SSI Rapport
SSI report

2003:12 M. J. EGAN, M. C. THORNE, R.H. LITTLE AND R.F. PASCO

Analysis of Critical Issues in Biosphere Assessment Modelling and Site Investigation

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

SSI rapport: 2003:12
juli 2003
ISSN 0282-4434

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DEPARTMENT/ AVDELNING: Waste Management & Environmental Protection/ Avd. för avfall och miljö

TITLE/ TITEL: Analysis of Critical Issues in Biosphere Assessment Modelling and Site Investigation / En analys av kritiska frågor för modellering av biosfären och platsundersökningar.

SUMMARY: The aim of this document is to present a critical review of issues concerned with the treatment of the biosphere and geosphere-biosphere interface in long-term performance assessment studies for nuclear waste disposal in Sweden. The review covers three main areas of investigation:

- a review of SKB's plans for undertaking site investigations at candidate locations for the development of a deep geological repository for spent fuel;
- identification of critical uncertainties associated with SKB's treatment of the geosphere-biosphere interface in recent performance assessments; and
- a preliminary modelling investigation of the significance of features, events and processes in the near-surface environment in terms of their effect on the accumulation and redistribution of radionuclides at the geosphere-biosphere interface.

Overall, SKB's proposals for site investigations are considered to be comprehensive and, if they can be carried out to the specification presented, will constitute a benchmark that other waste management organisations will have to work hard to emulate. The main concern is that expertise for undertaking the investigations and reporting the results could be stretched very thin. The authors have also identified weaknesses in the documentation concerning the collection of evidence for environmental change and on developing scenarios for future environmental change.

A fundamental assumption adopted in the renewed assessment of the SFR 1 repository, which is not discussed or justified in any of the documentation that has been reviewed, is that radionuclides enter the water column of the coastal and lake models directly, without passing first through the bed sediments. The modelling study reported herein suggests that SKB's models are robust to range of alternative conceptual descriptions relating to the geosphere-biosphere interface. There are however situations, in which contaminated groundwater is released via sediment rather than directly to the water column, which may lead to significantly higher doses than indicated by the SKB models. It is recommended that alternative groundwater discharge and system evolution models should therefore be considered in future assessments. It is also recommended that care should be taken to ensure that releases from the geosphere to the biosphere are represented in a consistent manner, based on careful integration of processes at the interface.

SAMMANFATTNING: Denna rapport redovisar en kritisk granskning av hur övergången mellan urberget och de överliggande jordlagren och biosfären hanteras i säkerhetsanalyser för slutförvaring av kärnavfall i Sverige. Granskningen omfattar tre huvudområden:

- en granskning av SKB:s planer för genomförande av platsundersökningar på kandidatplatser för lokalisering av ett slutförvar för använt kärnbränsle;
- en identifiering av kritiska osäkerheter i SKB:s hantering av gränszonen mellan geosfär och biosfär i nyligen genomförda säkerhetsanalyser; och
- en preliminär utvärdering av betydelsen av olika processer och egenskaper i den marknära miljön och deras påverkan på ackumulation och omfördelning av radionuklider.

SKB:s planer för platsundersökningar bedöms, överlag, vara grundliga. Förutsatt att platsundersökningarna kan genomföras enligt specifikationerna kommer de att utgöra en milstolpe som andra kärnavfallsorganisationer måste arbeta hårt för att kunna efterlikna. Den viktigaste invändningen är att det finns risk att den expertis som krävs för undersökningarna och rapporteringen inte räcker till. Författarna har vidare identifierat brister i dokumentationen av hur man planerar att samla in data kring pågående förändringar i miljön och för framtagande av scenarier för framtida, t.ex. klimatrelaterade, förändringar i miljön.

Ett grundläggande antagande i den senaste säkerhetsanalysen för SFR 1, som inte tillräckligt diskuterats eller rättfärdigats i de rapporter som granskats, är att radionuklider från slutförvaret introduceras direkt i sjöar och hav, utan att först passera med grundvattnet genom bottensedimenten. Den modelleringsstudie som redovisas i denna rapport visar att SKB:s modeller är relativt okänsliga för olika konceptuella beskrivningar av gränszonen mellan geosfär och biosfär. Det finns dock vissa situationer, när förorenat grundvatten tillåts strömma igenom bottensedimenten istället för att introduceras direkt i ytvattnet, som kan leda till betydligt högre radiologiska doser än de som förutsägs av SKB:s modeller. Författarna rekommenderar därför att genomströmning av grundvatten i sediment bör beaktas i de modeller som används för att beskriva förvarssystemets utveckling i framtida säkerhetsanalyser. Vidare rekommenderas att större insatser bör göras för att tillse att utläckage av radionuklider från geosfären till biosfären beskrivs på ett konsistent sätt, utifrån en noggrann analys av hur olika processer samverkar i denna gränszon.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Förord

Statens strålskyddsinstitut driver oberoende forskning och modellutveckling som ett led i förberedelserna för kommande granskningar av kärnkraftindustrins (SKB) program för slutförvaring av använt kärnbränsle och kärnavfall. Syftet är att ha tillgång till hög vetenskaplig kompetens och egna modeller inom centrala områden för granskning och bedömning av strålskydd och miljöpåverkan. I samband med att SKB påbörjat platsundersökningar för slutförvaring av använt kärnbränsle har bl.a. frågor om hur radionuklider ackumuleras och sprids i den marknära miljön aktualiserats.

Denna rapport redovisar en konsultgranskning av SKB:s program för karakterisering av hur radionuklider omsätts i biosfären och i övergången till det djupare berget. Granskningen omfattar dels SKB:s planer för platsundersökningar, dels SKB:s redovisning i samband med den senaste säkerhetsanalysen för slutförvaret SFR 1 vid Forsmark. Konsulterna har även fått i uppdrag att genomföra en modelleringsstudie för att belysa betydelsen av vissa exponeringsvägar och ackumulering av radionuklider i sjö- och havssediment.

Arbetet har utförts av fyra olika experter på konsultbolaget *Quintessa Limited* i England, på uppdrag av Björn Dverstorp, avdelningen för avfall och miljö.

Författarna svarar själva för innehållet i denna rapport.

Foreword

The Swedish Radiation Protection Authority (SSI) is in the process of developing and upgrading the modelling tools it uses to carry out independent radiological safety assessments of solid radioactive waste disposal. These models are used to simulate radionuclide behaviour in the biosphere and at the geosphere-biosphere interface, as well as to evaluate potential radiological impacts on humans and the environment. SSI's objectives in reviewing its capabilities is to ensure that it is properly prepared to undertake reviews of site investigations and forthcoming licence applications for the encapsulation and final disposal of spent fuel.

The Swedish Nuclear Fuel and Waste Management Company (SKB) has submitted a series of safety assessments, as well as descriptions of its research programme, for regulatory review. From SSI's perspective, the outcome of these regulatory reviews highlighted the need to enhance understanding of important processes in the near-surface environment and their influence on the fate of radionuclide releases from a geological repository, as well as their importance in determining radiological impacts.

In the light of this, Quintessa was commissioned by SSI in 2002 to:

- review SKB's plans for undertaking site investigations at candidate locations for the development of a deep geological repository for spent fuel, with particular attention to characterisation of the biosphere and geosphere-biosphere interface;
- identify critical uncertainties associated with SKB's treatment of the geosphere-biosphere interface in recent performance assessments; and
- carry out a modelling study to assess the significance of features, events and processes in the near-surface environment in terms of their effect on the accumulation and redistribution of radionuclides at the geosphere-biosphere interface.

The outcome of this work was originally delivered to SSI in the form of three separate Quintessa documents. These technical notes have been collected together here in a single SSI report. The authors alone are responsible for the contents of the report, and the conclusions do not necessarily reflect the formal position of SSI.

Summary

The aim of this document is to present a critical review of issues concerned with the treatment of the biosphere and geosphere-biosphere interface in long-term performance assessment studies for nuclear waste disposal in Sweden. The review covers three main areas of investigation:

- a review of SKB's plans for undertaking site investigations at candidate locations for the development of a deep geological repository for spent fuel;
- identification of critical uncertainties associated with SKB's treatment of the geosphere-biosphere interface in recent performance assessments; and
- a preliminary modelling investigation of the significance of features, events and processes in the near-surface environment in terms of their effect on the accumulation and redistribution of radionuclides at the geosphere-biosphere interface.

It is worth noting at the outset that the concept of an 'interface' between the geosphere and biosphere is artificial, as indeed is the distinction between geosphere and biosphere. Typically, the interface has to be introduced in assessments because simulations of the hydrogeological system used to determine flow and transport from the repository to the surface environment depend on boundary conditions for recharge and discharge that are not necessarily well integrated with more detailed understanding of the features, events and processes that affect the near-surface hydrogeological and hydrological regime.

There are a range of considerations and sources of uncertainty relevant to treatment of the geosphere-biosphere interface in a comprehensive assessment, including:

- variation in the geographical location of the geosphere-biosphere interface, caused by the effects of landform evolution on hydrogeology and far-field transport pathways;
- changes in the type and characteristics of the geosphere-biosphere interface as a function of time, resulting from landform evolution;
- definition of conceptual models associated with mass transport processes during transient conditions (e.g. complex changes in the dominant processes controlling sediment turnover and redistribution as a function of gradual changes in water column depth and water body type);
- specification of radionuclide-dependent parameters (such as soil/water distribution coefficients) for different biosphere systems and their variation with time according to changing water chemistry etc.

The main findings associated with each component of the study are summarised below.

SKB's Plans for Site Investigation

SKB has provided detailed proposals for multi-stage site investigations. Overall, these proposals are considered to be comprehensive and, if they can be carried out to the specification presented, will constitute a benchmark that other waste management organisations will have to work hard to emulate. The main concern is that expertise for undertaking the investigations and reporting the results could be stretched very thin. It is recommended that SKB should produce an analysis of resource requirements for the investigations and their interpretation, and a statement of how those resource requirements would be met.

In respect of characterisation of the biosphere and the geosphere-biosphere interface, it is planned that comprehensive data should be provided on all aspects of relevance. The availability of such comprehensive and spatially extensive data sets suggests that there would be an opportunity for SKB to calibrate and validate a physically-based model of local surface-water catchments against the present-day information provided from the site investigations. Although there are inevitable limitations to the predictive capability of a model calibrated to present-day conditions, such an approach could nevertheless be used to explore the potential significance of future changes in climate and land use for groundwater flow and radionuclide transport.

In view of the long-term nature of post-closure performance assessments, the SKB documentation does not provide much information concerning the collection of evidence for environmental change and on developing scenarios for future environmental change. In particular, the potential significance of greenhouse-gas warming and associated changes in global sea level as influences on the anticipated evolution of a repository and its surroundings seems to have been under-rated.

The proposed use of ecological system models is welcomed and it is considered that they have the potential to be closely integrated with surface and near-surface hydrological, hydrogeological and hydrogeochemical models.

SKB's Treatment of the Geosphere-Biosphere Interface in Recent Assessments

In recent assessments for the SAFE project, SKB has placed specific emphasis on the importance of uplift and associated coastal migration as processes influencing recharge and discharge patterns. Against this background, they have attempted to develop an understanding of factors affecting the evolution of flow paths in the geosphere and their sensitivity to assumptions regarding changes (or not) to topography, caused by sedimentation and erosion processes. Given the zone of discharge defined for the SAFE assessment, SKB has identified a ‘reasonable biosphere development’ sequence (coastal waters → lake → agricultural land) for the projected changes in the type and characteristics of biosphere receptors as a function of time, as a consequence of environmental change.

A fundamental assumption adopted in the SAFE assessment, which is not discussed or justified in any of the documentation that has been reviewed, is that radionuclides enter the water column of the coastal and lake models directly, without passing first through the bed sediments. It seems likely that this was judged to be a conservative assumption, on the basis that all the exposure pathways associated with the coastal and lake models are ultimately dependent on the estimated concentration of each radionuclide within the water column. Hence, for a given model configuration, assuming that the release enters the water column directly will effectively maximise the calculated potential exposures to members of the local community.

However, such an approach effectively disregards the possible importance of the accumulation of radionuclides in bed sediments as a mechanism for enhancing exposures at later stages, when the sea bed and (subsequently) lake bottom sediments have been uncovered and drained. A more realistic picture of how discharge of groundwater would in fact take place is that groundwater discharge would enter the surface environment by advection through the bed sediments, allowing for sorption en route.

Moreover, it is worth noting that concentration ratios for aquatic organisms are typically expressed relative to radionuclide concentrations in water, being derived from field data that emphasise effluent discharges either to atmosphere or to the aquatic environment. In assessments where discharges are to the soil system, this is not a major issue. However, with discharges to coastal waters or lakes, the bottom sediment may contain much higher concentrations of radionuclides than suspended sediment within the water body. In these circumstances, it would be advisable to review the primary literature for the radionuclides of greatest interest and then to consider what results (in terms of concentration ratios) would be obtained by calculating radionuclide concentrations in sediments and then using organism:sediment concentration ratios (for which some data do exist).

Modelling Study

The design of the modelling study is based on reviews of existing SKB work, taking account of identified modelling uncertainties. The emphasis is on preserving as much as possible of SKB’s exposure models and parameter values; however, attention has been given to refining the treatment of processes relevant to the migration, accumulation and dispersion of radionuclides associated with coastal seabed and lake bottom sediments.

The results of the study indicate that the SKB models are, in the main, quite robust to a range of alternative conceptual formulations relating features, events and processes associated with the geosphere-biosphere interface. For five of the seven models considered, differences in the dose (and radionuclide distributions) between the SKB approach and a proposed alternative configuration are less than a factor of two or three. The two significant exceptions are: (a) an alternative groundwater discharge model for surface water bodies, in which contaminated groundwater is released via sediment rather than directly into the water column; and (b) an alternative system evolution model in which there is a constant linear decrease of the lake volume to a minimum value. For both these cases, doses to certain exposure groups exceed those indicated by the SKB models by about an order of magnitude.

It is recommended that alternative groundwater discharge and system evolution models should therefore be considered in future assessments. It is also recommended that care should be taken to ensure that releases from the geosphere to the biosphere are represented in a consistent manner, based on careful integration of processes at the interface.

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1 Introduction

1.1 Background and Aims

This report has been produced as the outcome of a project undertaken by Quintessa Limited for the Swedish Radiation Protection Authority (SSI). The overall aims of this project were to assist SSI in:

- reviewing SKB's plans for undertaking site investigations at candidate locations for the development of a deep geological repository for spent fuel; and
- developing an improved understanding of important processes in the near-surface environment in terms of their effect on the accumulation and redistribution of radionuclides at the geosphere-biosphere interface (and hence determining radiological impact) in a time-evolving biosphere system.

The work includes: a review is provided of documents relating to site investigations (Part 1), a review of the treatment of the geosphere-biosphere interface in recent SKB modelling studies (Part 2), and a modelling investigation of the importance of features, events and processes affecting the retardation, accumulation and redistribution of radionuclides in Quaternary deposits and sediments (Part 3).

Results of the project will guide SSI in developing and upgrading the modelling tools it uses to undertake independent radiological safety assessments. SSI's objective in reviewing its capabilities is to ensure that it is properly prepared to undertake reviews of site investigations and forthcoming licence applications for nuclear waste disposal in Sweden.

1.2 Structure of the Report

Following this introduction, the report is divided into three parts. Part 1 describes the review of SKB's plans for site investigation. Section 2 identifies the SKB documents that have been reviewed, while Section 3 provides a summary of the main points arising from each report. Finally, Quintessa's views on the adequacy of the characterisation programme in respect of representation of the biosphere and the geosphere-biosphere interface in the assessments of safety performance are summarised in Section 4.

Part 2 of the report then describes the outcome of Quintessa's review of SKB's approach to representing the geosphere-biosphere interface, notably that adopted in the recent SAFE project, which updates the safety report for the SFR-1 repository at Forsmark. The focus of attention is on the features, events and processes the determine the radiological implications of potential ‘natural’ discharges of contaminated groundwater to the surface environment, rather than alternative interfaces or release pathways, such as gaseous transport, facility disruption or groundwater abstraction via wells.

Section 5 of the report identifies the SKB documentation that has been reviewed in the current study, while Section 6 provides a summary of relevant aspects of these documents. Comments on the extent to which SKB’s modelling approach is considered to provide an adequate representation of key factors affecting the accumulation and redistribution of radionuclides at the geosphere-biosphere interface are then provided in Section 7. Finally, in Section 8, proposals are made for approaches to be adopted in the complementary modelling investigation.

The final part of this report, Part 3, describes the outcome of a short modelling study undertaken by Quintessa, aimed at developing an improved understanding of important processes in the near-surface environment. The focus of the modelling study is therefore on the potential radiological implications of the accumulation and redistribution of radionuclides at the geosphere-biosphere interface.

Section 9 describes the overall approach adopted in undertaking the modelling study, which is based initially on a replication of the models and data used by SKB in the SAFE assessment and then on an investigation of the sensitivity of the results to alternative conceptual and mathematical models representing a number of key features, events and processes. The model replication exercise is described in Section 10, while the alternative models are presented and their implications investigated in Section 11. Key findings and recommendations from the modelling study are summarised in Section 12. An Appendix to the main report gives more detailed information regarding the definition of mathematical models and calculation cases for the sensitivity study.

PART 1 – SKB'S PLANS FOR SITE INVESTIGATION

2 Material Reviewed

The Swedish Nuclear Fuel and Waste Management Company (SKB) has submitted a series of safety assessments, as well as descriptions of its research programme for regulatory review. From SSI's perspective, the outcome of these reviews has highlighted the need to enhance understanding of important processes in the near-surface environment and their influence on the fate of radionuclide releases from a geological repository as well as their importance in determining radiological impacts.

Relevant material to be taken into account in the review has been agreed between Quintessa and SSI. This material was defined to include the following SKB reports:

TR-00-20: Geoscientific programme for investigation and evaluation of sites for the deep repository. This document provides a general description of the SKB's plans for site investigation, the investigation methods to be used, and the programme by which it will be delivered. Information from this report was subsequently summarised in TR-01-03.

TR-01-29: Site investigations – Investigation methods and general execution programme. This report is complementary to TR-00-20, in so far as it present a more extensive and detailed description of how the geosphere and biosphere investigations can be carried out, including specifications for what will, or can (if required), be measured, the methods to be used, and how site-descriptive models will be set up. It is recognised that some site-specific adaptations may be required when applying the approach to a particular site (see for example P-02-03).

P-02-03: Execution programme for the initial site investigations at Forsmark. This recently-published document describes the adaptation of general methods described in TR-01-29 to the specific needs of the investigations for the Forsmark area.

TR-01-30: RD&D Programme 2001. This document describes SKB's overall programme of research, development and demonstration up to 2004; however, it incorporates specific chapters on biosphere research (Section 9), as well as instruments and methods for site investigation (Section 13).

In addition to these reports, reference has also been made in the review to the gathering and reporting of information by SKB in relation to assessments for the SFR-1 repository, located at Forsmark, as summarised in the following report:

R-01-09: The terrestrial biosphere in the SFR region. This report was produced as part of the SKB SAFE project (Safety Assessment of the Final Repository for Radioactive Operational Waste).

Another further relevant document is SSI's review of TR-01-30 (published as SSI Rapport 2002:13).

In each case, the aim of the review is to focus on those aspects of site investigation that are most directly relevant to the current study – with particular attention to characterisation of the biosphere and the geosphere-biosphere interface. In this context, it is recognised that the biosphere characterisation component of site investigation is necessarily wider in scope than long-term safety assessment alone, since it must also provide 'baseline' information relevant to the EIA process. Nevertheless, the review should comment on the extent to which SKB has identified and focused activities in the site investigation programme on critical factors required as a basis for assessments of safety performance. As such, recognition will be given to the fact that biosphere systems representative of the long-term, used in such assessments, necessarily invoke a range of assumptions and simplifications, not least in relation to the treatment of system evolution and the representation of human communities and their influence on environmental characteristics.

3 Summary of Documentation Considered

3.1 SKB Report TR-00-20

3.1.1 Scope of Site Investigations

The emphasis of this report is on the methodology and technology to be used for investigating and evaluating rock characteristics. However, surface ecosystems and other aspects of the surface environment are discussed. It is stated that the material gathered during site investigations must be sufficiently comprehensive to:

- show whether the selected site satisfies fundamental safety requirements and whether civil engineering prerequisites are met;
- permit comparisons with other investigated sites; and

- serve as a basis for adaptation of the deep repository to the properties and characteristics of the site, with an acceptable impact on society and the environment.

The requirement for site investigations begins with the identification of candidate areas in various municipalities selected for feasibility studies. The size of a candidate area can be up to a couple of hundred square kilometres. In initial site investigations, the tasks are:

- to bring the areas up to a comparable knowledge level;
- define a priority site within each area for further, in depth, investigations; and
- acquire preliminary knowledge on rock conditions at repository depth at those sites.

Here, site is defined to mean the area required to accommodate and characterise a deep repository and its immediate environs. This is estimated as roughly 5 to 10 km^2.

If the overall assessment shows that prospects for siting a deep repository on the investigated sites are good, 'complete site investigations' are to follow on those sites. At this stage, the aim is to increase knowledge of the rock and its properties such that:

- a geoscientific understanding of the site can be obtained as regards current conditions and naturally ongoing processes;
- a site-adapted repository layout can be arrived at;
- an analysis of the feasibility and consequences of the construction project can be undertaken; and
- a safety assessment can be carried out to determine whether long-term safety can be ensured on the site.

The main product of the investigations is a site description. This is to present collected data and interpreted parameters that are of importance for:

- obtaining an overall scientific understanding of the site; and
- use in analyses and assessments relating to repository layout and construction, as well as its long-term performance and radiological safety.

The information that is collected will be stored in a database. It is required to present an integrated description of the geosphere and the biosphere of the site and its regional environs. Furthermore, this integrated description is to address both the current state of the system and naturally ongoing processes.

It is recognised that the field work required during the site investigation will vary from site to site. Measurements will be made from the air, from the ground and in boreholes. Cored and percussion boreholes will be drilled (with up to 20 cored boreholes per site over a few months). Activities will be adapted to the natural and cultural values of the site, and protected areas will be avoided wherever possible. This also applies to other areas that may be sensitive to disturbances, e.g. breeding areas for rare bird species.

Initial site investigations are estimated to take around 2 years. Complete site investigations would take 3.5 to 4 years, with several drilling stages.

The airborne measurements will comprise geophysical surveys and flight-line separations of 50-100 m are proposed. Magnetic, electromagnetic and radiometric surveys are mentioned as possibilities. Ground-surface surveys are stated to be likely to include:

- inventory and documentation of the area's ecosystem;
- geological mapping;
- ground geophysical surveys;
- hydrological surveys; and
- hydrogeochemical studies.

Documentation of ecosystems will include follow-up studies of how they are affected by the site investigations. Geological mapping will include sampling of rock and soil. In some areas, shallow excavations may be necessary to expose bedrock. In areas of deep soil, drilling may be used to help determine the depth of the rock surface and to obtain samples.

3.1.2 Types of Information to be Determined

The investigations are required to determine the following types of information:

- the distribution and homogeneity of the rock types (and in particular whether potentially exploitable valuable minerals are present);
- locations of regional plastic shear zones, and locations of regional and local major fracture zones;
- statistical description of fractures and local minor fracture zones;
- initial rock stresses, as well as the distribution of the mechanical properties of the rock and the fractures (strength, deformation properties and coefficient of thermal expansion);

- the thermal conductivity of the rock and natural temperature conditions at repository depth;
- the statistical distribution of groundwater flux within the planned deposition areas;
- permeability and assessment of possible technical construction difficulties related to the fracture zones that need to be passed during the underground construction work;
- the natural hydraulic gradient conditions at repository level;
- chemical parameters that indicate the absence of dissolved oxygen in the groundwater, i.e. redox potential, occurrence of divalent iron, or occurrence of sulphide;
- total salinity of the groundwater;
- pH, concentrations of organic substances, colloid concentrations, ammonium concentrations, concentrations of calcium and magnesium, and concentrations of radon and radium;
- statistical description of the transport resistance of flow paths from the deposition area;
- statistical distribution of matrix diffusivity and matrix porosity along conceivable flow paths; and
- description of surface ecosystems and other ground conditions.

It is stated that discipline-specific programmes are being developed. The seven disciplines identified are:

- surface ecosystems;
- geology;
- hydrogeology;
- hydrogeochemistry;
- rock mechanics;
- thermal properties; and
- transport properties of the rock.

Surface ecosystems, geology, hydrogeology and hydrogeochemistry, as well as rock mechanics, to some extent, are stated to be the disciplines that dominate the field investigations. Geophysics is considered as a supporting activity under geology. Geophysical activities include lineament interpretation from digital topographic databases as a complement to interpretation of airborne geophysical maps, seismic surveys, and gravimetry and resistivity measurements. Geodetic levelling for the study of slow neotectonic (or glaciotectonic) movements is also mentioned, as is the establishment of a seismological observation grid at an early stage.

As a particular emphasis in this review is the geosphere-biosphere interface, it is relevant to note that surface water and groundwater conditions and chemistry will mainly be studied by:

- hydrological mapping;
- inventory (not well defined); and
- sampling of watercourses, springs and existing wells.

It is stated that a monitoring programme is being established for all hydrological and meteorological parameters that should be recorded over the long term. Examples of parameters of interest are the groundwater table in the area, deeper groundwater hydraulic heads, precipitation, temperature, potential evaporation and runoff in water courses.

Descriptions of ecosystems are to include biotope (presumably intended to mean community or habitat) and vegetation mapping, and interpretations of aerial and satellite images. A principal emphasis of this work seems to be on identifying areas requiring special consideration from the point of view of nature conservation. However, proposals are included for long-term measurements of water chemistry, hydrology, and flora and fauna.

Once a priority site has been identified within the candidate area, exploratory drilling to depth is proposed. This is to comprise a few (2-3) deep cored boreholes (to depths of 500-1000 m) and a number of percussion boreholes (to depths of about 200 m). Both vertical and inclined boreholes are proposed. A primary aim of the programme is to identify and characterise deformation zones. It is stated that drilling will probably be preceded by seismic reflection surveys comprising intersecting profiles a couple of kilometres in length. Such seismic surveys would provide complementary information on deformation zones.

The report recognises that drilling of the first deep borehole will entail disturbance of the deep groundwater conditions. It states that it is essential to carry out an optimal hydrogeological and hydrochemical programme in this particular hole.

Rock stress measurements are also proposed, both by overcoring and by hydrofracturing, with the hydrofracturing studies deferred until all water sampling and sensitive hydraulic tests have been carried out.

Following from the ‘initial investigation programme’, the ‘complete investigation programme’ is characterised by an expanded drilling programme. It is stated that the total number of boreholes required to achieve sufficient knowledge cannot be determined in advance. However, a typical number of 10-20 is estimated.

The overall information to be obtained by discipline and at different stages of the programme is conveniently summarised in a series of tables. Those for surface ecosystems, geology, hydrogeology and hydrochemistry are reproduced as Tables 3.1 to 3.4 below. The succession of activities is feasibility studies (FS), initial site investigation (ISI), complete site investigation (CSI) and detailed characterisation (DC).

Table 3.1: Characterisation of Surface Ecosystems

Parameter Group	**Parameter**	**Determined Primarily During**			
		FS	**ISI**	**CSI**	**DC**
Forestry	Quantity		*	*	
	Production		*	*	
	Rotation		*	*	
	Age structure	*	*		
Agriculture	Production, crops		*	*	
	Animal husbandry, meat production		*	*	
	Number of farms	*	*		
	Position	*	*		
	Area	*	*		
Fishing/ Hunting	Fishing licences, number	*	*		
	Catches	*	*		
	Professional fishermen, number	*	*		
Outdoor recreation	Berry and mushroom picking			*	
Climate	Ground frost, number of days and depth		*		
	Ice formation and break up		*		
	Wind force and direction			*	
	Air pressure			*	
	Sunshine, hours of daylight, insolation and angle			*	
	Vegetation period			*	
Deposits	Soil, type and thickness		*	*	
Toxic pollutants and radionuclides	Radionuclides in biomass		*		
	Toxic pollutants in biomass		*		
Flora	Type of vegetation	*	*		
	Key habitat	*	*		
	Population		*		
	Production		*		
	Species of vascular plants, fungi, lichens, mosses and algae		*		
	Red-listed species		*		
Flora (cont.)	Species and number (mammals, reptiles and birds)				
	Biomass		*		
	Production		*	*	
	Red-listed species	*	*		
Lakes and watercourses	Lake types		*		
	Sediment type		*		
	Oxygen content		*		
	Oxygenation		*		
	Stratification		*		
	Light conditions		*		
	Temperature		*		

Table 3.1: Characterisation of Surface Ecosystems (cont.)

Parameter Group	Parameter	Determined Primarily During			
		FS	ISI	CSI	DC
Sea	Water turnover		*	*	
	Currents		*	*	
	Degree of exposure (shore)		*		
	Sediment type		*		
	Oxygen content		*		
	Oxygenation		*		
	Stratification		*		
	Light conditions		*		
Supporting data	Surface geology		*	*	
	Surface hydrogeology		*	*	
	Surface hydrogeochemistry		*	*	
	Surface transport properties		*	*	

Table 3.2: Characterisation of Geology

Parameter Group	**Parameter**	**Determined Primarily During**			
		FS	**ISI**	**CSI**	**DC**
Topography	Topography	*	*		
Soil cover	Thickness of soil cover		*	*	
	Mineral soil distribution	*	*		
	Mineral soil description		*		
	Soil		*		
	Bottom sediment		*	*	
	Indication of neotectonics		*		
Bedrock rock types - occurrence	Rock type distribution (spatial and percentage)	*	*	*	*
	Xenoliths			*	*
	Dikes	*	*	*	*
	Contacts		*	*	*
	Age			*	
	Ore potential – industrial minerals	*	*		
Bedrock types - description	Mineralogical composition		*	*	*
	Grain size			*	*
	Mineral orientation			*	*
	Microfractures			*	*
	Density		*	*	
	Porosity			*	
	Susceptibility, gamma radiation *etc.*		*		
	Mineralogical alteration/weathering		*	*	*
Bedrock structures - plastic	Folding (extent/age)		*	*	*
	Foliation (extent/age)		*	*	*
	Lineation (extent/age)		*	*	
	Veining (extent/age)		*	*	
	Shear zones (extent/age/properties)	*	*	*	
Bedrock structures – brittle – regional and local major fracture zones	Location	*	*	*	
	Orientation		*	*	
	Length	*	*	*	
	Width		*	*	
	Movements (size/direction)			*	
	Age			*	
	Properties (no. of fracture sets, spacing, block size, fracture roughness, fracture filling, weathering/alteration)		*	*	*
Bedrock structures - local minor fracture zones	Location/density		*	*	*
	Orientation			*	*
	Length		*	*	*
	Width			*	*
	Movements (size/direction)			*	*
	Age			*	*
	Properties (no. of fracture sets, spacing, block size, fracture roughness, fracture filling, weathering/alteration)			*	*

Table 3.2: Characterisation of Geology (cont.)

