Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Russell Walke

Technical Note

2014:34

Modelling Comparison of Simple Reference Biosphere Models with LDF Models

Main Review Phase

Report number: 2014:34 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Det övergripande syftet med projektet är att ta fram synpunkter på SKB:s säkerhetsanalys SR-Site för den långsiktiga strålsäkerheten hos det planerade slutförvaret i Forsmark. Det specifika syftet med detta uppdrag är att jämföra så kallade referensbiosfärmodeller med SKB:s LDF-modellering. Jämförelsen innebär att kontrollera om de LDF värden som beräknas med SKB:s metod är rimliga i jämförelse med resultat beräknade med en enklare referensbiosfärsmetodik.

Författarens sammanfattning

Denna rapport beskriver utvecklingen av enkla referensbiosfärsmodeller. Utvecklingen görs för att undersöka den s.k. LDF (Landscape Dose conversion Factor) metoden som SKB använder i säkerhetsanalysen (SR-Site) för det föreslagna slutförvaret för använt kärnbränsle i Forsmark. Modellerna utvecklas och beskrivs på ett systematiskt sätt, baserat på internationella riktlinjer som återspeglas i IAEA:s BIOMASS metod.

Modelleringen sätts i sitt sammanhang och SR-Site dokumentation används för att beskriva den nuvarande biosfären och landanvändningen i Forsmark. Denna information används för att underbygga utvecklingen av biosfärsmodeller som representerar potentiella framtida radionuklidutsläpp från förvaret till havs-, sjö-, myr-, skogs-, betesmarks- och jordbrukssystem. Ett enkelt tillvägagångssätt för modelleringen används, vilket innebär att de olika systemen modelleras oberoende av varandra. Det betyder att successionen mellan biosfärssystem som drivs av landhöjning som en följd av isostatisk post-glacial upplyftning av landmassa inte representeras med denna modellering till skillnad mot modelleringen i säkerhetsanalysen i SR-Site.

Jämförelsen i denna Technical Note av LDF i SR-Site med likvärdiga faktorer, beräknade med de enkla biosfärsmodellerna, visar att:

- Potentiella effekter underskattas i allmänhet inte för viktiga radionuklider i SR-Site vid utsläpp till ytjord/sediment via grundvatten.
- För 17 radionuklider resulterar den explicita representationen av övergången mellan havs-, sjö-, myr- och terrestrasystem i dosfaktorer som är mer än en storleksordning större än de som beräknas med de enkla modellerna med biosfärssystem som inte förändras över tid.
- För 6 radionuklider resulterar de enkla biosfärsmodellerna i dos-

faktorer som är mer än en storleksordning större än de dosfaktorer som används i SR-Site och
- Fokus på exponering av vuxna i SR-Site är berättigad, men det bör betänkas att potentialen för doser till barn och spädbarn är ungefär upp till en faktor sju högre för vissa radionuklider.

Om potentiell exponering från användningen av grunda brunnar för småskalig trädgårdsodling inkluderas i de enkla modellerna (de beaktas inte i LFD i SR-Site) resulterar det i dosfaktorer som är mer än en storleksordning större än LDF i SR-Site för 16 av 39 radionuklider.

Projektinformation
Kontaktperson på SSM: Shulan Xu
Diarienummer ramavtal: SSM2011- 4246
Diarienummer avrop: SSM2013-2539
Aktivitetsnummer: 3030012-4050

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The general objective of the project is to provide review comments on SKB's postclosure safety analysis, SR-Site, for the proposed repository at Forsmark. The objective of this assignment is to compare so called reference biosphere models with SKB's LDF modelling approach. The purpose of doing the comparison is to check if the LDFs derived from SKB's approach are bonded by the results from simple reference biosphere modelling approaches.

Summary by the author

This Technical Note describes the development of simple reference biosphere models as a means of exploring the Landscape Dose Factor (LDF) approach adopted by SKB in the SR-Site safety assessment for the proposed final disposal of spent nuclear fuel at the Forsmark site. The models are developed and described in a systematic manner, based on international guidance reflected in the International Atomic Energy Agency's BIOMASS approach.

The context for the modelling is described and SR-Site documentation is used to provide a description of the current biosphere and land uses at Forsmark. This information is used to justify development of biosphere models to represent potential future radionuclide releases to marine, lake, mire, forest, pasture and arable systems from the repository. A simple modelling approach is adopted, so, unlike the SR-Site safety assessment, the systems are modelled independently and the succession between the biosphere systems, which is driven by land rise resulting from isostatic post-glacial rebound, is not represented.

The development of simple biosphere models enables the way in which the biosphere is represented in the SR-Site safety assessment to be explored; some of the main observations are summarised below.

- The SR-Site safety assessment adopts a complex landscape evolution model, but then uses a relatively simple and coarsely discretised compartment model for 'objects' within the landscape. This approach means that that, although the timescales of landscape change are well-represented, the dynamics of radionuclide accumulation within the context of the evolving system are not.
- The emphasis on representing transition from marine through to terrestrial systems in SR-Site means that the assessment focuses on

development and subsequent exploitation of organic soils. Clayey silty till soils are given limited consideration, even though they are a significant component of the present-day Forsmark system and are better suited to long-term agriculture.
- Surveys of present-day groundwater usage in the Forsmark area show that shallow groundwater can be used for irrigation. Irrigation is only considered in side calculations in SR-Site and it is not included in the LDFs.
- Specific observations are also made about the biosphere models, data and their documentation, which limit confidence in the results. These include (i) the aggregation of sorption data for significantly different soils and sediments, (ii) the degree of abstraction and normalisation of groundwater flow modelling results and the way in which they are then used in the assessment model, (iii) assumptions concerning short-lived daughters are not explicitly described and their contributions to dose coefficients presented in the reports do not appear to have been properly represented, (iv) the carbon based approach to the definition of parameters (including equilibrium concentration ratios, transfer factors and habits) means that they cannot easily be understood or compared with other assessments.

Comparison of the SR-Site LDFs with equivalent factors calculated with the simple biosphere models described in this Technical Note indicates that:

- potential impacts are generally not underestimated for important radionuclides in SR-Site for releases to surface soils/sediments via groundwater;
- for 17 radionuclides, the explicit representation of transitions between marine, lake, mire and terrestrial systems results in dose factors that are more than an order of magnitude greater than those calculated with simple, non-evolving biosphere systems;
- for six radionuclides, the simple biosphere models resulted in dose factors more than an order of magnitude higher than those used in SR-Site; and
- a focus on exposure of adults in SR-Site is justified, but it should be borne in mind that potential for doses to children and infants are up to about a factor of seven higher for certain radionuclides.

If potential exposures arising from the use of shallow wells for small-scale horticulture is included in the simple models (it is not considered in the SR-Site LDFs), the resulting dose factors are more than an order of magnitude higher than the SR-Site LDFs for 16 out of 39 radionuclides.

Project information

Contact person at SSM: Shulan Xu

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Russell Walke
Quintessa Ltd., Henley-on-Thames, UK

Technical Note 58

2014:34

Modelling Comparison of Simple Reference Biosphere Models with LDF Models

Main Review Phase

Date: November, 2013
Report number: 2014:34 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Contents

1. Introduction

The project aims to develop simple reference biospheres as a means of exploring the Landscape Dose Factor (LDF) approach adopted by SKB in SR-Site. A separate project team is undertaking independent modelling of evolving systems.
The simple reference biospheres have been developed in a systematic manner, based on, for example, international guidance reflected in the BIOMASS approach (IAEA, 2003). A full application of the BIOMASS approach is inappropriately detailed, given the scope of the project, so a simplified approach is adopted, which draws on the guidance and also builds on the assessment team's experience of developing reference biosphere models. The approach is illustrated in Figure 1.

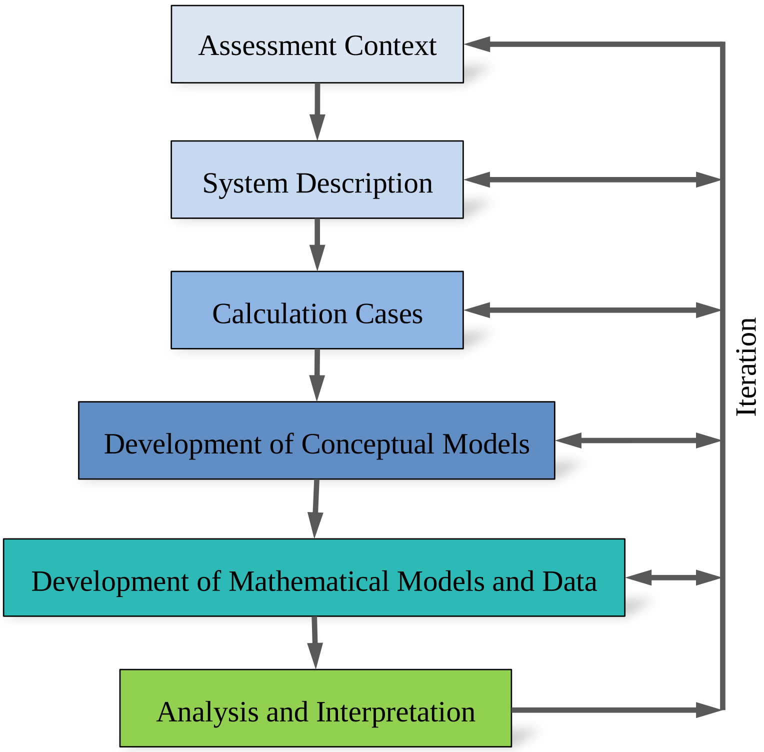


Figure 1: Approach to the development of simple reference biospheres.

This report presents the development of the simple reference biosphere models and the comparison of the results against the LDFs used in support of the SR-Site assessment. The report is structured consistent with the approach set out above:

- the assessment context is described in Section 2;
- the system description is presented in Section 3;
- the calculation cases are defined in Section 4;
- the conceptual models are described in Section 5;
- the mathematical models are presented in Section 6;
- the data are presented in Section 7;
- the implementation of the models and data is briefly described in Section 8;
- the results presented in Section 9, including comparison against the LDFs used in support of SR-Site; and

- conclusions are drawn together in Section 10.

References are given in Section 11. Appendix 1 provides a complete set of results for the reference calculations with the simple biosphere models.

2. Assessment Context

The assessment context is described in the subsections below, each of which addresses one of the components identified in the BIOMASS approach (IAEA, 2003).

2.1. Purpose of the Assessment

The purpose is to evaluate the suitability of SKB's biosphere dose assessment model for non-disruptive scenarios through comparison with simpler models developed using a 'reference biosphere' approach. Simplified reference biosphere models have been developed that include the most plausible transport processes and that represent various types of biosphere systems, including use of a well, agricultural land, lake and mire. The models draw on the SR-Site data to help ensure meaningful comparison of the results with SKB's results.

The simpler models do not include explicit representation of succession between difference biosphere systems (e.g. succession from marine to lake to mire to terrestrial systems). Such transitions are the subject of the separate independent modelling study mentioned in Section 1.

2.2. Endpoints of the Assessment

The safety regulations (SSM, 2008) stipulate a requirement that a repository will be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk. If the exposed group only exists of a few individuals, the criterion can be considered to be complied with if the highest calculated individual risk does not exceed 10^{-5}; an example where drinking water from a drilled well is the dominant exposure pathway is given for such a group.

The SR-Site biosphere dose assessment model is based on the calculation of LDFs, which are expressed as Sv Bq^{-1}. They provide a dose rate (Sv y^{-1}) per unit release (Bq y^{-1}) to the biosphere from the repository in groundwater via the fractured geosphere.

Although the regulations define risk criteria (as described above), the biosphere models necessarily provide dose factors (Sv Bq^{-1}) for comparison against the LDFs used in the SR-Site assessment.

Doses to non-human biota are outside the scope of this study.

2.3. Assessment Philosophy

Regulatory guidance (SSM, 2008) indicates that assessments should use a realistic set of biosphere conditions, with a focus on today's conditions at the repository and surrounding area, unless they are clearly inconsistent with the evolution that provides the basis for the analysis.

Realistic assumptions are adopted in defining and parameterising the biosphere systems to be considered, while more cautious assumptions will be adopted regarding human behaviour and potential exposure pathways. Such an approach seeks to avoid overly pessimistic assessment, while seeking to ensure that potential doses and risks are not underestimated.

The requirement for simple biosphere models means that a deterministic approach is adopted in the selection of parameters. Where information on uncertainties is readily available (e.g. where data is drawn directly from parameter distributions used in the SR-Site assessment), it is included to support potential future sensitivity calculations.

Plausible conservative deterministic assumptions are adopted for human behaviour, which seek to be consistent with the biosphere systems described.

2.4. Repository System

The proposed repository system is based on the 'KBS-3' method, in which corrosion resistant copper canisters with a load-bearing cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in groundwater saturated, granitic rock, see Figure 2 and Figure 3. The fractured granitic rock provides a potential pathway for contaminants released from the canisters to reach the biosphere.

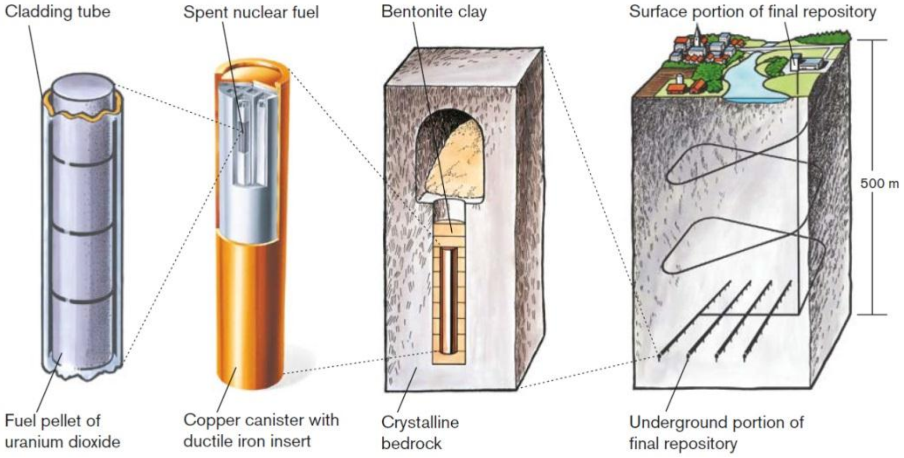


Figure 2: The KBS-3 disposal concept (Figure 5-2 from SKB, 2011).

