	1.13E+03
Basin 518	no data	1.73E+08	no data	2.28E+02	1.73E+08	no data	0.00E+00	2.37E+02	5.10E+04	2.79E+03	1.62E+03	4.38E+04
Basin 515	no data	1.10E+07	no data	2.61E+02	1.10E+07	no data	1.28E+03	7.43E+01	6.52E+04	1.49E+04	5.89E+03	4.39E+04
Basin 517	no data	9.27E+07	no data	2.01E+03	9.28E+07	no data	4.96E+03	9.17E+02	4.83E+05	7.24E+04	4.09E+04	3.63E+05
Basin 520	no data	1.66E+07	no data	6.81E+02	1.66E+07	no data	0.00E+00	4.06E+02	9.51E+04	0.00E+00	6.20E+03	8.51E+04
Basin 519	no data	1.88E+05	no data	1.77E+02	1.88E+05	no data	0.00E+00	9.71E+01	2.63E+03	0.00E+00	3.15E+02	2.12E+03
Allbasins	**no data**	**1.50E+10**	**no data**	**3.56E+04**	**1.83E+10**	**no data**	**1.76E+04**	**2.41E+04**	**1.75E+07**	**5.58E+05**	**6.93E+05**	**1.59E+07**