Parameter Group	Parameter	Determined Primarily During			
		FS	ISI	CSI	DC
Bedrock structures – fractures – data for stochastic description	Density (different sets)		*	*	*
	Orientation		*	*	*
	Trace length		*	*	*
	Contact pattern			*	*
	Aperture width			*	*
	Roughness			*	*
	Weathering/alteration			*	*
	Fracture filling			*	*
	Age			*	*

Table 3.3: Characterisation of Hydrogeology

Parameter Group	**Parameter**	**Determined Primarily During**			
		FS	**ISI**	**CSI**	**DC**
Deterministically modelled fracture zones	Geometry – regional and local fracture zones	*	*	*	*
	Deterministic or statistical distribution of transmissivity or hydraulic conductivity		*	*	*
	Storage coefficient		(*)	*	*
Stochastically modelled fracture zones, fractures and rock mass	Geometry – rock volumes with similar hydraulic properties	(*)	*	*	*
	Statistical description of the spatial distribution and geometric properties of the fracture zones. Statistical distributions of transmissivity or hydraulic conductivity.		*	*	*
	Statistical distributions of specific storage and storage coefficient		(*)	*	*
Soil strata	Geometry – soil volumes with similar hydraulic properties		*	*	
	Hydraulic conductivity		(*)	*	
	Specific storage		(*)	*	
Hydraulic properties of groundwater	Density, viscosity and compressibility		*	*	*
	Salinity		*	*	*
	Temperature		*	*	
Boundary conditions and supporting data	Meteorological and hydrological data	*	*	*	(*)
	Recharge/discharge areas		*	*	*
	Pressure or head in borehole sections and surface water courses		*	*	*
	Groundwater flow through boreholes		(*)	*	*
	Regional boundary conditions: historic and future development		*	*	(*)

Table 3.4: Characterisation of Hydrochemistry

Parameter Group	**Parameter**	**Determined Primarily During**			
		FS	**ISI**	**CSI**	**DC**
Variables	pH, Eh		*	*	*
Main components	Total dissolved solids: Na, K, Ca, Mg, HCO_3, SO_4, Cl, Si		*	*	*
Trace substances	Fe, Mn, U, Th, Ra, Al, Li, Cs, Sr, Ba, HS, I, Br, F, NO_3, NO_2, NH_4, HPO_4, Rare Earth Elements (REE), Cu, Zr		*	*	*
Dissolved gases	N_2, H_2, CO_2, CH_4, Ar, He, C_xH_x, O_2		*	*	*
Stable isotopes	^{2}H in H_2O, ^{18}O in H_2O and SO_4, ^{13}C in dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC), ^{34}S in SO_4 and HS, $^{87}Sr/^{86}Sr$, ^{3}He, ^{4}He		*	*	*
Radioactive isotopes	Tritium, ^{14}C in DIC and DOC, $^{234}U/^{238}U$, ^{36}Cl, ^{222}Rn		*	*	*
Others	DOC, humic acids, fulvic acids, colloids, bacteria		*	*	*
Fracture-filling minerals	$\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, $^{235}U/^{238}U$, morphology in calcite and iron oxides			*	*

Based on the investigations, it is proposed that a three-dimensional, geoscientific model of the rock should be developed. This model would consist of different geometric units in the soil and bedrock, these being essentially determined by the geometry of the fracture zones, and the distribution of Quaternary deposits and rock types. Each geometric unit would be characterised by:

- the geological conditions;
- the mechanical, thermal, hydraulic and chemical properties; and
- other properties of importance for radionuclide transport.

In addition, surface ecosystems would be described.

The geoscientific model is mainly to be developed to permit forecasts of the future evolution of the repository with the aid of mathematical modelling tools in safety assessment.

Both local site and regional models are proposed, with the regional site models being used to set boundary conditions and to put the local models in their context.

In the context of surface ecosystems, it is stated that they will be described in terms of biotopes (flora and fauna), activity (land use, uptake rate), transport of water and particles (meteorological and hydrological data) and hydrogeological properties of the soil strata (permeability, thickness and porosity). In addition, the processes of post-glacial land uplift and shoreline displacement are to be described. Shoreline displacement is stated to be used for erosion models that describe the transport of sediments and the formation of Quaternary deposits. Succession models are proposed to describe how vegetation changes with time and to give information on potential resource utilisation in the area. System ecology models are also mentioned as descriptions of the flow of materials through ecosystems.

The proposed strategy for geoscientific model development is given in Table 3.5.

Table 3.5: Proposed Schedule for Geoscientific Model Development

Investigation Phase	**Basis**	**Coverage**	**Geoscientific product/model**
Initial site investigation	Feasibility studies. Processing of existing data. Field checks.	Part of municipality and regional environs where priority site will be chosen.	General model on regional scale (version 0).
	General surveys from air, surface and short boreholes.	Candidate area (and priority site)	General model (version 1.1). Choice of priority site.
	Investigations from surface and some deep boreholes.	Priority site. (Regional environs)	Preliminary model on local and regional scale (version 1.2).
Complete site investigation	Investigations in many deep boreholes and supplementary ground surveys.	Priority site. Regional environs.	Model on regional and local scale, site description (version 2.1).
	Further deep borehole and supplementary ground surveys.	Priority site. Regional environs.	Revised model on regional and local scale, site description (version 2.2).
	More supplementary surveys.	Priority site. Regional environs.	Finished model on regional and local scale, site description (version 2.x).

3.2 SKB Report R-01-09

SKB Report TR-00-20, discussed in Section 3.1, deals mainly with characterisation of sites as they are at the present day. Although processes such as post-glacial uplift are mentioned, they are not covered in detail. This means that SKB Report TR-00-20 provides only limited insight into the types of palaeoenvironmental data that might be collected and the methodology that might be used for interpretation of those data. However, insight into this aspect of site investigation can be obtained from SKB Report R-01-09, which summarises SKB's characterisation of the terrestrial biosphere in the SFR region. The report was produced as part of the SKB SAFE project (Safety Assessment of the Final Repository for Radioactive Operational Waste). The aim of the SAFE project was to update the previous safety analysis for SFR-1, a facility for disposal of low and intermediate level radioactive waste that is situated in bedrock beneath the Baltic Sea, 1 km off the coast near the Forsmark nuclear power plant in Northern Uppland about 60 km north of Stockholm.

Report R-01-09 emphasises development of vegetation in the area, on the grounds that production, decomposition and storage of organic material vary strongly between vegetation types, and that this has substantial implications for the transport of radionuclides. Overall, the history of vegetation in the area is shown to be due to interactions between changes in climate, shore displacement, local vegetation development and human activities. The history of vegetation change is followed from just after the Last Glacial Maximum (LGM) through to the present day. A general outline of the likely future evolution of vegetation in the area to the year 5000 AD is presented.

The SFR site is located in Köppen-Trewartha climate class DClo. However, it is only marginally continental, with an annual mean monthly temperature range of 18^{o}C, from about -2^{o}C (February) to 16^{o}C (July and August). The annual precipitation is about 650 mm, peaking in late summer. The region is transitional between inland woodlands and the coasts and archipelagos of the Baltic Sea. Rich soils exist on the sub-Cambrian peneplain, but areas closer to the coast exhibit more exposed bedrock. The coastal location creates a mosaic of small habitats that results in enhanced biodiversity, particularly in respect of the number of breeding bird species.

In the terrestrial environment, large areas of wetland and coniferous forest are developed over a calcareous moraine. The most common forest type is 70-year-old pine forest with Pine (*Pinus sylvestris*) 40-60%, Spruce (*Picea abies*) 20-40%, Birch (*Betula pendula*) 10-20%, Oak (*Quercus robur*) <1% and other broad-leaved trees 5-10%. Closer to the coast, the amount of Pine increases relative to Spruce. The most common undergrowth is of herbacious plants that flourish in nutrient-rich, calcareous areas. Arable agriculture and grazing land together occupy about 30% of the land area (see Figure 2-3 of R-01-09).

The Forsmark catchment area has a high percentage of wetlands compared with Uppland overall. Oligotrophic hardwater lakes surrounded by mires are characteristic. Undergrowth mainly comprises various shrub species and peat mosses. Streams and rivers are rare, because of the flat terrain. There are only a few unexploited lakes in the vicinity, as the majority are dammed, lowered or turned into cultivated land. These lakes originated as cut-offs from the Baltic Sea and have been subsequently raised as a result of post-glacial uplift, with its associated shoreline displacement. The lakes are often small and shallow and their swampy shores are vegetated with Rush (*Schoenoplectus lacustris*), Reed (*Phragmites australis*) and Sedges (*Carex spp.*).

Because of post-glacial uplift (currently 5.5 mm y^{-1}), new land areas are continually emerging from the sea. Inshore islands are dominated by broad-leaved trees and thickly wooded vegetation. However, the small islands of the outer archipelago have a high degree of exposed bedrock. Their vegetation is highly influenced by guano, which favours specific lichens. Inland on these small islands, the poor, thin soil tends to favour drought-resistant species such as Sea Campion (*Silene uniflora*), Biting Stonecrop (*Sedum acre*), Woad (*Isatis tinctoria*), Scentless Mayweed (*Matricaria perforata*) and Chives (*Allium schoenoprasum*). Rocky and sandy shores are often colonised by Hawthorn (*Hippophaë rhamnoides*). Groups of trees also develop on these outer islands.

Historic changes in the vegetation of the archipelago were characterised in terms of several spatial and temporal scales. Long-term changes included regional changes in the species ‘pool’ due to migration and altered environmental conditions. On a shorter timescale, colonisation from the mainland to the islands was considered to create a continuous regional succession, resulting in an acceleration of the early stages of vegetation development of a particular island. Superimposed on these natural changes, there are the effects of human management, as the archipelago has, during some periods, been actively managed for cattle breeding and farming.

Södertörn, a peninsula 60 km south east of Stockholm has been well-investigated in terms of palaeoenvironmental reconstructions of the period since the LGM. It was, therefore, used as a model of likely changes in the SFR region. Ice retreat from the area began at around 10 ka Before Present (BP). A decrease of about 50 m in relative sea level occurred between about 9 ka BP and 8.5 ka BP. Thereafter, sea-level has declined more slowly, with another 50 m of fall over the last 8.5 ka. The fall over this period is approximately linear. However, oscillations have resulted in brief periods of rising sea level and associated marine transgressions.

In terms of vegetation, Pine (*Pinus sylvaticus*), Birch (*Betula spp.*) and Hazel (*Corylus avellana*) were the first to colonise the skerries that emerged from the sea at around 10 ka BP. A few hundred years later, Elm (*Ulmus glabra*) and Oak (*Quercus robur*) reached the region. Both Lime (*Tilia cordata*) and Ash (*Fraxinus excelsior*) arrived later. Spruce (*Picea abies*) expanded much later, at about 2.5 ka BP). Although the palynological data show strong similarities in the vegetation successions on the emerging islands, differences do occur. These may be due to distinctions in micro-climate or land use. Clear biogeographical distinctions are also present, with the number of species of vascular plants present on each island decreasing from west to east, reflecting distance from the mainland. Soil development on the islands is dependent on debris, litter from established organisms and guano. Therefore, organic-rich soils are characteristic. Winter ice at the coastline can create scars in which Alder (*Alnus glutinosa*) flourishes.

Based on the historical data on environmental change, projections are made of potential changes in the SFR region at around 3000 AD, 4000 AD and 5000 AD. In making these projections, the basic assumptions adopted are that:

- the climate is not changing, but that change is driven mainly by shore displacement;
- shore displacement occurs at the current rate throughout the period;
- the species 'pool' remains relatively constant, i.e. the species that are the dominating elements in the vegetation remain the same;
- the species do not change their ecological habits and the niches remain constant; and
- human agriculture is absent in the area and the vegetation is left for free development or managed for forestry, i.e. the cultural landscape is not taken into account.

Around 3000 AD, the flora is assessed as very close to that seen in corresponding areas today. However, the spatial distribution of that flora will be somewhat different because of shoreline displacement. By 4000 AD, the major part of the area is assessed to have become terrestrial. There remains a bay with a narrow mouth, which is considered to be encroached with reeds and rushes, making it appear as open, wet grassland. The lower parts of the coastal area are considered to be covered by deciduous forests, dominated by Alder (*Alnus glutinosa*) in wet areas and Ash (*Fraxinus excelsior*) in less wet sites. The deciduous forests are assumed to be successively invaded by pine (drier areas and mires) and spruce (wetter areas). Such pine and spruce forests are considered to dominate at higher altitudes. By 5000 AD, a large and a small lake remain in the SFR area. Coniferous forests dominate, with some mixed forest at lower altitudes. Pure deciduous forest is considered to remain in moister areas in depressions, along the shores of lakes, and in areas where the terrestrial habitat is of recent date.

3.3 SKB Report TR-01-29

3.3.1 Overview

This report expands upon the material in SKB Report TR-00-20. It describes proposed site investigation methods and the overall programme of such investigations. Like Report TR-00-20, it is generic in nature and does not describe the adaptations of the methods and programme that would be required at a particular site.

As there is considerable duplication of material that is covered in Report TR-00-20, this summary describes only additional material presented in Report TR-01-29.

A key feature is that the main stages of initial and complete site investigations are to be broken down into smaller steps. In general, each new step consists of confirming or rejecting the main results of a preceding step, answering questions that have come up and achieving the goals set for a particular stage. It is made clear that characterisation of surface ecosystems needs to be commenced early and is, therefore, concentrated in the initial site investigation, with follow up measurements and monitoring performed in later stages.

In the stage of initial site investigation leading up to selection of the primary site, the geological investigations will be focused on creating a regional understanding of rocks and soils. The hydrogeological investigations will be mainly focused on a preliminary definition of the area that must be included in the regional hydrogeological model. It is made clear that the emphasis will be on characterisation of the near-surface zone, as well as providing a general description of hydraulic boundary conditions and natural variations in groundwater level. Hydrochemical activities will relate primarily to investigations of near-surface groundwaters, lakes and watercourses, sampling in percussion boreholes after drilling and the initiation of long-term monitoring.

When the primary site has been selected, the investigations will be focused on characterising conditions at depth. Work on surface ecosystems will involve data collection only within the primary site, though regional monitoring will also continue. Geological investigations will focus on fractures and fracture zones, using seismic reflection analyses to complement results from 2-3 deep boreholes. Rock mechanical investigations will focus on rock stresses measured in one or more cored boreholes. Thermal studies will involve downhole temperature measurements and studies of the thermal properties and composition of core.

The initial hydrogeological investigations of the site are stated as being aimed at providing a general picture of water-bearing properties of the rock from the ground surface down to a depth of approximately 1,000 m. In addition, a continued and expanded regional monitoring programme is to be undertaken, to improve understanding of boundary conditions. Pump and flow tests in the boreholes will give an indication of conditions at depth, but SKB acknowledges that a comprehensive description cannot be provided from only 2-3 boreholes.

Hydrogeochemical studies will be directed to obtaining details of groundwater composition from a chemistry prioritised borehole complemented by less detailed studies in all other boreholes, including those constructed by percussion drilling. Studies of fracture-fill minerals will be initiated towards the end of this stage of investigation.

Transport properties of the rock will be estimated mainly on the basis of the hydrogeological and hydrogeochemical description, combined with generic information. However, where mineralogy and/or groundwater chemistry differ significantly from the generic database, laboratory investigations, e.g. through diffusion measurements, will be initiated.

During the complete site investigations, more deep boreholes will be drilled in sub-steps of 2-4 cored boreholes. Studies of surface ecosystems will comprise follow-up investigations of seasonal variations, continuation of long-term monitoring and the generation of quantitative inventories of terrestrial and aquatic flora and fauna. Geological investigations will be dominated by borehole studies. Surveys and measurements at the ground surface will mainly be a supplement to more extensive earlier programmes of work. Expanded rock mechanical and thermal programmes will be carried out, with an emphasis on the zone in which a repository would be located. The hydrogeological programme will involve a large number of hydraulic tests in boreholes. However, regional monitoring will be continued and extended. It will include measurements of meteorological characteristics, runoff and groundwater levels. Hydrochemical studies will be concentrated on deep groundwaters. Studies on transport properties are likely to include laboratory experiments on extracted materials and *in situ* tests, including tracer tests.

Major aspects of the complete site investigation are defined by SKB as follows.

- The site shall be well-defined geographically and the site-descriptive models shall cover the entire volume (local model). Similarly, the depth boundary of the investigation area shall be well-defined.
- The regional model area shall be geographically well-defined.
- Borehole positions and directions are chosen in order to locate and characterise individual fracture zones and different rock units. Different borehole directions

and inclinations are to be used to achieve statistical representativeness for parameters that may be directionally dependent, such as fracture frequency and hydraulic conductivity.

- The investigation boreholes are to be planned and executed to minimise disturbance of other ongoing investigations, particularly hydrochemical sampling and hydraulic tests. Two holes may be drilled simultaneously to provide drilling-free lulls for investigations.
- Measurement data are to be recorded, samples taken and tests performed during drilling to satisfy the data needs of the various disciplines.
- Which investigations are to be conducted in a finished borehole depends on the main purpose of the borehole in question. However, in order to obtain a uniform body of basic knowledge for all boreholes, a base programme will be carried out in each one. This base programme will differ for cored and percussion-drilled boreholes.
- Certain boreholes will be prioritised for particular disciplines, but will also be used for other purposes.

The continuation of monitoring programmes on the ground surface and in boreholes is considered to be an important component of the complete site investigation phase, so that uninterrupted time series are obtained. It is also noted that one objective of the ongoing investigations of surface ecosystems is to ensure that the execution of site investigations can be adapted to protect valuable landscape elements and biological diversity.

Primary data from the site investigations are to be entered into a site-specific database. Based on this information, a three dimensional, primarily geoscientific, site descriptive model is to be built up. SKB states that it intends to build up and present discipline-specific models within this overall geometric framework. A brief presentation of the structure and content of discipline-specific models is provided and is reproduced as Table 3.6.

Table 3.6: Structure and Content of Discipline-specific Models

Name of model	
Purpose of model	Presentation of what the model will be used for.
Process description	Explanation of which process is handled in the model; equations used in the process description are identified where applicable.
Constituents of Model	
Geometric framework	Presentation of the dimensions of the model and the geometric boundaries of the model area. Specification of the model's (geometric) units, how they are generated and which geometric parameters are included in the background material.
Parameters	Specification of which parameters are included in the model. Presentation of the origin of data and/or how values are determined.
Data representation	Presentation of how parameter values have been distributed within the model's geometric units.
Boundary conditions	Specification of type and geometry for boundary conditions, as well as initial state and how they have been determined.
Numerical tools	Presentation of mathematical formulas or computer programs that are used in process simulation.
Calculation results	Presentation of the results that are obtained in numerical simulation/calculation.

The site descriptive model will be represented using GIS and the CAD-based Rock Visualisation System (RVS). SKB states that conversion procedures are being developed so that the RVS model can be exported to mathematical calculation tools.

The report includes an extensive discussion on borehole siting emphasising the need for optimising locations and characteristics with respect to information acquisition. However, there is little that can be said quantitatively prior to developing investigation plans at a specific site. A key point is that a 'respect distance' is proposed between the boreholes and the deposition area. Thus, the deposition area and the rock column immediately above it would appear not to be investigated in borehole studies.

In the interpretation of results from field investigations, consideration is given to issues of upscaling. Stochastic approaches are mentioned at the local scale. However, it is explicitly stated that, at the regional scale, it is sufficient for most purposes to stipulate mean values for the properties of each geometric unit. This implies the prescription of deterministic boundary conditions for the local model, if these boundary conditions are computed from the regional model.

Prediction of the results of forthcoming investigations is an integral part of the programme. The point is made that such predictions can be used both to optimise investigation work and to test the reliability of the predictive models. Uncertainties in interpretation are recognised and it is stated that these will be assessed and quantified after each investigation step. There is clear recognition that the data must be interpreted in an historical context. Thus, SKB states that it is essential that the models can credibly explain the current state of the site based on processes that are changing this state, e.g. by taking into account the earlier climatic evolution with associated changes in hydrogeological and chemical boundary conditions.

3.3.2 Programme for Initial Site Investigations

Much of the information on the characterisation of surface ecosystems during the initial site investigation is as described in relation to Report TR-00-20. However, under geology, it is made clear that excavations across major fracture zones will be used to ascertain the character of those zones. It is further stated that any indications of post-glacial movements in rock and soil strata will also be investigated in this context.

Additional information is given on the hydrogeological mapping that is proposed. This will be done at the same time as the geological mapping. It will include mapping of springs, streams, discharge areas, dam projects, drainage schemes and land use. Existing wells will be characterised, e.g. in terms of production and drawdown. The need for soil texture analyses is explicitly recognised and hydraulic testing of soils is recognised as relevant. The need for a local meteorological station is recognised, as is the requirement for flow monitoring of water courses.

The hydrogeological model prepared at the time of the initial site investigation will be prepared, for the most part, on a regional scale and will be based chiefly on two-dimensional information. The hydrological description will include information on discharge basins, runoff, meteorology and interpreted recharge and discharge areas. Descriptions of groundwater recharge and natural variations in groundwater level will also be included. A subdivision of soil layers into hydraulic units will be made, based on the Quaternary geological mapping. Rock transmissivities will be roughly determined for the near-surface portions of major fracture zones and for the bulk rock on a spatial scale of ~100 m. Based on this information, regional-scale calculations of groundwater flow will be undertaken to determine recharge and discharge areas and to study how different boundary conditions influence the calculated flow field.

Hydrochemical sampling is complementary to the hydrogeological studies. Hydrochemical data will be used to provide a general description of the hydrological systems in the area and to confirm hydrogeologically identified recharge and discharge areas.

Before the area is overly affected by drilling, a comprehensive analysis of surface waters and near-surface groundwaters is proposed. This will be followed by a two-year monitoring campaign at selected locations to give an indication of temporal (including seasonal) variations. Long-term monitoring will then continue through into the detailed site characterisation phase.

Precipitation sampling and analysis will also be carried out. In addition, a limited programme of sampling and analysis of pore waters from sediments will be undertaken.

Samples will be taken from wells during the survey campaign. Water samples will be taken from soil pipes. These are expected to provide a good picture of near-surface groundwater systems. Results can usefully be compared with those obtained for well-water samples. Soil pipes can provide good coverage over the area and can be used to investigate the hydrogeochemistry associated with different land use types. In total, up to 200 soil boreholes could be constructed at a site (with up to 150 in the two sub-steps of the initial site investigation).

When the priority site has been identified, the deep borehole programme will be complemented by field mapping of soil types. Eexcavation and drilling techniques will be used to obtain samples in order to study the sequence of soil strata and the character of the soils.

Hydrogeological studies in the deep boreholes are described and include:

- pumping tests performed every 100 m during core drilling and whenever water samples are taken during drilling;
- pumping and flow logging after borehole completion, with pressure responses monitored in adjacent boreholes, as appropriate;
- hydraulic injection tests or differential flow logging over limited lengths (~20 m) within the 100-700 m depth interval;
- possible pumping tests between packers, e.g. if the borehole penetrates a fracture zone of high hydraulic conductivity; and
- groundwater flow measurements in a selection of short sections of a couple of cored boreholes.

In the context of hydrogeochemistry, it is noted that hydrochemical logging of each borehole will be undertaken shortly after completion of drilling. Complete chemical characteriation using a mobile field laboratory will be commenced within one month of drilling.

3.3.3 Programme for Complete Site Investigations

In the context of complete site investigation, more details are given on what is meant by the determination of quantitative inventories of flora and fauna. The coverage of dominant vegetation types and faunal belts will be determined, stratified sampling will be used to provide total biomass estimates (g C m^{-2}) and species determinations will be made of the dominant taxa. For lakes and mires (and possibly the sea), biological production and nutrient turnover will be measured at different seasons. During complete site investigation, more deep boreholes will be constructed, but the range of studies conducted will be similar to that in the initial deep boreholes. Extensive studies of rock stress and thermal properties will take place at this stage, but these are of limited interest in the current context. Hydrogeological tests in boreholes include interference tests. Initial tests are proposed with pumping for three days and monitoring recovery over one day. However, towards the end of the site investigation, one or two interference tests are proposed with pumping for 3-6 months and recovery monitored for 1-2 months. SKB states that one of these tests may be combined with a large-scale tracer test.

SKB has set out what is to be achieved through the hydrogeological programme at the end of the complete site investigation phase. This is summarised below.

- Most regional fracture zones and some local major fracture zones within the regional area will be described in general terms with respect to transmissivity and location. Deeper parts of the fracture zones will be based on statistics from within the area where there is knowledge of the rock at depth.
- All known local major fracture zones and regional fracture zones within the site will be described with respect to transmissivity and location.
- Some of the local minor fracture zones within the site will be described with respect to transmissivity and location.
- Local minor fracture zones and fractures will be described statistically with respect to transmissivity, frequency of occurrence and spatial distribution. The degree of detail will be higher at repository depth.
- Hydraulic conductivity on the 100 m scale will be specified statistically within the site from the ground surface down to ~1,000 m and will be specified roughly statistically within the regional area down to at least 1,000 m.
- Hydraulic conductivity on the 20 m scale will be specified statistically within the site from the ground surface down to ~1,000 m and will be specified roughly statistically within the regional area down to at least 1,000 m.
- Hydraulic conductivity on the 5 m scale will be specified statistically within the site from a depth of 300 m down to about 700 m.

- An assessment will have been made as to whether anisotropic hydraulic conditions prevail, based on geological and rock mechanical models, and the results of injection tests and interference tests.

On this basis, both regional and local groundwater flow calculations will be undertaken.

Hydrochemical analyses at this stage are an extension of, and supplementary to, those described for the initial phase of site investigations.

In the context of transport properties of the rock, laboratory studies will include batch sorption, through diffusion, gas diffusion and porosity measurements. Field measurements will include groundwater flow measurements, single-hole tracer tests and multi-hole tracer tests. New methods are being developed for measuring *in situ* sorption in single-hole tracer tests, radon measurements of transport resistance and resistivity measurements of matrix diffusivity.

3.3.4 Detailed Aspects of Site Investigation

Having provided an overview of the site investigation programme, Report TR-01-29 gives more detailed accounts of the work to be undertaken on a discipline-by-discipline basis. In general more information is provided than is relevant to this overall review. Furthermore, the material largely documents standard techniques and good practice. However, the following specific points are noted.

- A geological evolution model is proposed, describing how the rock types were formed and altered. This also includes Quaternary geological evolution.
- The hydrogeological description of the soil cover is based on a system of domains, with the hydraulic properties within each domain regarded as uniform.
- Fracture network and continuum models are proposed for groundwater flow modelling.
- Measurement stations for lake levels and sea level may be established, as well as measurement stations for river flows.
- The inventory of existing wells will also include observation pipes. It will include the taking of water samples and measurements of groundwater levels. A slug test is recommended in all observation pipes to be used for groundwater level observations. Capacity tests will be conducted as needed.
- Under hydrogeochemistry, it is recognised that, for safety assessment purposes, parameter values are needed for pH, Eh, colloids, fulvic and humic acids, other organic material, bacteria, nitrogen compounds, sulphide, sulphate, carbonate, phosphate and total salinity. Equilibrium and reaction path codes are proposed

for use in modelling the hydrogeochemical data. The main aim is characterisation of the distribution and mixing of water masses, taking into account the perturbative effects of site investigations.

- Fracture-fill mineral analyses will include U-Th and ^{14}C dating, as appropriate. Gouge materials as well as minerals will be subject to analysis.
- The main aims of the surface ecosystem programme are: to characterise the undisturbed ecosystems in the candidate areas; to collect relevant data for safety assessment and design; to obtain a general understanding of the candidate area's surface ecosystems, so as to be able to develop and justify models and make predictions of the area's future evolution; and, with the aid of collected data, to present a framework for the further execution of the investigations with consideration for nature and the environment.
- Reference is made to the need to describe future ecosystems up to the next ice age. However, almost all the discussion relates to characterisation of the ecosystem at the present day.
- Table 10-1 of the report shows that many components of geology, hydrogeology, and hydrogeochemistry feed into the overall description of surface ecosystems.
- In ecological characterisation, a high emphasis seems to be placed on the characterisation of key habitats in which red-listed (threatened) species are found. However, more general vegetation mapping is planned. There is an emphasis on determination of the production of biomass, as a basis for determining flows of carbon, water and nutrients. In turn, these flows are to be used to calculate radionuclide turnover in the ecosystems.
- Current levels of toxic pollutants and radionuclides in biota will be determined from existing monitoring data held by the Swedish Environmental Protection Agency and SSI. Supplementary data may also be obtained, as appropriate.
- Peat bogs in the area will be investigated in terms of thickness and stratigraphy.
- Lake types and ecological functioning will be characterised using a model based on the constituent lake parameters. Considerations include climate zone, altitude, drainage area, morphometry, ecosystems and human impacts. Water courses will be characterised similarly to lakes.
- Characterisation of the sea will include compilation of data on temperature, salinity, currents and water-level variations. Supplementary measurements of hydrochemical and physical characteristics will be collected, as appropriate. Quantitative bottom mapping will be undertaken to determine plant and animal zonation and bottom type. Long sediment cores will also be extracted. During the complete site investigation, water turnover in the area and the exposure of the bottom to wave action will be calculated. The sedimentation environment

will be modelled and compared with conditions over the last 10,000 years, and an assessment will be made of the future sedimentation environment.

3.4 SKB Report P-02-03

Some guidance on the implementation of SKB's procedures for initial site investigation can be obtained from the summary of investigations planned to be carried out at Forsmark and reported in SKB Report P-02-03. The Forsmark area lies between the Forsmark nuclear power plant and the Kallrigafjärden bay. It has an area of 10 km^2, which is relatively small for a candidate area. The main aims of the investigations are identified as:

- determination of the three-dimensional shape of the potential host rock (a tectonic lens);
- evaluation of the potential for occurrences of metal ore at depth;
- investigation of the potential occurrence of gently dipping fracture zones; and
- investigation of the possibility of occurrence of high rock stresses.

More general questions to be addressed related to the frequency of dykes and fracture zones, the hydraulic conductivity of the fracture zones and surrounding bedrock, flow paths for groundwater, and chemical, thermal and rock-mechanical conditions. Long-term changes in surface runoff, groundwater flow and groundwater chemistry were also identified as requiring assessment.

The initial site investigation studies seem to be almost entirely focused on five deep boreholes to ~1,000 m and complementary percussion boreholes to ~150 m. The complete site investigation is characterised primarily in terms of the construction of additional deep boreholes. The studies to be carried out are characterised as:

- core drilling and measurements in the boreholes;
- percussion drilling and measurements in the boreholes;
- geophysical measurements from a helicopter aerial survey;
- geophysical measurements at ground level;
- marine geological investigations;
- mapping of the bedrock;
- studies of the transport properties, strength and thermal properties of the bedrock;
- mapping of soil types and soil thickness, plus hydrological tests in boreholes in the soil;
- hydrological and ecological studies; and

- vegetation mapping, and inventories of birds and mammals.

Monitoring studies are also identified. These cover mainly:

- meteorological and hydrological conditions;
- the natural environment;
- radionuclides and environmental contaminants;
- seismic activity; and
- deformation of the bedrock.

Details of the planned activities are provided in an appendix to the report. In general this adds little to information provided in Report TR-01-29. However, more quantification and detail of surveys and sampling is sometimes given. For example, detailed vegetation mapping will be carried out in six circular sampling plots each with a diameter of about 1 km. Other examples are that sampling of surface waters will take place about 20 times per year at 20 locations and that soil sampling will involve digging sampling pits.

Overall, the main value of the report is as evidence of a commitment to put the procedures set out in TR-01-29 into practice at a specific site.