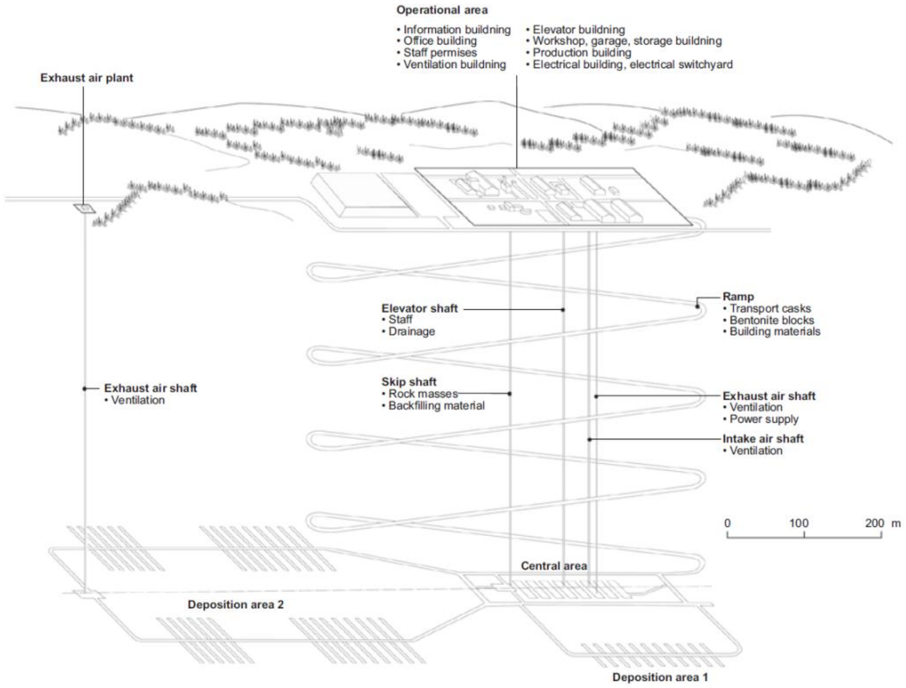


Figure 3: Proposed repository layout (Figure 5-3 from SKB, 2011).

2.5. Site Context

Regulatory guidance (SSM, 2008) places an emphasis on the first 1000 years after repository closure as a period whereby there is a high level of credibility, thereafter, results are increasingly considered as being illustrative. Unless clearly inconsistent, today's biosphere conditions are evaluated.

The Forsmark site is situated on the Baltic coast of Sweden (see Figure 4), in the vicinity of the Forsmark nuclear power plant (see Figure 5). SKB has undertaken extensive characterisation of the site and modelling of its development into the far future; this work is well summarised in support of SR-Site in Lindborg (2010)[1].

The land at Forsmark is rising due to post-glacial uplift, which is projected to continue for in excess of ten thousand years. As the land rises, there is a transition from being submerged under the sea through isolated lakes to mires to terrestrial land. The Forsmark site began to emerge from the sea about 2500 years ago.

The area has a relatively shallow topography, mostly being below 20 m above the present-day sea-level. The Quaternary deposits are dominated by glacial till, including sandy and clay till with other areas being dominated by till containing large boulders. Given the relatively recent emergence due to post-glacial up-lift most of the soils are immature and lack distinct soil horizons. Peat occurs in former lakes that have become mires.

---

[1] Much of the descriptive text in this report is drawn from Lindborg (2010).

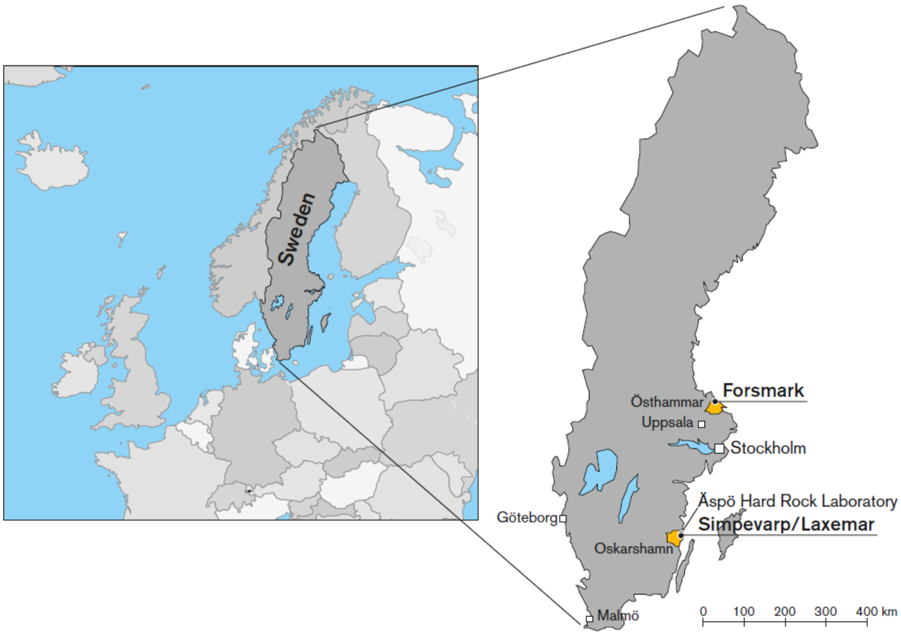


Figure 4: Location of Forsmark; two sites were originally considered for the final repository and the location of the Laxemar site is also illustrated (Figure 1-2 from SKB, 2011).

Lakes in the Forsmark area are classified as oligotrophic (low in nutrients) hardwater lakes. The lakes tend to be small and shallow, with theoretical water retention times generally shorter than 1 year.

The marine ecosystem at Forsmark is situated in a relatively productive coastal area in a region of otherwise fairly low primary production. This is due to up-welling of higher-nutrient water along the mainland.

The Forsmark area has a history of forestry, which is seen today as a fairly high percentage of younger and older clear-cuts in the landscape. Wetlands occur frequently and cover 10–20% of the area in the three major catchments and up to 25–35% in some sub-catchments. A major part of the wetlands are coniferous forest swamps and open mires. Arable land, pastures and clear-cuts dominate the open land. Arable land and pastures are found close to settlements. The pastures were intensively used earlier, but are today a part of the abandoned farmland following the nation-wide general regression of agricultural activities.

Figure 5: The Forsmark site, showing the nuclear power plant in the background, village in the foreground and with the approximate candidate area for the repository highlighted in red (adapted from Figure 1-4 of Lindborg, 2010).

2.6. Source Terms and Geosphere-Biosphere Interface

Potential radionuclide releases to the biosphere via groundwater transport are the focus of the present study. There is also potential for gas release from the repository (see Section 13.8 of SKB, 2011), although its consideration is outside the scope of this report.

The proposed repository would be constructed in crystalline bed-rock. Groundwater would transport radionuclides released from canisters and from the bentonite backfill via fractures. SKB has undertaken extensive modelling of groundwater flow with codes including DarcyTools, ConnectFlow and MIKE-SHE. Particle tracking is employed to identify potential flow paths from the deposition holes within the repository to the biosphere (as well as providing other performance measures, including travel times).

The particle tracking simulations show:

- discharges focus on topographic lows, which are typically associated with greater fracture densities;
- associated with this, many (but not all) of the discharge points are associated with lakes or rivers/streams (either with direct release to the surface water body or to land adjoining it); and
- discharges occur further from the proposed location of the repository as the shoreline retreats.

Solute modelling following release to the near-surface groundwater system shows that there is variety in transport behaviour between different parts of the area considered. However, the results also show common features, such that the initial transport from the sources is mainly vertical and that high concentrations are found within relatively small areas and usually directly above the modelled sources (Lindborg, 2010).

Groundwater wells are common in the Forsmark area (Ludvigson, 2002) and range in depth from about 25 m to about 90 m. Groundwater in some wells is fit for drinking, however, many suffer problems of salinity, hardness and high mineral content (iron in particular). A survey of private wells in the local area showed that some of the water that cannot be used for drinking is used ‘for irrigation’ (Ludvigson, 2002).

2.7. Time Frames

Regulatory guidance (SSM, 2008) states that the risk analysis should at least cover one hundred thousand years, or the period of a glaciation cycle. After this period, calculations should extend only for as long as the results provide important information about the possibility of improving the protective capability of the repository, to a maximum period of one million years.

2.8. Societal Assumptions

Regulatory guidance (SSM, 2008) indicates that the risk analysis should be based on the diversity of human use of environmental and natural resources which can occur in Sweden today.

3. System Description

The Forsmark site and area are well described in Lindborg (2010). This section summarises that description, drawing largely from the text in that report, to both:

- confirm its interpretation, as the basis for the subsequent model development, and
- to support self-consistent documentation of the model development, minimising the need for the reader to cross-reference supporting documentation.

The description is sub-divided into the categories used in the BIOMASS approach (IAEA, 2003).

3.1. Climate

The present-day climate in Sweden and in Forsmark is summarised in Section 3.1.1, drawing directly on SKB (2010). Given the long timescale over which the spent fuel remains hazardous, associated assessments need to consider timescales extending to hundreds of thousands of years (see Section 2.7). The global climate and the climate at Forsmark will change on such extended timescales. The potential evolution of the climate at Forsmark is described in Section 3.1.2.

3.1.1. Present-day Climate

Sweden is located in the northerly west wind belt, an area where the prevailing winds come from the south and west. The North Atlantic Drift and the numerous areas of low pressure produce a climate with winters that are 20–30°C warmer than at corresponding latitudes in Siberia and Canada. The precipitation brought by the frequent low pressures gives fairly plentiful rain and snow, although there is some rain shadow effect east of the Norwegian mountains.

Sweden has a temperate, moist climate with year-round precipitation. Along the coasts of southern Sweden, the climate is warm-temperate, with a natural cover of deciduous forest. The climate in the rest of the country is cool temperate, the predominate vegetation being coniferous forest. Tundra conditions prevail in the mountains. Changes in wind direction can result in dramatic changes in weather.

Summer temperatures are largely governed by altitude, and to a lesser extent by latitude. Thus the mean temperature in July is 15 to 16°C along the entire coast. The mean temperature in summer drops by 0.6°C with every 100 m of altitude. The vegetation growing season, defined as the part of the year when the mean diurnal temperature is over 5°C, varies considerably over the country. It lasts for between 210 and 220 days in southernmost Sweden, but is only half as long in the far north.

Although local conditions can have a significant affect, in northern Sweden the January mean temperature is generally between -9 and -14°C, except along the coast in the south of the region where, as in much of the central inland region, the mean January temperature is -5 to -8°C. In the southern and eastern part of central Sweden, the mean temperature is -3 to -5°C in January, while it is -1 to -2°C in southern coastal areas owing to the ameliorating effect of the nearby open sea. Over much of Sweden annual precipitation is between 600 and 800 mm.

In more or less the entire country, precipitation is heaviest during July to November. Most precipitation falls along fronts as areas of low pressure move across the country. But several weeks may sometimes go by in spring and early summer without any rain. Most of Sweden usually has a snow cover in winter. Most northern Sweden outside the mountains of Lapland is covered in snow for more than 150 days a year. In central Sweden and upland areas of the south, there is a snow cover on average between 100 and 150 days each winter. In the rest of southern Sweden, there is a snow cover for between 50 and 100 days, except along the west coast and the far south, where snow lies for less than 50 days each winter. Air pressure distribution over the European continent causes winds from south and west to predominate.

The climate in the Forsmark region has typical values for the climate on the Swedish east coast, with a mean annual air temperature recorded between 1960 and 1990 of +5°C and an annual mean precipitation of 576 mm. The mean summer temperature during this period was +14.9°C and the mean winter temperature -4.3°C. Over the last few years (2004–2006), a time series of meteorological observations made specifically at the Forsmark site showed that the annual mean air temperature for this short period was +7°C and the annual mean precipitation 546 mm.

The present-day climate demonstrates a strong west-east gradient in the precipitation in north-eastern Uppland. At the meteorological station located c. 15 km west of the Forsmark area the long-term mean precipitation is 690 mm per year, whereas at Örskär, a meteorological station located c. 15 north-east of Forsmark, it is 490 mm per year. There is also a gradient in the temperature with a slightly milder climate on the coast than at the inland stations. The dominating wind direction in the area is from the south-west.

3.1.2. Climate Evolution

SKB identify three climate domains of relevance to the Forsmark site:

- the temperate climate domain;
- the periglacial climate domain; and
- the glacial climate domain.

SKB consider six climate cases, which are summarised in Table 1. The projected climate sequences associated with five of the cases are illustrated in Figure 6. The extended ice-sheet duration, maximum ice-sheet configuration and severe permafrost cases are primarily included in SR-Site as extreme cases to test the response of the repository system to potentially important sub-surface processes.

Table 1: Climate cases considered in SR-Site (Table 3-1 from Lindborg, 2010).

Climate case	Short description
1 Reference glacial cycle	Repetition of reconstructed last glacial cycle conditions
2 Global warming	Longer period of initial temperate conditions than in case 1
3 Extended global warming	Longer period of initial temperate conditions than in case 2
4 Extended ice-sheet duration	Longer duration of ice-sheet coverage than in case 1
5 Maximum ice-sheet configuration	Largest ice configuration in past two million years
6 Severe permafrost	Favourable for early and deep permafrost growth

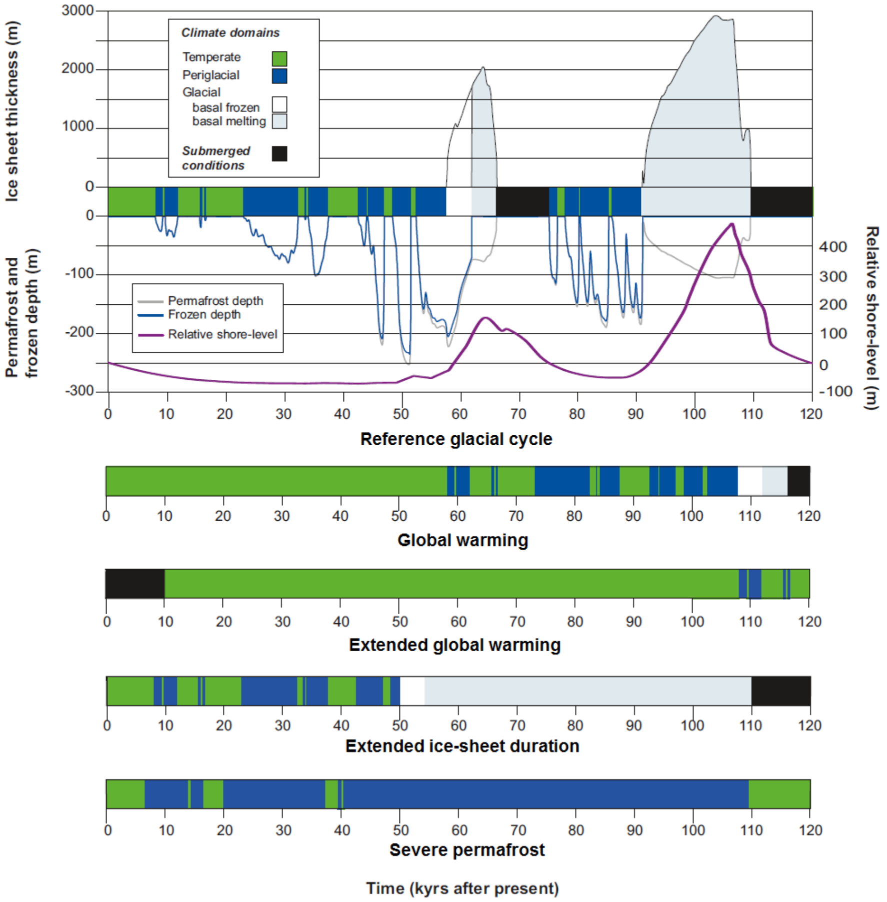


Figure 6: Projected climate sequences considered in SR-Site (based on SKB, 2010) with the evolution of important climate-related variables illustrated for the reference glacial cycle.