3.5 SKB Report TR-01-30

SKB Report TR-01-30 comprises an overview of the SKB RD&D programme for 2001. SSI has undertaken a review of this programme. Comments from that review are compiled in Section 3.6, below. Much of Report TR-01-30 relates to issues of limited relevance to site investigation, or which are covered in greater depth in Report TR-01-29. However, TR-01-30 does include a very useful discussion of biosphere and climate evolution issues and it is this material that is summarised below.

3.5.1 Biosphere Issues

Reviews of the SR 97 safety assessment and the preliminary safety assessment of SFL 3-5 were provided by international experts. Reviews of SR 97 were also provided by SKI and SSI.

SKB comment that, in general, these reviewers were positive towards SKB's handling of the biosphere. However, they pointed out shortcomings in the arguments and documentation for the chosen ecosystems, models and data, and a lack of structure in the process descriptions. The reviewers pointed out the lack of a forest ecosystem model, the incompleteness of assumptions regarding peat bogs, and the incompleteness of the description of the transition and interaction between the geosphere and the biosphere. SKB have responded to these various issues and summaries of developments reported in TR-01-30 are provided below.

Some reviewers also commented that they considered time-dependent biospheres to be important. SKB report that they have developed such biospheres in the SAFE project.

SKB demonstrates that it is taking a systematic approach to developing process descriptions in the biosphere by displaying an illustrative example of an interaction matrix. Detailed inspection of this matrix shows it to be well structured and it appears to be developed at an appropriate level for biosphere system description. SKB also draws attention to various review reports in which systematic compilations of biosphere information, e.g. bioaccumulation factors, are provided.

In the context of modelling, SKB describes the move to systems ecology models discussed above. Such models have been developed for ^{14}C and the approach is reported to be promising for caesium. The extent to which the approach can be extended to other radionuclides and elements of interest remains to be determined.

Developments in transport models include a new model for the Baltic Sea that can be used to investigate sensitivities to climate change, salinity alterations and land uplift.

The importance of near-surface hydrology is recognised and studies of near-surface dilution are reported. Modelling of discharge zones is reported and it is stated that a literature study of transport processes in soils is being prepared.

In the context of forest ecosystems, SKB refers to involvement in the Forest Working Group of BIOMASS Theme 3 and to initiation of a project modelling radionuclide transport from groundwater. Forest ecosystem studies are proposed under the SAFE project. The need to differentiate between different types of forest is recognised, as is the close link with surface hydrological studies. The particular importance of wetland forests developing from mires in depressions is highlighted.

The evolution of a marine area to lakes and then mires is included in the SKB programme. Forthcoming work is summarised as:

- description of important processes in the form of a literature compilation;
- refinement of current models;
- studies of the hydrology of mires and wetlands; and
- field studies of mires that exist in candidate areas in order to determine growth rates, isolation times and other parameters, and also to provide information on the long-term evolution of the area.

It is noted that studies on this last point will form part of the site investigation programme.

Studies on sediments are featured in the SKB research programme, largely because radionuclides from a repository are likely to pass through a layer of marine, riverine or lacustrine sediments on entry into the biosphere. Such sediments are identified as potential zones of accumulation of radionuclides that can later be remobilised in association with processes such as land uplift. Organisms associated with sediments can also form a component of food chains to man. Furthermore, although not mentioned in the report, protection of these organisms may be an issue in its own right.

In connection with the SAFE project, the sedimentation environment in northern Uppland has been modelled from approximately 10 ka BP to 5 ka After Present (AP). The study is reported to have shown unexpectedly good agreement with the Quaternary geological map of the area. At present, attempts are being made to predict the thickness of sediment layers using this model. To calibrate the model, new field data have been collected and older, unpublished, data have been compiled. Existing knowledge concerning processes in and on the sediments has also been compiled in two literature reviews. The sequential development of closed-off marine bays, lakes and mires, and the influence of such development on sediment formation have been described. Relevant hydrological processes have both been modelled and studied in two lakes in northern Uppland. A project has also been started to investigate the extent and causes of intense erosion incidents that occurred about 8 ka BP on the bottom of the Baltic Sea. Studies have also been made of the cycling, transport and sedimentation of Chernobyl-derived ^{137}Cs along the Baltic coast.

In future, a major effort is to be initiated to study experimentally the chemical, physical and biological processes that affect sediments from the coast (and possibly lakes). This will be complemented by hydrological modelling of groundwater movement through the sediments and by modelling of radionuclide migration. There will also be modelling of the reworking and accumulation of sediments, supplemented by field data. This overall programme of work is to be integrated with site investigations.

Studies of shoreline displacement since the LGM has been described and variations over several glaciations have also been discussed by SKB. It is noted that future sea-level increases could result in a hiatus in sea-level rise and that a future glacial episode would result in a substantial sea-level fall. Effects of glacial episodes on the salinity of the Baltic Sea are illustrated through a comparison of data and model predictions. It is noted that a compilation has been made of climate changes that have occurred over the last 200 ka and feasibility studies have been undertaken of the possibility of using dripstones from Swedish caves to trace past changes in temperature and precipitation.

In terms of future developments, SKB states that climate change in Scandinavia during an interglacial stage will be studied, with an emphasis on effects on precipitation and runoff. It is identified that more information is required on processes and rates in connection with permafrost and how this affects surface ecosystems. The importance of tundra for radionuclide transport in the biosphere is highlighted. Global warming is addressed only briefly through a declared intention to follow the global warming discussion.

International collaboration is discussed by reference to the BIOMASS and FASSET programmes.

3.5.2 Issues in Climate Evolution

SKB notes that the climate scenario in SR 97 was based on three expected climate-driven process domains: temperate/boreal, permafrost and glacial. At that time a number of areas for further study were identified:

- possible variations of the Scandinavian climate – for the purpose of improving biosphere descriptions, and as a basis for studies of permafrost and ice development;
- development of permafrost in Scandinavia, and the hydrological conditions associated with permafrost;
- the relationship between ice load and stresses/movements in the bedrock;
- mixing of waters of different origins in the rock's system of fractures and pores;
- canister strength (it is not clear why this is listed here);
- buffer erosion with extremely ion-poor groundwater compositions; and
- evolution and performance of the backfill in conjunction with climate change.

Commenting on these issues, SKB states that:

- land uplift processes require further investigation on a 100 ka timescale;
- climate variations due to the greenhouse effect are judged to be covered by the variations included in the temperate/boreal domain; and
- better knowledge of climatic conditions during a glacial cycle is needed to assess the occurrence of permafrost in Sweden – the position of the coastline is important in this context as well.

In the context of studies of the glacial domain, SKB comments that a conceptual model describing hydraulic conditions under a continental ice sheet was presented in SR 97. Several uncertainties in the model were identified requiring further investigation:

- basal thermal regime and occurrence of melt water at the ice-bed interface;
- influx and importance of meltwater from the surface of the ice;
- variations of flows and pressures in time and space; and
- the coupling between hydraulic and mechanical processes beneath, and in the vicinity of, an ice sheet (including the large-scale state of stress and the potential for induction of earthquakes).

Attention is drawn to the description of the palaeohydrology programme provided in the RD&D report for 1998. The purpose of that programme was to:

- identify and improve the understanding of principal climate-driven processes that can influence the performance of a deep repository; and
- compile material for long-term performance and safety assessments.

Subsequently, the European Commission research projects EQUIP (Evidence from QUaternary Infills for Palaeohydrology) and PAGEPA (PAleohydrogeology and GEoforecasting for Performance Assessment) have been concluded. EQUIP tested methods for investigating fracture-fill minerals and evaluated their usefulness for tracing earlier hydrochemical and hydrological conditions. PAGEPA deployed a glaciation model, different hydrological model and a geochemical model to simulate how the composition of groundwater may have varied during the Weischel (Late Devensian) glaciation.

Ongoing work relates to:

- studies of land uplift, integrated with large-scale studies of the tectonic evolution of the Scandinavian Shield;
- compilation of an inventory of the different geological and biological archives on past climate that are available in Scandinavia;
- studies of permafrost and its importance for the safety of a deep repository in collaboration with Finland, Canada and the UK (including a survey of present-day areas with permafrost, model calculations and field studies at a site in Canada);
- coupling between hydraulic and mechanical processes in glacial conditions and their influence on the near field of a deposited canister (EU project BENCHPAR).

3.6 SSI Report 2002:13

This report comprises a review by SSI of the SKB RD&D programme for 2001. Aspects of this review are relevant to site investigation, with particular emphasis on characterisation of the biosphere and the biosphere-geosphere interface. These aspects are summarised below.

a) SSI considers that SKB should prioritise the production of a systematic description of processes in the biosphere, and the transition from the geosphere to the biosphere, in order to provide an adequate foundation from which to carry out site investigations that are geared to the purpose of safety analysis.

b) SSI feels that it may be necessary to carry out simplified scenario and consequence analyses to test the adequacy of the data and models produced for the biosphere, and the transition between geosphere and biosphere.

c) In respect of biosphere research, SSI believes that SKB should:

   - Record the degree of importance given to biosphere issues in the selection of a final site and how the importance of biosphere issues is evaluated in the safety report;
   - Devise a timetable clearly showing how far the biosphere work needs to have progressed prior to the complete site investigations;
   - Present definite plans relating to: the description of biosphere processes, e.g. as recorded in interaction matrices; modelling transitions between ecosystems; process-based, system-ecological model development, including discussion of its importance for the design of complete site investigations; compliance with protection of the environment and the significance of this for complete site investigations; radionuclide transport in the transition between geosphere and biosphere.

d) SSI takes the view that SKB's choice of two sites close to the coast places great demands on the evaluation of climatic effects and places emphasis on the role of the biosphere in safety assessment. SSI recommends that SKB should:

   - evaluate the importance of future changes in sea level for radiological consequences, e.g. releases of radionuclides that have earlier accumulated in sea sediments; and
   - report on expert assessments on the choice of climate scenarios that shed light on discharges in the Baltic Sea, including the possibility that discharges alternatively take place to a terrestrial environment.

e) SSI emphasises the importance of SKB giving priority to R&D activities relating to the collection of biosphere data.

f) SSI regards it as positive that SKB is planning detailed studies of hydrogeological conditions in the transition between geosphere and biosphere. This is an area that should be prioritised, in order, among other things, to obtain access to the knowledge and modelling tools required for carrying out site investigations.

On the topic of scenarios, SSI draws attention to the need to:

- develop the choice of scenarios so that it is more evident how well the chosen scenarios cover the processes and events that can affect the functioning of the repository;
- produce more comprehensive scenarios to ensure that the effects of important disturbances such as earthquakes and glaciation can be evaluated in a complete way;
- clarify scenario safety in a more comprehensive way, e.g. through alternative climate developments; and
- clarify the link between choice of scenarios and evaluation of risk.

SSI further notes that the strategy for selection of scenarios is linked to how probabilities are dealt with, how a weighting together of risks from different scenarios is made and the evaluation of scenario uncertainties.

In the context of geosphere modelling, SSI notes that SKB intends to prepare a validity document for the most important models for consequence calculations. These are identified as models for groundwater flows in the geosphere and for radionuclide transport in the adjacent area, the geosphere and the biosphere. SSI emphasises the need to document biosphere models in a comparable way to other models.

On the topic of system-ecological model development, SSI considers this to be a good complement to the compartment models that have been used to date. System-ecological models are based on mass flows in ecosystems. These flows are, in turn, conditioned by overall productivity. Both flows and productivity are measurable. However, SSI notes that a basic difficulty for all types of model is to determine the constant of proportionality between flows of mass and radionuclides for the large number of radionuclides that are of interest. Nevertheless, SSI supports further development of process-based models. This is because they are based on a fundamental understanding of the structure and function of ecosystems, can make important contributions to the validation and verification of compartment models, and, thereby, also lead to the improvement of such compartment models.

SSI points out that the SKB RD&D programme for 2001 lacks a clear report on selection of radionuclides and further approaches to model development. Furthermore, a timetable is lacking and there is no clear link to site investigations.

On climate development, SSI notes that SKB has underlined the importance of a better description of hydrogeology in permafrost and glacial conditions, the impact of a future ice load on rock and barriers, and changes to the coastline in a glaciation perspective. A timescale of 100,000 years is selected by SKB for the evaluation of climate change.

On the question of inflow and outflow areas, SSI notes that Swedish Nuclear Power Inspectorate (SKI) has drawn attention to a research report produced by the United States Geological Survey (USGS) on behalf of SKI. On the basis of this report (which has not been reviewed as part of this study), SKI considers it evident that flow patterns of the groundwater and depth of the salt groundwater are important for long-term safety and should be taken into account in the siting of a repository. SKI recommends that a preliminary assessment of these issues should be undertaken on the basis of existing data, recognising the substantial uncertainties that are involved. SKI notes the declared intention of SKB to undertake a project on recharge and discharge areas and on the link between near-surface hydrology and deeper groundwater flow.

4 Adequacy of the Proposed Programme

4.1 General Remarks

It is emphasised that, given its scope, the review provided herein can only cover the adequacy of the proposed programme at a high level. In particular, it is not possible to comment on aspects such as the adequacy of techniques or protocols, e.g. in respect of numbers and spatial distributions of samples. Indeed, it would be inappropriate so to do, as SKB emphasises that investigations must be adapted to individual areas and sites.

It is very important that options for site selection should not be foreclosed at an early stage in the programme. Although it will never be possible to demonstrate that the best possible site has been selected, it is appropriate to ensure that a wide range of possibilities has been investigated and that a well-structured decision process has been used in determining the preferred repository location. In this context, the identification of several candidate areas and the undertaking of initial investigations to bring them all up to the same knowledge level are commended. In particular, it is important not to prejudge the preferred repository site within each candidate area until the initial investigations have been completed and evaluated.

The implication that more than one site may be carried through to complete site investigations is also appropriate, as a comprehensive characterisation of the geological and hydrogeological characteristics at depth can only be achieved through an extensive programme of deep borehole construction. The comprehensive programmes of hydrogeological and hydrogeochemical studies that are planned should place substantial and useful constraints on the uncertainties associated with conceptual hydrogeological models and on the parameterisation of the mathematical representations of these conceptual models.

SKB should also be commended for recognising that the results of site investigations need to be incorporated into an integrated framework. Inclusion of primary results in a single site-specific database is a first step in this process. However, SKB goes the next step in proposing that this database should be interrogated to produce a geoscientific, site descriptive model. It is encouraging that this geoscientific model is to include both surface and subsurface processes. In particular, it is important that the hydrogeological system should be considered as an integrated whole and not artificially distinguished into near-surface and deep components at the conceptualisation stage. Because of distinctions in timescales for groundwater flow, mathematical modelling of the near-surface (and surface) hydrology and hydrogeology may be undertaken separately from modelling of the deep hydrogeology. However, if distinct mathematical models are used, it is likely to be appropriate to ensure consistency across a three-dimensional zone that is common to the two modelling domains, rather than to consider that there is a simple two-dimensional interface between them. Similar remarks relate to radionuclide transport modelling. This point is emphasised because the concept of a geosphere-biosphere interface largely arises because of the necessity of distinguishing an integrated system into modules (typically near field, geosphere and biosphere) for performance assessment purposes. However, there is no reason why information from site investigations should be stored and interpreted with respect to these artificial distinctions. Indeed, one result of site investigations may be to challenge the adequacy of existing performance assessment tools.

Notwithstanding the importance of an overall system understanding, data from site investigations cannot practically be handled as a single monolithic compilation of information. Distinctions have to be made for convenience of interpreting the disparate data sets that arise. SKB has chosen to make this distinction by discipline. The disciplines adopted are: surface ecosystems, geology, hydrogeology, hydrogeochemistry, rock mechanics, thermal properties and transport properties of the rock. This distinction seems broadly appropriate, as different specialists will typically be involved in each of the disciplines. However, SKB will need to ensure that the conceptual models developed under each discipline are appropriately integrated. For example, it is difficult to see how a conceptual model for hydrogeochemistry can be developed separately from those for geology and hydrogeology. SKB could usefully set out a detailed programme showing how the various data sets will be integrated into the conceptual models proposed. It may be that a natural hierarchy can be developed with a conceptual geological model providing a context for a hydrogeological model that is tested with hydrogeochemical data before being used to represent radionuclide transport parameterised using information from the transport conceptual model.

Site investigations provide information for a number of distinct purposes. Not the least important of these is the demonstration to stakeholders (including regulators, non-governmental organisations (NGOs) and the general public) that there is a good understanding of the current characteristics of the site, irrespective of whether those characteristics are of relevance in other contexts, e.g. long-term performance assessment. Also, baseline and monitoring data are required in the context of environmental impact assessment, both for the planning of site investigations and possible subsequent developments, and for demonstrating that such investigations and developments do not result in unacceptable environmental consequences. These various purposes are particularly relevant in the context of surface ecosystems, as much more information may have to be collected about present-day ecosystems than is required for long-term performance assessments, e.g. in relation to the spatial distribution of threatened species. SKB clearly has these considerations in mind when specifying the amount of detail to which current ecosystems will be characterised.

Whereas SKB presents a very detailed programme for the characterisation of areas of interest and preferred sites at the present day, much less is said in reports TR-00-20 and TR-01-29 about characterisation of the history of the areas and sites. From the other reports reviewed, it is clear that SKB has a good appreciation of the importance of the environmental history in determining the current characteristics of the sites, but investigations of palaeoenvironmental conditions at those sites do not come through strongly in the site investigation programme. To take one example, though permafrost development and effects are emphasised in the RD&D programme for 2001, there is no mention in the site investigation programme of studies of ice-relict structures or of evaluation of the subsurface thermal profile in terms of past climate.

Overall, the proposed scope of the site investigations is such that they could be expected to provide more than adequate data for use with the current generation of performance assessment tools, particularly when combined with the compilations of generic data that are produced by SKB. However, report TR-01-29 in particular reads rather like a wish list of all the investigations one might reasonably wish to see performed at a site. Also, the timescale proposed for completing these investigations is very short, particularly taking into account the need to investigate more than one candidate area or site simultaneously. Expertise for undertaking the investigations and reporting the results could be stretched very thin. It would be desirable for SKB to produce an analysis of resource requirements for the investigations and their interpretation, and a statement of how those resource requirements would be met. It is stressed that the concern here is not financing, but the finite pool of senior staff with appropriate skills, even when potential inputs from overseas contractors are taken into account.

4.2 Characterisation of the Biosphere and the Geosphere-Biosphere Interface

As has already been mentioned, the geosphere-biosphere interface is, to a large degree, a modelling concept. It is probably better to consider whether the site investigation programme will provide adequate characterisation of the surface environment in relation to near-surface geology, hydrogeology, hydrogeochemistry and radionuclide transport. For the present day, this is clearly the case. Meteorological data will be available, terrestrial environments will be characterised at the surface-water catchment scale, soils will be mapped and characterised, patterns of vegetation will be determined, surface water bodies will be subject to level and flow monitoring, groundwater levels and flows will be measured and the hydrological and sedimentation characteristics of the marine environment will be determined, as appropriate. The availability of such comprehensive and spatially extensive data sets suggests that there will be an opportunity for both calibrating and validating a physically based, surface-water catchment model against the present-day information provided from the site investigations. Although there are inevitable limitations to the predictive capability of a model calibrated to present-day conditions, such an approach could nevertheless be used to explore the potential significance of future changes in climate and land use for groundwater flow and radionuclide transport.

For long-term safety assessments, it is important to recognise that radionuclide discharges are often projected to occur many thousands or tens of thousands of years into the future. Thus, even if such discharges occur during an interglacial period, it may not be the current interglacial, but some future interglacial. If so the patterns of uplift, lake and river development, soil formation and vegetation succession may differ substantially from those that have conditioned environmental characteristics at the present day. This comment seems particularly important for coastal marginal sites and supports the remark made by SSI that the choice of two sites close to the coast makes great demands on the evaluation of climatic effects and places emphasis on the role of the biosphere in safety assessment.

In the context of interglacial conditions, it is often assumed that greenhouse-warming effects will only be of transient significance and that, within a few thousand years, the global climate will revert to the pattern of glacial-interglacial cycling that has occurred throughout the Quaternary. This view is now being strongly challenged and model simulations performed as part of the EC BIOCLIM project suggest that greenhouse warming could result in the current interglacial being prolonged for 100 ka or longer (see http://www.andra.fr/bioclim). Furthermore, this super-interglacial is associated with complete ablation of the Greenland ice sheet and potentially substantial ablation of the West Antarctic ice sheet on a timescale of no more than a few thousand years. Taken together with the thermal expansion of sea water and a smaller contribution due to the melting of valley glaciers, a global sea-level rise of more than 10 m is projected. In such a scenario, current coastal regression in the Baltic Sea would be reversed and a marine transgession would be expected to occur. Furthermore, because greenhouse warming tends to be enhanced at high latitudes, mean annual temperatures several degrees higher than those of the present day could occur. In view of these considerations, the low emphasis that SKB places on greenhouse-warmed conditions is surprising. It is recommended that SKB should develop a wider range of scenarios for future climate change that place greater emphasis on greenhouse-warmed scenarios.

In the longer-term, the research on permafrost and glacial conditions is appropriate. It should be noted that the Nirex programme includes work on mathematical modelling of the growth and retreat of the Fennoscandian and British ice sheets both for the last glacial-interglacial cycle and for the long-term future (see, for example, Nirex (1995)). This modelling includes detailed representation of the interplay between ice-sheet loading and isostatic effects. It is suggested that there is the potential for future collaboration between SKB, Nirex and other interested parties in this area of common interest. The modelling of ice-sheet development and retreat is also an integral part of the EC BIOCLIM project.

In the context of scenarios, it is noted that SKB places emphasis on the use of interaction matrices. Such matrices are a useful tool in characterising the processes operating in particular biosphere systems. However, complementary approaches are required when developing scenarios of environmental change. This matter was discussed in relation to BIOMASS Example 3 (IAEA, 2001) and is being explored further in BIOCLIM. Distinctions between global factors, landscape factors and process system factors can be useful. The use of a descriptive evolving landscape model, within which a quantitative model of radionuclide distribution and transport can be embedded, has been explored and work is ongoing to identify the aspects of transitions between climate states that could be of importance in performance assessments. SKB will need to take note of these developments in developing scenarios for environmental change that are in line with best international practice.

SKB has recognised the potential importance of environmental transitions in its ongoing work on sediments. There is a high likelihood that the discharge zone for a contaminant plume from a deep repository would enter the accessible environment through such sediments. Radionuclide sorption to both mineral and organic matter in such sediments could result in their becoming sinks. Radionuclides trapped in such sinks could become rapidly mobilised at a later time, e.g. by the exposure of the sediments or as a result of altered chemical conditions within them. This area has not been adequately explored in the past and the SKB work is likely to enhance understanding on this topic substantially. Although this is primarily a research issue, it does imply that the characterisation of surface water bodies and their sediments is properly an important part of the SKB site investigation programme.

In the past, SKB has used compartmental models to represent radionuclide transport and distribution in the biosphere as part of the total system performance assessment. There is now a move towards using sub-system models based on the estimation of biomass production and on mass flows of carbon, water and nutrients to complement the existing compartment models for radionuclide transport. Not surprisingly, this approach has been found to work well for ^{14}C. It also appears promising for caesium, which may be because of chemical and biochemical analogies with potassium (an important nutrient element). This approach might also be expected to work well with ^{36}Cl and ^{129}I, because the corresponding stable elements are ubiquitous in the environment. However, establishing relationships between radionuclide and nutrient flows will be much more difficult for elements that have only poor analogues, e.g. ^{99}Tc, ^{237}Np and ^{242}Pu.

An advantage of moving to the type of system models being proposed by SKB is that they seem likely to be much more closely related to distributed hydrological models than were the earlier compartmental models. It will be of interest to explore how these models compare with related developments, e.g. the new version of the SHETRAN model developed by Newcastle University that has User Ports where biogeochemical transformation models can be attached and the two-dimensional biogeochemical model of the soil zone that has recently been developed at Imperial College of Science, Technology and Medicine.

In the context of the soil zone, it is noted that whereas SKB intends to apply geostatistical models of the deeper geology, it seems likely that the soil zone will be represented by domains characterised by uniform, constant properties. Although this is likely to be adequate for characterising boundary conditions on the deeper hydrogeology, it should be kept in mind that water flows and radionuclide transport in the soil zone are likely to be strongly influenced by small-scale heterogeneities. However, this is a matter that is only now beginning to be investigated in research studies and it would not be appropriate to address it in the proposed site investigations.

Soil characterisation seems mainly to be contemplated in terms of texture, though brief mention is made of hydrological characterisation. It would probably be useful to place greater emphasis on explicit determinations of soil hydrological characteristics under unsaturated conditions (K-θ and ψ-θ relationships). Although these can be inferred from textural analyses, such inferences are not very secure.

Although not explicitly stated in the site investigation programme, it is assumed that the computation of water balances for relevant surface water catchments will be undertaken and that efforts will be made to demonstrate adequate closure of those water balances.

4.3 Overall Evaluation

Overall, it is considered the proposed SKB programme of site investigations is comprehensive and well structured. If it can be carried out to the specification presented, it will constitute a benchmark that other waste management organisations will have to work hard to emulate.

PART 2 – SKB'S TREATMENT OF THE GEOSPHERE-BIOSPHERE INTERFACE IN RECENT ASSESSMENTS

5 Material Reviewed

The overall approach adopted by SKB in its recent updated safety reporting for the SFR-1 repository is documented in Chapter 4.3 (Description of Geosphere and Biosphere) and Chapter 5 (Assessment of Long-term Performance) of the Project SAFE Main Report.

The main SAFE project report is supported by several more detailed technical documents describing the technical basis and assumptions that underpin the radiological safety assessment. The following supporting material has been identified as relevant to the current review:

R-01-02: Modelling of Future Hydrogeological Conditions at SFR. The purpose of this report is to estimate the future groundwater movements at the SFR repository and to produce input to the quantitative safety assessment of the SFR. The report demonstrates the extent to which coupling between near-surface and deep groundwater systems has been taken into account in evaluating concentrations and fluxes at the geosphere-biosphere interface.

R-01-13: Project SAFE – Scenario and System Analysis. This report describes the scenario analysis conducted within the SAFE project, which has resulted in a qualitative description of the SFR disposal system.

R-01-14: Project SAFE – Compilation of data for Radionuclide Transport Analysis. This document summarises the data used by the near-field, geosphere and biosphere models in the SAFE assessment.

R-01-18: Project SAFE – Radionuclide release and dose from the SFR repository. The objective of this report is to describe the radionuclide release and dose calculations for the SFR 1 repository within the SAFE study. Assessment results for the biosphere help to demonstrate some of the key features of the behaviour of the assessment models.

R-01-27: The biosphere today and tomorrow in the SFR area. This report summarises several pieces of work that have been undertaken on behalf of SKB to characterise the biosphere and its evolution as a basis for assessment modelling.

TR-01-04: Models for dose assessments – Models adapted to the SFR-area, Sweden. This report describes the development and testing of a biosphere modelling system for the SAFE project, designed to encompass key components of the biosphere from the perspective of assessing the potential radiological impacts of releases from SFR.

The aim of the review is to identify, from a survey of these documents, the key features, events and processes that are relevant to treatment of the geosphere-biosphere interface in the context of a geological repository sited on the Baltic coast of Sweden, and to comment on the extent to which these have been effectively represented in SKB's assessments.

Where appropriate, the commentary also draws on parallel reviews already undertaken by Quintessa (Chapman et al., 2002; Maul and Robinson, 2002) and other SSI contractors (Shaw, 2002; Klos and Wilmot, 2002).

6 Summary of Documentation Considered

6.1 SAFE Main Report (SFR 1, SSR)

6.1.1 Geosphere and Biosphere System Description

Chapter 4.3 of the Project SAFE Main Report is entitled "Description of the Geosphere and Biosphere". This summarises the key present-day characteristics of the rock mass and surrounding biosphere in the vicinity of SFR, based on detailed site characterisation studies. The description provides the point of departure for undertaking the long-term performance assessment. Key aspects of the site description relevant to consideration of the geosphere-biosphere interface are summarised here.

SFR is situated is a fractured crystalline bedrock, which is overlain by the sea bed sediments of the western coast of Öregrundsgrepen. At the present day, the mean sea water depth in the region adjacent to SFR is approximately 10m, extending to a maximum of around 18m.

The sediments in this immediate area consist of largely continuous glacial boulder till, with limited quantities of fines and occasional areas of outcropping rock. Rates of sediment accretion (both mineral and organic) are low. The fine fraction in particular is affected by wave action and bottom currents.

The predominant plant life on the sea bed are macroalgae; primary benthic animal species are mussels and molluscs, which show higher population densities in deeper waters that are less disturbed by waves and bottom currents.

Organic material cycling within the local marine environment is dominated by bottom macro-fauna and plankton. Although there is a surplus of organic material production over decomposition, it is believe that the majority of fixed organic carbon is exported from the immediate area. Because of the high rate of water turnover within the immediate area of interest, the greater part of any residual particulate organic carbon that is captured by sediment will tend to be 'through-flow' from adjacent areas.

Adjacent coastal land areas are characterised by a largely flat terrain. There is some outcropping rock, but the majority of the land surface area is covered with a sandy, lime-rich, boulder-bearing till. The depth of soil cover is generally less than 1m, and more than the 70% of the local catchment area is covered by forest vegetation. Protected parts of the shoreline are characterised by meadows, which are periodically inundated and rich in vegetation; those exposed to wave action are rocky and boulder-strewn. The proportion of agricultural land in the wider region is low, with no agricultural areas in the immediate vicinity of SFR.

Lakes and wetlands constitute a important part of the local terrain; the marshes are classed as rich/extremely rich in plant species, owing the lime-rich groundwater. Lakes tend to be low in nutrients, with high pH. Acidic peat bogs, in which most of the water originates from precipitation, have formed on areas of higher land (up to 25 m above sea level). Although farming activity is generally low, human influences on the terrain are also expressed through artificial land drainage and regulation of lake water content, both of which are associated with agricultural land use in the region.

6.1.2 Safety Performance Assessment

Chapter 5 of the Project SAFE Main Report is entitled "Assessment of long-term performance". Most of the detailed aspects of the assessment relevant to the current review are summarised in the various document reviews presented below (Sections 6.2 to 6.7). An overview of key aspects of the assessment in so far as they relate to consideration of the geosphere-biosphere interface is presented here.

Scenarios

A range of assessment scenarios has been defined (SKB R-01-13), based on projections of the anticipated evolution of the repository and its surrounding environment. The **base scenario** represents the situation in which land uplift is assumed to progress according to present-day understanding of the implications of this process for future shoreline displacement. However, no change to climate is assumed, and ecosystem types are assumed to be the same as those of today, except for the fact that ecological succession is assumed to take place in response to the effects of land uplift, principally as a result of changes to surface hydrology and near-surface hydrogeology resulting from shoreline displacement (SKB R-01-27). Hence the temporal vegetational succession at a given location corresponds to a spatial translation to the east, due to migration of the coastline. Implications of spatial gradients of biodiversity are discussed in the review of SKB's site investigation plans (Part 1 of this Report).