Temperate

The temperate climate domain is defined as an environment without permafrost or the presence of ice sheets. The temperate domain has the warmest climate of the three climate domains and is dominated by cold winters and either cool or warm summers. Precipitation falls all year round, i.e. there is no dry season. Precipitation may fall as rain or snow, depending on the season.

The temperate domain includes periods that follow-on from glacial episodes and therefore includes periods where the Forsmark area may be submerged by water due to glacial depression (see Figure 6).

The temperate domain does not only encompass the present-day climate, but also that influenced by further global warming. A global warming climate may result in the Forsmark region experiencing a mean annual air temperature increase by ~3.5°C and an increase in mean annual precipitation by ~20% as compared to the climate during 1961–2000.

Periglacial

The periglacial climate domain is defined as an environment with fully or partly perennially frozen ground surface without being covered by an ice sheet. The permafrost occurs either in sporadic, discontinuous, or continuous form. In general, the permafrost domain has a climate colder than the temperate domain and warmer than the glacial domain. Depending on season, precipitation may fall either as snow or rain. Within the periglacial climate domain, part of the region may be submerged by water.

Glacial

The glacial climate domain is defined as an environment that is covered by glacial ice. The ice sheet may have a frozen or thawed bed, which is only partly dependent on prevailing climate conditions. In general, the glacial domain has the coldest climate of the three climate domains. Snow is the predominant form of precipitation.

3.2. Near-surface Lithostratigraphy

The near-surface lithostratigraphy encompasses the unconsolidated deposits overlying the bedrock; it is referred to as the regolith in SR-Site and includes both the Quaternary deposits and the soils.

The Quaternary deposits in the Forsmark area have been deposited in the varying environments that have occurred during and after the latest glaciation. In these environments, Quaternary deposits with very different properties have, and still are, formed. The younger Quaternary deposits are always superimposed upon older deposits and it is therefore easy to determine the relative age of the deposits. Figure 7 illustrates the regolith thickness in the Forsmark area, based on modelling.

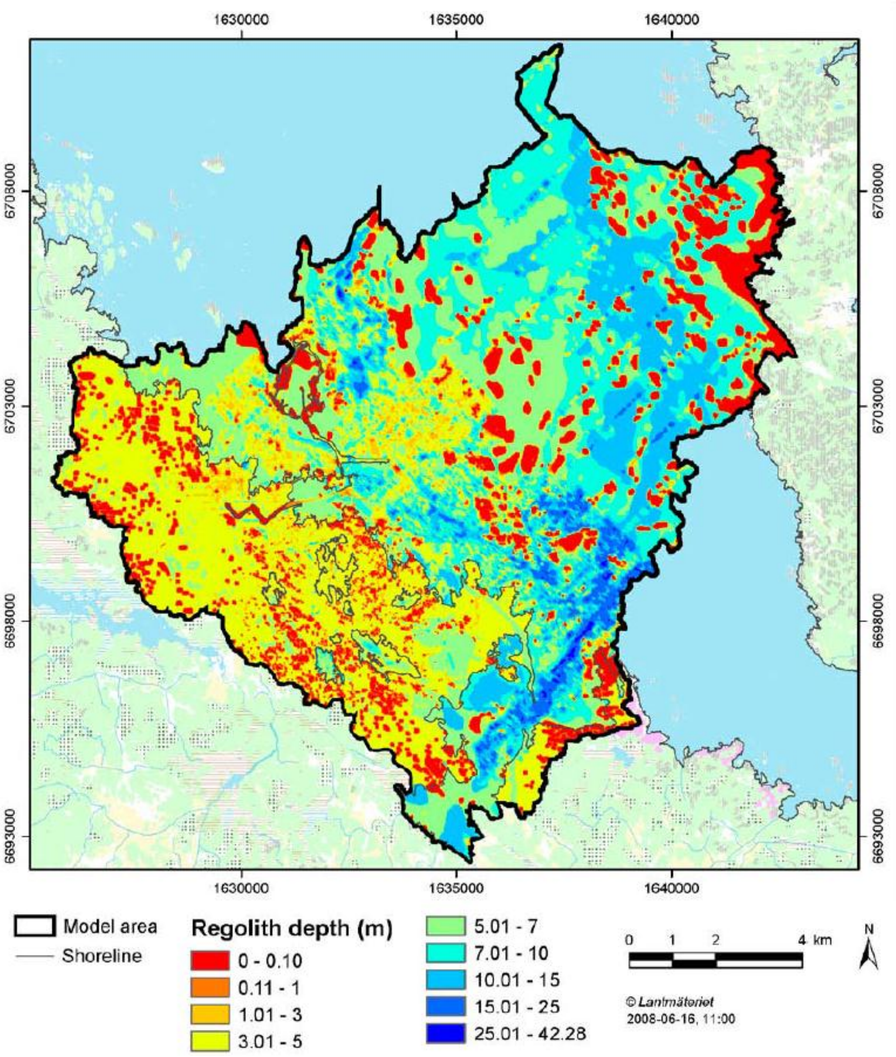


Figure 7: Total modelled regolith depth (Figure 4-12 from Lindborg, 2010).

The terrestrial part of the Forsmark area is today dominated by till deposited during the latest glaciation. The till is relatively fine grained and in some areas clayey (clay content 5–15%). This is because the till contains redistributed sedimentary bedrock and possibly also pre-glacial clays. The sedimentary bedrock, mainly limestone, originates from the floor of the Bothnian Bay and has consequently been transported several tens of kilometres. Figure 8 shows how the Quaternary deposits at 0.5 m depth vary over the study area.

At the floor of the sea, in Öregrundsgrepen, large areas are covered with clay. That general distribution of Quaternary deposits is typical for the County of Uppsala and the region around Lake Mälaren. In that region the topographically high areas are dominated by till and outcrops, whereas the valleys are covered with clay. One feature typical of the Forsmark area and the surrounding coast is the high content of calcium carbonate in the soils.

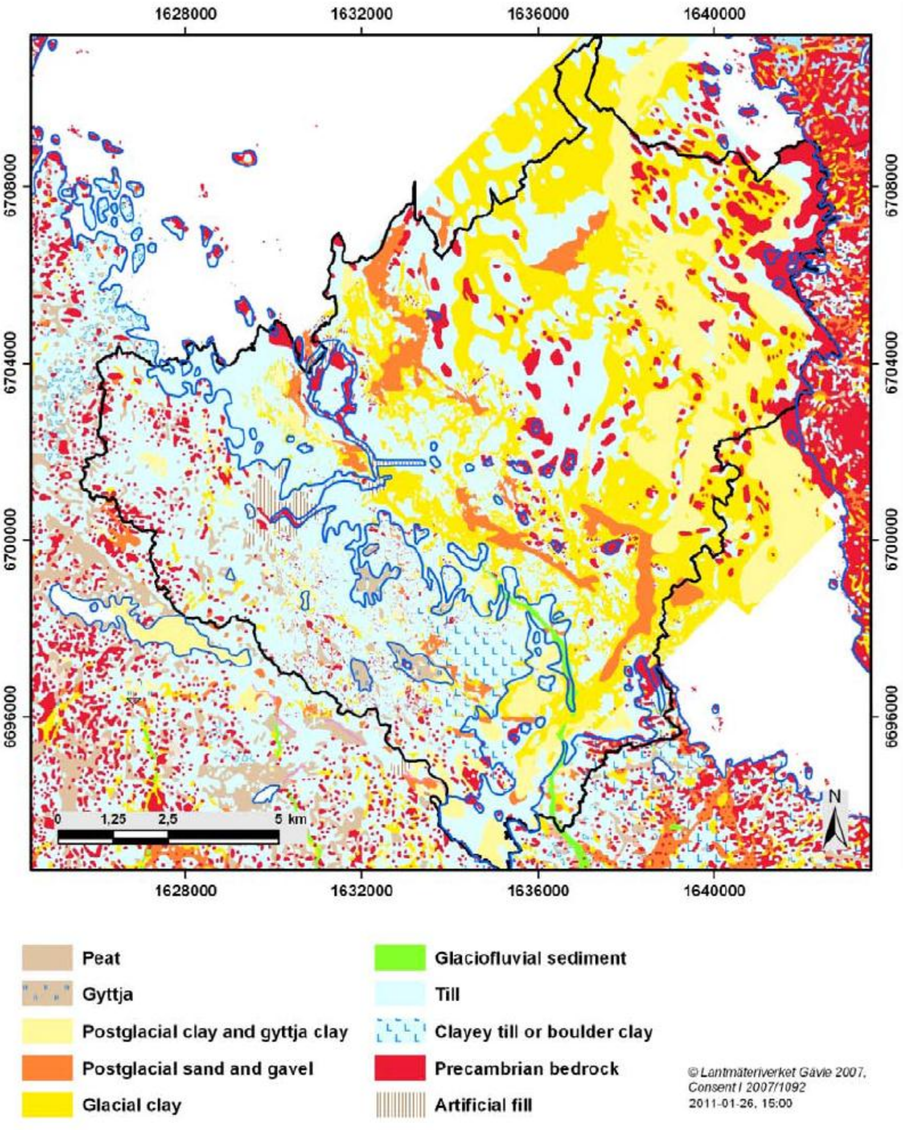


Figure 8: Distribution of Quaternary deposits at 0.5 m depth in the Forsmark area (Figure 4-10 from Lindborg, 2010).

The regolith in the Forsmark area has only been subjected to soil-forming processes for a relatively short period (<2500 years) and most of the soils are therefore immature and lack distinct soil horizons. Figure 9 shows the present-day distribution of soil types in the Forsmark area, brief descriptions of the different soils are provided in Table 2.

In the terrestrial part of the Forsmark area, three main types of till have been defined (see Figure 10): (i) sandy till with a normal boulder frequency, (ii) clayey till and (iii) till with high frequency of large boulders in the surface. The clayey till is partly used for agriculture whereas the other two till types are dominated by forest. In the Forsmark area, only 4% of the terrestrial area has glacial clay as the surface layer but glacial clay covers c. 40% of the marine area. It can consequently be assumed that the area with glacial clay will increase in the future as marine regression continues.

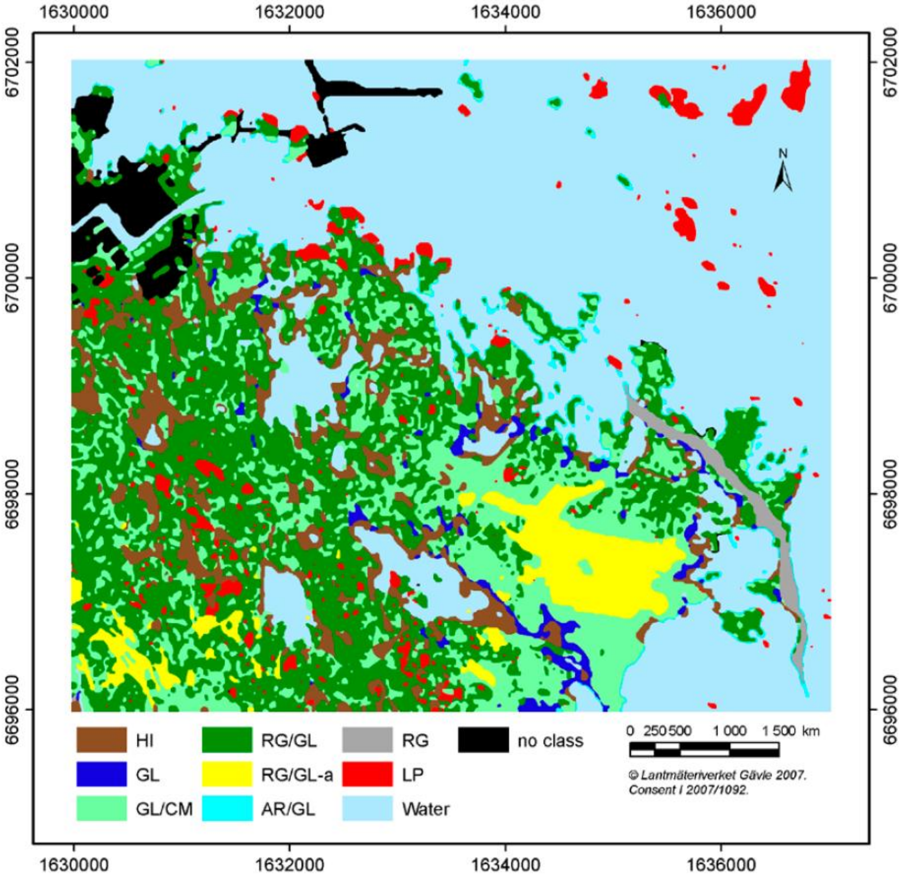


Figure 9: Distribution of soil types in the Forsmark area (Figure 3-2 from Löfgren, 2010). HI = histosol, GL = gleysol, CM = cambisol, RG = regosol, Ar = arenosol, LP = leptosol and -a indicates arable land.

Figure 10: Different types of fill in the Forsmark area (Figure 4-8 of Lindborg, 2010). A) sandy till with a normal frequency of boulders, B) clayey till with a low frequency of boulders, C) till with a high frequency of large boulders.

Table 2: Brief descriptions of the soil types found in the Forsmark area, based on Section 5.1.3 of Hedenström and Sohlenius (2008).

Class	Description
Histosol	Peatland soils including open mires and forest-covered peatland. Organic soils of at least 0.4 m depth. These soils are typically covered by a sparse tree layer of birch, pine and alder. Also includes reed areas surrounding lakes, although these often grow directly on till.
Gleysol	Moist soils that are not peatland, e.g. swamp forests. Soils that are periodically saturated with water. This leads to reduced conditions and gives rise to the typical gley properties, which should be found within a depth of 0.5 m. The soil wetness is moist and the parent material is coarse-textured mineral soil. The humus type is peaty mor. Forests include spruce and deciduous trees and herbs dominate the field layer.
Gleysol/ cambisol	Fertile forest soils on fine-textured parent material often located low in the landscape. Cambisol is a young soil that develops on fine textured material and has no visible horizons in the topsoil. Below the topsoil, the mineral soil has developed into a distinct B horizon. The humus form is of the mull type. This class is assigned to areas where the tree layer consisted of deciduous trees and where the field layer is of the herb or herb-heath type.
Regosol/ gleysol	Forest soils found in upslope locations with a fresh soil moisture class. The Regosol is formed on unconsolidated, coarse-textured parent material and is characterised by a minimal soil profile development as a consequence of its young age. A soil type also present is Gleysol. Humus forms are moor or moder. The mixed coniferous forests are dominated by spruce with herbs and heath in the field layer. The arable areas also include fertile land located on clayey till with soils of the Cambisol type. The soil moisture class is fresh or fresh-moist and the humus form is mainly of the mull type. Broad-leafed grass and cereal crops dominates the field layer.
Arenosol/ gleysol	Shoreline soil and is influenced by its closeness to water. The Arenosol soils are formed on sandy material of sedimentary origin, which has been deposited in different stages of shoreline displacement. In places that are periodically inundated, the soil type becomes a Gleysol. The humus forms are peaty moor.
Regosol	The soil moisture class is mainly fresh or partly dry. The texture is rich in coarse material, such as gravel and stones. The humus forms are mull or mull-like moder. The tree layer is sparse and the field layer is dominated by grass.
Leptosol	Shallow soils typically found in upslope locations. Leptosols have a soil depth of less than 0.25 m overlying the bedrock or very coarse soil material. This soil class also includes bedrock outcrops. The tree layer is dominated by pine and some spruce, and the field layer is mainly of the heath type.