Among the remaining scenarios defined for assessment, only **climate-related scenarios** require separate consideration here in terms of their potential relevance to alternative treatments of the geosphere-biosphere interface for groundwater release. It is assumed that present-day climate (as in the base scenario) persists for the next 5000 years, after which a gradually colder climate is experienced, with the possibility of permafrost conditions at some stage before the Fennoscandian ice sheet encroaches on the site; however, this is not expected until after 20 000 years. Local sea level is assumed to be affected first by continuing land uplift (as in the base scenario), then to regress further as a result of the effects of northern hemisphere ice sheet growth. However, the implications of an additional fall in sea level after 5000 years, beyond that associated with uplift alone, are not considered to be significant from the perspective of the geosphere-biosphere interface, because groundwater transport pathways from SFR are thought to be confined to the area that is anticipated to be exposed as a result of shoreline displacement over the next two to three thousand years. Eventually, marine transgression is anticipated as a consequence of downwarping caused by the advancing ice sheet. As a general rule, the main effect of transgression is anticipated to be a reduced rate of groundwater flow and greater dilution of any radionuclides released to the surface environment.

Apart from isostatic and eustatic changes in sea level, a further climate-related consideration that is of potential interest in the context of the geosphere-biosphere interface is the effect of permafrost. It is anticipated that permafrost would be unlikely to be continuous, although frozen ground effects might be relevant in persistent periglacial local climate conditions prior to encroachment of the ice sheet. Ecosystems are expected to differ (though not markedly) from those of the present day and it is considered that there would be an effect on hydraulic gradients and flow patterns. One possibility, not discussed in any detail, is an increased 'focus' of discharge on particular areas; however, the nature of the geosphere-biosphere interface itself may not necessarily be significantly altered.

Examination of geomorphological evidence indicates the area of interest to have been well within the ice-sheet limits at the last glacial maximum. However, the Late Devensian ice sheets were very extensive and is not necessarily the case that all future glacial episodes will be as extreme (particularly when the possible long-term implications for glacial-interglacial cycling of anthropogenic greenhouse gases are taken into account). It may therefore be reasonable to consider the possible implications of landform evolution scenarios in which the ice margin approaches, but does not cross, the site area. Such scenarios, if associated with discontinuous permafrost, could have substantial implications for the groundwater flow regime and the nature of the discharge zone. Moreover, the area just beyond an ice sheet could be subject to forebulge effects, which would enhance, rather than counteract, the local effects of global sea-level fall. There would seem to be scope for SKB to adopt a more coherent approach to the definition of scenarios of ice-sheet development that take into account glaciohydroisostatic effects and implications for groundwater flow.

It is acknowledged by SKB that global warming may mean that local sea level might not fall as rapidly as would be predicted by land uplift alone; however this possibility is not studied in the safety assessment. This is presumably because the implication of a lower apparent rate of regression (or even transgression, were there to be a substantial rise in global sea level associated with ablation of the Greenland and West Antarctic ice sheets) would simply tend to increase the length of time for which discharges from SFR might be expected to occur to the marine environment – giving rise to enhanced dilution and (therefore) lower radiological impacts. However, it could also be relevant to consider the possibility of more complex fluctuations in coastline displacement, in which transgression occurred following a period in which discharge had already taken place to lake/wetland environment. In such a situation, changes in the chemical environment (e.g. salinity and redox conditions) might possibly have consequences in terms of the remobilisation of adsorbed radionuclides from freshwater sediments.

In addition, no consideration appears to have been given to the possibility that the effects of anthropogenic greenhouse gases might have a much longer-term impact on the glacial-interglacial cycling, extending substantially (perhaps by many tens of thousands of years) the period over which the releases from the facility could occur to a terrestrial environment in milder climate conditions (see references to the BIOCLIM project in Section 4.2, above). It is possible that many of the implications of such an effect might, in principle at least, already be substantially catered for simply through extension of the time frame represented in the base scenario, although there is the potential for more marked changes in ecosystem type (e.g. the drying of topographical depressions and associated vegetational succession) linked to an extended interglacial period in a greenhouse-warmed world. The fact that changes within the biosphere are identified by SKB as being of potential interest to the overall safety assessment suggests it would be advisable to ensure that more systematic consideration is given to the implications of alternative, credible system evolution narratives in the definition and implementation of assessment scenarios.

Groundwater flow and transport

SKB's description of evolving hydrogeological conditions at SFR within the SAFE main report is drawn from supporting technical documentation, in particular SKB report R-01-02 (discussed in Section 6.2 below)

For as long as the sea remains above the repository, regional groundwater flow and transport paths from the waste are essentially in a vertically upwards direction along interconnected open rock fractures to the sea bed. The principal driving force for this flow is considered to be the effects of ongoing land uplift; flow rates are small. As uplift takes place, and the shoreline retreats to a location above, and eventually beyond, the repository, the pattern of flow is expected to change over time to a more horizontal direction, with increasing flux driven by topographically-defined hydraulic gradients. The physical location of the region of discharge is therefore expected to move, under the influence of shoreline displacement and the topography of the present-day sea bed, from above the repository to a position further to the north. After some 2000 years, flow paths are anticipated to terminate above the shoreline, while the discharge volume is expected to include a contribution from uncontaminated groundwater following pathways that do not intercept the repository. After a further 1000 years, it is expected that flow in the local system associated with groundwater transport pathways from the waste will have substantially equilibrated and the location of discharge will no longer be affected by continuing regional uplift. However, there will be continuing changes in the nature of the geosphere-biosphere interface owing to ecosystem change associated with changes to surface hydrology and ecological succession.

One of the key uncertainties in projections of groundwater flow paths and discharge locations concerns the effect of topography. Because the regional topography is very subdued, comparatively small changes in local topography can potentially have an important effect on near-surface flow patterns. In discharge areas exposed by the coastline regression, the possible accumulation of sediments in topographic hollows and lake beds is acknowledged as a potential dynamic influence on discharge location, tending to divert near-surface flows to physical locations closer to the shoreline. Different assumptions regarding the rate (and type) of sediment accumulation give rise to different rates of movement of the discharge areas. For releases that take place initially to an emergent lake (once the shoreline has been sufficiently displaced), the subsequent location of release over time will depend on whether there is significant sediment accumulation in the lake (in which case flow paths will tend to be diverted further north towards the displaced coastline) or if there is comparatively limited accumulation (in which case the lake may remain the final discharge area). SKB acknowledges that, currently, the scientific basis for making quantitative projections of sediment accumulation and its effect on near-surface groundwater flow patterns is not robust.

Apart from future sediment accumulations and their impact on topography and groundwater flow, the potential importance of discontinuities of the existing glacial boulder till merits some consideration. For example, an important case might relate to groundwater focusing through a high conductivity domain in a layer of otherwise low conductivity. Such a discharge might not be into a lake.

The more general point can be made that, in a fractured hard rock system, once the coastline has retreated such that discharge would be expected to be to a terrestrial environment, the pattern of flow will be determined largely by the fracture system. Meteorically controlled lakes will lie in depressions in the topography, but there is no absolute guarantee that fracture discharges of contaminated water will occur at these locations. For example, it is possible that there could be spring lines or seepages at breaks of slope. This type of interface does not seem to have been discussed at all in SKB's analysis.

Biosphere evolution and characterisation

Material describing biosphere system evolution in the SAFE main report is drawn from supporting technical documentation, in particular SKB report R-01-27 (discussed in Section 6.6 below), and is also linked within the overall assessment documentation to the identification of assessment scenarios as well as models for the near field and far field (see above). Attention is focused on undertaking a careful review of changes anticipated during the first 1000 years or so after repository closure, and certain critical stages in biosphere evolution thereafter. As far as the SFR assessment is concerned, SKB does not consider it to be meaningful to speculate on future biospheres after the next expected ice age; however, the reasoning behind this judgment is not evident from the assessment report.

SKB describes the most significant implications of biosphere system evolution for the structure and content of the safety assessment as being associated with the implications of shoreline displacement on the nature of the biosphere in the assumed region of contaminated groundwater discharge. At first, the gradual formation of shallower sea areas also has implications for water turnover as well as for sedimentation/erosion rates, and consequent impacts on ecosystem types, in the region of the geosphere-biosphere interface. As coastal regression continues, there is a change from brackish water to freshwater in the region of discharge owing to the formation of shallow lakes in depressions of the former sea bed. With continuing regional uplift, eutrophication and sedimentation within such lakes causes them to be translated over time into wetland and marsh. At this stage, artificial drainage could be implemented (consistent with present-day practices), causing the sediment layers to be exploited as agricultural land. Alternatively, the natural ecological succession would lead to further infilling and eventual forestation.

It is notable that the primary focus of the discussion in this part of the SAFE main report is the description and characterisation of ecological successions within the 'model region', with comparatively limited discussion of the correlation with (and implications for) physical and chemical processes affecting radionuclide mobility at the geosphere-biosphere interface and how these should be described in assessment models. Nevertheless, it is noted that radionuclides could accumulate over time in the bottom sediments of shallow lakes and marshland and remain there (or become slowly eroded) as the location of discharge shifts towards the coastline. On the basis of bathymetric measurements within the model region under present-day conditions, it is considered that this would lead to the release of radionuclides into a deeper lake. During this period it is anticipated that radionuclides could enter the lake sediments either as a result of the through-flow of contaminated groundwater, or by accumulation of (contaminated) eroded material from sources higher up the catchment. This lake then becomes progressively in-filled, following the same general sequence as the smaller lakes, but on a larger scale and over a longer period. However, it is not immediately clear what is expected to happen to the location of the groundwater discharge as the lake becomes in-filled, as the effects of isostatic uplift on shoreline displacement are expected by that time to have ceased. Eventually, it is again envisaged that artificial drainage of the wetland may take place (and may indeed be more appropriate in this situation, given the comparatively greater depth of sediment).

It is assumed that most of the important aspects of climate effects on properties and characteristics of the biosphere can be addressed either through logical argument in the justification of modelling assumptions or through parameter variation and sensitivity analysis (e.g. in relation to turnover rates). In some cases, this results in the definition of alternative calculation cases; for example, it is noted that the coastal ecosystem may be quite sensitive to fairly small changes in parameters such as sea water salinity (affected by rainfall/runoff). In a gradually cooling (and less humid) regime, it is assumed that there will a gradual transition to more taiga-like vegetation and, ultimately, to a possible treeless tundra in more periglacial conditions. Although such changes are discussed, the approach adopted for the purposes of radiological impact assessment calculations appears to be to ignore possible changes in vegetation type and related human behaviour associated with climate change. It is notable, however, that there is no significant discussion of the potential implications of an extended interglacial period with regional temperatures being sustained at a few degrees above present-day levels for many thousands of years.

As noted above, the effects of colder global climate on sea level do not have a major impact on the location and type of the geosphere-biosphere interface, since by the time this occurs it is anticipated that groundwater transport pathways from SFR will have substantially equilibrated, to the extent that they will no longer be affected by continuing coastline displacement.

Representation of the geosphere-biosphere interface in calculation cases

Biosphere and dose calculations for the groundwater release pathway in the SAFE Project are based on the assumption that the release takes place at a fixed physical location within a dynamically changing biosphere. In relation to the **base scenario**, the main emphasis is on potential releases occurring first, for some 3000 years after repository closure, to Öregrundsgrepen (in which turnover rate etc. changes with time) and subsequently (for the next 3000 years) to a large (>2m depth) lake, which becomes progressive in-filled, until the wetland is drained for use as agricultural land (for a further 4000 years).

Alternative calculations have been undertaken in relation to the base scenario for different geosphere-biosphere interfaces, including: a well located downstream of the repository (between 2000 and 10 000 years after closure – not discussed further here); and marshland, or 'mire', representative of shallow depressions in the former seabed areas that become in-filled with contaminated sediment (also between 2000 and 10 000 years after closure); as well as the 'reference' assumption of continued release to Öregrundsgrepen throughout the period of the assessment. The intention of these alternatives is stated as being to "shed light on" uncertainties in discharge areas and the expected biosphere evolution. Reference is also made to a more detailed evaluation of the migration of radionuclides in different ecosystems, described in SKB Report TR-01-04 (discussed in Section 6.7 below).

As far as the **climate-related scenario** is concerned, the only additional calculation case is a study of the possible implications of deep permafrost. In this situation, it is assumed that the release occurs directly to Öregrundsgrepen (i.e. based on present-day biosphere conditions). Whilst this is not altogether inconceivable, especially if a measure of marine transgression is assumed to have occurred as a result of downwarping in advance of the Fennoscandian ice sheet, there is no discussion in the report of possible alternative implications for the biosphere.

It is notable that, for simplicity, several sets of calculations are based on the assumption that calculated discharges from the near field enter directly into the biosphere, thereby ignoring the possible implications of groundwater travel time and retardation in the geosphere. This avoids the need to devise a complicated representation of the changing flow pathways (from vertical to sub-horizontal) caused by uplift and shoreline displacement. Even for those calculations where retardation effects and travel time are taken into account, they are based on the assumption of a hypothetical non-varying flow pathway.

A key assumption in the calculation cases is that releases from the repository (or far field) into the coastal waters of Öregrundsgrepen and the lake are assumed to enter directly into the water column, where they become distributed between solution and suspended sediment phases. Radionuclides may then be transported out of the lake as a result of water turnover or accumulated in bed sediment as a result of sedimentation and mixing. No account appears to be taken of the accumulation of radionuclides in the seabed or lake bed sediments at the geosphere-biosphere interface itself, and there is no commentary on the validity and implications of this assumption in the discussion of the calculation cases. However, it is assumed that any radionuclides that become accumulated in sea bed (and subsequently lake) sediments remain there when the ecosystem is assumed to change to the next stage. After the lake is drained and the sediment used as agricultural soil, it is assumed that radionuclides within the former sediments may be mobilised, together with contamination from the continuing groundwater discharge, which enters the unsaturated top soil by root uptake and capillary rise.

In this context, it is also worth noting that bottom sediments incorporate redox fronts and may also incorporate specific organic horizons, depending on the history of ecosystem development within the water body. Both of these may act as very effective localised traps for radionuclides, with vertical spatial dimensions of substantially less than 1 m.

A critical part of the model for the accumulation of radionuclides in seabed and lake bottom sediment, and its later translation into agricultural soil, is the manner in which activity in the sediment is sub-divided within the soil profile. This has to be achieved via an ad hoc method because the depths of the model compartments used to represent coastal and lake sediment differ from those used in the soil model. It is stated that activity accumulated in lake sediment is assumed to be transferred to the unsaturated ‘top soil’ layer (depth 20-30 cm), while that which was accumulated in the coastal water stage is divided in proportions 1:4 between unsaturated subsoil (depth 70-80 cm) and the underlying saturated zone. This justification for this approach is not entirely clear, and no description of the method could be found in any of the supporting documents.

SKB does acknowledge that there is a major difference between the model for release to soil and those representing releases to the lake and coastal waters, in so far as it considers discharge into a porous medium rather than a water volume. In particular, it is noted that accumulation of radionuclides in the soil profile is a key process in the agricultural land model, whereas dilution is the “most important” process in the coast and lake models.

A wide range of exposure pathways are associated with each ecosystem (e.g. including both drinking water and irrigation water from the lake) in order to evaluate potential individual doses.

The only situation in which direct contamination of sediments is assumed at the geosphere-biosphere interface is in relation to possible releases to marshland, or ‘mire’. There is no sedimentation in the mire, only a through-flow of water through the saturated system, in which the radionuclides are distributed between the solid and aqueous phases. Accumulation of radionuclides in the solid phase leads to exposure based on the assumption that it is extracted as peat and used as a domestic fuel and soil conditioner.

It is worth noting that both peat and overlying vegetation typically exhibit rapid successional development, which also affects the hydrology of a mire system. As peat develops, groundwater discharges tends to be deflected around it, so the concept of a through-flow of water may in fact be misleading. In a raised bog, the peat is saturated above the level of the regional water table, so both meteoric inputs and groundwater discharges tend to be directed to a ‘lagg’ of shallow water dominated by sedges around its periphery. More generally, a discussion of the various types of wetland system that could arise in the context of landform evolution would be helpful as part of the justification for the modelling approach that has been adopted.

Calculations and results

Calculations of migration in the biosphere and corresponding exposure pathways within the SAFE assessment were undertaken using time-dependent source terms based on calculated release rates from the near and far field. The calculations were undertaken probabilistically, with the probability distribution assigned for each parameter being intended to reflect uncertainties in the their values (including possible changes associated with different climate conditions) as well as natural variation within the region of interest. However, dose coefficients (for converting exposure to dose) were set as constants, based on recommended values.

Where possible, data describing physical transport processes were based on locally-obtained information. However, radionuclide-dependent data, such as uptake into plants and sorption to sediments, were based on more generally available published information. Data used in the calculations are not given in the SAFE main report, but are provided in supporting technical documentation (SKB report R-01-14, discussed in Section 6.4 below).

The overall results for the assessment are reported on the basis of the arithmetic mean of the distribution of results obtained from the biosphere models.

As a general rule, doses are higher for the lake than for the coastal biosphere, which is judged to be a consequence of the decreased dilution (smaller water volume and lower turnover rate) as well as the increased number and variety of exposure pathways that are taken into account. Doses associated with virtually all radionuclides for the agricultural land biosphere are at their peak 6000 years after closure (i.e. immediately after the end of the ‘lake’ period), which indicates that – as far as the SAFE models and release assumptions are concerned – the accumulation of contaminated bed sediment is a more effective mechanism for transferring activity into ‘soil’ than upward transfer from saturated to unsaturated soil layers.

The accumulation of radionuclides in the ‘mire’ model reaches equilibrium quite rapidly, with the maximum dose associated with a continuous, essentially uniform release being achieved within a few hundred years of the start of the calculation.

In discussion of the results, SKB notes that there are a range of uncertainties involved in the biosphere calculations, but that these have been addressed by a range of strategies (e.g. parameter variation, conservative parameter assignment, alternative models) for defining and implementing calculation cases. One of the most important areas is considered to be identification of the form of biosphere that acts as the ‘receptor’ for discharge from the repository. In particular, assumptions regarding the possible drilling of wells, which would provide the opportunity for the extraction and use of essentially undiluted contaminated groundwater, are considered important.

There is virtually no acknowledgement of potential uncertainties associated with representation of the geosphere-biosphere interface. In relation to the modelling of ^{14}C, which is one of the most important radionuclides for SFR in terms of releases to the marine and surface freshwater environments, it is noted that precipitation of the radionuclide may have been underestimated; however, it is claimed that this is pessimistic, in so far as it implies that concentrations in the water column will be correspondingly overestimated. It is also argued that, at least as far as ^{14}C is concerned, underestimates of uptake into sediment (and hence agricultural soil) are not important in terms of projections of maximum dose. However, no consideration is given to the possible implications of accumulation in sediment at the geosphere-biosphere interface (i.e. prior to entry into the water column) which, even if sediment accumulation is ignored altogether, might be expected to give rise to higher concentrations in sediment and (ultimately, when equilibrium had been achieved – as in the mire calculations) to similar concentrations in coastal and lake waters. Indeed, the importance of ^{14}C further emphasises the need to develop a full range of scenarios in which the spatial and temporal development of organic sediments is taken into account.

6.2 SKB Report R-01-02

This report presents a modelling study in which a finite-difference model is used to represent groundwater flow in the repository tunnels, the surrounding rock mass and in regional and large-scale fracture zones, for a period of 6000 years. The model is used to estimate flow path lengths, discharge locations and advective transport times for water that travels from the storage tunnels to the surface environment.

Regional and large-scale fracture zones are represented as homogeneous zones of elevated hydraulic conductivity relative to the rock mass. Separate calculation grids are established for the regional and local scales, with the regional grid being used to establish projected time-dependent boundary conditions for the local-scale grid. Overall boundary conditions at the top of the model account for the implications of decreasing relative sea level, with specified groundwater head conditions.

The calculated equivalent hydraulic conductivity (for uniform applied hydraulic gradient) of the local-scale grid, within which more intensive characterisation has been undertaken, is used as a representative estimate for similar-sized blocks in the regional grid. Variations are used to the evaluate the potential implications of regional-scale, uncorrelated heterogeneity, outside the local domain.

A significant proportion of the report is devoted to estimates of flow within, and in the immediate vicinity of, the repository, as well as anticipated transport pathways and flow rates towards the surface environment. Because the focus of this review is on representation of the geosphere-biosphere interface, the implications of these aspects of the model for calculations of risk within the SAFE project are not considered. Instead, the emphasis here is on the calculations undertaken to consider possible variations in near surface flow paths and discharge zones.

The models indicate that discharge areas for flow paths from the repository change with time as a consequence of shoreline displacement. The most important controls on the discharge area are the topography and position of the sea, with most discharge areas occurring along low-lying parts of the topography, particularly where permeable fracture zones intersect at low-lying parts of the topography. In the ‘base case’ calculations (assuming constant topography at all times), all discharge is assumed to take place within 700m of the disposal tunnels. However, it is expected that topography will change over time in response to the changing magnitude of processes of erosion and sedimentation in the surface environment. An attempt has therefore been made to evaluate the influence of such processes on effective boundary conditions at the surface (see discussion above in relation to the SAFE main report).

As the authors note, the model of the sediment accumulation process and its influence on near-surface flows is quite speculative and highly generalised. It would therefore be unwarranted to place much reliance on the predicted effects (such as longer discharge path lengths) as an integral part of the repository safety case. Nevertheless, the overall discussion provides a useful perspective on one aspect of attempting to define the nature of the geosphere-biosphere interface, namely the geographical location of the discharge.

The modelling provides estimates for the ‘dilution’ of the final discharge of contaminated groundwater from the repository by non-polluted groundwater that is also discharged in the same region. Typically, water that has passed through the disposal tunnels comprises only a few percent of the total flow within the total area over which paths from the different flow paths terminate. However, no account is taken of the additional dilution by near-surface flows that are not part of the regional fracture network flow system.

It is worth noting that, as far as implementation within the assessment is concerned, the assumption is made that all the calculated geosphere discharge is delivered to a single biosphere receptor, whether this is coastal waters/lake/agricultural land or to the ‘mire’. In practice, contamination originating from different components of the disposal facility are quite likely to emerge over a wide area; indeed, the models project that this would be similar in size to, or larger than, the overall plan area of the disposal facility (excluding the access tunnel).

6.3 SKB Report R-01-13

This report describes the systematic approach to describing the SFR system that is used to evaluate processes and their interactions. This, in turn allows issues to be identified that need to be incorporated into PA calculations and scenarios that provide the overall structure of the PA. The key to the methodology is the use of expert judgement and comprehensive documentation of decisions taken.

The systems approach is based on earlier SKB experience with interaction matrices of sub-systems of the repository and its environment that are constructed by groups of experts. The matrices contain parameters that affect system behaviour, and interactions between parameters. Both parameters and interactions can be directly compared with and audited against lists and descriptions of FEPs that are widely available.

A FEP audit is undertaken, using the NEA International FEP List, which allows the identification of FEPs not included in the SFR sub-system interaction matrices (EFEPs); the report discusses how these were managed so as to produce a reasonable set of scenarios of possible evolution of the repository on which to base the PA calculations. 'Scenario generating' EFEPs were identified and combined to produce a 'Base Scenario' (reasonably expected evolution of the system) and others (as discussed above in relation to the SAFE main report). It is concluded that most scenario-generating events and conditions can be analysed as calculation cases within the Base Scenario, or within parameter variants of it.

‘Accumulation within sediments’ is identified as a Biosphere FEP (as are similar expressions for peat, soil, and organic debris). Also included as Biosphere FEPs are ‘sediment resuspension in water bodies’, ‘sediment transport including bioturbation’ and ‘sedimentation in water bodies’. Detailed consideration of the way in which these and other FEPs have been treated in the analysis is not easy, however, as the basis on which the analysis was organised and presented is difficult to follow. Elsewhere in the FEP analysis, as well as for the biosphere, the impression is given that many of the decisions relating to modelling choices within the PA had already been taken before the system evaluation had considered possible importance on a more systematic basis.

It would appear from the way in which the calculations were structured (see Section 6.1) that the perceived importance of FEPs relevant to the behaviour of radionuclides at the geosphere-biosphere interface, and the way in which they were considered for incorporation in the assessment models, reflected underlying judgments about the mode of release at the geosphere-biosphere interface that are not made explicit as part of the overall analysis. Specifically, the description of the first leading diagonal element of the biosphere matrix (i.e. 1.1 Geosphere (Boundary condition)) makes no reference to assumptions adopted in the PA regarding the assumed mode of release at the interface, whether to the water column or via the underlying sediments.

One potential ‘interface’ between the geosphere and biosphere that has not been included in the overall assessment is the possibility of gross disruption of the residual wastes (for example, in the aftermath of the next major glaciation). The implications of large-scale erosion by ice are potentially interesting to consider in terms of the final ‘fate’ of that fraction of the longer-lived inventory of radionuclides (e.g. uranium series) that had not by then leached out of the repository vaults

6.4 SKB Report R-01-14

This report compiles the data used by SKB in the radionuclide transport calculations in the SAFE project. The report includes a good summary of the scenarios and models used, and this is followed by a description of the data used in the following areas:

- repository description, including inventory information;
- groundwater flow through the repositories;

- physical and chemical data for the engineered barriers;
- radionuclide transport in the geosphere; and
- biosphere modelling.

As far as the biosphere models are concerned, relevant physical data are also presented in the corresponding modelling report (TR-01-04, discussed in Section 6.7 below). It is evident from the presentation that the physical parameters used in the coastal and lake models are focused on physical turnover of the water column and an effective 'sediment growth rate' to describe the accumulation of radionuclides removed from the water column by particle settling. However, there are no parameters describing the physical mixing of sediments or their potential disturbance and erosion. The implication (see also Section 6.7, below) is that the focus is transfer of radionuclides from the water column to bed sediment, rather than vice versa. However, the physical depth of the upper sediment layer is assumed to be a variable (between 5 mm and 5 cm), reflecting uncertainty in the assumed depth of mixing by bioturbation.

The effective water retention time in the coastal model area is estimated to be in the range from less than half a day to one and a half days, while that in the lake model is approximately in the range 60 to 120 days. With high water turnover rates and very low rates of sediment accretion, it seems likely that the rate of radionuclide transfer to sediment from the water column will also be very low.

6.5 SKB Report R-01-18

This report describes the PA calculations made for radionuclide releases from SFR by the groundwater pathway. It provides a summary of the results but does not discuss them in a safety or performance context. Appendices give more information on the selection of the 'indicator' radionuclides, the models and some sample input files for the calculations.

The emphasis is on the description of calculation cases selected for the Base Scenario, on which most of the study is focused. The report provides a brief description of the computer codes used in the analysis, summarising basic assumptions and key data used in the calculations. Information on the structure and content of the calculations is broadly at the same level as summarised in the SAFE main report (see Section 6.1). As in the main report, there is no discussion or justification of the assumption that radionuclides released to Öregrundsgrepen or the lake model are assumed to enter directly into the water column, where they are distributed between the aqueous phase and suspended particulate matter.

The results are presented as release and dose versus time curves for a selected group of individual radionuclides. No details are provided of the results of the biosphere calculations; instead they are simply summarised in tabular form as the arithmetic mean of the distribution of results (presented as individual dose (Sv y^{-1}) per unit release (Bq y^{-1}) for each radionuclide) obtained from the probabilistic calculations. Indeed, only the results for the coastal model (as used in the 'permafrost' scenario) are reported.

6.6 SKB Report R-01-27

This report summarises several pieces of work that have been undertaken on behalf of SKB to characterise the biosphere and its evolution as a basis for assessment modelling. The report identifies three main study areas, reflecting the different spatial scales on which it has been deemed relevant to describe change and to evaluate the dispersion of radionuclides released from SFR – (a) the local area adjacent to the facility within which contaminant releases to the surface environment are expected to occur; (b) Öregrundsgrepen, the strait between the mainland and the islands of Gräsö and Örksär in which the facility is situated; and (c) the Baltic Sea. The main focus of the descriptive work is on the identification and characterisation of local biosphere systems within contaminant concentrations arising from possible releases are likely to be the highest; however, this involves giving consideration to the implications of changes taking place on a regional scale and beyond.

Characterisation of the present-day biosphere and its projected future development covers the following topics:

- climate, including long-term change associated with glacial-interglacial cycling;
- shoreline displacement and its effect on water depth;
- bed sediment accretion and erosion (and soil formation);
- water turnover;
- salinity;
- coastal ecosystems;
- local terrestrial and lake ecosystems; and
- human communities and resource exploitation practices, including agriculture and wells.

The report concludes with a synthesis of projected landscape evolution and its implications for the definition of assessment biospheres over a period of approximately 10 000 years from the present-day. This description provides the foundation for assumptions adopted in the development and implementation of radionuclide distribution and exposure models used in the SAFE assessment.

The main ‘external’ drivers of change considered by SKB are climate and shoreline displacement. These two aspects of change are, of course, connected: for example, the current rate of apparent sea level change in the east of Sweden is attributed to isostatic rebound following ice melt at the end of the last glaciation. At the same time, global warming (both following the last glaciation and into the future) is a cause of global sea level rise, linked to the melting of continental ice sheets and mountain glaciers, as well as thermal expansion of water in the seas and oceans.

The report draws the following conclusions regarding the implications of these drivers of change:

- The impact of global climate change on regional climate in the vicinity of SFR is believed to fall within the range of natural variations in mean annual temperature and precipitation, for a substantial fraction of the period of interest. It is not projected that there will be significant change in regional climate until the onset of the next ice age, with a reduction in precipitation and the development of periglacial conditions.

- It is calculated that there will be an effective reduction in the local sea level at Forsmark, as a result of the continuing effects of glacio-isostatic rebound, by some 20m over the next 4000 years. The shoreline is projected to be above the repository within 1000 years, and the connection of local waters to the open sea in the vicinity of SFR cut off within a further 2000 years. This has a major influence on the type and characteristics of the biosphere into which possible releases of radionuclides may occur.

These primary controls on environmental change set the frame of reference for subsequent discussions of change within the report (and, ultimately, the definition of scenarios for assessment). Responses to change within the biosphere are described in terms of local processes, such as water turnover, the filling of lakes by sediment and the invasion of vegetation.

There is limited discussion of the uncertainties associated with these projections of change. For example, it is not evident from the report to what extent the underlying research documents address the sources, or implications, of uncertainty associated with either the main drivers of change, or the implications of such change as propagated through the biosphere system. However, it is slightly surprising to find references being made to the “next ice age”, starting as a cold climate in about 5000 years, when long-term climate projections of the effects of global warming (such as those being undertaken within EC BIOCLIM research project – see http:///www.andra.fr/bioclim) are now indicating that the current interglacial could be prolonged by 50 000 years or more. Indeed, as noted previously (Section 6.1), the validity and completeness of SKB’s conclusions in relation to the possible long-term implications of greenhouse warming is debatable, in view of the possibility that this could lead to climate conditions that would be warmer than the warmest interglacial periods observed in the Quaternary record.

Other sources of uncertainty that might be relevant to consider include, inter alia:

- possible implications of global warming over the next thousand years on eustatic sea level (e.g. substantial loss of valley glaciers in the northern hemisphere, stability of the Greenland ice sheet) and hence on the effective rate of shoreline displacement at Forsmark;
- possible effects of a super-interglacial warming episode on regional climate, including implications of possible changes to the north Atlantic circulation; and
- possible long-term effects of global warming on the glacial-interglacial cycle over the next 100 000 years.

It is perhaps worth noting that uncertainties associated with the impact of global warming (sea level rise, local climate) on a timescale of 1000 years (10% of the overall timescale represented in the assessment) could be rather larger than is implied by the simple statement that "*uncertainties will increase dramatically with time in the future*" (Chapter 9). Whatever simplifications have been adopted in undertaking the assessment, and for whatever reason, it is important that potentially relevant uncertainties are identified so that can be properly taken into account in interpreting the significance and implications of the modelling results.