3.3. Topography

The overall topography in the Forsmark region is flat. The study area is almost entirely below 20 m above sea level. The Precambrian bedrock is overlain by till with no or only minor morphological features. The till is in negative morphometric areas (channels and pits) overlaid by glacial clay that tends to flatten the surface. Geological processes during the Holocene, such as postglacial sedimentation in the sea and the lakes, wave-generated sediment dynamics in the sea, and infill processes in lakes, have flattened the surface even more.

The altitude range of the bedrock in the model area is –59 to +27 metres. The average thickness of the till is c. 60 centimetres and of the glacial clay c. 4 centimetres (Section 4.1.1 of Lindborg, 2010). Thus, the overall topography in the model area is controlled by the bedrock topography. The bedrock surfaces generally dip towards north-east but many bedrock lineaments (joints and faults) change that general picture. One major fault runs in a north-south direction west of the island Gräsö and has caused the deep channel called the Gräsörännan.

3.4. Water Bodies

The present-day landscape at Forsmark is dotted with lakes (see Figure 11), which become isolated from the sea as the land rises and follow a succession through mires to forest.

Figure 11: Photograph of the present-day Forsmark area (Figure 3-1 from Lindborg, 2010).

Lakes

The Forsmark area lakes are small (lake areas range from 0.01 to 0.75 km^2). The lakes are in general shallow; all the lakes in the study area have mean depths ranging from 0.1 m to 1 m. The vertical mixing of lake water is mainly driven by wind. Due to the limited depths, the vertical mixing is likely to be almost complete for most parts of the year. The inlet and outlet of the lakes are often located at opposite ends of the lake. In the shallow near-shore areas covered by reed, water may be more stagnant.

Most of the lakes are underlain by fine-grained sediments. The typical sediment stratigraphy from the bottom up is; glacial and/or post glacial clay, sand and gravel, clay-gyttja and gyttja.

Water Courses

No major water courses flow through the study area. Small brooks, which often dry out in the summer, connect the different sub-catchments. The brooks downstream of the larger lakes carry water most of the year, but can be dry during dry years. The long-term runoff for the area has been estimated to c. 160 mm per year.

Groundwater

Direct groundwater recharge from precipitation is the dominating source of recharge. During summer, some of the lakes in the area may act as recharge areas. Water uptake from plants lowers the groundwater level in the vicinity of the lakes and some of the lakes switch from being a discharge area to being a recharge area. Wetlands are typically discharge areas for deep groundwater, whereas forests are mostly recharge areas and agricultural land may be either.

Due to a high infiltration capacity of the upper Quaternary deposits, overland flow rarely occurs, except from saturated areas where the groundwater level reaches the ground surface. The runoff in the brooks is dominated by water of groundwater origin. During intensive rain events or snow-melt, overland flow contributes to the runoff.

The small-scale topography implies that many small catchments are formed with local, shallow groundwater flow systems in the Quaternary deposits. The decreasing hydraulic conductivity with depth and the anisotropy of the tills dominating in the area (higher horizontal than vertical hydraulic conductivities), imply that most of the groundwater will move along very shallow flow paths. Groundwater levels in Quaternary deposits are shallow with mean levels within a depth of less than a metre in most of the area. The groundwater level in the Quaternary deposits is strongly correlated with the topography of the ground surface. This local flow system in the Quaternary deposits overlies a larger scale flow system in the bedrock.

Off-Shore

Large parts of the Forsmark marine area are open sea and are delimited by the steep sloping island of Gräsö in the east and the gradual slope of the mainland to the south-west. Most of the area consists of shallow exposed hard bottoms (boulders, bedrock) and areas with glacial clay covered by sand interspersed with deeper valleys with soft bottoms. Postglacial clays and mud deposits (accumulation bottoms) are found only in sheltered inshore settings. The exchange rate of water off-shore is very rapid in the area; the hydraulic residence time is less than a day on average.

3.5. Biota

Marine Ecosystems

The primary producers in the pelagic habitat, the phytoplankton, vary throughout the year with regard to species composition as well as biomass. After a spring bloom of diatoms, dinoflagellates and other smaller flagellates become more important, later to be followed by maximum densities of the cyanobacteria and zooplankton. The zooplankton species in Forsmark are generally the same species as in the rest of the Baltic. The most common zooplankton taxa in the Baltic are the small crustaceans, copepods and cladocerans, but rotifers, ciliates and larvae from other organisms are also present.

The fish fauna is a mixture of freshwater and marine species, where the freshwater species like perch and pike inhabit coastal areas and marine species like herring and sprat dominate offshore areas. Forsmark harbours bird species that feed in the marine habitat as piscivores or herbivores. Most of the bird species migrate between winter grounds and nesting grounds in the spring and summer. Thus, most birds leave Forsmark to winter further south, although some species also stay the winter and breed in the area such as cormorants and the white-tailed eagle. In Forsmark, the grey seal also inhabits the area, although not in high densities.

The primary producers in the benthic habitat, the phytobenthos, consist of large photosynthesising algae and vascular plants (macrophytes) and microscopic unicellular organisms (microphytes including cyanobacteria). They are limited to the photic zone, which is roughly between the surface and twice the average water transparency attenuation depth. For the bays and coastal areas the average water transparency depth is not more than 3.4 to 3.6 m and, large areas deeper than 7 m lack vegetation cover. However, in the deeper more off-shore basins, the water transparency depth is larger, and vegetation can be found down to c. 20 m. In shallow soft bottom areas where the salinity often is lower than in more offshore areas, soft bottom-dwelling phanerogams are present. In deeper secluded areas yellow-green algae is found in high densities.

Limnic Ecosystems

Due to shallow depths and low water colour, primary producers flourish in the benthic habitat of the lakes. The dominant vegetation is stoneworts (*Chara* sp.). At the top of the bottom sediment, algae and cyanobacteria are often found in unusually thick layers (>5 cm). The lakes are surrounded by reed belts, which are extensive around smaller lakes.

The dense stands of *Chara* harbour various kinds of benthic fauna and also function as refuges for smaller fish. Common fish species are perch and roach, as well as tench and crucian carp. This last species survives low oxygen levels and is the only fish species present in the smaller lakes, where oxygen levels can be very low during winter. The present oligotrophic hardwater lakes are net autotrophic, i.e. primary production exceeds respiration. The autotrophy of present-day lakes, although common in Forsmark, is unusual in Sweden and world wide.

Long stretches of the streams connecting the lakes dry out during summer. Nonetheless, the streams may host a large community of biota and be important for wildlife in terms of passages for aquatic biota and transport of nutrients.

Terrestrial Ecosystems

A major part of the wetlands in the Forsmark area are coniferous forest wetlands and fens (approximately 25 and 75% of the wetlands within the regional model area, respectively). The wetlands are characterised by a high calcareous influence, resulting in the extremely rich to intermediate fen types common in this area. These fen types lack the dominance of Sphagnum species in the bottom layer and are instead dominated by brown mosses e.g. Scorpidium scorpioides. Forested wetlands may be dominated by conifers, mostly Norway spruce (*Picea abies*) or by birch (*Betula pubescens*) and/or alder (*Alnus glutinosa*). Many wetlands in the Forsmark area show indications of terrestrialisation where a fen replaces a shallow lake. This characterises many younger wetlands that are heavily dominated by dense and high stands of common reed (*Phragmites australis*). In the Forsmark area, large bogs are rare because they have had too little time to develop in the young terrestrial environment. Bogs or fens with partially bog-like vegetation are, however, found further inland.

Forests contain different types of vegetation, all of which have a more or less dense tree cover (>30%). A forest is often regarded as the climax stage under the present conditions in most parts of the landscape and forest trees are quick to colonise areas previously kept open by human land-use. The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce situated mainly on wave-washed till. Spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. Bare rock is not a widespread substrate in the Forsmark area, making pine forest on acid rocks quite scarce.

Deciduous forests represent 4% of the land area and mixed forests represent 6%. They are dominated by birch (*Betula pendula*), aspen (*Populus tremula*), alder and rowan (*Sorbus acuparia*), but Norway maple (*Acer platanoides*) and ash (*Fraxinus excelsior*) are also fairly common. Especially ash may be abundant along sheltered seashores.

3.6. Human Activities

3.6.1. Historical Land Use

Over the past several thousand years, the landscape in southern Sweden has been shaped by human-use. Native forests were cleared for cultivation; as soil nutrients depleted, cultivation changed to grazing and then areas were abandoned for 30 to 40 years, while nutrient levels recovered, after which land was again cleared for cultivation.

In the past, there were no sharp borders between forest and agricultural land, as forests were grazed and areas were mowed or cultivated in non-permanent fields. Extensive grazing of livestock in the forests is believed to have been an important factor affecting the plant communities around villages in the more densely populated parts of Sweden. Iron mining has had an important role in the Forsmark region since the Iron Age. As the iron industry became more organised in the 16th century, forests were cut down to feed furnaces and mines with wood and charcoal.

The modernisation of agriculture made it possible to drain areas with peat and clay for cultivation. Mires, especially fens, have been converted to arable land from the mid-19th century. This has been done by lowering the groundwater table in mires and lakes by ditches.

The usage of peat as arable land is a rather recent phenomenon. Extensive draining of wetlands started a bit more than hundred years ago and peaked in the 1930s in Sweden. The proportion of peat used as arable land was largest during the mid-part of the 20th century and has thereafter decreased. Many mires in Sweden have been be drained and in some areas in the south of Sweden as much as 90% of the wetlands have been drained.

The successional stage of a wetland is of importance for the possibility to drain the wetland and use it for agricultural purposes. A mire may be considered to be a discharge area. At a certain point, the peat accumulation will raise the ground level and make the surface of the mire hydrologically independent of the landscape, and a bog has developed. Peat that develops within a bog is of low nutrient value and low pH and is therefore relatively unsuitable for cultivation. However, fen peat is often suitable for cultivation due to larger amounts of plant-accessible nitrogen.

Peat is generally unsuitable for long-term cultivation because the peat layers subside fast after the onset of ditching. The ditches therefore require frequent maintenance and the peat needs to be more than a metre thick to make cultivation possible, if it is underlain by deposits that are unsuitable for cultivation.

The proportion of open landscape was largest in the late 19th century. However, this trend came to an end as management was rationalised by the use of fertilisers and better equipment in the early 20th century. Sweden has subsequently experienced a nationwide regression in agricultural activities. During the late 1900s, farmers have been encouraged to plant coniferous trees on arable land, thereby accelerating the succession into forest.

3.6.2. Present-day Land Use

Present-day land uses in Sweden and in the Forsmark area are summarised below, with a focus on agricultural land uses. The descriptive of agriculture in Sweden draws on information from the Swedish Board of Agriculture (Jordbruks Verket, 2009a), whilst information about Forsmark is drawn from Lindborg (2010).

Agricultural Land Use in Sweden

Most farms in Sweden are family businesses in which the family itself does most of the work and combines farming with employment in other activities.

Crop production is dominated by cereals, accounting for some 40% of arable land. Different climate conditions across Sweden are reflected in yields and the distribution of crops. In the north, crop production mostly comprises forage and coarse grains. Bread grain is mostly grown in the plain districts of south and central

Sweden. Potatoes are grown in all of Sweden, whereas sugar beets are only grown in the southernmost parts.

Fruit, vegetables and berries are cultivated professionally both outdoors and in greenhouses, mostly in the south of Sweden. Carrots and lettuce are the most important vegetables, whilst other commercial outdoor horticultural crops include cauliflower, cucumber, onions, cabbage, leek, apples and strawberries. Glasshouse crops include tomatoes and cucumbers.

Cattle (both dairy and beef) and pig farming dominate over sheep farming across Sweden as a whole. Chicken farming is also important.

Land Use in the Forsmark Area

In the Forsmark are, the agricultural land is the most intensively managed land in the landscape and is a major provider of food for human consumption, either directly as crop production or as production of fodder for animals. The agricultural land is further divided into semi-natural grasslands and arable land.

Although the proportion of peat used as arable land has decreased in the last few decades, peat is still used as arable land. It is, however, likely that many areas that today consist of postglacial clay or clay gyttja formerly were covered by peat layers. Today it is generally not allowed to make new ditches in areas unaffected by ditches, and peat-covered wetlands are at present not converted to arable land in Sweden.

Today, a large part of livestock grazing and hay-making takes place in former arable fields with richer soils and higher nutrient content due to fertilisation. According to the land-use data, the agricultural area in the Forsmark area comprises 84 ha, of which 34 ha is arable area and 50 ha is classified as semi-natural grasslands or pastures. Only around 10% of the total agricultural area (arable area and pasture) is used for production of grain and vegetables.

The Forsmark area has a long history of forestry, which is seen today in a fairly high frequency of younger and older clear-cuts in different successional stages in the landscape. Birch is the dominant species in many of the earlier successional stages until it is replaced by young Norway spruce or Scots pine depending on soil type and/or management.

3.6.3. Potential Future Land Use

The discussion of historical and present-day land use in Sweden, and the Forsmark area in particular, provides a guide to potential future land use. Present-day land uses in southern and northern Sweden provide an indication of potential land uses in the Forsmark area under warmer and cooler temperate climate conditions, respectively. Periglacial conditions are characterised by frozen ground, which would be accompanied by less intensive human occupancy and use and would reasonably exclude agriculture.

Lindborg (2010) notes that, although it is likely that the peat in the area generally does not fulfil the demands of the present peat industry, this may change in the future. The demands of the industry might change, and it is also possible that the properties of the peat might change in the future. It is therefore possible that some of the peat in the Forsmark area will be used as fuel.

4. Definition of Calculation Cases

The following types of biosphere system are identified from the system description above:

- marine;
- lake;
- mire;
- forest;
- pasture; and
- arable.

Simple reference biosphere models are therefore developed for each of these systems.

The present-day temperate climate in the Forsmark area is represented. Initial consideration is also given to alternative climate states, for example, a warmer climate with increased irrigation requirements and/or variants representing periglacial conditions, although arable and pasture systems would not be appropriate under such conditions.

Each system is modelled independently (i.e. without exchanges between different modelled biosphere systems) to avoid the necessity to explore potentially complex interactions and distributions of releases, consistent with the scope of developing ‘simple’ models.

A brief description of each system is provided below.

Temperate Marine System

This system represents the local marine system, which may be contaminated by groundwater discharge. Potential exposure arises through pathways including spending time in the local marine environment and consuming potentially contaminated sea food.

Release in an area of sediment accumulation is considered as a reference case, on the basis that it will result in greater retention on bed sediments and that direct exposure to be sediments may be an important exposure pathway. Potential to represent releases to an area of eroding bed sediments is included as a variant.