Set against uncertainties associated with global warming and other aspects of change, some of the descriptions of projected changes within the biosphere (e.g. in discussion of coastal ecosystems and vegetation successions) could be seen as inappropriately detailed. Although the overall synthesis (Chapter 13) is presented at a much simpler level, such considerations highlight the importance of presenting this kind of analysis in a systematic fashion, so that assumptions, approximations and simplifications are highlighted and justified according to the context of the assessment, and set against the development of a clear narrative thread.

The focus in the report is on identifying a range of possible biosphere 'receptors' at the geosphere-biosphere interface, according to the environment changes resulting from land rise and coastline displacement. One important geosphere-biosphere interface that arises from consideration of change, and is discussed within the report in the context of changes to local human communities, is the possibility that wells might be drilled in the vicinity of SFR. Because the shoreline is projected to migrate beyond the repository, the possibility arises that a drinking water well might intersect a contaminated groundwater flow path, or even the repository itself, beyond 1000 years or so. The way in which wells are taken into account in the assessment (e.g. the representation of dilution in the near-surface hydrological system) is not directly relevant to the scope of the this report – however, the fact that they have been identified in this way highlights the importance of the analysis of change that SKB has undertaken.

6.7 SKB Report TR-01-04

This report describes the development and testing of a biosphere modelling system for the SAFE project. The model system is designed to encompass key components of the biosphere from the perspective of assessing the potential radiological impacts of releases from SFR. The models evaluate the transport and distribution of radionuclides in a broad range of ecosystem types, representative of the potentially contaminated environment under present-day conditions as well as those anticipated as a result of landform evolution over the next 10 000 years. Discussion is also provided of the methods used to evaluate radiation dose rates to individual members of hypothetical critical groups, as indicators of the most exposed individuals from communities that could inhabit the contaminated surface environment in the vicinity of SFR at some time in the future.

The report begins with a short description of the region represented in the models and brief overview of the model system. The description highlights the role of shore level displacement in modifying the biosphere in the vicinity of SFR as land emerges from the present-day brackish waters between the Swedish mainland and the island of Gräsö. Over the period of time covered by the assessment, pathways associated with groundwater transport from SFR to the surface environment could terminate in a broad range of ecosystem types, including coastal waters, lakes, marshland (“mire”) and agricultural land.

The models are described as dynamic, since they compute the distribution of radionuclides between physical components of the system as time-dependent solutions to coupled first-order differential equations representing the identified transport processes, including sorption/desorption kinetics. However, the model system is not itself time-dependent, which is to say that the physical characteristics of individual model components and the rate constants representing transfers between them do not change with time. Evolution of the biosphere system is therefore represented by a sequence of distinct, time-invariant models for the individual ecosystem types. No attempt was made in the SAFE project to construct networks of different ecosystem types – at any stage in the sequence of change within a given calculation case, only one model was used.

The structures of the individual ecosystem models are described in turn. In addition to the possibility of natural releases to different ecosystem types, consideration is given to situations where the release to the biosphere could occur as a result of human intervention – for example as a result of the use of wells and/or contaminated irrigation water. For each model, radionuclide concentrations in environmental media and foodstuffs are determined assuming that they are in equilibrium with the calculated radioactivity content in corresponding physical components of the system; these concentrations then form the basis for evaluating radiation doses associated with multiple pathways of exposure. The system is configured for probabilistic analysis of the implications of parametric uncertainty, based on the specification (and, in some cases, correlation) of statistical distributions of parameter values, including assumptions about human habits and diet.

Models for calculating doses from a range of exposure pathways are based on standard techniques. Estimates of potential ingestion dose are based on average diet, but are maximised by assuming that all relevant contributions to diet are produced in the local contaminated area.

The simulations described in the report correspond to a set of studies undertaken to investigate the rate at which contaminants migrate through the different (time-invariant) model ecosystems under varying assumptions about sorption properties. These indicate the potential importance (for more strongly-sorbed species) of residual contamination from earlier stages in the sequence of landscape evolution (e.g. sea bed and lake sediments), which might become a secondary source in the new, altered ecosystem as land rise takes place. However, no detailed consideration is given to how such transitions would be simulated in practice within the PA. Ecosystem-specific dose conversion factors (EDFs) (i.e. individual dose rate per unit release of radioactivity) are directly relevant to PA calculations, but are reported (Appendix B) for the coastal model only.

General characteristics of the model system

A compartment modelling approach to the representation of the biosphere, based on time-invariant system properties, is generally consistent with international practice. However, because substantial attention has been focused elsewhere in the SAFE assessment (e.g. SKB R-01-27, see Section 6.6) on the question of biosphere change, it is natural to ask how such a modelling system can be practically deployed within the PA to reflect the key considerations associated with the analysis of change. Consideration is given in the report (notably in Chapter 10) to the rate at which contaminants with different chemical properties move through the model system, highlighting the potential implications of the dynamics of contaminant transport within an evolving, rather than a static, system. But it is not clear from this analysis how an overall understanding of biosphere change and its potential importance in generating indicators of radiological impact has been deployed in practice within the PA using the available models. As noted earlier (Section 6.1), for example, certain aspects of the transfer of accumulated contamination from the sediment compartments of the coastal and lake models to the soil compartments of the agricultural land model, are not particularly clear.

Very few published performance assessments have adopted a fully time-dependent approach to representation of the biosphere system, allowing the physical characteristics of individual model components and the rate constants representing transfers between them to change continuously with time. Indeed, such a strategy presents particular problems from the perspective of biosphere modelling, because of the difficulties in representing moving boundaries, the identification of potentially relevant processes associated with changing environment, and the fact that the models need to be integrated with assumptions about human communities and their exploitation of the environment. Representation of the evolution of the biosphere system within the SAFE assessment is achieved through the definition of a sequence of distinct, time-invariant models for the individual ecosystem types. The report provides some useful justification for the configuration of the selected biosphere models, although there are questions regarding the detailed approach that has been taken in defining the physical dimensions of some compartments and the transfer coefficients representing the transport of radionuclides through the system.

The model system provides the capability to undertake a probabilistic analysis of parametric uncertainty. This is reasonably straightforward to implement, but care needs to be taken in the way such a capability is used and the results interpreted, particularly in relation to biosphere models. On the one hand, uncertainties in the basic process models that relate to radionuclide behaviour may be reasonably well represented using such an approach, particularly if due consideration is given to possible changes in the range of parametric uncertainty under different assumptions about climate conditions etc. relevant to each ecosystem model and there is sufficient information to be able to make adequate correlations between factors such as soil/sediment type, sorption and bioaccumulation factors. On the other hand, it should be recognised that important aspects of the surface environment (e.g. vegetation, drainage pathways, animal populations etc.) are influenced by factors (particularly future human actions) that are inherently unpredictable. Uncertainties in the conceptualisation of the biosphere system (components, features, characteristics and mass transfers) do not therefore necessarily derive from the interpretation of what, in principle, ought to be verifiable information, based on system characterisation; rather, they reflect the adoption of a range of assumptions and hypotheses (albeit constrained by the site-specific factors) that are geared towards providing suitable indicators of radiological impact. In these circumstances, substantial emphasis is placed on the arguments deployed to justify the particular assumptions adopted in defining the conceptual models; to address 'uncertainty' simply by using probability distributions of parameters is not necessarily an appropriate strategy.

Coastal model

The inventory/concentration in ‘local’ waters, adjacent to SFR, is the most important physical component from the perspective of evaluating individual doses associated with a release to the marine environment. Water turnover in the present-day local coastal environment is rapid and is the critical factor in determining the contamination for radionuclides released directly into the water column. It is also reasonably straightforward to characterise (as an annual rate) with some confidence. Sorption to suspended sediments, which then accumulate on the sea bed, is catered for in the model and recognised as potentially important as a secondary source of contamination, becoming exposed at later times as a result of land rise.

There is an explicit representation of sorption/desorption kinetics in the model for transfer between solution and suspended material, but no obvious attention has been given to the potential importance of this aspect of the model. Data given in the report indicate that the rate constant is assigned a (radionuclide-independent) range of variability of four orders of magnitude, with a mid-value roughly equivalent to the turnover rate for ‘local’ waters. This suggests that, for the majority of simulations, it is likely to have an influence on the estimated local accumulation of contamination in bed sediments (though not necessarily on the evaluation of individual doses for the coastal model itself). Some discussion of the importance of this modelling assumption, and its potential relationship to the choice of Kd values, is therefore merited. In practice, sorption processes will often exhibit (at least) two characteristic times; a quasi-instantaneous phase associated with surface processes and a longer period, linked to diffusion into the body of the particle; if a single time constant is assumed, short-term sorption may be significantly underestimated – leading to an overestimate of the loss of contamination from the model system. Moreover, the kinetics of sorption and de-sorption may have different characteristic times and will vary between different radionuclides; hence, it may be inappropriate to assume a single value, uncorrelated with contaminant (or water/sediment) chemistry. Further, it is relevant to note that many of the equilibrium Kd values reported in the literature for suspended marine sediments have been measured *in situ*, so kinetic processes are implicit in the measured values, depending on the sampling regime and its location relative to the source of contamination.

A further modelling uncertainty relates to the exchange of contamination between the sea bed and the overlying water column. Again, this is not particularly important for evaluating individual doses associated with the marine environment, but its characterisation is particularly relevant for determining the long-term accumulation of contamination in bed sediment and the rate at which contamination may subsequently be remobilised. The model incorporates a particulate remobilisation flux, resulting from bed stresses, calculated as the difference between gross and net accumulation of sediment. Data given in the report indicate that the net accumulation is assumed to vary between zero and 44% of the total mass flux from the settling of fine particles, representing a potentially significant range of uncertainty in terms of influence on the estimated rate at which contamination is accumulated on the sea bed. If attention is to be given in the assessment to the long-term implications of such accumulation, and particularly if proper account is to be taken of long-term changes in sea level leading to the eventual exposure of such contamination, then further testing of the modelling approach and associated data is merited. In particular, it may be relevant to consider the role of sediment turnover and mixing in the near-bed boundary layer, rather than representing the exchange of contamination solely on the basis of gross sediment flux averaged over the depth of the water column.

Sea/sea bed interactions, and the specification of compartment depths for model components representing the bed sediment, would be much more critical to the dose calculation if the model allowed for the possibility of release radionuclide via the sea bed (rather than directly into the water column). There is no discussion of this important assessment assumption (and potentially significant source of uncertainty) in the report.

Potential sources of secondary contamination associated with discharges to the marine environment (e.g. sea spray transfer to land, or use of seaweed as fertiliser) are not represented in the model system, because the biosphere assessment for the SAFE study does not account for networks of different ecosystem models. However, it is pessimistically assumed that livestock graze on coastal aquatic plants, which provides a secondary route for exposure arising from the consumption of food products (milk and meat) derived from those animals.

Lake model

The basic structure of the lake model is similar to that of the local compartment of the coastal waters model. It includes many of the same features, including the use of similar process models for kinetic sorption, particle deposition and remobilisation. Key data differences include the specification of parameters relating to physical properties of the system (turnover rate, suspended sediment load etc.), as well as radionuclide-dependent data (e.g. Kd values), reflecting differences in water chemistry.

One important difference in implementation of the lake model is that it appears to provide a capability for considering contamination to enter the system not only in water (as in the coastal model), but also via suspended matter or sediment. However, it is clear from the subsequent simulations reported in the document (Chapter 10) that this ‘source’ is considered only in terms of the potential for residual contamination from accumulation during the ‘coastal’ phase, and not as a continuing receptor for releases at the geosphere-biosphere interface.

Data given in the report indicate that the net accumulation of bed sediment within the lake is assumed to vary between zero and 100% of the total mass flux from the settling of fine particles, with a best estimate of 20%. Given the possibility of considering radionuclide release to the biosphere via lake sediments, the wide range of uncertainty in effective rates of remobilisation is potentially a very significant parameter, and some indication of potential sensitivity would be merited. However, evaluation of the lake model in Chapter 10 appears to be restricted to consideration of sensitivity to variation in Kd values. This is potentially important, because the decision was taken – without apparent consideration of the importance of the remobilisation component of the model – not to represent lake bed sediments as a potential source of radionuclides in the SAFE study.

The specification of physical parameters for the lake system is an example of a situation where care needs to be taken in the use of a probabilistic approach to the treatment of uncertainty. The area, depth and turnover rate of the lake are based on rough estimates, reflecting the difficulty of making precise predictions of future surface hydrological conditions in a dynamically-changing environment. However, these parameters are presented as distributions, implying an intention to consider the implications of such uncertainty as part of the overall probabilistic analysis, rather than seeking to justify a particular set (or sets) of assessment assumptions as providing suitable indicators of radiological impact.

It is interesting, in passing, to note that correlation coefficients for some of the parameters specified as probability distributions within the lake model are specified with a precision of two significant figures. Given the probabilistic approach that has been taken in addressing biosphere model uncertainties, it would be interesting to consider the extent to which model results are sensitive to the precise values of such correlations.

Agricultural land model

The basic structure of this model is a simple top soil/deep soil system, with an underlying saturated zone. Additional complexity is unlikely to be merited; however, care needs to be taken to ensure that the characteristic length scales and transfer rates represented in the model are consistent with best judgments regarding the conditions under which contamination could occur. For example, it is relevant to recognise that there may be seasonal variations in water table depth when computing annually-averaged flows. Within the model, it is assumed that the water table is maintained approximately 1 m below the ground surface, if necessary by artificial drainage systems, thereby providing a suitable substrate for agriculture.

Groundwater in this region may be contaminated directly, or the soils (assumed to be former sea bed and/or lake sediments) may be assumed to include residual contamination resulting from releases in previous system states.

Loss of contamination from the model system is assumed to arise from one of two processes: top soil erosion and ‘horizontal’ flow of dissolved radionuclides within the saturated zone. The specification of these parameters is a critical consideration in determining overall coherence in implementation of the model. The possibility of considering contributions to losses from the system as a result of the cropping of vegetation is not discussed; as a general rule the rate would be low, but the potential significance of this pathway is increased in situations (as illustrated in Chapter 10) where the time-constants for other loss processes are slow.

Rates of topsoil erosion are uncertain (being assigned a variability of one order of magnitude in the model), but are considered to be slow, corresponding to loss rates of topsoil in the region of 0.0015% per year. Even so, if the model configuration is to remain valid over a long period of time, this mass flux needs to be compensated for by the addition of ‘new’ topsoil. If it is assumed that this is generated by the weathering of underlying soils, the contaminant transport model should include an equivalent upward migration term from deep soil. Alternatively, it might be assumed that erosion losses are addressed by the addition of new, uncontaminated topsoil from outside the spatial domain represented in the model. However, the potential role of migration as an effective transport parameter merits some consideration, especially given the very long characteristic timescales for accumulation of contamination, as illustrated by the model results shown in Chapter 10.

The approach used in this study includes an ‘aquifer’ as part of the assessment biosphere, with contamination assumed to enter (from the geosphere) in solution. However, outflow from the ‘aquifer’ is determined solely by meteoric water infiltrating from above – with no apparent contribution from sub-horizontal interflow associated with adjacent parts of the catchment, or regional discharge of the aquifer system. This begs questions of mass conservation and consistency with assumptions about the nature of the geosphere/biosphere interface, since it implies that the effective throughput of water in the both the unsaturated and saturated zones is the same. Given the long characteristic timescales associated with the agricultural land model (Chapter 10), the turnover of water within the saturated zone is a clearly critical parameter of the model, especially when it is configured to evaluate the radiological impacts of groundwater contamination.

Mire model

This is a very simple model of the physical domain of a marshland region, with consideration being given to the dynamics of exchange between model compartments representing the soluble and solid/organic phases. The overall status of long-term radiological assessment modelling for such ecosystems is in its infancy, so relatively simple conceptual approaches are probably most appropriate at the present time. In the light of this, however, the incorporation of a variety of conceptual uncertainties into an over-arching probabilistic parametric analysis (as has been done in the report) is probably not the best way of presenting this particular model.

It is interesting to note that, although consideration of this system state was introduced as a result of an evaluation of potential landform change, the possibility that residual contamination may be present as a result of accumulation in former lake and seabed sediments has not been considered in the SAFE-study. The importance of the model stems from the fact that it is considered a potentially relevant biosphere receptor for an extensive period of time, from 2000 to 10 000 years post closure.

Some key parameters of this relatively simple model have a broad range of uncertainty. For example, it incorporates an explicit representation of sorption/desorption kinetics in the model for transfer between the soluble and solid/organic phases. The assumption of reversible kinetics is questionable, in view of the fact that such systems are associated with the dynamic development of spatially extensive areas of organic soils and radionuclides are likely to be incorporated within (rather than sorbed onto) this material.

Furthermore, data given in the report indicate that the rate constant has been assigned a (radionuclide-independent) range of variability of four orders of magnitude. The possible significance of this parameter for the dose calculation, given that the half-time associated with the assumed outflow rate of water from the mire is approximately 5 years, is not clear. However, there are clearly a number of uncertainties associated with representing this process, similar to those highlighted above in discussion of the same component of the coastal model.

Effects of different sorption properties and contamination pathways

This report includes an interesting and informative analysis of some of the dynamics of contaminant transport within particular sub-models. However, as noted elsewhere, it begs several questions regarding the influence of, and sensitivity to, other elements of the system models (i.e. other than the choice of Kd) on the model results. Several conclusions appear to have been drawn regarding the value of representing residual contamination as a result of system evolution from one ecosystem to another, but these appear to be based solely on consideration of different sorption properties. In particular, no account appears to have been taken of the implications of assuming that the geosphere-biosphere interface (for the coastal and lake models) might be situated within the sediment, rather than emerging directly into the water column.

7 Commentary

This review is not intended as a general critique of the SAFE assessment itself; the aim is to focus on those aspects of the assessment that illustrate SKB's approach to representation of the geosphere-biosphere interface. Hence, while comments have been made above on aspects of the SAFE assessment such as the selection of scenarios, the intention here is to focus on specific considerations relating to the way in which source terms for the biosphere calculations have been defined.

It is worth noting at the outset that the concept of an 'interface' is something of an artefact of assessment modelling, as indeed is the distinction between geosphere and biosphere. Typically, the interface has to be introduced within the models because of the fact that simulations of the hydrogeological system used to determine flow and transport from the repository to the surface environment depend on boundary conditions for recharge and discharge that are not necessarily well integrated with more detailed understanding of the features, events and processes that affect the near-surface hydrogeological and hydrological regime.

SKB has attempted to take an integrated systems view in relation to providing a comprehensive system description, but this has not been followed in the assessment modelling. Similar observations have been made and concerns expressed in relation to the current site characterisation programme for spent fuel disposal (see Part 1 of this Report), for which it is proposed to assemble a comprehensive 'geoscientific' database to provide input to the assessment models. In order to ensure that appropriate and adequately justified interfaces are made between the assessment models (and particularly between the biosphere and the geosphere) it may be appropriate for SKB to introduce an additional tier of supporting models (e.g. in relation to near-surface hydrology and sedimentation/erosion processes) between the basic scientific data and the PA models.

There are a range of considerations and sources of uncertainty relevant to treatment of the geosphere-biosphere interface in a comprehensive assessment, including:

- variation in the geographical location of the geosphere-biosphere interface, caused by the effects of landform evolution on hydrogeology and far-field transport pathways;
- changes in the type and characteristics of the geosphere-biosphere interface as a function of time, resulting from landform evolution;

- definition of conceptual models associated with mass transport processes during transient conditions (e.g. complex changes in the dominant processes controlling sediment turnover and redistribution as a function of gradual changes in water column depth and water body type);
- specification of radionuclide-dependent parameters (such as soil/water distribution coefficients) for different biosphere systems and their variation with time according to changing water chemistry etc.

As far as the location of the interface is concerned, SKB has placed specific emphasis on the importance of uplift and associated coastal migration as processes influencing recharge and discharge patterns. Against this background, they have attempted to develop an understanding of factors affecting the evolution of flow paths in the geosphere and their sensitivity to assumptions regarding changes (or not) to topography, caused by sedimentation and erosion processes. Given the zone of discharge defined for the SAFE assessment, SKB has identified a 'reasonable biosphere development' sequence (coastal waters → lake → agricultural land) for the projected changes in the type and characteristics of biosphere receptors as a function of time, as a consequence of environmental change.

Given the particular zone of discharge defined for the SAFE assessment, SKB has identified a 'reasonable biosphere development' sequence for the projected changes in the type and characteristics of biosphere receptors as a function of time, as a consequence of environmental change. This sequence (coastal waters → lake → agricultural land) misses out the 'mire' stage, when the lake has been effectively completely in-filled with sediment prior to drainage for agricultural use. However, a mire model has been deployed separately within the assessment in order to provide an indication of the possible importance of this stage.

It is interesting to note that deployment of the mire model is undertaken as an independent calculation, without consideration of the prior stages of ecosystem development. However, because of the way in which the mire model has been set up (i.e. direct contamination of sediments at the geosphere-biosphere interface), it is unlikely that any prior contamination associated with the accumulation of sediment would give rise to important difference in the eventual outcome.

A fundamental assumption adopted in the SAFE assessment, which is not discussed or justified in any of the documentation reviewed here, is that radionuclides enter the water column directly, without passing first through the bed sediments. It seems likely that this was judged to be a conservative assumption, on the basis that all the exposure pathways associated with the coastal and lake models are ultimately dependent on the estimated concentration of each radionuclide within the water column. Hence, for a given model configuration, assuming that the release enters the water column directly will effectively maximise the calculated potential exposures to members of the local community.

However, such an approach effectively disregards the possible importance of the accumulation of radionuclides in bed sediments as mechanism for enhancing exposures at later stages, when the sea bed and (subsequently) lake bottom sediments have been uncovered and drained. As the models currently stand, they are not set up for simulating the effects of releases occurring via the bed sediment, which is in fact a more realistic picture of how discharge of groundwater would in fact take place. For example, the focus of attention in representing exchanges between the sediment and water column is on downward transfers associated with the settling and burial of suspended sediment.

By contrast, contamination entering from below would be transported through the sediment by advection in groundwater, allowing for sorption en route. It is worth pointing out that the total radionuclide flux to the water column in groundwater discharged via this route would ultimately (albeit after some retardation within the sediments) be same as that associated with a 'direct' release as in the current SKB models. At the same time, it is acknowledged that the situation is made more complex by the fact that radionuclides will enter the overlying sediment via a spatially constrained fracture. The degree of subsequent dispersion at the 'interface' will depend very much on the details of the particular situation under consideration.

Hence, assessment models that allowed for release via sediments would not necessarily generate lower concentrations in environmental media relevant to exposure pathways associated with the coastal and lake models, but they would potentially provide a more realistic estimate of the residual contamination in sediment when it eventually became drained and made available for use as agricultural soil. This is potentially important in view of the fact that model results reported for the SAFE assessment indicated that doses associated with virtually all radionuclides for the agricultural land biosphere are at their peak 6000 years after closure (i.e. immediately after the end of the 'lake' period). This implies that – even under the assumption that contamination enters directly into the sea water or lake water – the accumulation of contaminated bed sediment is a more effective mechanism for transferring activity into 'soil' than upward transfer from saturated to unsaturated soil layers.

Moreover, it is worth noting that concentration ratios for aquatic organisms are typically expressed relative to radionuclide concentrations in water, being derived from field data that emphasise effluent discharges either to atmosphere or to the aquatic environment. In assessments where discharges are to the soil system, this is not a major issue. However, with discharges to coastal waters or lakes, the bottom sediment may contain much higher concentrations of radionuclides than suspended sediment within the water body. In these circumstances, it would be advisable to review the primary literature for the radionuclides of greatest interest and then to consider what results (in terms of concentration ratios) would be obtained by calculating radionuclide concentrations in sediments and then using organism:sediment concentration ratios (for which some data do exist).

Some preliminary proposals for the sort of modelling that could be undertaken to investigate the possible significance of this route of entry into the biosphere in a dynamic system are therefore provided in Section 8. The emphasis is on preserving as much as possible of SKB's exposure models and parameter values; however, attention has been given to refining the treatment of processes relevant to the migration, accumulation and dispersion of radionuclides associated with coastal seabed and lake bottom sediments.

8 Preliminary Proposals for Model Investigation

In a fractured hard rock system with topographically-driven groundwater flows, only limited reliance can be placed on the host rock to retard the transport of radionuclides. Preferential flow and transport through connected fractures of wide aperture could lead to rapid transport of radionuclides to the near-surface environment, with only limited mixing with uncontaminated groundwater en route. If the discharge occurs to the marine environment, a very considerable degree of dispersion will occur, but only after the emerging radionuclides have penetrated through any seabed sediments that are present. Such sediments may be recent marine deposits, or they may be a till sequence of complex lithostratigraphy.

One useful model investigation would be to study the potential accumulation of radionuclides in such bottom sediments with a view to determining their potential radiological significance when exposed by uplift and shoreline retreat. In addition, a comparison of radionuclide concentrations in such sediments and the overlying waters would permit an evaluation of whether concentration factors for some radionuclides and classes of marine organisms should be expressed relative to sediments. Further questions would then arise as to whether the existing data are adequate for quantifying such concentration factors.

However, it is probably even more important to study the implications of spatially restricted discharges of radionuclides to terrestrial environments. Such discharges could emerge at spring lines and seeps, as well as into lake sediments and into wetland systems such as mires. The radiological implications of discharges at spring lines and seeps do not appear to have been investigated in SKB's modelling studies.

For lake sediments, it would also be useful to investigate the degree of distinction in accumulation that could arise in oligotrophic and eutrophic systems. In the case of wetlands, it seems likely that the evolution of the system will need to be represented explicitly, as spatial and temporal development is relatively rapid and has a strong influence on near-surface hydrology.

For both lakes and wetlands, there will be some radionuclides, e.g. ^{14}C, for which the use of distribution coefficients is inappropriate. In such cases, radionuclide fluxes need to be modelled using alternative concepts. A simple approach for ^{14}C may be to use a specific activity approach, taking into account the fractions of biotic carbon that arise from different sources. In particular, carbon flows originating from the fixation of atmospheric carbon in photosynthesis would need to be taken into account..

PART 3 – MODELLING STUDY

9 Modelling Approach

The approach followed for this modelling study is described below.

1. Four conceptual and mathematical models and associated data used in the SAFE Project dose assessments (Karlsson et al., 2001) have been implemented using the most recent version (version 4.4) of the AMBER modelling tool (Enviros QuantiSci and Quintessa, 2002). The models and data used by SKB to represent radionuclide migration in the biosphere and to estimate the doses to potentially exposed individuals have been implemented for the coast, lake, agricultural land and mire ecosystems (Figures 9.1-9.4). The results obtained from the models implemented in AMBER have been compared with those reported by SKB (Section 10 of Karlsson et al. (2001)) in order to ensure that SKB's models and data were correctly implemented.

Figure 9.1: Structure of the Coastal Model, from Karlsson et al. (2001)

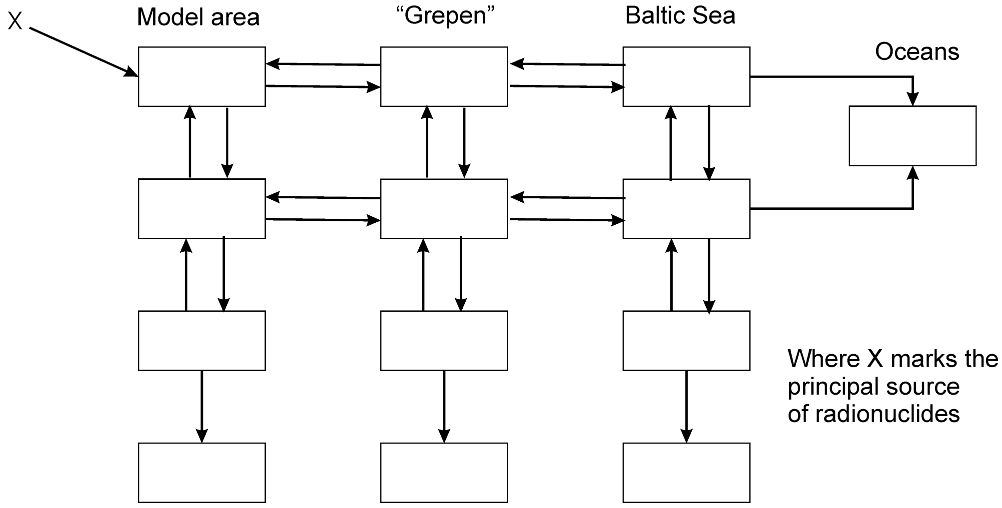


Figure 9.2: Structure of the Lake Model, from Karlsson et al. (2001)

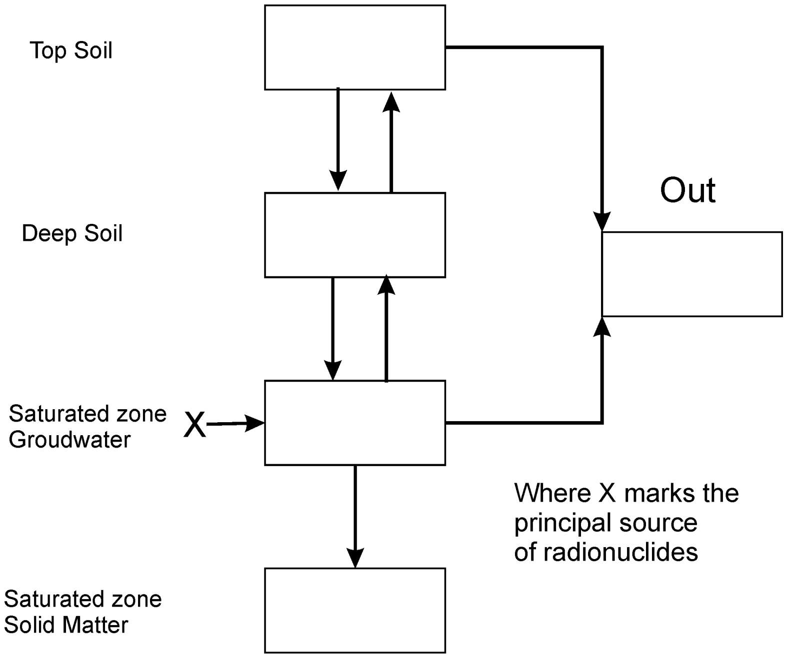


Figure 9.3: Structure of the Agricultural Land Model, from Karlsson et al. (2001)

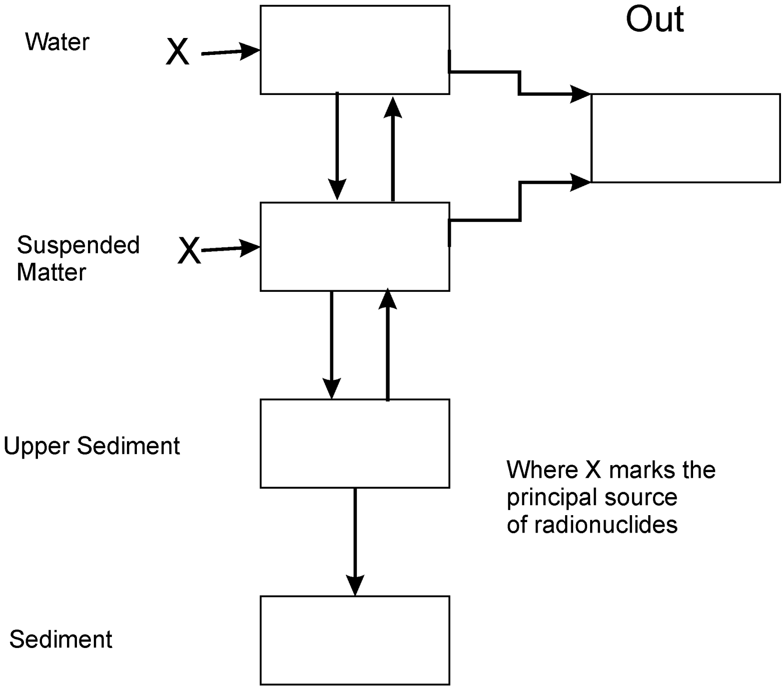
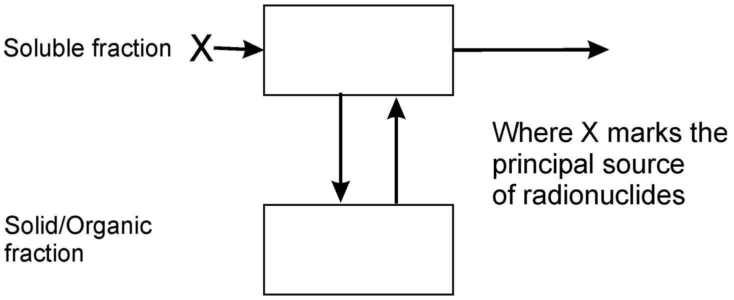


Figure 9.4: Structure of the Mire from Karlsson et al. (2001)



2. Alternative conceptual and mathematical models have been identified to address key issues highlighted in Quintessa's review of SKB's approach to the representation of the geosphere-biosphere interface in the SAFE Project (Part 2 above) and at the SSI OVERSITE meeting. These models and associated data have been implemented in AMBER and calculations have been undertaken to evaluate radionuclide migration in the biosphere and resulting doses to hypothetical exposed individuals.
3. The results obtained (in terms of environmental concentrations and dose to humans) using the SKB and alternative models have been compared and the key findings presented.