Temperate Lake System

This system represents a shallow oligotrophic freshwater lake in the Forsmark area, which may be contaminated by groundwater discharge. Potential exposures arise through pathways associated with spending time at the lake including consuming potentially contaminated produce obtained from the lake (notably fish).

Contaminated water from the lake may be used for irrigation and/or drinking if it is of appropriate resource and quality. However, these indirect pathways associated with discharges to lakes are not assessed directly for simplicity and because it is assumed that these pathways are adequately bounded by use of groundwater for such purposes.

Temperate Mire System

This system represents an intermediate successional stage in the progression from lake to forest, but with no explicit representation of the evolving system. The system is contaminated via direct groundwater discharge to the mire. Potential exposures arise through pathways associated with human use of the mire including collection of food from the wild and potential use of peat as a source of fuel.

Temperate Forest System

This system represents of mature forest, which may be contaminated by groundwater discharge to the sub-soil. Trees would be able to take-up some of their water/nutrients from the sub-soil, whilst other vegetation will take-up water/nutrients from the surface soil. Potential exposures arise through pathways associated with human use of the forests for hunting and forestry including use of the associated plant and animal produce.

Potential exposures arising from forestry (external irradiation from log housing; burning wood as fuel) are not included in the models. There is potential for further work to explore such pathways, given the importance of forestry in a Swedish context.

Temperate Pasture System

This system represents pasture areas receiving direct groundwater discharges, primarily to the sub-soil, but also to the top-soil during wetter months. These might be grazed in the summer months and used for growing hay as winter feed for animals. Potential exposures arise through pathways associated with human use of the pasture areas and associated consumption of animal produce.

Clayey silty till and peat variants are considered, which are characterised by different soil properties and hydrology.

Temperate Arable System

It is reasonable to assume that land that is suitable for growing crops is not subject to direct groundwater discharge. Nonetheless, there is potential for contamination of such areas through the use of groundwater for irrigation and exposure via the use of well water for other purposes, including drinking. An arable system is therefore considered and is conservatively conceived to be relatively small, supplying a self-sufficient small-holding supplying a broad range of crops, akin to a kitchen garden or allotment.

There is potential for such a group to also graze animals on pasture contaminated by groundwater discharge, however, these pathways will be considered separately to keep the systems simple and the potential implications of such combinations considered in the text.

There is potential to consider a number of variant calculations for this case to represent:

- clay silty till or peat based soils, characterised by differing soil properties;
- irrigation or groundwater source terms to the soil;
- temperate or warm-temperate conditions, the latter being associated with higher irrigation rates; and
- cases with or without cereal production, which is considered unlikely for a small-holder, but may be plausible, especially in a warmer climate.

Periglacial Systems

There is potential for further work to explore periglacial variants for marine, lake, mire and forest systems, although it is considered implausible for agricultural uses under periglacial conditions.

Age Groups

Calculations will focus on calculating potential effective doses to adults, which is considered adequate given the inherent uncertainties involved (ICRP, 2013). However, for completeness and to quantify the distinction between age groups in this case, potential doses to infants and children are assessed for the agricultural systems.

Summary of Calculation Cases

The calculation cases considered are summarised in Table 3. Additional variants that merit future consideration are presented in Table 4.

Table 3: Summary of simple reference biosphere calculation cases.

Climate	Biosphere System	Case	Notes
Temperate	Local marine	Reference	Contaminated via groundwater discharge through accumulated sediment. Exposures via fishing and associated occupancy.
		Erosion variant	Contaminated via groundwater discharge through eroding sediment.
	Lake	Reference	Contaminated via groundwater discharge. Exposures via fishing and occupancy during use of the lake.
	Mire	Reference	Contaminated via groundwater discharge. Exposures via collection of wild food stuffs and associated occupancy along with use of peat for fuel.
	Forest	Reference	Contaminated via groundwater discharge. Exposures via collection of wild food stuffs, with associated occupancy, including hunting.
	Pasture	Reference	Contaminated via groundwater discharge to sub-soil. Based on clay soil. Exposures via animal farming and associated occupancy.
		Peat variant	Based on organic soil.
	Arable	Reference	Clayey silty till contaminated via use of well water for irrigation; well water is also used for other purposes, including drinking. Small-holding producing as much home-grown food as is reasonable, including chickens and pigs. Excludes cereal production.
		Peat variant	Based on organic soil.
		Cereal variant	Includes cereal production.

Table 4: Potential additional cases that merit future consideration.

Climate	Biosphere System	Case	Notes
Temperate		Warm variant	Warm temperate variant, with increased irrigation.
Periglacial	Local marine Lake Mire Forest	Reference Reference Reference Reference	Characterised by lower temperatures and lower occupancies, so exposure pathways and potential doses are likely to be reduced in comparison to temperate systems. However, there is also potential consumption rates of some foods to increase in these conditions (e.g. fish), so they merit explicit consideration.

5. Conceptual Models

Conceptual models for radionuclide transport and exposure associated with the biosphere systems identified in Section 4 are illustrated as interaction matrices shown in Figure 12 to Figure 17 and discussed below.

The geosphere modelling provides a radionuclide flux (Bq y^{-1}) in groundwater to the regolith. The surface soils and sediments are distinguished from the underlying unconsolidated materials (lower regolith) in the interaction matrices below.

Potential transport of radionuclides back to the lower regolith and geosphere by diffusion is conservatively ignored. In cases of direct groundwater discharge to the surface, all of the contaminated groundwater is taken to discharge to the surface, such that loss via groundwater flow outside the area of interest is conservatively ignored.

Radionuclide releases from the geosphere will occur over periods that are long in relation to some relatively rapid processes in the biosphere, including atmospheric transport and uptake by plants and animals. Radionuclide concentrations in the atmosphere, plants and animals can therefore be represented as being in equilibrium with those in soils, sediments and water. Losses of radionuclides from the system in air flow and in the removal of plant and animal produce are conservatively ignored.

Uptake of radionuclides by plants from the atmosphere and release via respiration is potentially important for C-14. However, a detailed model for C-14 is outside the scope of the current study, so the processes are screened-out from the interaction matrices.

External irradiation from radionuclides within the water column whilst above (e.g. boating) or adjacent to (e.g. standing on the shoreline) water and external irradiation from the atmosphere are taken to be relatively insignificant, due to associated dilution and little potential for accumulation, and are screened out.

Radon exposures are also not included in the simple models (other than in its contribution in secular equilibrium with its parent, where data exists).

Temperate Marine System

The local marine system consists of areas of exposed bedrock and areas where the bed rock is covered with clays, mud and sand. Contaminated groundwater is taken to have potential to be released either directly to the water column, in areas of exposed bedrock, or through the bed sediments.

Resuspension from bed sediments into the water column is modelled, together with sediment deposition (sedimentation). The systems are to be represented as non-evolving, so no net sedimentation or erosion is represented.

Marine water is exchanged with the surrounding marine system. The potential for radionuclides to be lost with sediment leaving the local marine system is taken to be adequately represented with the loss of suspended sediment with sea water, such that bed load need not be explicitly represented.

The system is taken to include inter-tidal margins, with sediment and bedrock being exposed at low tides. There is therefore potential for atmospheric resuspension of dust and volatilisation from exposed sediments and associated exposure of humans during occupancy. Although the tidal range is low, so there is limited potential for humans to be exposed to bedrock through which contaminated groundwater is discharging.

Humans are taken to spend some time in the inter tidal region and some time in or on the water, both for recreation and for gathering food.

Temperate Lake System

There is no exposed bedrock providing a direct connection between the bedrock and the lake water, so radionuclides are released via the lower regolith and lake bed sediments. Radionuclides are lost from the lake with outflowing water. As with the marine system, there is taken to be no net sedimentation or erosion and bed load need not be explicitly represented.

Humans are taken to spend time in and on the lake for recreation and for gathering food, but are not taken to live on the water (e.g. in house boats). There is potential for people to spend time on exposed bed sediment (e.g. when water levels are low), so an external irradiation pathway is included.

Temperate Mire System

Contaminated groundwater can discharge to the mire sediments via the lower regolith. Radionuclides can be lost from the mire sediments with through-flowing water. The non-evolving nature of the system means that net sedimentation is not represented.

Humans are taken to spend time in the mire both for recreation, for gathering wild foods and for digging peat. They are not taken to live on the mire (e.g. in elevated houses), although they may be exposed through the use of peat as fuel.

Temperate Forest System

Contaminated groundwater can discharge to the forest soils/sediments via the lower regolith. Radionuclides can be lost from the forest soils/sediments with through-flowing water. Erosion is taken to be insignificant in the forest system.

Humans are taken to spend time in the forest both for recreation, for gathering wild foods and for forestry. They are not taken to live in the forest; there is potential for people to be exposed through the use of wood for construction and as fuel, although these pathways are not considered further in the present study.

Temperate Pasture System

Contaminated groundwater can discharge to the pasture soil via the lower regolith. Radionuclides can be lost from the pasture soil with through-flowing water and with erosion. The loss of material via erosion is taken to be compensated by the input of uncontaminated material (e.g. from up-slope and/or organic matter), so there is no net erosion of the soil.

Humans are taken to spend time in the area for recreation, for maintaining the pasture and for animal husbandry. They are not taken to live in the pasture area.

Temperate Arable System

Contaminated groundwater can discharge to the lower regolith. There is no direct discharge of groundwater to the surface soil, which can become contaminated through the use of groundwater for irrigation. Water from groundwater wells is also conservatively taken to be used for domestic purposes and as drinking water for livestock.

The groundwater flow rate in the lower regolith will likely exceed the groundwater abstraction rate, therefore radionuclides can also be lost from the lower regolith with through-flowing groundwater to maintain a water balance.

Radionuclides can be lost from the arable soil with infiltrating water and with erosion. As with the pasture system, the loss of material via erosion is taken to be compensated by the input of uncontaminated material (e.g. from up-slope and/or organic matter), so there is no net erosion of the soil.

The system is taken to represent a small-holding/kitchen gardening group, growing crops largely for their consumption and keeping some animals, such as chickens and pigs. The irrigated area is taken to be close to their housing and gardens, such that potential exposures arise through both recreational use of the land and through working the land. However, the housing is not built on contaminated ground.

Geosphere Model	Source flux		Source flux				External irradiation	
Diffusion	**Lower Regolith**	Groundwater discharge Diffusion						Groundwater flow
	Diffusion	**Marine Sediments**	Groundwater discharge Resuspension Diffusion	Volatilisation from exposed sediments Resuspension from exposed sediments		Ingestion	Inadvertent ingestion External irradiation	Bed load Net sedimentation
	Diffusion	Sedimentation Diffusion	**Marine Water**	Volatilisation Resuspension of sea spray and spume	Uptake	Uptake	External irradiation Immersion Inadvertent ingestion	Exchange
		Deposition	Deposition	**Atmosphere***		Inhalation (mammals)	Inhalation External irradiation	Air flow
		Exudates Decay	Exudates Decay		**Marine Flora***	Ingestion	Ingestion	
		Excretion Decay	Excretion Decay	Exhalation		**Marine Fauna***	Ingestion	
							Exposure of Humans*	
								Losses to Elsewhere

Figure 12: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate local marine system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.

Geosphere Model	Source flux							
Diffusion	**Lower Regolith**	Groundwater discharge Diffusion	Groundwater discharge Diffusion					Groundwater flow
	Diffusion	**Lake Sediments**	Groundwater discharge Resuspension Diffusion			Ingestion	Inadvertent ingestion External irradiation	Bed load Net sedimentation
	Diffusion	Sedimentation Diffusion	**Lake Water**	Volatilisation Resuspension of spray	Uptake	Uptake	External irradiation Immersion Inadvertent ingestion	Outflow
		Deposition	Deposition	**Atmosphere***		Inhalation (mammals)	Inhalation External irradiation	Air flow
		Exudates Decay	Exudates Decay		**Lake Flora***	Ingestion	Ingestion	
		Excretion Decay	Excretion Decay	Exhalation		**Lake Fauna***	Ingestion	
							Exposure of Humans*	
								Losses to Elsewhere

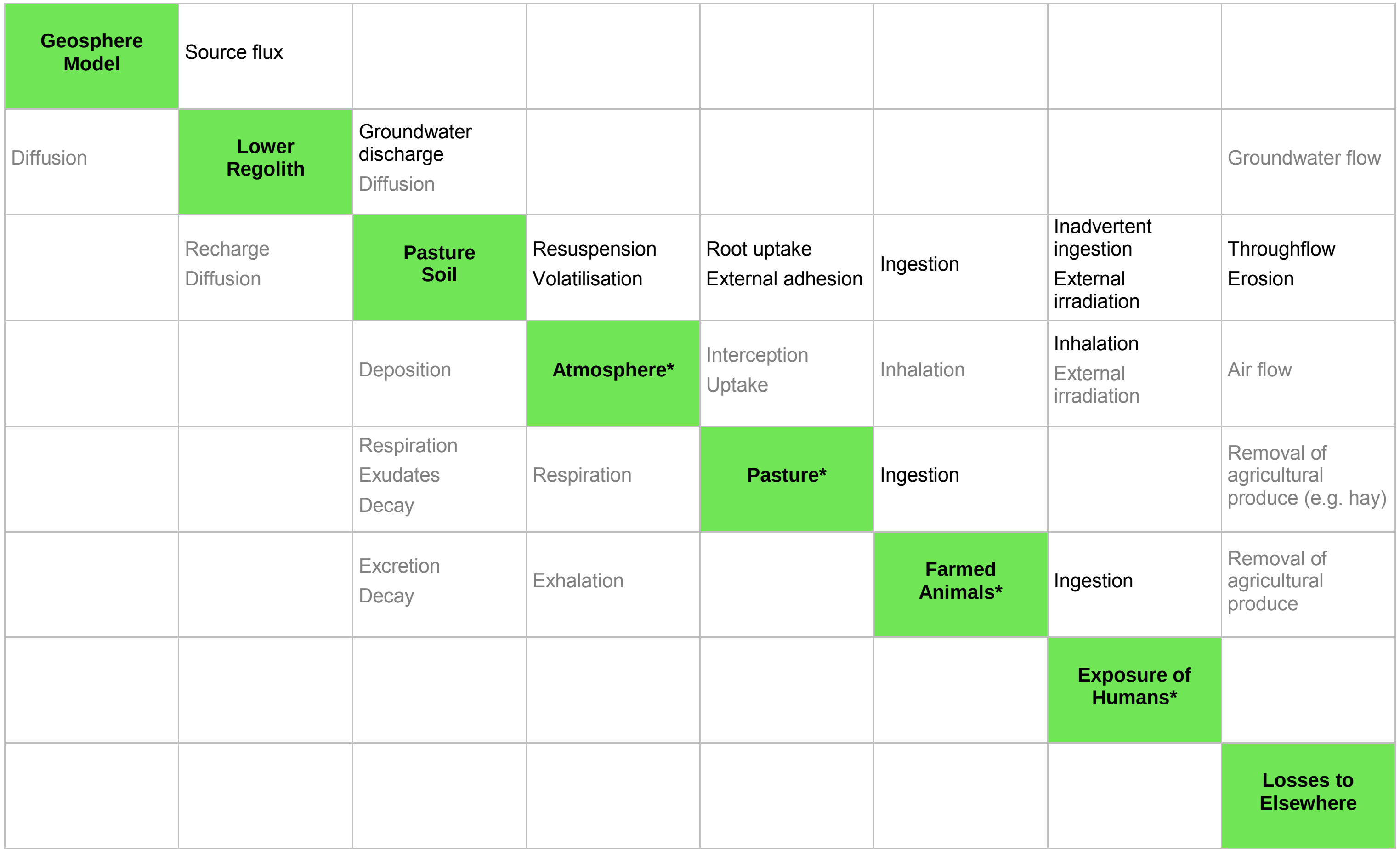
Figure 13: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate lake system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.