10 Replication of the SKB Models

A three step approach has been followed.

First, exactly the same conceptual and mathematical models and data for the coast, lake, agricultural land and mire as those documented by Karlsson et al. (2001) have been implemented in AMBER 4.4 (see for example Figures 10.1 and 10.2). The radionuclide migration models, dose models and associated data have all been implemented and their implementation checked.

Figure 10.1: AMBER Representation of the Coastal Model

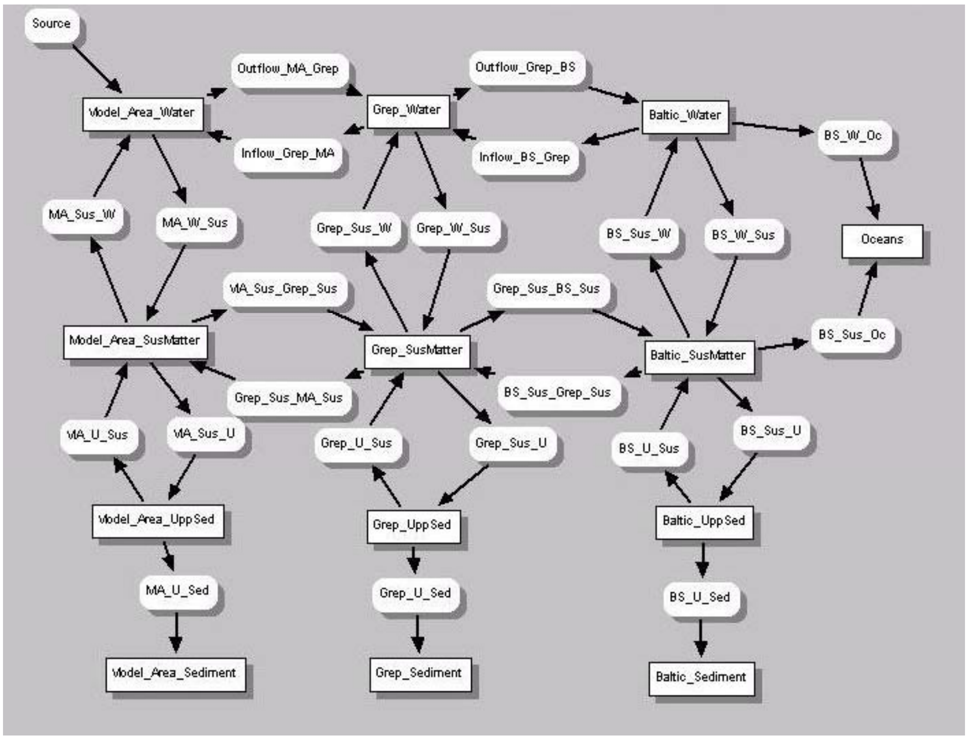
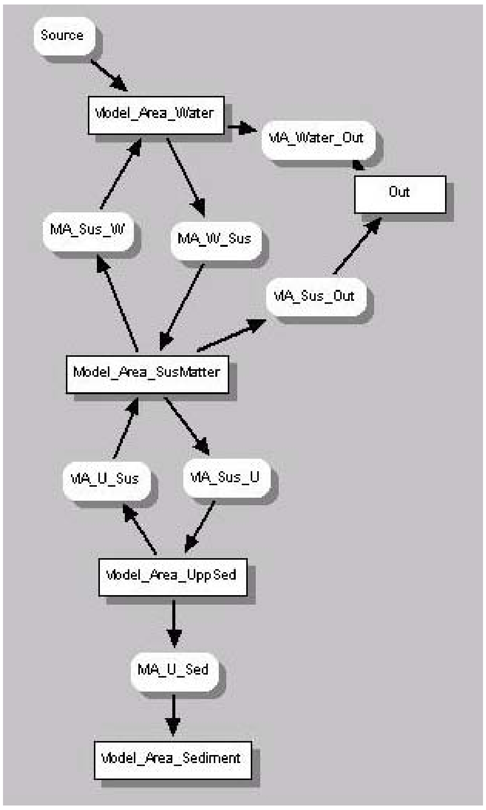
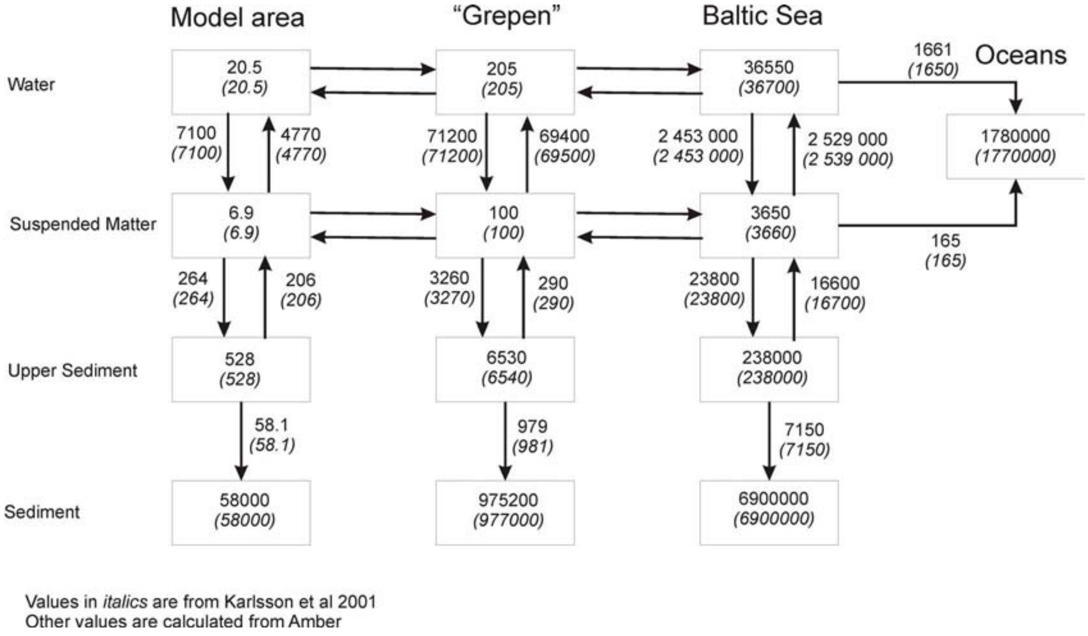


Figure 10.2: AMBER Representation of the Lake Model



Second, in order to verify further that the models and data for radionuclide migration in the biosphere were correctly implemented using AMBER, a unit release of 10 000 Bq y^{-1} of long-lived radionuclides with differing sorption coefficients was introduced to the coast, lake, and agricultural land models and the compartment inventories and fluxes compared with those given in Section 10 of Karlsson et al. (2001)[1]. Agreement to two or more significant figures with the results given by Karlsson et al. (2001) were obtained for the inventories and fluxes in the coast and lake models (see, for example, Figures 10.3 and 10.4).

Figure 10.3: Comparison of calculated compartment inventories (Bq) and annual fluxes (Bq y^{-1}) for the Coastal Model at the end of a 1000 year period assuming constant input (10 000 Bq y^{-1}) of a long-lived radionuclide with K_d 100 m^3 kg^{-1}



Values in *italics* are from Karlsson et al 2001
Other values are calculated from Amber

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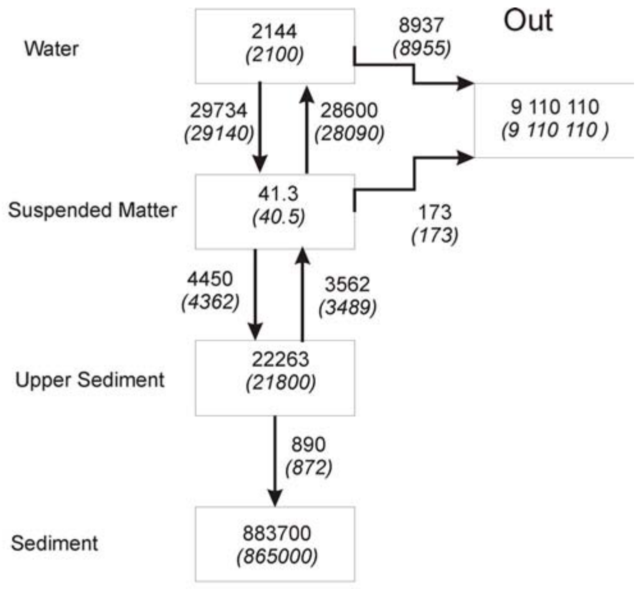
[1] Initial comparisons were also made for calculated compartment concentrations. Whilst good agreement was obtained between the results of the AMBER models and those reported by Karlsson et al. (2001) for the water compartments, there were significant (orders of magnitude) differences between the projected concentrations in soil and sediment compartments of the coastal and lake models. An attempt was therefore made to reproduce the compartment concentrations reported by Karlsson et al. (2001), based solely on the indicated compartment inventories and model parameters given in their report, using a simple spreadsheet. No information is given by Karlsson et al. (2001) for how the reported concentrations in soil and sediment compartments are calculated – it is simply noted that they are "taken from the dispersion model". Standard formulae were therefore encoded in the spreadsheet. This met with no success, indicating that it would be futile to pursue further any investigation of possible reasons for the differences between the concentrations reported by SKB and those obtained using the AMBER model. Instead, it was decided to focus attention (for the purposes of verifying the AMBER model implementation) on comparisons of projected compartment inventories and fluxes.

Figure 10.4: Comparison of calculated compartment inventories (Bq) and annual fluxes (Bq y^{-1}) for the Lake Model at the end of a 1000 year period assuming constant input (10 000 Bq y^{-1}) of long-lived radionuclide with K_d 10 m^3 kg^{-1}



Values in *italics* are from Karlsson et al 2001
Other values are calculated from Amber

For the agricultural land model, agreement between the calculated compartment inventories to one or two significant figures was found for the cases assuming sorption coefficients of 0.01 and 100 m^3 kg^{-1} (see Figures 10.5 and 10.6). However, such agreement was obtained only when a correction was made to the values reported in Figure 10-12 of Karlsson et al. (2001), reducing them by two orders of magnitude[2]. For the case with a sorption coefficient of 1 m^3 kg^{-1}, the agreement between the SKB results and those obtained with the model implemented in AMBER was not as good, especially for the top soil and deep soil compartments (see Figure 10.7).

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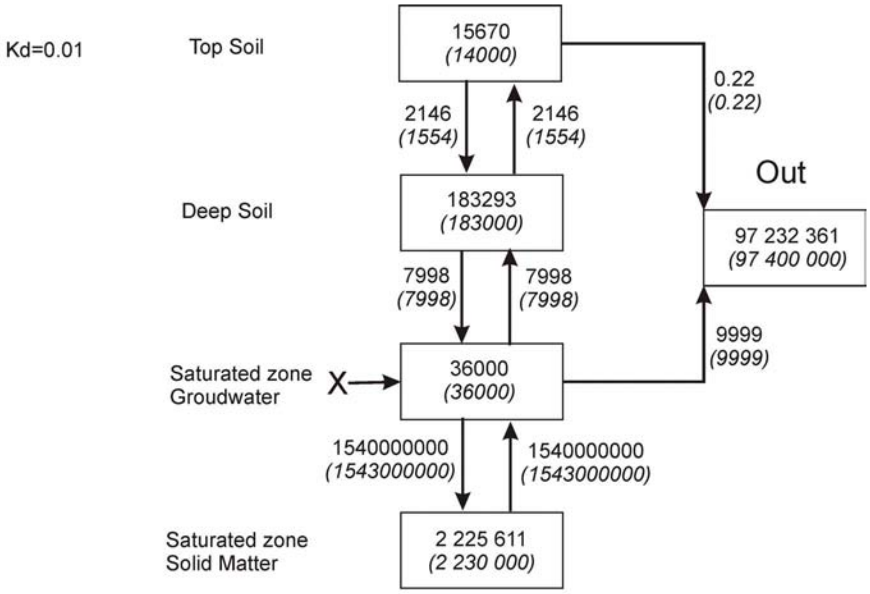
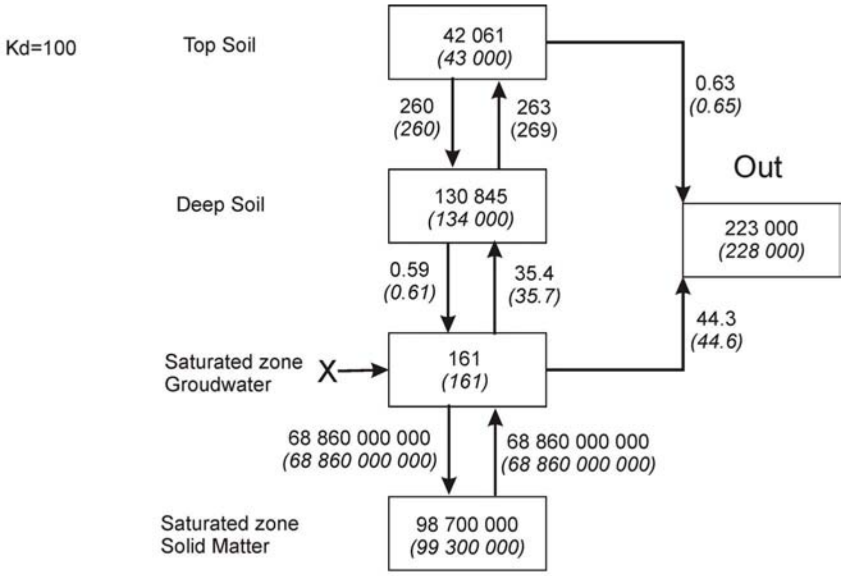
[2] Figure 10-12 of Karlsson et al. (2002) is meant to show the projected distribution of activity in the biosphere following the long-term (10 000 Bq y^{-1} over 10 000 years) release of a long-lived radionuclide. The total activity in the system should therefore be 10^8 Bq, but the sum of activity in the biosphere compartments, as shown in Figure 10-12, is in fact 10^{10} Bq. It is therefore assumed that an error has been made in drawing the Figure, and that all compartment inventories should be reduced by two orders of magnitude.

Figure 10.5: Comparison of calculated compartment inventories (Bq) and annual fluxes (Bq y^{-1}) for the Agricultural Land Model at the end of a 10 000 year period assuming constant input (10 000 Bq y^{-1}) of a long-lived radionuclide with K_d value 0.01 m^3 kg^{-1}



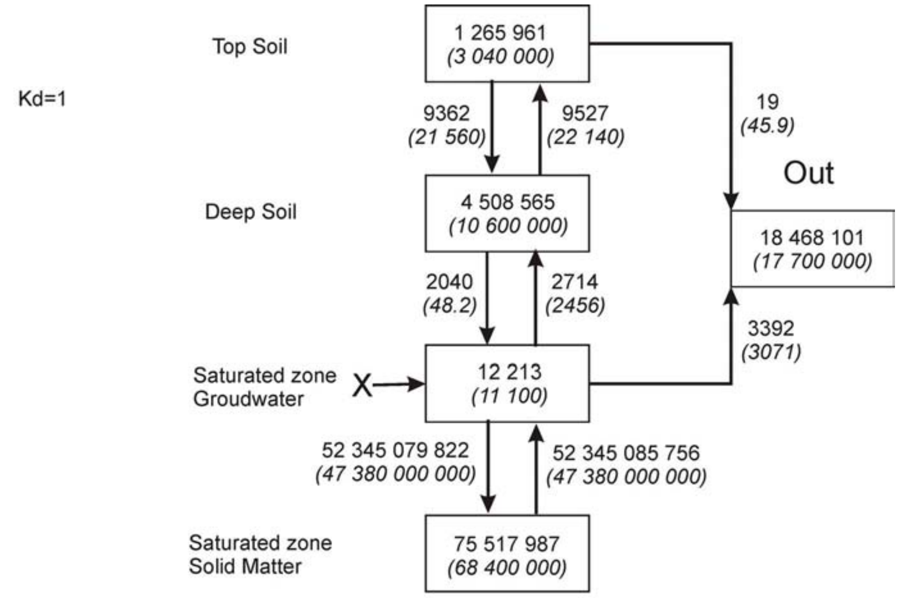
Values in *italics* are from Karlsson et al 2001 (adjusted by a factor of 0.01)
Other values are calculated from Amber

Figure 10.6: Comparison of calculated compartment inventories (Bq) and annual fluxes (Bq y^{-1}) for the Agricultural Land Model at the end of a 10 000 year period assuming constant input (10 000 Bq y^{-1}) of a long-lived radionuclide with K_d value 100 m^3 kg^{-1}



Values in *italics* are from Karlsson et al 2001
Other values are calculated from Amber

Figure 10.7: Comparison of calculated compartment inventories (Bq) and annual fluxes (Bq y^{-1}) for the Agricultural Land Model at the end of a 10 000 year period assuming constant input (10 000 Bq y^{-1}) of a long-lived radionuclide with K_d value 1 m^3 kg^{-1}



Values in *italics* are from Karlsson et al 2001
Other values are calculated from Amber

Reasons for differences between the AMBER and SKB results for the agricultural land model were investigated further by comparing the transfer rates (y^{-1}) between the compartments for the different sorption coefficient values (see Figure 10.8). Figure 10.8 indicates that, for a sorption coefficient of 0.01 m^3 kg^{-1}, the transfer rates are identical, except for some minor differences in the two transfers between the top and deep soil. Similarly good agreement occurs for the case where the sorption coefficient is set at 100 m^3 kg^{-1}, where the only difference is a small discrepancy in the transfer rate from the top soil to the ‘out’ (sink) compartment. For the case where the sorption coefficient is set to 1 m^3 kg^{-1}, all transfer rates are the same, except for the transfer from deep soil to the saturated zone groundwater, for which there is a discrepancy of two orders of magnitude. The transfer rate implied by the results for the SKB model would appear to be too low, being more consistent with that appropriate to a radionuclide with sorption coefficient of 100 m^3 kg^{-1}.

The third and final step in verifying replication of the SKB models was to combine the coastal, lake, agricultural land and mire models into a single AMBER case file. This allowed the “reasonable biosphere development case” defined for the SAFE assessment, as specified by Lindgren et al. (2001), to be modelled and dose calculations to be undertaken. For this case, the biosphere is assumed to evolve according to the following sequence:

- 2000 AD to 4000 AD – present-day conditions with discharge to coastal biosphere;
- 4000 AD to 5000 AD – discharge to reduced coastal area, with smaller volume and water turnover;
- 5000 AD to 8000 AD – discharge to lake; and
- 8000 AD to 12 000 AD – discharge to agricultural land.

In order to be able to make a comparison between the results given by Lindgren et al. (2001) and those obtained from the AMBER implementation of the model, it was necessary to specify the time history of the flux of radionuclides from the geosphere into the biosphere. Information relating to this flux was obtained[3] and implemented in AMBER for a range of radionuclides. Resource limitations meant that it was not possible to implement all the source terms for all the SFR disposal units; nevertheless, Figure 10.9 shows the resulting dose calculation as a function of time for a number of selected radionuclides and release scenarios. Doses obtained using AMBER are generally in good (within a factor of two) agreement with those documented by Lindgren et al. (2001). The main exception is Pu-239, for which the dose calculated using AMBER for is several orders of magnitude lower than that reported by Lindgren et al. (2001). Constraints on time and resources have meant that it was not possible to determine the reason for this discrepancy.

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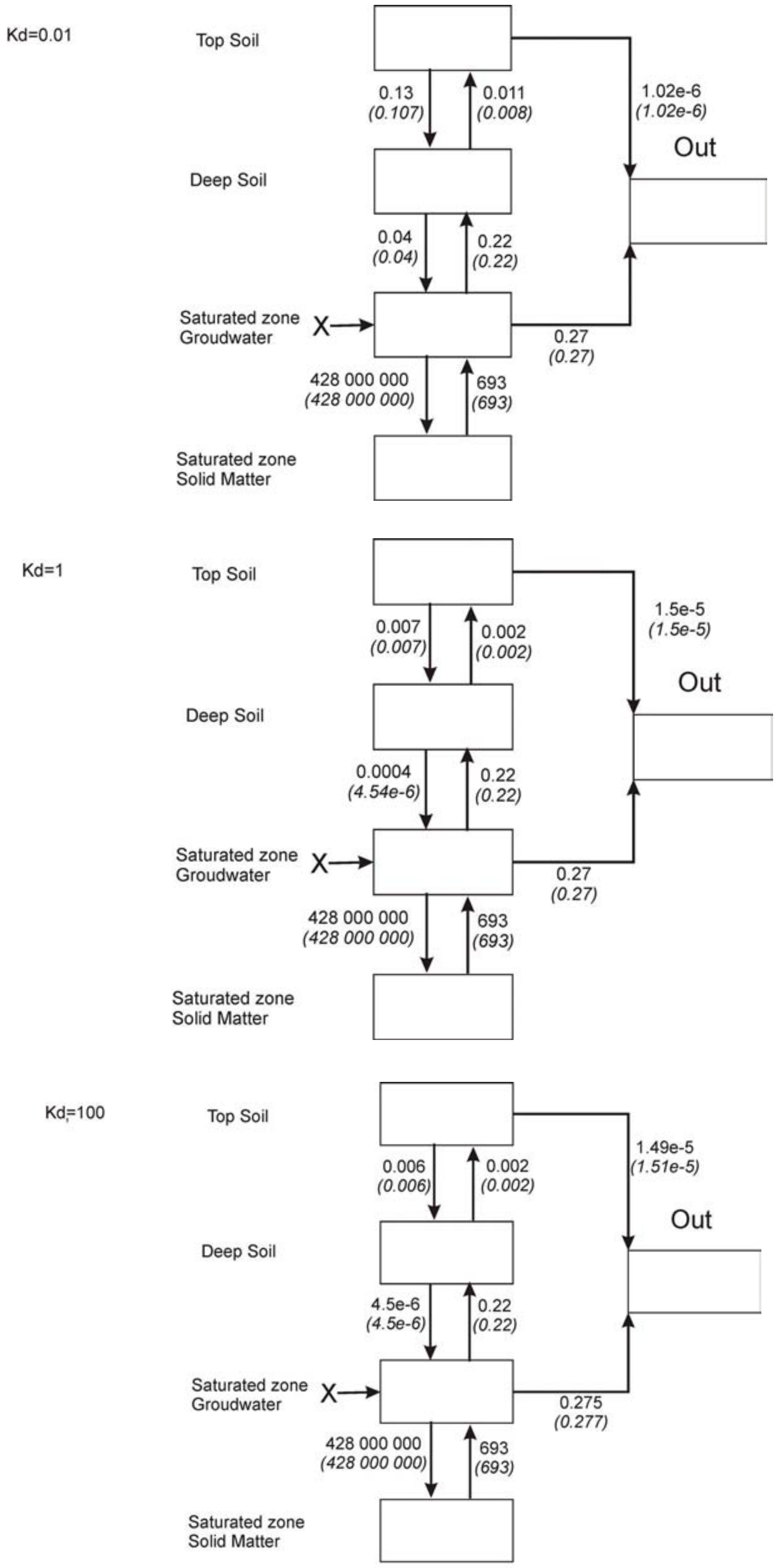
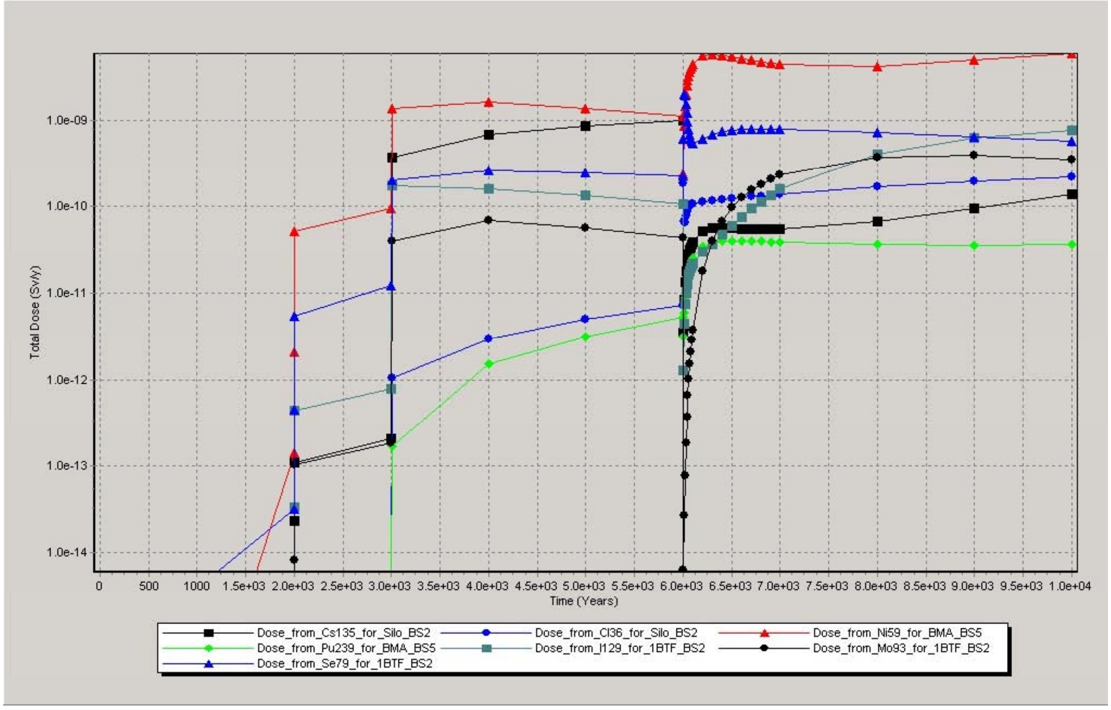
[3] Data provided by Kristina Skagius Elert, Kemakta Konsult AB (personal communication, 2003).

Figure 10.8: Comparison of calculated compartment transfer rates (y^{-1}) for radionuclides with K_d values 0.01, 1 and 100 m^3 kg^{-1} in the Agricultural Land Model



Values in *italics* are from Karlsson et al 2001
Other values are calculated from Amber

Figure 10.9: Total Individual Dose (Sv y^{-1}) associated with SFR Release Scenarios for Selected Radionuclides and Disposal Units (based on time-dependent source terms used by SKB in the SAFE Project)



Note: In comparing AMBER results in Figure 10.9 above with those reported for the SAFE assessment, the relevant results in Lindgren et al. (2001) are: Figure 5-2 (Silo-BS2), Figure 5-20 (BMA-BS5) and Figure 5-26 (1BTF-BS2).

11 Investigation of Alternative Models

11.1 Potential Issues for Investigation

The review of SKB's representation of the geosphere-biosphere interface in the SAFE Project (Part 2) led to the following conclusions.

1. There is an inadequate representation in current SKB assessments of the mode and implications of the release of radionuclides into surface water bodies, associated with the following considerations:
    - release of radionuclides via the sea bed or lake bed, rather than directly into the water column;
    - potential implications of accumulated contamination in bed sediments for subsequent exposures and secondary sources;

    - coupling of coastal/lake sediment inventory to subsequent agricultural soil inventory;
    - suitable characterisation of sediment dynamics and its implications; and
    - suitability of concentration ratio data under conditions of sea or lake bed release.

2. The current representation of the ‘mire system’ is highly simplified, involving a stationary (as opposed to dynamic) system representation, with radionuclide retention being reflected in a reversible linear sorption coefficient rather than via accumulation of radionuclides into deposited peat.

3. There is limited consideration of the possible implications of spatially restricted discharges – e.g. as a distribution of localised releases.

4. No consideration appears to have been given to the possibility of releases via seepage lines or springs.

The above findings from the review were discussed at the OVERSITE Group meeting. Following discussion, it was agreed that the modelling study should be focused on the topics summarised under item 1 above. Thus the study would not investigate uncertainties associated with alternative interpretations of the near-surface hydrology and the physical location of the geosphere-biosphere interface, nor the biosphere type into which releases might occur (i.e. items 3 and 4). Instead, attention would be given to developing a set of quantitative results using alternative conceptual and mathematical models to those adopted by SKB for representing the accumulation of radionuclides in coastal and lake sediments and the subsequent translation of such sediments into agricultural soil. In particular, it was agreed that attention should be given to:

- the representation of features, events and processes (FEPs) relevant to the behaviour of radionuclides at the geosphere-biosphere interface within the aquatic (coastal or lake) environment, especially under circumstances where the release takes place via the sediment, rather than directly into the water column;

- the implications of adopting an explicit approach to representation of lake evolution (including dynamic physical and chemical changes – i.e. accumulation and burial, and changing redox conditions – within the bed sediments) and the translation of the radionuclide contamination profile from sediments to soils.

Although certain weaknesses had been identified in the ‘mire’ model (item 2), it was agreed that these should not be addressed in the current study. Nevertheless, an attempt would also be made to consider the potential importance of accumulated contamination in mire sediments as a secondary source of contamination released into the lake.

It was agreed that the overall level of complexity of the biosphere models used in the study should be comparable with those used by SKB, allowing a direct comparison to be made between alternative approaches. It is not the intention to consider significantly new levels of complexity. Moreover, the implications of parameter uncertainty would not be investigated in detail, except where sensitivity studies are related to the detailed evaluation of FEPs and their potential importance.

11.2 Selection of Calculation Cases

In light of the above guidance, the following calculation cases were identified for investigation. Details of the specification for each case are provided in the Appendix.

1. **Case 1: Advective groundwater release to coastal/lake bed sediment, coupled with alternative conceptual model for agricultural land.** SKB's use of coastal and lake ecosystem models used within the SAFE assessment is based on the assumption that the groundwater release occurs directly into the water column (i.e. without passing first through the sediment). An alternative conceptual model is given by the assumption that the discharge of groundwater occurs via the bed sediment and from there into the upper sediment and finally into the water column. Consideration of such releases allows an alternative analysis to be made of the potential for radionuclides to accumulate in sediment and of the associated implications for subsequent exposures (particularly when the sediment is assumed eventually to be converted to agricultural land).
2. **Case 2: More realistic transition between coastal, lake and agricultural land models.** Karlsson et al. (2001) assumed any accumulated radioactivity in coastal sediments from the Model Area is incorporated into the deep saturated region of agricultural land only once the lake has dried out (in 8000 AD). In **Case 2A**, an alternative model has been considered in which radionuclides accumulated within coastal sediments are incorporated in the lake sediments when the lake first appears (5000 AD). In **Case 2B**, explicit consideration is given to the evolution of physical and chemical conditions in the changing coastal/lake environment, affecting characteristics such as salinity concentration and redox potential and their implications for parameters (such as sorption coefficients) that govern radionuclide distributions in the environment. The implications of such factors for radionuclide concentrations and potential exposures are therefore considered. Consideration has also been

given to time-evolving physical conditions such as a more gradual (rather than piecewise) change in the physical properties of the model compartments.

3. **Case 3: Alternative conceptual and mathematical models for the coastal and lake models.** The SKB models differentiate between water and suspended sediment and use separate dynamic compartments to represent them. An alternative conceptual model that uses a single compartment to represent both the water and suspended sediment (assumed to be in equilibrium) has been investigated (**Case 3A**). In addition, two alternative mathematical models for sediment accumulation in the marine and lake models have been considered (**Cases 3B and 3C**).
4. **Case 4: Incorporation of the mire model into the "reasonable biosphere development case".** In SKB's assessment, the mire model is considered separately as an alternative evolution case, distinct from the models used to define the "reasonable biosphere development" case. However, Lindgren et al. (2001) note that mires can occur during the period from 4000 to 12 000 AD and so it is considered appropriate to include them as part of the reference case, especially since they could potentially act as secondary source of radionuclides.

11.3 Results and Comparison of SKB and Alternative Models

Because of the difficulties encountered in attempting to verify the implementation of SKB's models within AMBER (Section 10), it was decided not to make a direct comparison between the published results of the SAFE assessment (as reported by Lindgren et al. (2001)) and those obtained using the alternative models outlined above (and described in the Appendix). In particular, several of the uncertainties identified in carrying out the verification exercise suggest either that mistakes were made in documenting SKB's biosphere model performance (Karlsson et al., 2001), or that the models themselves might possibly have been incorrectly implemented.

The following approach has therefore been adopted to facilitate the presentation of the results generated by the various calculation cases and their comparison against the SKB models. In each case reported here, the results obtained for the 'SKB models' correspond to the implementation within AMBER of model specifications provided by Karlsson et al. (2001).

A constant flux of 10 000 Bq y^{-1} over 10 000 years has been assumed for every radionuclide represented in SKB's biosphere assessment for SFR[4]. For the first

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[4] Consistent with Karlsson at al. (2001), the in-growth of radioactive daughters is not explicitly considered in the results discussed below. Some AMBER calculations were, however, undertaken to assess the potential importance of representing daughter in-growth. These calculations demonstrated that, for the 10 000 year period used here as a basis for the model intercomparison, daughters do not contribute significantly to dose compared with that arising from their parents, *provided that* it it assumed that the daughters are not themselves released into the biosphere at a rate similar to that determined for their parents.

3000 years, the release is assumed to occur to the coastal environment, for the following 3000 years to the lake environment, and for the final 4000 years to agricultural land. Ideally, the full time-history of the flux of all radionuclides into the biosphere from all SFR disposal units could have been used instead of a constant release rate of 10 000 Bq y^{-1}; however, since the main focus of the calculation cases is to compare the alternative models with the original SKB models (rather than to perform an absolute evaluation of potential radiological impacts), a constant unit flux was considered appropriate. Furthermore, defining the calculations in this way allowed for a more rapid implementation of the alternative models and thus represented a more efficient use of project resources.

For each calculation case, the inventory of two indicator radionuclides (one with a relatively low sorption coefficient for soils and sediments (Tc-99), the other with a relatively high sorption coefficient (Cs-135 – except for peaty soils)) has been tabulated for each model compartment at specific time points. The selected time points for reporting the model results are:

- 1000 years (i.e. approximately mid-way through the 'coastal discharge' period);
- 4000 years (i.e. approximately mid-way through the 'lake discharge' period);
- 5999 years (i.e. at the end of the 'lake discharge' period);
- 6001 years (i.e. at the start of the 'agricultural land discharge' period); and
- 10 000 years (at the end of the 'agricultural land discharge' period).

Not all the time points are reported for each calculation case. In addition, plots have been generated of the total dose (summed across all radionuclides) as a function of time[5]. In each of these tables and figures, the results from the relevant alternative model are compared against those generated using the SKB (Base Case) model, as implemented in AMBER (Section 10).

11.3.1 Alternative GroundwaterDischarge Model (Case 1)

Tables 11.1 to 11.4 illustrate the effect of the alternative groundwater discharge model on the calculated model compartment inventories at different time points. When compared with the corresponding inventories obtained using the Base Case (SKB) Model at 1000 and 4000 years, it is evident that there are order-of-magnitude differences for several of the coastal and lake model compartments. Because of the sorption of radionuclides onto sediment along the discharge pathway into the water column, the (deep) sediment compartments have much

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[5] All times referred to in the tables and on the figures in this study are times from the start of the calculation – this is different from the style (years AD) adopted in SKB's reports.

higher inventories than for the Base Case, whilst the water compartments have much lower inventories (see Tables 11.1 and 11.2).

It notable that, even though the sorption coefficient for Tc-99 is two orders of magnitude smaller than that assumed for Cs-135; the accumulated inventory in coastal sediment after 1000 years, as projected by the variant release model, is much the same for both radionuclides, being 99.8% or more of the total discharge up to that time (Table 11.1). A similar observations can be made in relation to predicted accumulation in lake bottom sediments after 1000 years of discharge (Table 11.2).

By the end of the 'lake discharge' period (Table 11.3), it is remains the case that the majority of the total discharge up to that point (95% of Tc-99, close to 100% of Cs-135) is retained in the lake sediment compartment. However, the inventory within the water column is now rather closer to that projected using the Base Case (SKB) model, particularly for the less strongly sorbed radionuclide (Tc-99) (8.3% at 5999 years, compared with 2.8% at 4000 years). Neglecting the effects of radioactive decay, if discharge to the lake ecosystem were to continue indefinitely, it could be anticipated that predicted concentrations in the water column resulting from a discharge via bed sediments would eventually achieve the same value as those associated with a continuous discharge directly into the water column. Equilibrium in the water column will also be achieved more rapidly for radionuclides that are less strongly sorbed than Tc-99 (e.g. C-14, Mo-99 and, in brackish waters, Cl-36).

The higher inventories within the coastal/lake sediment compartments, as projected by the alternative release model, result in higher (by several orders of magnitude) initial inventories in all compartments of the agricultural land model (see Table 11.4). This is because it is assumed that, on the drying out of the lake and draining of its sediments, the radionuclide inventories of the coastal (Model Area) and lake sediments are transferred to the saturated and unsaturated soil compartments of the agricultural land model (Karlsson et al., 2001). The difference in projected soil compartment inventories between the Base Case and Case 1 models is larger for the less strongly sorbed Tc-99 than for the more highly retarded Cs-135 (two to three orders of magnitude compared with about an order of magnitude, respectively). In the SKB Model, where radionuclides are released directly into the water column, most of the released Tc-99 inventory is lost from the Model Area compartments as a result of water turnover, without interacting with the sediment. By contrast, for the Case 1 release model, there is interaction with the sediments because the discharge of radionuclides occurs via the sediment column.

By the end of the simulation time (10 000 years – see Table 11.5), differences between the Base Case and Case 1 models are less than an order of magnitude. However, the soil compartment inventory remains higher in those cases where it has been assumed that the original release to surface waters takes place via bed sediments, indicating that the initial accumulated inventory in sediment can have an important effect on doses over a long period of time.

Table 11.1: Model Area Compartment Inventories (Bq) for Calculation Case 1 and the SKB Base Case Model at 1000 years

Compartment	Radionuclide	Inventory (Bq) Base Case	Inventory (Bq) Case 1	Ratio of Case 1 Inventory to Base Case Inventory
Model_Area_Water	Tc-99	2.91E+01	2.64E-04	9.1E-06
Model_Area_UppSed	Tc-99	7.78E-01	3.43E-01	4.4E-01
Model_Area_Sediment	Tc-99	8.52E+01	9.98E+06	1.2E+05
Model_Area_Water	Cs-135	2.76E+01	3.45E-03	1.3E-04
Model_Area_UppSed	Cs-135	7.34E+01	1.21E-06	1.7E-08
Model_Area_Sediment	Cs-135	8.05E+03	1.00E+07	1.2E+03

Table 11.2: Lake Compartment Inventories (Bq) for Calculation Case 1 and the Base Case at 4000 years

Compartment	Radionuclide	Inventory (Bq) Base Case	Inventory (Bq) Case 1	Ratio of Case 1 Inventory to Base Case Inventory
TopSoilLake	Tc-99	5.69E-01	1.61E-02	2.8E-02
DeepSoilLake	Tc-99	1.71E+00	4.72E-02	2.8E-02
Lake_Area_Water	Tc-99	2.40E+03	6.82E+01	2.8E-02
Lake_Area_SusMatter	Tc-99	4.62E-01	4.18E-01	9.1E-01
Lake_Area_UppSed	Tc-99	2.49E+02	2.05E+03	8.2E+00
Lake_Area_Sediment	Tc-99	9.88E+03	9.84E+06	1.0E+03
TopSoilLake	Cs-135	2.16E+01	3.87E-03	1.8E-04
DeepSoilLake	Cs-135	4.45E+01	5.91E-03	1.3E-04
Lake_Area_Water	Cs-135	2.14E+03	6.19E-01	2.9E-04
Lake_Area_SusMatter	Cs-135	4.14E+01	1.61E-02	3.9E-04
Lake_Area_UppSed	Cs-135	2.23E+04	2.74E+01	1.2E-03
Lake_Area_Sediment	Cs-135	8.84E+05	1.00E+07	1.1E+01

Table 11.3: Lake Compartment Inventories (Bq) for Calculation Case 1 and the Base Case at 5999 years

Compartment	Radionuclide	Inventory(Bq)		Ratio of Case 1 Amount to Base Case Amount
		Base Case	Case 1	
TopSoilLake	Tc_99	5.69E-01	4.71E-02	8.3E-02
DeepSoilLake	Tc_99	1.71E+00	1.40E-01	8.2E-02
Lake_Area_Water	Tc_99	2.40E+03	1.99E+02	8.3E-02
Lake_Area_SusMatter	Tc_99	4.62E-01	1.22E+00	2.6E+00
Lake_Area_UppSed	Tc_99	2.49E+02	5.96E+03	2.4E+01
Lake_Area_Sediment	Tc_99	2.96E+04	2.86E+07	9.6E+02
TopSoilLake	Cs_135	4.50E+01	2.36E-02	5.3E-04
DeepSoilLake	Cs_135	1.21E+02	5.53E-02	4.6E-04
Lake_Area_Water	Cs_135	2.14E+03	1.87E+00	8.7E-04
Lake_Area_SusMatter	Cs_135	4.14E+01	4.85E-02	1.2E-03
Lake_Area_UppSed	Cs_135	2.23E+04	8.25E+01	3.7E-03
Lake_Area_Sediment	Cs_135	2.66E+06	3.00E+07	1.1E+01

Table 11.4: Agricultural Land Compartment Inventories (Bq) for Calculation Case 1 and the Base Case at 6001 years

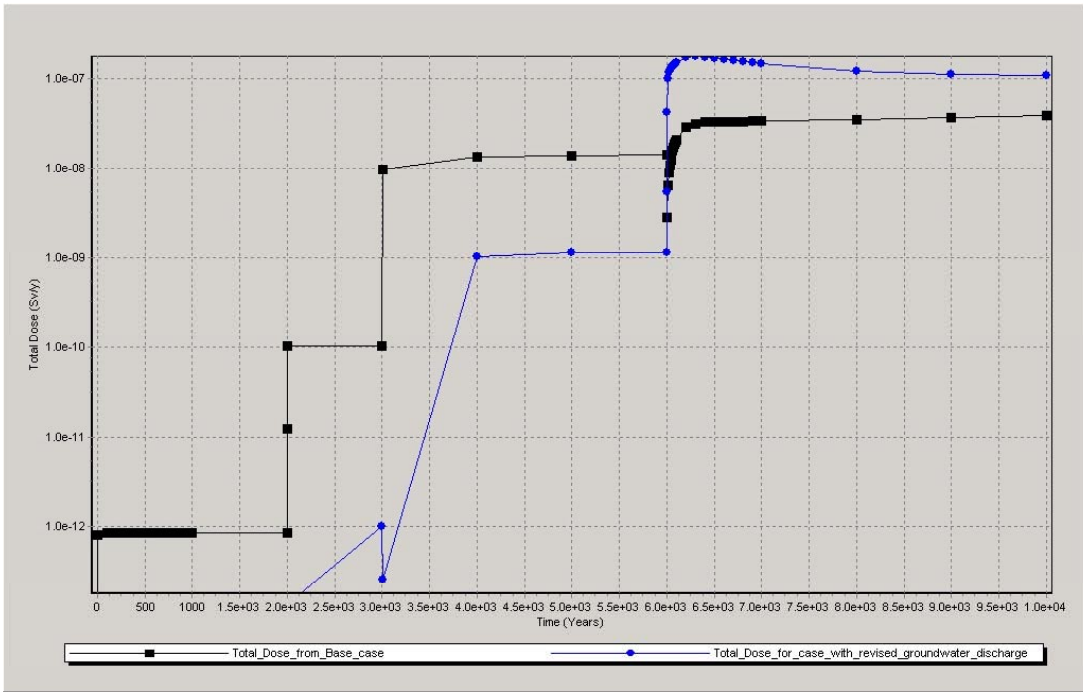
Compartment	Radionuclide	Inventory (Bq)		Ratio of Case 1 Inventory to Base Case Inventory
		Base Case	Case 1	
Top_Soil	Tc-99	3.78E+02	3.28E+05	8.7E+02
Deep_Soil	Tc-99	1.40E+04	1.51E+07	1.1E+03
SatZ_GW	Tc-99	4.30E+02	2.36E+05	5.5E+02
SatZ_SM	Tc-99	1.33E+04	7.31E+06	5.5E+02
Top_Soil	Cs-135	1.40E+04	3.86E+04	2.8E+00
Deep_Soil	Cs-135	1.39E+06	1.68E+07	1.2E+01
SatZ_GW	Cs-135	3.89E+01	1.21E+03	3.1E+01
SatZ_SM	Cs-135	2.41E+05	7.48E+06	3.1E+01

Table 11.5: Agricultural Land Compartment Inventories (Bq) for Calculation Case 1 and the Base Case at 10 000 years

Compartment	Radionuclide	Inventory (Bq) Base Case	Inventory (Bq) Case 1	Ratio of Case 1 Inventory to Base Case Inventory
Top_Soil	Tc-99	9.72E+03	2.40E+04	2.5E+00
Deep_Soil	Tc-99	9.50E+04	1.70E+05	1.8E+00
SatZ_GW	Tc-99	3.60E+04	3.58E+04	9.9E-01
SatZ_SM	Tc-99	1.11E+06	1.11E+06	9.9E-01
Top_Soil	Cs-135	4.70E+05	2.58E+06	5.5E+00
Deep_Soil	Cs-135	1.64E+06	8.27E+06	5.0E+00
SatZ_GW	Cs-135	5.83E+03	7.76E+03	1.3E+00
SatZ_SM	Cs-135	3.61E+07	4.80E+07	1.3E+00

The implications of these differences in compartment inventories for radiological impact is illustrated in Figure 11.1. For the coastal and lake models, the total dose is more than an order of magnitude lower for the alternative model than for the Base Case, because of the comparatively low inventory of radionuclides in the water column (Tables 11.2 and 11.3). This is most important model compartment from the perspective of determining potential exposures associated with these ecosystem types.

Figure 11.1: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 1 (Alternative Discharge Model) and Base Case, assuming constant release of 10 000 Bq y^{-1}



The detailed results shown in Figure 11.1 for the period up to 6000 years are, in part, an artefact of the way in which the calculations have been structured, assuming a constant uniform discharge rate for all radionuclides. In particular, the dominant radionuclide in the Base Case calculations is Cs-137, which in practice could not be released at a constant rate over such a long period, because of its comparatively short half-life. When released via bed sediments, Cs-137 is strongly sorbed to the sediments and decays in situ, without reaching the water column. Consequently, for the Case 1 model, there can be no contribution to total dose from Cs-137. The second most important radionuclide in the Base Case calculations (contributing approximately 10% of the total dose) is C-14, which has a much longer half-life than Cs-137 and is also only weakly sorbed to bed sediments. By the end of the 'lake discharge' period, the projected concentration of C-14 in the lake water column (and hence the calculated individual dose) is essentially the same for both the Base Case and Case 1 release models.

For the agricultural land model (which gives rise to the highest total doses for the constant release rate assumed here), the dose is initially almost an order of magnitude higher in the Case 1 model (and even by 10 000 years remains about a factor of three higher) than for the Base Case, because of the increased initial top soil inventory associated with sorption to bed sediments.

11.3.2 Alternative Evolution Models (Cases 2A and 2B)

Explicit modelling of the sequence from coastal sediment to lake sediment to soil (Case 2A) results in slightly higher initial doses for agricultural land model as a result of the higher top soil inventory (Figure 11.2). One reason for this is that no account is taken, within this simple alternative model of radionuclide accumulation, of the progressive accretion of fresh sediment during the lifetime of the coastal and lake ecosystems. Hence activity that has been accumulated in top sediment will always be translated into contamination of unsaturated soils in the subsequent transition to agricultural land. Nevertheless, the increase, compared with the Base Case SKB model, is only marginal (less than 10%) because the sorption coefficients for lake sediments are higher than those for coastal sediments (compare Tables A-8 and A-9 in Karlsson et al. (2001)), which means that there is greater retention of radionuclides in bed sediments of the lake environment than in the coastal environment.

A different approach to representing environmental change, as a gradual rather than simple step-wise process (Case 2B), results in generally similar total doses to those estimated using the Base Case model. However, there is an order of magnitude increase in doses estimated for the lake exposure group (Figure 11.3), which can be linked to the assumption of a steadily falling lake volume to a minimum value of $4\ 10^4\ m^3$, compared with the steady value assumed in the Base Case model (see Appendix). Projected concentrations in the water column are also affected by the assumed increase in the ‘retention time’ of water within the lake from an initial value of 0.24 years (as in the Base Case) to a maximum value of 0.4 years.

Figure 11.2: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 2A (Alternative Model for Sediment Incorporation in Soil) and Base Case, assuming constant release of 10 000 Bq y^{-1}

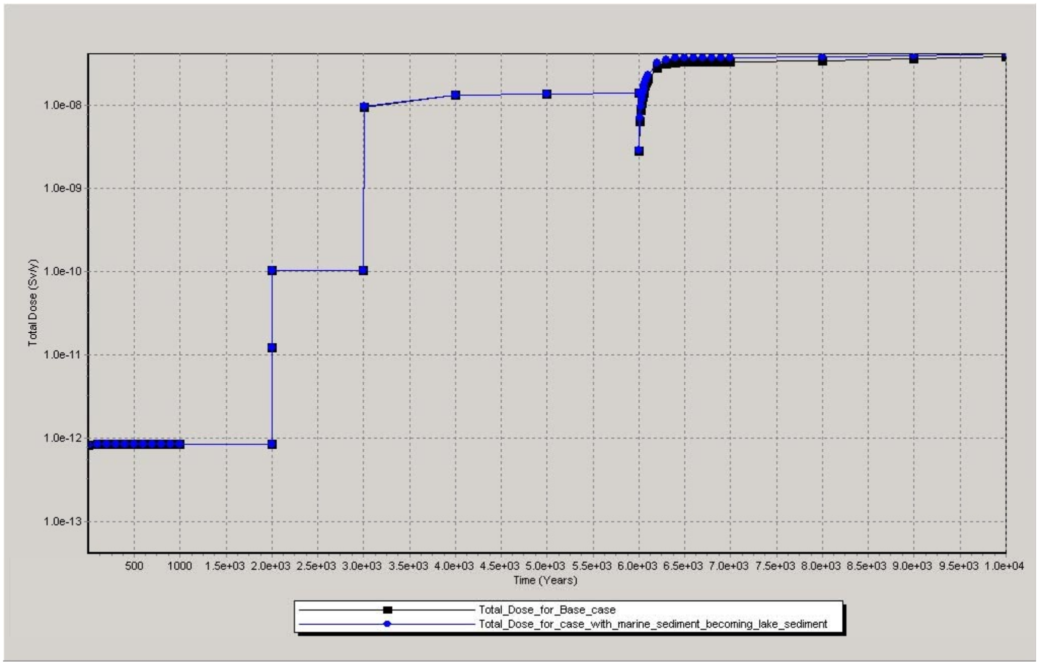
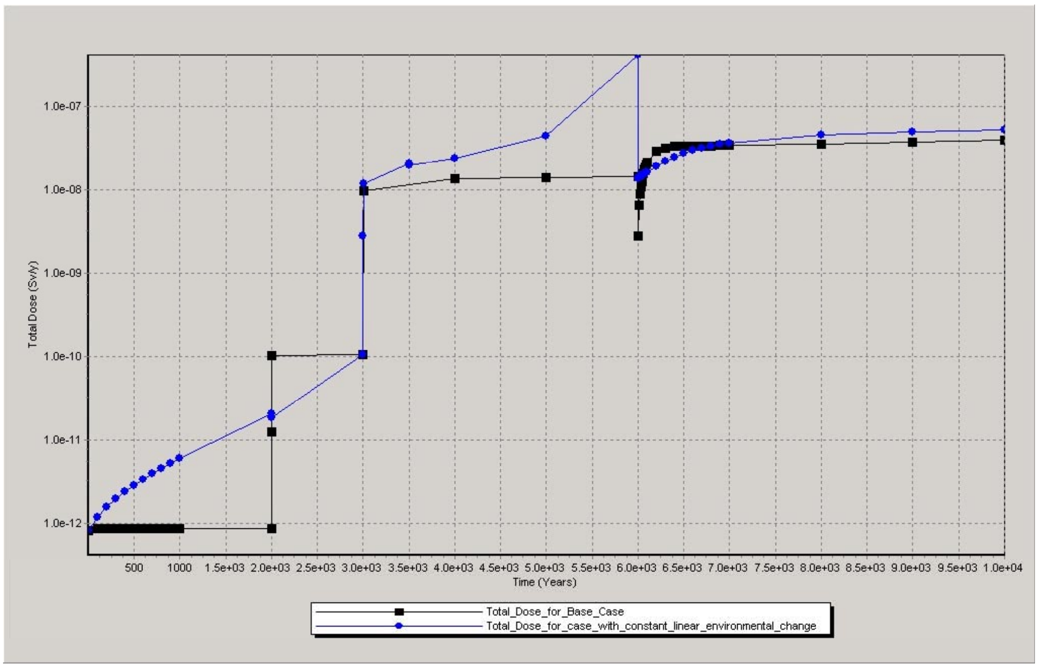


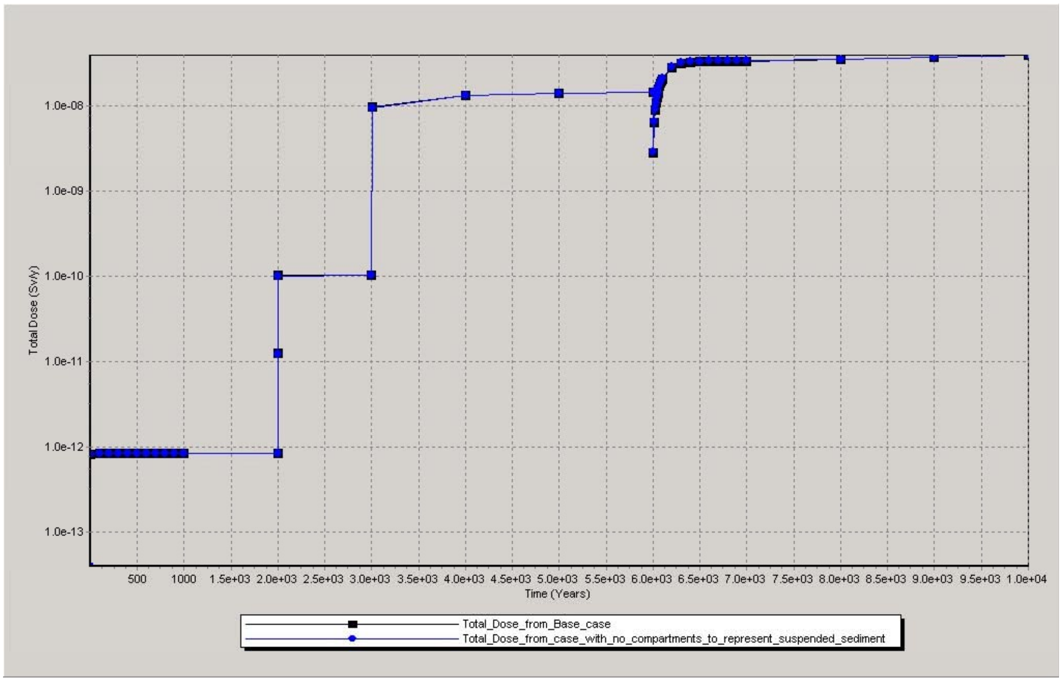
Figure 11.3: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 2B (Alternative Representation of System Evolution) and Base Case, assuming constant release of 10 000 Bq y^{-1}



11.3.3 Alternative Coastal/Lake Models (Cases 3A, 3B and 3C)

Representation of the water column and associated suspended sediment by a single dynamic compartment (Case 3A), but nevertheless retaining the Base Case models for sedimentation and resuspension processes, had no significant effect on either the predicted compartment inventories or the resulting total doses (see Figure 11.4).

Figure 11.4: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 3A (Alternative Representation of Suspended Sediment) and Base Case, assuming constant release of 10 000 Bq y^{-1}



Implementation of alternative models for sedimentation and resuspension did, however, result in some differences in compartment inventories and total doses. The first model (Case 3B – see Appendix) had only a very minor effect on the inventory of the selected indicator radionuclides in the water column (Tables 11.6 and 11.7). This model compartment is the principal contributor to individual dose for exposure groups associated with both the coastal and lake ecosystems. Hence projected doses for these groups remained essentially unchanged in the period up to 6000 years (Figure 11.5). However, the Case 3B model resulted in somewhat higher (albeit by less than a factor of two) inventories of radionuclides in the coastal and lake sediment compartments (Tables 11.6 and 11.7). Consequently, with the transfer of the sediment inventory to the land following the draining of the lake, slightly higher initial inventories in agricultural soils (Table 11.8) and total doses to the agricultural land exposure group (Figure 11.5) are projected.