Geosphere Model	Source flux						
Diffusion	**Lower Regolith**	Groundwater discharge Diffusion					Groundwater flow
	Diffusion	**Mire Sediments**	Resuspension Volatilisation Combustion	Root uptake External adhesion	Ingestion	Inadvertent ingestion External irradiation	Throughflow/ groundwater discharge Net sedimentation
		Deposition	**Atmosphere***	Interception Uptake	Inhalation	Inhalation External irradiation	Air flow
		Respiration Exudates Decay	Respiration	**Mire Flora***	Ingestion	Ingestion	
		Excretion Decay	Exhalation		**Mire Fauna***	Ingestion	
						Exposure of Humans*	
							Losses to Elsewhere

Figure 14: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate mire system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.

Geosphere Model	Source flux						
Diffusion	**Lower Regolith**	Groundwater discharge Diffusion					Groundwater flow
	Recharge Diffusion	**Forest Soil/ Sediments**	Resuspension Volatilisation	Root uptake External adhesion	Ingestion	Inadvertent ingestion External irradiation	Throughflow Erosion
		Deposition	**Atmosphere***	Interception Uptake	Inhalation	Inhalation External irradiation	Air flow
		Respiration Exudates Decay	Respiration	**Forest Flora***	Ingestion	Ingestion External irradiation	
		Excretion Decay	Exhalation		**Forest Fauna***	Ingestion	
						Exposure of Humans*	
							Losses to Elsewhere

Figure 15: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate forest system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.



Geosphere Model	Source flux						
Diffusion	**Lower Regolith**	Groundwater discharge Diffusion					Groundwater flow
	Recharge Diffusion	**Pasture Soil**	Resuspension Volatilisation	Root uptake External adhesion	Ingestion	Inadvertent ingestion External irradiation	Throughflow Erosion
		Deposition	**Atmosphere***	Interception Uptake	Inhalation	Inhalation External irradiation	Air flow
		Respiration Exudates Decay	Respiration	**Pasture***	Ingestion		Removal of agricultural produce (e.g. hay)
		Excretion Decay	Exhalation		**Farmed Animals***	Ingestion	Removal of agricultural produce
						Exposure of Humans*	
							Losses to Elsewhere

Figure 16: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate pasture system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.

Geosphere Model	Source flux						
Diffusion	**Lower Regolith**	Irrigation	Spray from irrigation	Interception of irrigation	Ingestion	Water ingestion Immersion	Groundwater flow
	Recharge Diffusion	**Arable Soil**	Resuspension Volatilisation	Root uptake External adhesion	Ingestion	Inadvertent ingestion External irradiation	Throughflow Erosion
		Deposition	**Atmosphere***	Interception Uptake	Inhalation	Inhalation External irradiation	Air flow
		Weathering of intercepted contamination Respiration Exudates Decay	Respiration	**Crops***	Ingestion	Ingestion	Removal of agricultural produce
		Excretion Decay	Exhalation		**Farmed Animals***	Ingestion	Removal of agricultural produce
						Exposure of Humans*	
							Losses to Elsewhere

Figure 17: Interaction matric showing the conceptual model for radionuclide migration and exposure for releases to a temperate arable system. Components represented in the mathematical model using equilibrium assumptions are highlighted (*); processes that do not require explicit representation in the mathematical model, either due to being relatively unimportant, conservatively ignored or being implicitly represented in equilibrium assumptions are highlighted in grey text.

6. Mathematical Models

The modelling approach is presented in Section 6.1. The discretisation of each system is described in Section 6.2. The mathematical expressions used to represent transfer processes and to calculate potential exposures are given in Section 6.3.

6.1. Modelling Approach

A compartment modelling approach is adopted, whereby each system is discretised into compartments that represent the components to be modelled dynamically. Each dynamic component may be represented with one or more compartments, as discussed in Section 6.2.

The evolving amount of a radionuclide *N* in compartment *i* (denoted N_i and calculated in Bq) is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j \neq i} \lambda_{ji} N_j + \lambda_M M_i + S_{N,i} \right) - \left(\sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \tag{1}$$

where:

λ_{ji} are transfer rates from other (*j*) compartments to compartment i (y^{-1});
N_j is the amount of radionuclide *N* in each other *j* compartment (Bq);
λ_M is the decay rate for a parent radionuclide to N (y^{-1});
M_i is the amount of the parent radionuclide *M* in compartment *i* (Bq);
$S_{N,i}$ is an external source term of radionuclide *N* to compartment *i* (Bq y^{-1}), for example representing a source flux from geosphere modelling;
λ_{ij} are transfer rates out of compartment *i* to other (*j*) compartments (y^{-1}); and
λ_N is the decay rate for radionuclide *N* (y^{-1}).

Note that dependence on radionuclide and compartments is supressed in the subsequent mathematical expressions for simplicity of presentation, but that the dependence is evident from the supporting data, which is given in Section 7.

6.2. Discretisation

The dynamic biosphere components in each system need to be represented with one or more compartments. The degree of discretisation should be such that the spatial distribution of radionuclides within a compartment is unimportant, either because:

- the compartment is sufficiently well-mixed that the concentration can be taken to be uniform throughout;
- a more detailed distribution of contaminants within a compartment can be sufficiently calculated, e.g. distinctions in concentrations between solid and liquid phases within a compartment; or
- a finer level of detail is not needed for the purpose of assessing doses, e.g. because human behaviour will average exposure over the area of the compartment.

The discretisation of the dynamic components is discussed further below.

Lower Regolith

In most cases, the lower regolith represents an advective groundwater transport pathway between the bedrock and the surface soils and sediments (the exception being the arable system, where it provides a pathway to a groundwater well). Radionuclides will be subject to advection and dispersion as they are transported through the lower regolith. Dispersion lengths are typically taken to be 10% of the path length in porous media. For an appropriate level of discretisation, the numerical dispersion that is implicit in compartment models can be used to represent dispersion along an advective pathway. For these types of system, Quintessa (2005) shows that discretisation into five compartments will give an appropriate breakthrough without the need to explicitly include dispersive transfers[2].

The lower regolith compartments include both solid and liquid phases.

Soils and Sediments

Soils and sediments are represented with two compartments, representing an upper layer and a lower layer. This allows for distinctions in properties and processes, e.g. the degree of bioturbation and/or the depth of digging/ploughing.

The soil and sediment compartments include solid, liquid and gas phases.

Water

The local marine water and the water in lakes within the Forsmark area are relatively well mixed. This means that there is little opportunity for stratification and that they can effectively each be represented with a single compartment.

The compartment includes water and suspended sediment.

6.3. Mathematical Expressions

The interaction matrices in Section 5 give the transfer and exposure processes that need to be represented in the mathematical models. The associated expressions, together with those for intermediate parameters, are given in the sub-sections below.

6.3.1. Dynamic Processes

Transfer rates from a compartment due to groundwater discharge, groundwater flow, irrigation and throughflow, λ_{adv} (y^{-1}), are given by:

$$\lambda_{adv} = \frac{Q}{V\,\theta_w\,R} \tag{2}$$

where:

Q is the associated groundwater flow rate from the compartment ($m^3\ y^{-1}$);
V is the volume of the compartment (m^3);

---

[2] It is noted that a greater degree of precision can be provided by using a greater number of compartments to represent an advective pathway and explicitly representing dispersion (with an adjustment to account for numerical dispersion). However, this additional degree of complexity is not warranted in the current context.

θ_w is the water-filled porosity of the compartment (unitless); and
R is the retardation coefficient.

The water-filled porosity, θ_w, is given by:

$$\theta_w = \theta_t\, \varepsilon \tag{3}$$

where:
θ_t is the total porosity of a compartment (unitless); and
ε is the degree of saturation (unitless).

The retardation coefficient, R, is given by:

$$R = 1 + \frac{\rho_b\, K_d}{\theta_w} \tag{4}$$

where:
ρ_b is the dry bulk density of the compartment (kg m^{-3}); and
K_d is the equilibrium solid-liquid distribution/sorption coefficient for the compartment (m^3 kg^{-1}).

The dry bulk density, ρ_b, is given by:

$$\rho_b = \rho_g (1 - \theta_t) \tag{5}$$

where:
ρ_g is the dry grain density of the compartment (kg m^{-3}).

The transfer rates from surface water compartments due to exchange and water flow, λ_{flow} (y^{-1}), are given by:

$$\lambda_{flow} = \frac{Q_{flow}}{V} \tag{6}$$

where:
Q_{flow} is the associated volumetric flow rate of water (m^3 y^{-1}).

Transfers due to diffusion are represented with two-way transfers between the adjacent compartments, with the transfer rates, λ_{diff} (y^{-1}), given by:

$$\lambda_{diff} = \frac{A_I\, D_{free}}{\Delta V_i\, R_i} \tag{7}$$

where:
A_I is the interface area (m^2);
D_{free} is the free pore water diffusion coefficient (m^2 y^{-1});
Δ is the diffusion distance, which is taken as the distance between the mid-points of the compartments (m);
V_i is the volume of the donor compartment (m^3); and
R_i is the retardation coefficient of the donor compartment (unitless).

The loss of radionuclides in soils due to erosion, λ_{eros} (y^{-1}), is given by:

$$\lambda_{eros} = \frac{E}{H} \tag{8}$$

where:
E is the rate of erosion (m y^{-1}); and
H is the depth/thickness of the soil compartment (m).

Bioturbation is represented with a transfer with a two-way transfer of equal mass between two compartments. The transfer rate from each is given by:

$$\lambda_{bio} = \frac{B\,A}{\rho_b\,V} \tag{9}$$

where the properties relate to the donor compartment and where:

B is the rate of bioturbation across the boundary (kg m^{-2} y^{-1}); and

A is the area (m^2).

The transfer of radionuclides from bed sediment to the water column due to resuspension, λ_{resus} (y^{-1}), is given by:

$$\lambda_{resus} = \frac{Z\,A\,K_d}{(\theta_w + K_d\,\rho_b)V} \tag{10}$$

where:

Z is the resuspension rate (kg m^{-2} y^{-1}).

.

The transfer of radionuclides from the water column to bed sediment due to sedimentation, λ_{sed} (y^{-1}), is given by:

$$\lambda_{sed} = \frac{S\,A\,K_d}{(1 + K_d\,\alpha)V} \tag{11}$$

where:

S is the sedimentation rate (kg m^{-2} y^{-1}); and

α is the suspended sediment concentration in the water (kg m^{-3}).

6.3.2. Environmental Concentrations

Given an external source term (Bq y^{-1}), AMBER will solve the evolving amount of radionuclides in each compartment over time. The resulting time-history of amounts, *Amount* (Bq), can then be used to evaluate environmental concentrations.

The total volumetric concentration in a compartment, C_V (Bq m^{-3}), is given by:

$$C_V = \frac{Amount}{V}. \tag{12}$$

The concentration in the liquid phase of a compartment, C_L (Bq m^{-3}), is given by:

$$C_L = \frac{C_V}{\theta_w + \rho_b\,K_d}. \tag{13}$$

The concentration on the solid phase of a compartment, C_S (Bq kg^{-1}), is given by:

$$C_S = K_d\,C_L. \tag{14}$$

The total concentration in a compartment by dry weight, C_T (Bq kg^{-1}), is given by:

$$C_T = \frac{C_V}{\rho_b}. \tag{15}$$

6.3.3. Equilibrium Models

The concentration due to spray/spume in air above water compartments, C_{spray} (Bq m^{-3}), is given by:

$$C_{spray} = C_V\,\chi_L\,T_{ss} \tag{16}$$

where:

χ_L is the concentration of suspended spray/spume (m^3 spray/spume m^{-3} air); and

T_{ss} is an element-dependent enrichment factor for sea-spray and spume[3] (unitless).

The concentration due to dust in air above soil/sediment compartments, C_{dust} (Bq m^{-3}), is given by:

$$C_{dust} = \chi_S \, C_S \tag{17}$$

where:

χ_S is the concentration of suspended soil/sediment in breathable air (kg m^{-3}).

The concentration due to volatilisation from soils/sediments, C_{gas} (Bq m^{-3}), is given by:

$$C_{gas} = \frac{Amount \;\; \lambda_{vol}}{W_{air} \, H_{air} \, u} \tag{18}$$

where:

$Amount$ is the amount in the underlying soil/sediment or water compartment (Bq);

λ_{vol} is the associated volatilisation rate (y^{-1});

W_{air} is the width of the underlying compartment perpendicular to the wind direction (m);

H_{air} is the atmospheric mixing height (m); and

u is the wind speed (m y^{-1}).

The concentration due to burning of contaminated peat as fuel, C_{fuel} (Bq m^{-3}), is based on the model adopted in Section 9.2 of Karlsson et al. (2001):

$$C_{fuel} = C_{T[Peat]} \, FC \; RC \; FE \tag{19}$$

where:

$C_{T[Peat]}$ is the radionuclide concentration in dry peat (Bq kg^{-1} dry weight);

FC is the fuel load (kg dry weight s^{-1});

RC is the relative concentration as an annual mean value (s m^{-3}); and

FE is the fraction of radionuclides that leave the combustion apparatus via exhaust gases (relating to the efficiency of the filter system).

The concentration in aquatic plants and animals, C_{aq} (Bq kg^{-1} fresh weight), is given by:

$$C_{aq} = CR_{aq} \, C_V \tag{20}$$

where:

CR_{aq} is the equilibrium concentration ratio from the water to the edible tissue (Bq kg^{-1} fresh weight) per (Bq m^{-3}).

Note that the concentration in aquatic food is conservatively based on unfiltered water concentrations, to reflect ambiguity in the supporting data.

The concentration in plants, C_{plant} (Bq kg^{-1} fresh weight), comprises both root uptake and contamination from intercepted irrigation water and is given by:

$$C_{plant} = CR_{plant} C_T + f_{\text{int}} \, q_{irr} \, C_{well} \left(\frac{f_{ext} (1 - f_{abs}) e^{(-w \, t_{irr})} + f_{abs} \, f_{trans}}{Y} \right) \tag{21}$$

where:

CR_{plant} is the equilibrium soil to edible plant concentration ratio (Bq kg^{-1} fresh plant) per (Bq kg^{-1} dry soil);

---

[3] Note that enrichment of actinides and lanthanides in sea-spray is not a sediment loading effect, they are enriched in the organic component of the sea-surface microlayer rather than because of sorption to sediment (Coughtrey et al., 1984).

f_{int} is the fraction of irrigation intercepted by the plant (unitless);
q_{irr} is the irrigation rate (m y^{-1});
C_{well} is the concentration in irrigation water (Bq m^{-3});
f_{ext} is the fraction of externally intercepted contamination that is associated with the edible part of the plant (unitless);
f_{abs} is the fraction of intercepted contamination that is absorbed to the internal plant (unitless);
w is the weathering rate of external contamination (y^{-1});
t_{irr} is time between irrigation and harvest (y);
f_{trans} is the fraction of absorbed contamination that is translocated to the edible plant tissues (unitless); and
Y is the yield of edible plant tissues (kg fresh weight m^{-2} y^{-1}).