Table 11.6: Model Area Compartment Inventories (Bq) for Calculation Case 3B and the SKB Base Case at 1000 years

Compartment	Radionuclide	Inventory (Bq)		Ratio of Case 3B Inventory to Base Case Inventory
		Base Case	Case 3B	
Model_Area_Water	Tc-99	2.91E+01	2.91E+01	1.0E+00
Model_Area_UppSed	Tc-99	7.78E-01	2.95E+00	3.8E+00
Model_Area_Sediment	Tc-99	8.52E+01	3.21E+02	3.8E+00
Model_Area_Water	Cs-135	2.76E+01	2.84E+01	1.0E+00
Model_Area_UppSed	Cs-135	7.34E+01	2.74E+02	3.7E+00
Model_Area_Sediment	Cs-135	8.05E+03	2.99E+04	3.7E+00

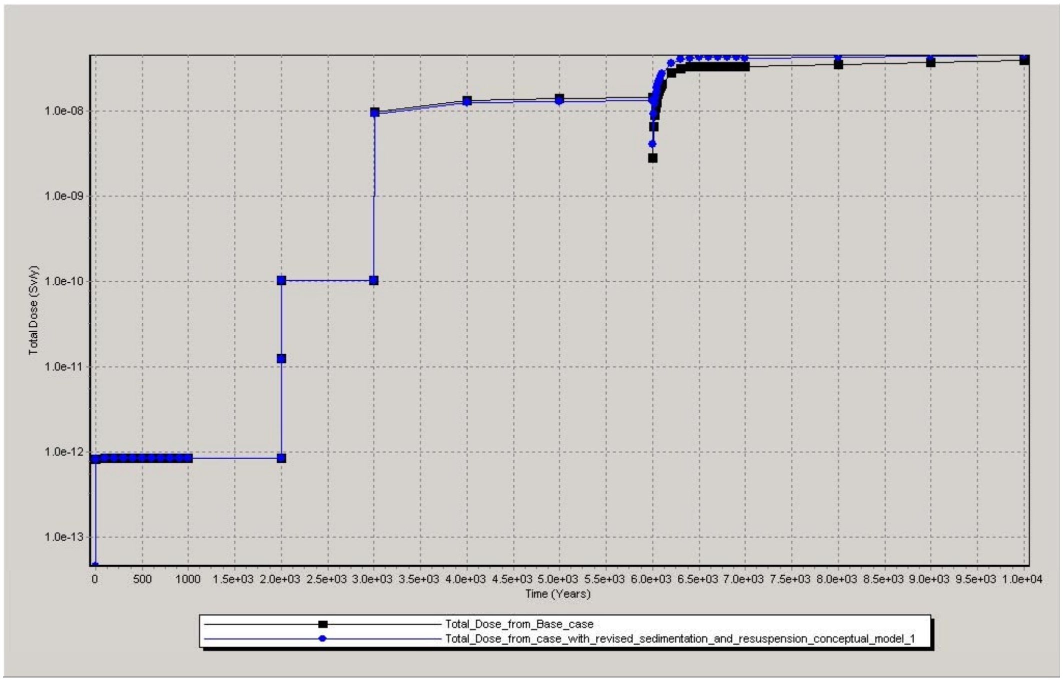
Table 11.7: Lake Compartment Inventories (Bq) for Calculation Case 3B and the Base Case at 4000 years

Compartment	Radionuclide	Inventory (Bq)		Ratio of Case 3B Inventory to Base Case Inventory
		Base Case	Case 3B	
TopSoilLake	Tc-99	5.69E-01	5.68E-01	1.0E+00
DeepSoilLake	Tc-99	1.71E+00	1.71E+00	1.0E+00
Lake_Area_Water	Tc-99	2.40E+03	2.40E+03	1.0E+00
Lake_Area_UppSed	Tc-99	2.49E+02	4.31E+02	1.7E+00
Lake_Area_Sediment	Tc-99	9.88E+03	1.70E+04	1.7E+00
TopSoilLake	Cs-135	2.16E+01	2.07E+01	9.6E-01
DeepSoilLake	Cs-135	4.45E+01	4.25E+01	9.6E-01
Lake_Area_Water	Cs-135	2.14E+03	2.05E+03	9.6E-01
Lake_Area_UppSed	Cs-135	2.23E+04	3.61E+04	1.6E+00
Lake_Area_Sediment	Cs-135	8.84E+05	1.43E+06	1.6E+00

Table 11.8: Agricultural Land Compartment Inventories (Bq) for Calculation Case 3B and the Base Case at 6001 years

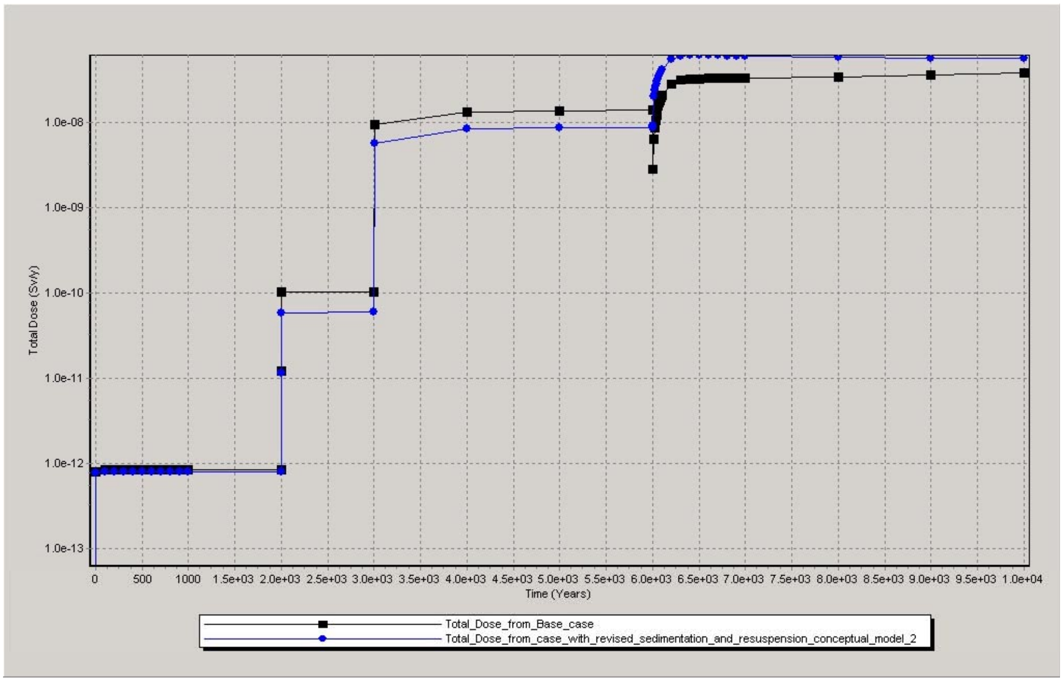
Compartment	Radionuclide	Inventory (Bq)		Ratio of Case 3B Inventory to Base Case Inventory
		Base Case	Case 3B	
Top_Soil	Tc-99	3.78E+02	6.50E+02	1.7E+00
Deep_Soil	Tc-99	1.40E+04	2.38E+04	1.7E+00
SatZ_GW	Tc-99	4.30E+02	4.65E+02	1.1E+00
SatZ_SM	Tc-99	1.33E+04	1.43E+04	1.1E+00
Top_Soil	Cs-135	1.40E+04	2.29E+04	1.6E+00
Deep_Soil	Cs-135	1.39E+06	2.21E+06	1.6E+00
SatZ_GW	Cs-135	3.89E+01	4.21E+01	1.1E+00
SatZ_SM	Cs-135	2.41E+05	2.61E+05	1.1E+00

Figure 11.5: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 3B (First Alternative Sedimentation Model) and Base Case, assuming constant release of 10 000 Bq y^{-1}



In contrast to the above, where changes in the projected concentrations in the water column of the coastal and lake environments were found to be very small, the other alternative model for sedimentation and resuspension (Case 3C – see Appendix) resulted in somewhat lower water inventories (and doses – Figure 11.6) during this period, owing to the comparatively higher rate of transfer to sediment, especially following the reduction in the depth of the water column after 2000 years. A further implication of the increased rate of transfer is a higher initial concentration of radionuclides in the soils of the agricultural land model (Figure 11.6).

Figure 11.6: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 3C (Second Alternative Sedimentation Model) and Base Case, assuming constant release of 10 000 Bq y^{-1}



11.3.4 Alternative Mire Model (Case 4)

Table 11.9 illustrates the effect on lake ecosystem compartment inventories (at 4000 years) of assuming that contaminated mires can act as secondary sources of radionuclides (see Appendix). There is an increase in the inventory for both indicator radionuclides, for both the water column and bed sediment compartments, as well as the associated irrigated land.

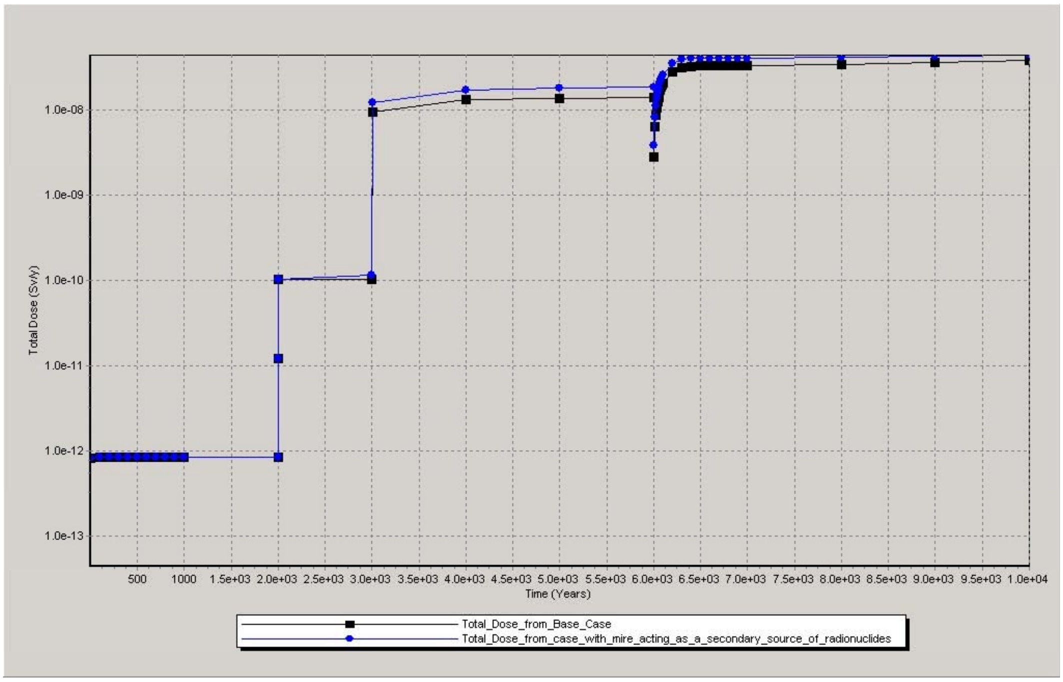
These differences are also reflected in the projected individual doses to members of hypothetical exposure groups (Figure 11.7). As noted in the Appendix, the model is intended as a simple illustration only, being based on the assumption that 10 000 Bq y^{-1} is released to both the coastal/lake environment and the mire, at the same time. Although there is a delay in the subsequent transfer of more strongly sorbed radionuclides from the mire to the lake, the less strongly-sorbed radionuclides are transported relatively rapidly to the lake, thereby increasing the inventory in its associated compartments by around a factor of two.

The overall effect is clearly strongly dependent on assumptions about the timing and magnitude of releases. For this very simple illustrative case, because the calculations are based on a constant rate of release over time; the overall effect is simply one of doubling the effective release rate into the lake system.

Table 11.9: Lake Compartment Inventories (Bq) for Calculation Case 4 and the Base Case at 4000 years

Compartment	Radionuclide	Inventory (Bq)		Ratio of Case 4 Inventory to Base Case Inventory
		Base Case	Case 4	
TopSoilLake	Tc-99	5.69E-01	1.14E+00	2.0E+00
DeepSoilLake	Tc-99	1.71E+00	3.41E+00	2.0E+00
Lake_Area_Water	Tc-99	2.40E+03	4.79E+03	2.0E+00
Lake_Area_SusMatter	Tc-99	4.62E-01	9.30E-01	2.0E+00
Lake_Area_UppSed	Tc-99	2.49E+02	5.01E+02	2.0E+00
Lake_Area_Sediment	Tc-99	9.88E+03	1.99E+04	2.0E+00
TopSoilLake	Cs-135	2.16E+01	3.53E+01	1.6E+00
DeepSoilLake	Cs-135	4.45E+01	7.09E+01	1.6E+00
Lake_Area_Water	Cs-135	2.14E+03	3.68E+03	1.7E+00
Lake_Area_SusMatter	Cs-135	4.14E+01	7.15E+01	1.7E+00
Lake_Area_UppSed	Cs-135	2.23E+04	3.84E+04	1.7E+00
Lake_Area_Sediment	Cs-135	8.84E+05	1.43E+06	1.6E+00

Figure 11.7: Total Dose (Sv y^{-1}), summed over all radionuclides, for Calculation Case 4 (Alternative Mire Model) and Base Case, assuming constant release of 10 000 Bq y^{-1}



12 Key Findings and Recommendations

It is recognised that the detailed results of this study are in part a reflection of the artificial nature of some of the assumptions that were adopted (particularly in terms of the representation of radionuclide release). Ideally, rather than assuming a constant release rate of all radionuclides represented in the SAFE assessment, the full time-history of the flux of all radionuclides into the biosphere, from all SFR disposal units, could have been simulated. Unfortunately, owing to the difficulties encountered in attempting to verify the implementation of the SKB's models using AMBER, there was no time available to implement more detailed source terms as part of the current modelling study. Nevertheless, since the main focus of the calculation cases is to compare the alternative models with the original SKB models (rather than to perform an absolute evaluation of potential radiological impacts), a constant unit flux was considered appropriate. Defining the calculations in this way allowed for a more rapid implementation of the alternative models and thus represented a more efficient use of limited project resources.

The results of considering a range of alternative approaches suggest that the SKB models are fairly robust to uncertainties associated with a range of differing modelling assumptions. For five of the seven alternative models that have been considered here, differences in the model compartment inventories (and resulting doses) between the SKB 'Base Case' model and the alternative model are less than a factor of two or three. The two significant exceptions are: (a) an alternative groundwater discharge model (Case 1), in which contaminated groundwater is released via sediment rather than directly into the water column; and (b) an alternative evolution model (Case 2B), in which there is a smoothly varying change in lake characteristics as a function of time.

In both these cases, the estimated doses to some exposure groups (based on the simplified release assumptions adopted for the purposes of this preliminary study) exceed those determined using the SKB models by approximately an order of magnitude[6]. For the variant discharge model, the key processes resulting in the increased doses to the agricultural land exposure group (and reduced doses for the coastal and lake exposure groups) are:

- increased sorption of radionuclides onto the coastal/marine bed sediments (as a result of the assumed discharge of contaminated groundwater via the sediment compartments); and

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[6] It is relevant to compare this order of magnitude conceptual model uncertainty with the seven orders of magnitude range in doses for the differing biosphere states considered in Lindgren et al (2001) (i.e. present day, reasonable, mire and well).

- subsequent use of bed sediments as agricultural soils, assumed to be drained following land rise, resulting in exposure to accumulated contamination.

For the alternative evolution model, the key process resulting in an increase in the projected dose to the lake exposure group is the progressive reduction in the assumed size of the lake (modelled as a constant linear process) and the associated increase in radionuclide concentrations (for a constant release rate).

It is therefore recommended that alternative groundwater discharge pathways and system evolution models should considered in future assessments.

Moreover, it is relevant to note that, owing to constraints on the current preliminary study, each of the proposed alternative models was investigated and compared separately against the Base Case SKB model, rather than in combination. It is possible that the combination of alternative models could have a more significant effect on projected radiological impacts than individual models on their own. For example, whereas the alternative models for sediment accumulation and mixing (Case 3B and 3C) did not have a particularly marked effect on projected compartment inventories and radiation exposures when considered separately, they could play a more important role when considered in conjunction with alternative discharge routes (Case 1) or representations of system evolution (Case 2). It is therefore recommended that the implications of such combinations of alternative approaches for overall modelling uncertainty should be considered as a basis for further study.

As noted in Part 2 above, the concept of an ‘interface’ between the geosphere and biosphere is essentially a modelling artefact, as indeed is any rigid distinction between geosphere and biosphere. Typically, the interface has to be introduced within assessment models because of the fact that simulations of the hydrogeological system used to determine flow and transport from the repository to the surface environment depend on boundary conditions for recharge and discharge that are not necessarily well integrated with more detailed understanding of the features, events and processes that affect the near-surface hydrogeological and hydrological regime.

SKB has attempted to take an integrated systems view in relation to providing a comprehensive system description, but this does not appear to have been followed through in the assessment modelling. In order to ensure that appropriate and adequately justified interfaces are made between the assessment models (and particularly between the biosphere and the geosphere) it may be appropriate for SKB to introduce an additional tier of supporting models (e.g. representing near-surface hydrology and sedimentation/erosion processes) to guide the representation and characterisation of FEPs in their PA models. One approach for ensuring that the geosphere-biosphere interface is represented in a consistent manner would be through the use of a single ‘system-level’ PA model that incorporated representation of both the geosphere and biosphere. In any case, careful liaison is required between geosphere and biosphere modelling teams to ensure that an integrated approach is adopted in representing processes at the interface.

Finally, in undertaking the study, a number of additional points have been identified for consideration by SSI in its evaluation of SKB’s recent assessments and in planning its own assessment modelling capability. These include:

- Confirming the detailed reporting and implementation of the ecosystem models described by Karlsson et al. (2001), which could not be comprehensively and successfully verified through parallel implementation using the AMBER code. Our attempts to replicate the SKB models indicated that there are, at the very least, transcription errors in some of the figures within this report, and there may be more systematic errors in the calculation of radionuclide concentrations for some model compartments. The approach used by SKB to determine radionuclide concentrations associated with soil and sediment compartments is not currently documented, and needs to be checked.
- Representation of the in-growth of radioactive daughters in the near-field, geosphere and biosphere, which was ignored in SKB’s recent assessment for SFR. Our preliminary investigation of this aspect of the assessment was not conclusive, and resource limitations prevented a more in-depth evaluation at this time. Although SKB’s approach may possibly have been adequate for the purposes of the SAFE assessment, it is unlikely to be justified in all circumstances.

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Appendix: Specification of Calculation Cases

A.1 Case 1

This calculation case considers the possible implications of the discharge of groundwater to the coastal and lake environment via bed sediment, coupled with an alternative conceptual model for near-surface water flows within agricultural soils.

For the coastal and lake models, the groundwater is assumed to be released first into the 'sediment' compartment, then to continue through the 'upper sediment' compartment before finally being discharged into the water column. For the period from 2000 to 5000 AD, the initial discharge is assumed to take place to the "Model Area" coastal sediment compartment, while from 5000 to 8000 AD it is assumed to occur within the lake sediment compartment. From 8000 AD onwards (as in the Base Case SKB model), the release is assumed to occur via the 'saturated zone groundwater' compartment of the Agricultural Land model.

The transfer coefficient for advective transport of radionuclides in groundwater between adjacent model compartments is given by:

$$\frac{V_{wflow}}{V_{sed}\,\theta_{sedw}\,R_{sed}} \tag{1}$$

where:

V_{wflow}	is the annual volume of water discharged from the compartment ($m^3\ y^{-1}$);
V_{sed}	is the volume of the compartment (m^3);
θ_{sedw}	is the water-filled porosity of the compartment (assumed to be equal to the total porosity); and
R_{sed}	is the retardation coefficient for the compartment, given by:

$$R_{sed} = 1 + \frac{(1-\theta_{sed})\,\rho_{g,sed}}{\theta_{sedw}} K_{d,sed} \tag{2}$$

where:

θ_{sed}	is the total porosity of the compartment;
$\rho_{g,sed}$	is the grain density of solid material within the compartment ($kg\ m^{-3}$); and
$K_{d,sed}$	is the element-dependent sorption coefficient of the compartment ($m^3\ kg^{-1}$).

The above equations have been implemented in the AMBER case file for Case 1, using data from Karlsson et al. (2001). However, Karlsson et al. (2001) do not provide information on the assumed rate of discharge of contaminated groundwater into the biosphere (V_{wflow}). For the purposes of the current preliminary modelling study, information was therefore derived from Chapman et al. (2002) and Holmén and Stigsson (2001).

Chapman et al. (2002) adopt an initial Darcy velocity for the vertical transport from the SFR repository to the sea bed of $5\ 10^{-4}$ m y^{-1}. Combined with a repository plan area in the region of $5\ 10^{4}$ m^{2}, this gives an overall groundwater discharge rate for water passing through the repository of around 25 m^{3} y^{-1}. This is consistent with information in Holmén and Stigsson (2001), which states that the total flow in the region of the repository is currently between 12 and 48 m^{3} y^{-1}. Chapman et al. (2002) further assume that, as sea level falls, the Darcy velocity increases by a factor of 10 over a period of around 2000 years, as the flow direction changes from the vertical to the horizontal. Combining this flow rate with the area of the lake given by Karlsson et al. (2001) ($1.06\ 10^{6}$ m^{2}) – assumed to be equal to the initial area over which the discharge takes place – results in an overall groundwater discharge rate through the sediment of $5.3\ 10^{3}$ m^{3} y^{-1}. For subsequent discharge to agricultural land, the area of discharge assumed to be to be $5.3\ 10^{5}$ m^{2} (i.e. the area of the agricultural land assumed by Karlsson et al. (2001)); this results in an overall groundwater discharge to the agricultural land model of $2.65\ 10^{3}$ m^{3} y^{-1}. Again, these assumed overall discharge rates are broadly consistent with the conclusions of Holmén and Stigsson (2001), who suggest that the total flow in the immediate vicinity of the repository (i.e. between 12 and 48 m^{3} y^{-1}) is likely to be only a few percent of the total discharge of groundwater in the discharge area.

Hence, for Case 1 the following time history of groundwater discharge (V_{wflow}) has been adopted:

- 0 to 1000 years: constant 25 m^{3} y^{-1};
- 1000 to 3000 years: linear increase from 25 m^{3} y^{-1} to $5.3\ 10^{3}$ m^{3} y^{-1};
- 3000 to 6000 years: constant $5.3\ 10^{3}$ m^{3} y^{-1}; and
- 6000 to 10 000 years: constant $2.65\ 10^{3}$ m^{3} y^{-1}.

In addition to these modifications relating to the modelling of groundwater release, changes have also been made to the transfer rates within the agricultural land model compared with those used by Karlsson et al. (2001). These modifications relate to transfers from the 'top soil' to 'deep soil' compartments, the 'deep soil' to 'saturated zone groundwater' compartments, and the 'saturated zone groundwater' to the 'out' (sink) compartments.

For the first two of these transfer rates, the downward flow term (*F*) has been excluded, since it was considered that inclusion of this term as well as the runoff[7] (*r*) term amounts to an effective double-counting of the advective component of downward migration through the soil column. Hence the transfer factors are given by:

$$\frac{r}{\theta_{ts}\, d_{ts} R_{soil}} + \frac{B}{(1-\theta_{ts})\, \rho_{g,soil}\, d_{ts}} \tag{3}$$

for the transfer from top soil to deep soil, and

$$\frac{r}{\theta_{ds}\, d_{ds} R_{soil}} \tag{4}$$

for the transfer from deep soil to the saturated zone groundwater, where:

r	is the 'runoff' (m^3/m^2 per year);
θ_{ts}, θ_{ts}	are the porosities of the top soil and deep soil compartments, respectively;
d_{ts}, d_{ts}	are the depths of the top soil and deep soil compartments (m);
B	is a mixing coefficient for bioturbation (kg/m^2 per year);
$P_{g,soil}$	is the assumed grain density of agricultural soil (kg m^{-3}); and
R_{soil}	is the retardation coefficient for the agricultural soil, given by:

$$R_{soil} = 1 + \frac{(1-\theta_s)\, \rho_{g,soil}}{\theta_s} K_{d,soil} \tag{5}$$

For the transfer from the saturated zone groundwater to the out (sink) compartment, the expression used by Karlsson et al. (2001) to represent the transfer due to 'runoff' has been augmented by adding the term given in Equation (1) above, in order to represent transfer resulting from groundwater discharge. This modification to the model is consistent with the conclusions in Part 2 of the main report, where it is noted that:

> *"The modelling approach used* [by SKB] *includes an 'aquifer' as part of the assessment biosphere, with contamination assumed to enter (from the geosphere) in solution. However, outflow from the 'aquifer' is determined solely by meteoric water infiltrating from above – with no apparent contribution from sub-horizontal interflow associated with adjacent parts of the catchment, or regional discharge of the aquifer system. This begs*

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[7] It is considered that a more appropriate descriptor for this term, as defined in the SKB model (i.e. precipitation minus evapotranspiration), would be infiltration or percolation. Runoff implies flow over the ground surface.

> *questions of mass conservation and consistency with assumptions about the nature of the geosphere/biosphere interface, since it implies that the effective throughput of water in the both the unsaturated and saturated zones is the same. Given the long characteristic timescales associated with the agricultural land model (Chapter 10), the turnover of water within the saturated zone is a clearly critical parameter of the model, especially as it has been configured to evaluate the radiological impacts of groundwater contamination."*

A.2 Case 2A

This calculation case considers the implications of incorporating the radionuclide inventory associated with the "Model Area" coastal sediments into the lake sediment at the time when the lake appears (at 5000 AD, i.e. after 3000 years). It is assumed that there is a direct translation of radionuclides from each of the coastal sediment compartments to the equivalent lake sediment compartments. This approach contrasts with the Base Case "reasonable biosphere development" SKB model, in which it is assumed that there is no transfer of the accumulated inventory from the coastal sediments to the lake sediments. Within the SKB model, the "Model Area" coastal sediment radionuclide inventory is instead transferred to the 'saturated zone solid matter' compartment of the agricultural land model after 6000 years (Lindgren et al., 2001).

A.3 Case 2B

In this calculation case, the time-evolving chemical and physical conditions within the biosphere are represented explicitly as a gradual, rather than a simple step-wise process. The key assumptions are listed below.

- The area associated with all the coastal compartments, as well as the assumed depth of the water column, decrease in a linear fashion with time between 0 and 3000 years from their initial best estimate values (Table 3-2 of Karlsson et al. (2001)) to the best estimate values defined for later times (Table 3-3 of Karlsson et al. (2001)).
- The assumed water retention time and the "fraction of accumulation bottoms" in the coastal compartments increase in a linear fashion between 0 and 3000 years from their initial best estimate values (Table 3-2 of Karlsson et al. (2001)) to the best estimate values given at later times (Table 3-3 of Karlsson et al. (2001)).
- At 2000 years, it is assumed that mire areas appear and remain present within the biosphere until the end of the simulation period. From 2000 years to 3000 years, the mire is assumed to discharged into the Model Area coastal system

(by drainage and erosion). From 3000 years to 6000 years, it is assumed to discharge to the lake system.

- At 3000 years there is an assumed step-change from discharge to a coastal environment to discharge to a lake environment.
- The area associated with all the lake compartments decreases in a linear fashion between 3000 and 6000 years to a minimum value of 40 000 m^2, while the assumed depth of the lake water compartment decreases from 1.7 m to 0.5 m.
- The assumed water retention time in the lake increases linearly between 3000 and 6000 years from 0.24 years to a value of 0.4 years, while the "fraction of accumulation bottoms" in the lake increases from 0.2 to 0.95.
- At 3500 years emergent land starts to be used for agricultural purposes.
- The time history of the radionuclide source term from the geosphere to the biosphere is assumed to follow the following pattern:
  - 0 to 2000 years: constant 100% (i.e. 10 000 Bq y^{-1}) to Model Area (coastal environment);
  - 2000 to 3000 years: constant 90% to Model Area, 10% to mire;
  - 3000 to 3500 years: constant 90% to lake, 10% to mire;
  - 3500 to 6000 years: linear increase from 10% to 90% to agricultural land, constant 10% to mire, and linear decrease from 80% to 0% to lake; and
  - 6000 to 10 000 years: constant 90% to agricultural land, 10% to mire.

A.4 Case 3A

This calculation case considers the implications of adopting an alternative approach to representing the partitioning of radionuclide between solution and attachment to suspended sediment in the water column of the coastal and lake models. Rather than representing these as separate dynamic compartments, as in the SKB Base Case model (Karlsson et al., 2001), the standard approach is taken of using a single compartment to represent the water column as a whole. Radionuclide transfer from suspended sediment to the upper sediment compartment, represented by Karlsson et al. (2001) using the transfer coefficient:

$$\frac{v_s}{d_w} \tag{6}$$

is therefore based on the total inventory within the water column compartment, modified to account for the fraction attached to suspended sediment, using:

$$\frac{K_{d,ssed}\alpha_w}{(1+K_{d,ssed}\alpha_w)} \tag{7}$$

where:

$K_{d,ssed}$ is the sorption coefficient for suspended sediment in the coastal/lake water compartment (m^3 kg^{-1});

v_s is the suspended sediment particle settling velocity (m y^{-1});

d_w is the mean water depth in the coastal water or lake system (m); and

α_w is the sediment load in the water column (kg m^{-3}).

Values for $K_{d,ssed}$ and α_w are taken from Karlsson et al. (2001).

A.5 Case 3B

This calculation case uses alternative models to represent radionuclide transport by sedimentation and resuspension in coastal and lake environments, based on those used by JNC (2000).

The transfer rate of radionuclides by resuspension from the 'top sediment' compartment to the 'water column' compartment (assumed – as in Case 3A – to include both suspended sediment and water) is given by:

$$\frac{(R_{used}-1)\ B_{used}}{R_{used}\ d_{used}^2} \tag{8}$$

where:

B_{used} is a mixing rate for transfer from the top sediment compartment to the water compartment due to physical disturbance and bioturbation (m^2 y^{-1});

d_{used} is the depth of the top sediment compartment (m);

R_{used} is the retardation coefficient for the top sediment compartment, calculated using Equation (2) using values from Karlsson et al. (2001), such that:

$\frac{R_{used}-1}{R_{used}}$ represents the particle-attached fraction of the radionuclide inventory within the upper sediment compartment.

The assumed depth of the 'top sediment' compartment, d_{used}, is also obtained from Karlsson et al. (2001), while B_{used} is assigned a value of 3.2 10^{-5} m^2 y^{-1}, based on data given by Klos et al. (1988) (although it is acknowledged that there may be considerable uncertainty associated with the value of this parameter). It is assumed that radionuclide transfer from sediment to the water column as a result of physical disturbance and bioturbation is always more significant than porewater mixing and diffusion.

The rate coefficient for the transfer of radionuclides due to gross sedimentation from the water compartment to the top sediment compartment is given by:

$$\frac{K_{d,ssed}\alpha_w v_s}{(1+K_{d,ssed}\alpha_w)\ d_w} \tag{9}$$

where all the terms are as previously described for Case 3A (Equations (6) and (7)).

The rate coefficient for the transfer of radionuclides from the 'top sediment' to the 'deep sediment' compartment as a result of burial by sediment accumulation is given by:

$$\frac{(R_{used}-1)\ \sigma}{R_{used}\ d_{used}} \tag{10}$$

where:

σ is the net sediment accretion rate (m y^{-1}), and other terms in the equation are as previously defined

The sediment accretion rate (or net sedimentation rate) is described by Karlsson et al. (2001) as the 'sediment growth rate'.

A.6 Case 3C

This case adopts an alternative approach to the representation of FEPs responsible for contaminant accumulation and dispersion in lakes and the coastal environment. In this approach, the particle settling velocity (so-called gross sedimentation) is ignored, and the transfer of particle-associated contamination from the water column to bed sediment is represented by the sum of a particle accretion (net sedimentation) term, coupled with a 'reverse' bioturbation term[8]. Such an approach has formed the basis of models for the coastal environment in studies undertaken by Nirex (1995).

The transfer rate of contaminants from the water column to the upper sediment is therefore given by a combination of terms:

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[8] The reverse bioturbation term is based on the sediment-attached fraction in the benthic boundary layer.

$$\frac{\sigma K_{d,ssed}\,\rho_{g,used}\,(1-\theta_{used})}{(1+K_{d,ssed}\alpha_w)\,d_w} + \frac{B_{used}K_{d,used}\,\rho_{g,used}\,(1-\theta_{used})}{(1+K_{d,used}\alpha_b)\,d_w\ d_b} \tag{11}$$

where:

σ	is the net sediment accretion rate (m y^{-1});
$K_{d,ssed}$	is the sorption coefficient for suspended sediment in the coastal/lake water column compartment (m^3 kg^{-1});
$\rho_{g,used}$	is the grain density for particulate material within the top sediment compartment (kg m^{-3});
θ_{used}	is the total porosity of the top sediment compartment;
α_w	is the mean sediment load over the depth of the water column (kg m^{-3});
d_w	is the mean water depth in the coastal water or lake system (m);
B_{used}	is a mixing rate for transfer between the top sediment compartment and the benthic boundary layer of the water column as a result of physical disturbance and bioturbation (m^2 y^{-1});
$K_{d,used}$	is the sorption coefficient for particulate material in the upper sediment compartment (assumed to be the same as for the suspended sediment) (m^3 kg^{-1});
α_b	is the sediment load in the benthic boundary layer of the water column (kg m^{-3}); and
d_b	is the depth of the benthic boundary layer (m).

The values for all the above parameters, except α_b and d_b, are taken directly from information given in Karlsson et al. (2001). For the purposes of this preliminary modelling study, the sediment load in the benthic boundary layer of the water column is assumed to be an order of magnitude higher than the average in the water column as a whole, because of near-bed mixing processes. The depth of the benthic boundary layer is assumed to be fixed at 0.1 m, independent of the depth of the water column. An alternative approach to defining the near-bed suspended sediment load would be to assume that, at any time, a given depth (perhaps 1 mm) of bed sediment is suspended within the near-bed water column as a result of disturbance by physical and biotic processes (Nicholson and MacKenzie, 1988).

A.7 Case 4

For this calculation case it is assumed that there is the possibility of continuing release (after 2000 years) to both the mire and the evolving coastal/lake/agricultural land system. Radionuclides discharged from the mire are not assumed to be lost to a 'sink' (as in the SKB assessment (Lindgren et al., 2001)), but are released either to coastal waters (between 2000 and 3000 years) or to the lake (between 3000 and 6000 years).

It is acknowledged that this provides only a very simple preliminary representation of the possible connection between the mire system and other parts of the biosphere. For example, in the absence of more detailed information on the projected distribution of releases from the geosphere as a function of space and time, a very simple approach has been taken to representing the release of radionuclides into the biosphere. Both the mire and the coastal/lake environments are assumed to receive a constant contaminant flux of 10 000 Bq y^{-1} for the whole period covered by the assessment.

A more detailed analysis of the potential importance of accumulated activity in mires for doses associated with the coastal, lake and agricultural land systems would require the development of a distributed model of the evolving catchment system, which is beyond the resources available for the current preliminary study.

Appendix References

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SSI-rapporter 2003

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