Note that consumption of external soil contamination of plants is taken to be included in soil ingestion pathways, to avoid potential double-counting.

The Chamberlain (1970) model is adopted for calculating the interception fraction, f_{int}:

$$f_{\mathrm{int}} = 1 - e^{(-\mu SB)} \tag{22}$$

where:
μ is the interception coefficient (m^2 kg^{-1} dry weight); and
SB is the above-ground standing biomass at the time of irrigation (kg dry weight m^{-2}).

It is noted that a model based on water retention on leaf surfaces is used in Avila et al. (2010); that the Chamberlain model is also widely used (e.g. Section 3.1 of IAEA, 2010) and is used here to provide an alternative representation.

The concentration in animal produce, C_{anm} (Bq kg^{-1} fresh weight), comprises the ingestion of feed, soil and drinking water and is given by:

$$C_{anm} = \frac{f_{contam}\left(IA_{feed}\, C_{plant} + IA_{soil}\, C_T + IA_{wat}\, C_{well}\right) TF_{anm}}{P_e} \tag{23}$$

where:
f_{contam} is the fraction of the animal’s life-time spent in the contaminated area;
IA_{feed} is the ingestion rate of feed by the animal (kg fresh weight day^{-1});
C_{plant} is the concentration in the plants providing the animal feed, as given above (Bq kg^{-1} fresh weight);
IA_{soil} is the ingestion rate of soil by the animal (kg dry weight day^{-1});
C_T is the associated soil concentration, as given above (Bq kg^{-1} dry weight);
IA_{wat} is the ingestion rate of drinking water by the animal (m^3 day^{-1});
C_{well} is the concentration in well water consumed by the animals (Bq m^{-3})
TF_{anm} is the equilibrium ingestion rate to animal produce transfer factor (days kg^{-1} fresh weight); and
P_e is the processing efficiency, which is the ratio of the fresh weight of the processed food to the weight of the original raw ingredients and is unitless.

For game, the concentration in meat, C_{game} (Bq kg^{-1} fresh weight), is based on a concentration ratio approach to enable the associated SR-Site data to be used:

$$C_{game} = \frac{f_{contam}\, CR_{game}\, C_{plant}}{P_e} \tag{24}$$

where:

CR_{game} is the concentration ratio for game meat[4] (Bw kg^{-1} fw meat)/(Bq kg^{-1} fw feed).

6.3.4. Exposure Models

The effective dose due to external irradiation from soils/sediments, E_{ext} (Sv y^{-1}), is given by:

$$E_{ext} = DC_{ext}\, O_{ext}\, C_V \tag{25}$$

where:

DC_{ext} is the dose coefficient due to external irradiation from soil/sediment contaminated to a semi-infinite depth (Sv y^{-1}) per (Bq kg^{-1}); and

O_{ext} is the fractional occupancy of the contaminated area (unitless).

The effective dose due to external irradiation whilst immersed in water (e.g. bathing), E_{imm} (Sv y^{-1}), is given by:

$$E_{imm} = DC_{imm}\, O_{bath}\, C_{wat} \tag{26}$$

where:

DC_{imm} is the dose coefficient due to immersion in contaminated water (Sv y^{-1}) per (Bq m^{-3});

O_{bath} is the fractional occupancy of immersion (unitless); and

C_{wat} is the associated water concentration (either local marine water, lake water or well water, depending on the case).

The effective dose due to the inadvertent ingestion of soil/sediment, E_{sed} (Sv y^{-1}), is given by:

$$E_{sed} = DC_{ing}\, I_{sed}\, C_T \tag{27}$$

where:

DC_{ing} is the dose coefficient due to ingestion (Sv Bq^{-1}); and

I_{sed} is the rate of inadvertent ingestion of soil/sediment (kg dry weight y^{-1}), which is specified either as an annual rate, or as an hourly rate to be used in conjunction with occupancy of soils/sediments.

The effective dose due to inhalation, E_{inh} (Sv y^{-1}), is given by:

$$E_{inh} = \left(DC_{dust}\, C_{dust} + DC_{spray}\, C_{spray} + DC_{gas}\, C_{gas}\right) O_{inh}\, BR \tag{28}$$

where:

DC_{dust} is the dose coefficient for inhalation of particulates (Sv Bq^{-1});

DC_{spray} is the dose coefficient for inhalation of spray/spume (Sv Bq^{-1});

DC_{gas} is the dose coefficient for inhalation of gas (Sv Bq^{-1});

O_{inh} is the fractional occupancy for inhalation exposure (unitless); and

BR is the breathing rate (m^3 y^{-1}).

The effective dose due to ingestion of water, E_{wat} (Sv y^{-1}), is given by:

$$E_{wat} = DC_{ing}\left(I_{drink} + I_{swim}\, O_{bath}\right) C_{wat} \tag{29}$$

where:

DC_{ing} is the ingestion dose coefficient (Sv Bq^{-1});

I_{drink} is the drinking rate (m^3 y^{-1}); and

I_{swim} is the incidental ingestion rate of water whilst swimming (m^3 y^{-1}).

---

[4] In some cases, ‘dw’ and ‘fw’ are used to indicate dry and fresh weight, respectively.

The effective dose due to ingestion of plant produce, E_{crops} (Sv y^{-1}), is summed over the potentially contaminated plant produce consumed and is given by:

$$E_{crops} = \sum_{crops} DC_{ing} I_{crop} C_{plant} \tag{30}$$

where:

I_{crop} is the ingestion rate of each crop (kg fresh weight y^{-1}).

The effective dose due to ingestion of animal produce, E_{anm} (Sv y^{-1}), is summed over the potentially contaminated animal produce consumed and is given by:

$$E_{anm} = \sum_{anm} DC_{ing} I_{anm} C_{anm} \tag{31}$$

where:

I_{anm} is the ingestion rate of each animal product (kg fresh weight y^{-1}).

The effective dose due to ingestion of aquatic foods, E_{aq} (Sv y^{-1}), is summed over the potentially contaminated aquatic produce consumed and is given by::

$$E_{aq} = \sum_{aq} DC_{ing} I_{aq} C_{aq} \tag{32}$$

where:

I_{aq} is the ingestion rate of each aquatic foodstuff (kg fresh weight y^{-1}).

7. Data

The parameter values required to support the biosphere models are presented in this section. The scope of the study includes the use of SR-Site data, as far as is appropriate. However, it is also necessary to present other data required by the models where:

- the models presented here include features and/or processes that are not included in the SR-Site assessment; and
- where the data used in SR-Site is inappropriate, either due to the differing contexts (e.g. non-evolving rather than evolving systems) or where the SR-Site data is considered inappropriate.

Consistent with Section 2.3, deterministic values are primarily presented. However, where information readily exists to support definition of associated parameter distributions, this has been included. The distribution data is largely limited to where data is drawn directly from SR-Site.

7.1. Dimensions

Areas and depths/thicknesses for the media to be represented are included in the sub-sections below. Areas are presented in Section 7.1.1 and depths/thicknesses in Section 7.1.2.

It is noted that a key component of the SR-Site assessment is the spatial discretisation of the system into 'basins' which are represented as distinct biosphere 'objects' in the assessment. These objects represent existing and/or future sub-catchments associated with potential radionuclide discharges in groundwater. The representation of the objects evolves with time, as uplift leads to a transition from marine through, lake and mire to terrestrial and potentially agricultural land. Areas and strata thicknesses within the SR-Site model therefore change with time and cannot therefore be used directly in support of the simple biosphere models used in the current study.

7.1.1. Areas

Areas are required for each of the biosphere systems, requiring consideration of appropriate discharge areas, spatial scales of natural processes operating where the discharge occurs and consideration of human utilisation.

Discharge points at the surface resulting from potential radionuclide releases from across the repository footprint are modelled and discussed in detail in Section 6 of Lindborg (2010). The primary scenarios considered in SR-Site concern potential impacts that arise if one or a few canisters fail. Releases to the biosphere under such conditions will therefore be focused on flow paths associated with such sources.

The SR-Site modelling represents such releases as being uniformly distributed across each of the 'basins' that are represented as biosphere 'objects'. At their smallest (at the maximum extent of terrestrialisation), the size of these objects range from about 4 ha to about 220 ha.

The areas considered for the simple biosphere models are described below and have been derived independently of the biosphere ‘object’ approach adopted in SR-Site.

Marine System

For the marine system, contamination released to the sea will be relatively rapidly dispersed with currents and tides. The size of biosphere ‘objects’ in SR-Site is based on consideration of the size of basins associated with future river, lake and mire catchments. The simple marine biosphere modelling presented here is not constrained by the dimensions of future catchments. Therefore, in determining a reasonable size for a local marine system, consideration is instead given to the present-day bathymetry and to the pattern of potential discharges.

The pattern of discharges described in Section 6 of Lindborg (2010) indicates a width of discharge points parallel to the coastline of about 2 km for releases from across the repository. Whilst releases from a single canister failure would be expected to occur over a smaller area, a length of coastline of 2 km is considered a reasonable basis for the marine area, given the dispersive nature of the system.

The present-day coastline is characterised by a line of islands that are approximately 1 km from the shore[5], which effectively semi-enclose the near-shore marine environment.

Given the above, an area of 2 km by 1 km is therefore considered for the marine system, which is 2,000,000 m^2.

Note that the discharge zone from a failed canister may be much smaller than this total area, for example, discharge may occur alone a line relatively close to the shore. If concentrations in the associated bed sediments are required, the sediments of the discharge zone would need to be represented distinct from those underlying the rest of the area.

Lake System

Consideration is given to the size of lakes in the present-day Forsmark area as the basis for the lake system to be modelled. Table 3-8 of Andersson (2010) gives a median size of lakes in the Forsmark area of 0.05 km^2. An area of 50,000 m^2 is therefore used for the lake (equivalent to a circular lake of diameter about 250 m).

SR-Site calculations of solute transport behaviour in the near-surface system indicate dispersion on a scale of a few hundred metres from individual discharge points (see Section 6.3.2 of Lindborg, 2010). This suggests that consideration of a lake of diameter of 250 m is not unreasonable for a single discharge point.

---

[5] The islands are also evident in the elevation profiles given in Figure 3-13 of Aquilonius (2010).

Mire System

Mires in the Forsmark area today vary significantly in size, with some that border lakes and others that are isolated. The average size of open mires in the Forsmark area is about 6000 m^2 (based on Table 4-3 of Löfgren, 2010). This is relatively small (with a circular diameter of only 87 m).

A mire size of 50,000 m^2 is adopted, which is consistent with the lake area described above (although no succession is explicitly modelled in this study) and with the spatial scale for distribution of contaminants released to the near-surface system.

Forest System

This system represents a forested mire that receives contaminated groundwater discharges. It will have become a forest due to both natural succession from a wetland and lower groundwater levels resulting from up-lift. The spatial scale adopted for the lake and mire systems is also adopted here. At 50,000 m^2, it represents a very small forested system, but is taken to represent the area over which discharges from a canister failure to a single discharge point in the biosphere might occur.

Pasture System

This system represents poor quality agricultural soils, relative to arable production, that receive direct groundwater discharge, potentially associated with an adjacent water course or man-made drainage.

The size of the pasture system can be calculated either based on the feed requirement of the number of animals. The meat and milk requirements of a small group (nominally two adults, a child and an infant) can be supported by a relatively small number of animals, therefore it is more appropriate to consider the smallest number of animals that might reasonably be raised. For the purposes of the assessment, this is taken to be four beef cattle, two dairy cows, four dairy goats and ten sheep. An area of about 7 ha would be sufficient to supply the annual feed requirements of these animals. Allowing for poorer quality land/wastage etc., a rounded value of 10 ha (100,000 m^2) is used.

Arable System

An area of one hectare (10,000 m^2) would be sufficient to provide the vegetable and root vegetable requirements of a small group (nominally two adults, a child and an infant), including the feed requirements of their animals. This is therefore used for reference calculations, where cereal production is not considered.

An area of 0.6 ha (6,000 m^2) would be sufficient to supply the grain requirement of the small group and their animals. However, this is considered too small an area to be considered for grain production and an area of two hectares is considered for grain production in variant calculations in which it is included.

An area of 50,000 m^2 is considered for the till that receives the contaminated groundwater discharge and is discussed in Section 7.3.

7.1.2. Layer/Strata Thicknesses

The thicknesses of compartments representing each of the temperate systems is given in Table 5 to Table 10 below.

Glacial clay layers are included beneath all but the arable system, on the basis that the modelled areas reflect locations that receive contaminated groundwater discharges and are likely associated with topographic lows where glacial clays will have accumulated.

Table 5: Layer thicknesses for the temperate marine system, m.

Media	Value	Notes
Water column	7.5	Based on consideration of the present-day near-shore system as illustrated in the elevation profiles given in Figure 3-13 of Aquilonius (2010); selected as a representative value of average depth over a distance of about 2 km from the coast.
Surface sediment	0.1	Thickness of upper sediment from Section 10.5.1 of Aquilonius (2010)
Deep sediment	1.3	Based on total regolith thickness of 6 m for near-shore bays from consideration of Figure 4-12 of Lindborg (2010)
Glacial clay	0.70	Average of thicknesses in Table 10-10 of Aquilonius (2010)
Till	3.9	Average of thicknesses in Table 7-8 of Lindborg (2010)

Table 6: Layer thicknesses for the temperate lake system, m.

Media	Value	Notes
Water column	0.7	Based on the mean depth of lakes in the present-day Forsmark area (Table 3-8 of Andersson, 2010)
Surface sediment	0.05	Based on mean thickness of the oxygenated zone in lake bed sediments on p382 of Andersson (2010)
Deep sediment	0.95	Total thickness of 1 m assumed based on the average thickness of gyttja in Table 13-4 of Löfgren (2010), plus allowance for upper gyttja and microphytobenthos layers excluded from that table, as noted on p40 of Andersson (2010)
Glacial clay	1.7	Average of thicknesses in Table 7-11 of Lindborg (2010)
Till	4.7	Average of thicknesses in Table 7-9 of Lindborg (2010)

Table 7: Layer thicknesses for the temperate mire system, m.

Media	Value	Notes
Surface peat	0.2	Taken to be the most biologically active layer
Deep peat	1.5	Total thickness of mire taken to be 0.7 m greater than lake, reflecting in-filling of former lake
Glacial clay	1.7	Based on thicknesses below lakes in Table 6
Till	4.7	Based on thicknesses below lakes in Table 6

Table 8: Layer thicknesses for the temperate forest system, m.

Media	Value	Notes
Surface peat	0.2	Taken to be the most biologically active layer
Deep peat	1.0	Overall thickness of peat taken to be less than mire
Glacial clay	0.5	Taken to be thinner than the glacial clay beneath the mire
Till	2.3	Based on overall thickness of 4 m, from consideration of the regolith depth beneath terrestrial areas in Figure 4-12 of Lindborg (2010).

Table 9: Layer thicknesses for the temperate pasture system, m.

Media	Value	Notes
Surface soil	0.1	Thinner than arable soils, in the absence of ploughing
Deep soil	1.1	Total thickness taken to be the same as that of peat in the forest system
Glacial clay	0.5	Taken to be the same as the forest system
Till	2.3	Taken to be the same as the forest system

Table 10: Layer thicknesses for the temperate arable system, m.

Media	Value	Notes
Surface soil	0.25	Thickness of layer that is regularly ploughed on p340 of Löfgren (2010)
Deep soil	0.75	Overall soil thickness taken to be 1 m
Note that there is taken to be direct connection between the soil and the till		
Till	4.0	Overall thickness beneath arable area taken to be 5 m, based on thickness beneath the notable arable area in the Forsmark region at the present-day

7.2. Media Properties

Properties are required for the media explicitly represented by compartments. Suspended sediment concentrations in lake and marine water are given in Table 11. Total porosity is given in Table 12 and grain density is given in Table 13. Finally, the degree of saturation of soils/sediments is given in Table 14.

For agricultural soils, both organic rich soils (consistent with SR-Site) and clayey tills are considered, the latter being consistent with the largest arable land unit in the Forsmark area (Section 10.4.2 of Löfgren, 2010). In SR-Site, organic soils are solely considered for agriculture because the areas are represented as evolving from mires.

The porosity and dry bulk densities used for accumulation sediments in SR-Site imply a grain density of 3150 kg m^{-3}, which is too high, as indicated in the supporting discussion which suggests that the value should be somewhere between 2650 kg m^{-3} and 1000 kg m^{-3} (e.g. p384 of Andersson, 2010). The porosity value of 0.96 for accumulation sediments used in SR-Site is high; it is based on two sets of observed data (given in Table 11-5 and 11-6 of Andersson, 2010). However, there is overlap in the lakes covered in both tables and the porosity values in Table 11-5 of Andersson (2010) are notably higher than those given for the same lakes in Table 11-6 of Andersson (2010). Using a porosity value solely based in Table 11-6 of Andersson (2010) gives an average porosity of 0.94 for accumulation sediments and implies a grain density of 2100 kg m^{-3}, which is more feasible. These porosity and grain density values are adopted here.

The sediments considered in the SR-Site modelling were always taken to be saturated (e.g., 9:2b on p306 of Löfgren, 2010). The surface forest soil and the agricultural soils considered in this study are taken to be partially saturated. The degree of saturation considered is given in Table 13 and is informed by consideration of Appendix B in Walke et al. (2012a).

Table 11: Suspended sediment concentration, kg m^{-3}.

Media	Value	Notes
Local marine water	0.003	Based on Table 10-21 of Aquilonius (2010)
Lake water	0.0011	Based on Table 11-20 of Andersson (2010)

Table 12: Total porosity (unitless).

Media	Value	Notes
Marine bed-sediment – accumulation	0.94	Based on average of values given in Table 10-7 of Aquilonius (2010)
Marine bed-sediment – erosion	0.32	Based on Table 10-9 of Aquilonius (2010)
Lake bed-sediment	0.94	Based on average of values given in Table 11-6 of Andersson (2010)
Mire sediment	0.89	Value for peat given on p338 of Löfgren (2010)
Forest soil	0.89	Based on peat value for mire sediment
Pasture soil – clay	0.31	Calculated from grain density of 2650 kg m^{-3} and dry bulk density of 1830 kg m^{-3} (average for clayey silty tills from the Forsmark area in Table 3-2 of Sheppard et al., 2009)
Pasture soil – peat	0.81	Value for agricultural soil given on p337 of Löfgren (2010)
Arable soil – clay	0.31	As for clayey pasture soil
Arable soil – peat	0.81	Value for agricultural soil given on p337 of Löfgren (2010)
Upper regolith – post-glacial deposits	0.93	Value for postglacial sediments on p339 of Löfgren (2010)
Mid-regolith – glacial clay	0.64	Value for glacial sediments given on p 339 of Löfgren (2010)
Lower regolith – till	0.21	Value for glacial till given on p 340 of Löfgren (2010)

Table 13: Grain density, kg m^{-3}.

Media	Value	Notes
Marine sediment - accumulation	2100	Based on dry bulk density of 126 kg m^{-3} in Table 10-4 of Aquilonius (2010) with the porosity given in Table 12
Marine sediment - erosion	2650	Based on dry bulk density of 1800 kg m^{-3} in Table 10-5 of Aquilonius (2010) with the porosity given in Table 12
Lake sediment	2100	Based on dry bulk density of 126 kg m^{-3} reported in Table 11-3 of Andersson (2010) with the porosity given in Table 12
Mire sediment	780	Based on dry bulk density of 86 kg m^{-3} reported on p338 of Löfgren (2010) with the porosity given in Table 12
Forest soil	780	Based on peat value for mire sediment
Pasture soil – clayey silty till	2650	Based on density of quartz to reflect clayey silty till, appropriate to agricultural usage in the Forsmark area (see Section 3.1 of Sheppard et al., 2009)
Pasture soil – peat	1700	Based on dry bulk density of 323 kg m^{-3} reported on p337 of Löfgren (2010) with the porosity given in Table 12
Arable soil – clayey silty till	2650	As for clayey silty till pasture soil
Arable soil – peat	1700	Based on dry bulk density of 323 kg m^{-3} reported on p337 of Löfgren (2010) with the porosity given in Table 12
Upper regolith – post-glacial deposits	1970	Based on dry bulk density of 138 kg m^{-3} reported on p338 of Löfgren (2010) with the porosity given in Table 12
Mid-regolith – glacial clay	1840	Based on dry bulk density of 663 kg m^{-3} reported on p338 of Löfgren (2010) with the porosity given in Table 12
Lower regolith – till	2670	Based on dry bulk density of 2132 kg m^{-3} reported on p340 of Löfgren (2010) with the porosity given in Table 12

Table 14: Fractional saturation (unitless).

Media	Value		Notes
	Surface	Deeper	
Marine bed-sediment	1	1	Fully saturated
Lake bed-sediment	1	1	Fully saturated
Mire sediment	1	1	Fully saturated
Forest soil	0.85	1	Upper soil close to full saturation; lower soil fully saturated
Pasture soil – clay	0.8	1	Upper soil has lower saturation than forest soils; lower soil fully saturated
Pasture soil – peat	0.85	1	Taken to be the same as forest soil
Arable soil – clay	0.7	0.8	Neither layer fully saturated; degree of saturation in lower soil is greater
Arable soil – peat	0.7	0.8	Taken to be the same as clay arable soil
Upper regolith – post-glacial deposits	1		Fully saturated
Mid-regolith – glacial clay	1		Fully saturated
Lower regolith – till	1		Fully saturated

7.3. Hydrology and Near-Surface Hydrogeology

In SR-Site, the representation of hydrology and near-surface hydrology is based on detailed dynamic modelling undertaken in MIKE SHE. The water fluxes calculated in MIKE SHE are averaged for six representative lake/mire systems to support a 'box model' of flows (see Figure 13-2 of Löfgren, 2010). The box model flows are then used to support the parameterisation of water flows in the radionuclide transport model. Several observations can be made about this approach adopted in SR-Site:

- Figure 13-2a from Löfgren (2010) is difficult to interpret due to a problem with formatting;
- the box model flows do not provide a water balance, potentially as a result of the averaging and 'normalisation' of MIKE SHE outputs;
- only some of the water flows are represented in the radionuclide transport model, e.g. infiltrating/downward flows from the middle to the lower regolith and 'lateral' exchanges between the mire and lake systems.

The degree of abstraction from the physically based MIKE SHE modelling (averaging, normalisation and then multiplying by modelled areas), the implied lack of a water balance, the use of net flows instead of calculated flows and the omission of downward and lateral water flows means that it is ultimately difficult to have confidence in what the water flows used in the radionuclide transport modelling actually represent.

The water flows used for the marine, lake, mire, forest and pasture systems in the current study are illustrated in Figure 18 and Figure 19. For the marine system, a consistent groundwater discharge rate of 8 mm y^{-1} is used, consistent with the SR-Site modelling (Section 10.6.1 of Aquilonius, 2010). For the terrestrial systems, the SR-Site parameterisation is not used directly here, both due to the reasons described above and due to the differing model structures. The terrestrial water flows use the same averaged MIKE SHE outputs as was used in SR-Site (Figure 13-2b of Löfgren, 2010), although the flows are adjusted to:

- to ensure internal water balance;
- to ensure that both upward and downward water flows are explicitly represented, rather than just net values; and
- to reflect progressively drier surface peat/soil conditions in the forest and pasture systems.

The soil in the arable system does not receive direct groundwater discharge, but is instead contaminated via irrigation. Precipitation and evapotranspiration data for the Forsmark area are available in Bosson et al. (2010) and in Larsson-McCann et al. (2002) and are summarised in Table 15. These show that annual precipitation is about 580 mm y^{-1}. Actual evapotranspiration will be less than potential evapotranspiration; nonetheless, the table suggests that soil moisture deficits may occur during May, June, July and August. There is therefore potential for irrigation during these months, which are important periods for crop development. For the purpose of a water balance for the arable system, the following assumptions are adopted:

- precipitation rate of 580 mm y^{-1};
- irrigation rate of 100 mm y^{-1};
- actual evapotranspiration of 380 mm y^{-1};
- infiltration/recharge rate of 300 mm y^{-1}.

Table 15: Precipitation and potential evapotranspiration for the Forsmark area

Month	Precipitation, mm y^{-1}	Potential evapotranspiration, mm y^{-1}
January	43	5
February	16	5
March	26	15
April	31	40
May	44	75
June	46	100
July	84	100
August	55	70
September	29	40
October	74	15
November	60	5
December	73	5
Total	581	475

Notes for Table 15: Precipitation based on Table 2-1 of Bosson et al. (2010). Evapotranspiration based on consideration of 1969-1990 mean values for the Örskär and Films Kyrkby stations in Tables App1-17 and App1-18 of Larsson-McCann et al. (2002).

The survey of wells summarized in Table 2-1 of Ludvigson (2002) shows that shallow wells are present in the Forsmark area; many are brackish and have high mineral content, however some of the shallow wells yield drinkable water and some are used for irrigation. The well is therefore taken to be shallow and water is drawn from the till. This means that the SR-Site well capacity is not used because it relates to deeper percussion drilled boreholes, which have a yield that is significantly higher than the local domestic wells (see Section 13.4.2 of Löfgren, 2010).

The soil water balance described above provides a recharge rate of 300 mm y^{-1} plus 8 mm y^{-1} groundwater discharge. An area of five hectares is used for several of the biosphere systems considered (see Section 7.1.1); such an area would yield 15,400 m^3 y^{-1}. This value is used for the flow rate through the till and is intentionally lower than the reference value of 82,502 m^3 y^{-1} for Forsmark in Löfgren (2010), for the reasons discussed above.

A well water extraction rate of 1500 m^3 y^{-1} can be calculated to provide the irrigation water, animal drinking water and based on a domestic water usage of 130 m^3 y^1 per person (Section 6.2.3 of Walke et al., 2011). This increases to 3500 m^3 y^{-1} if irrigation of cereals is included.

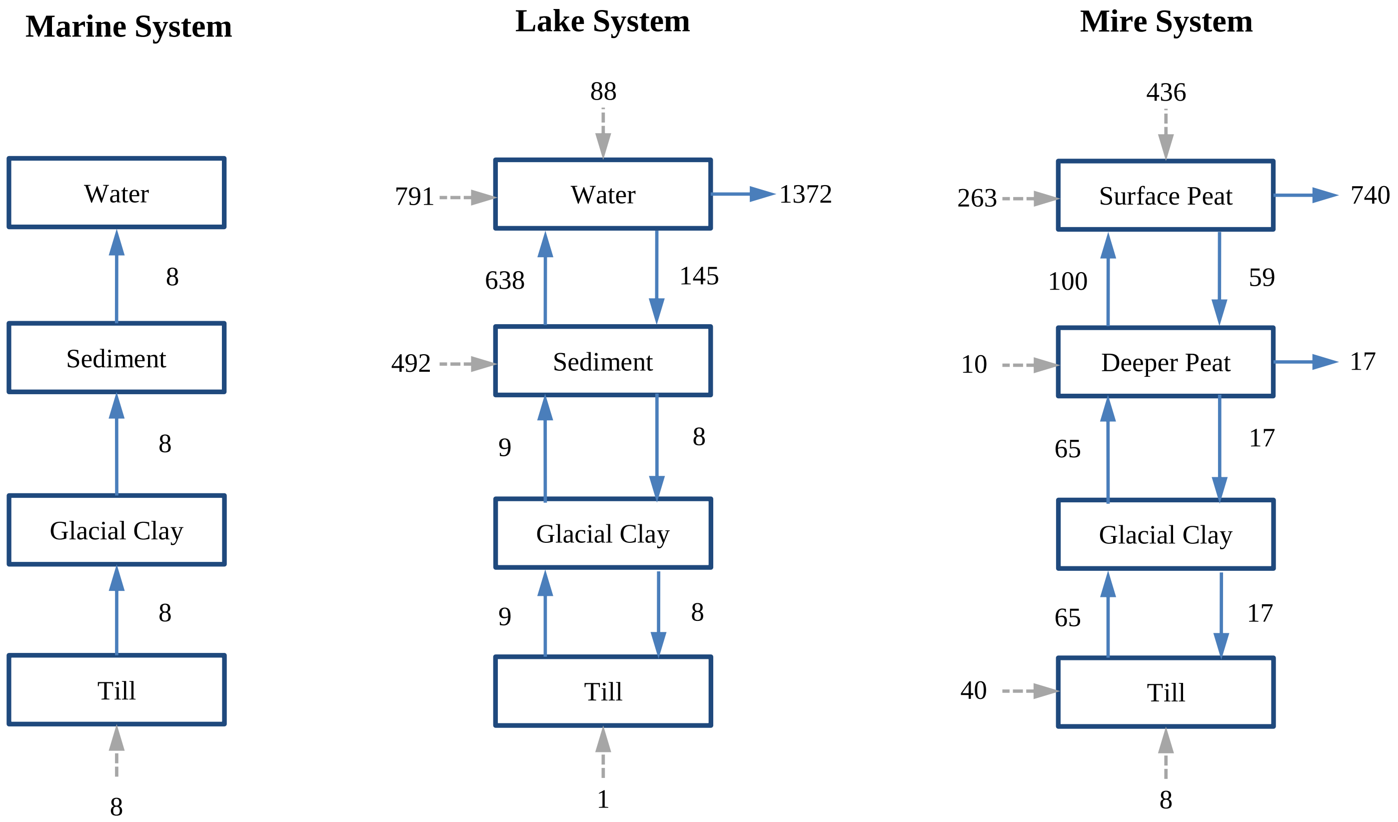


Figure 18: Water balances for marine, lake and mire systems, mm y^{-1}.

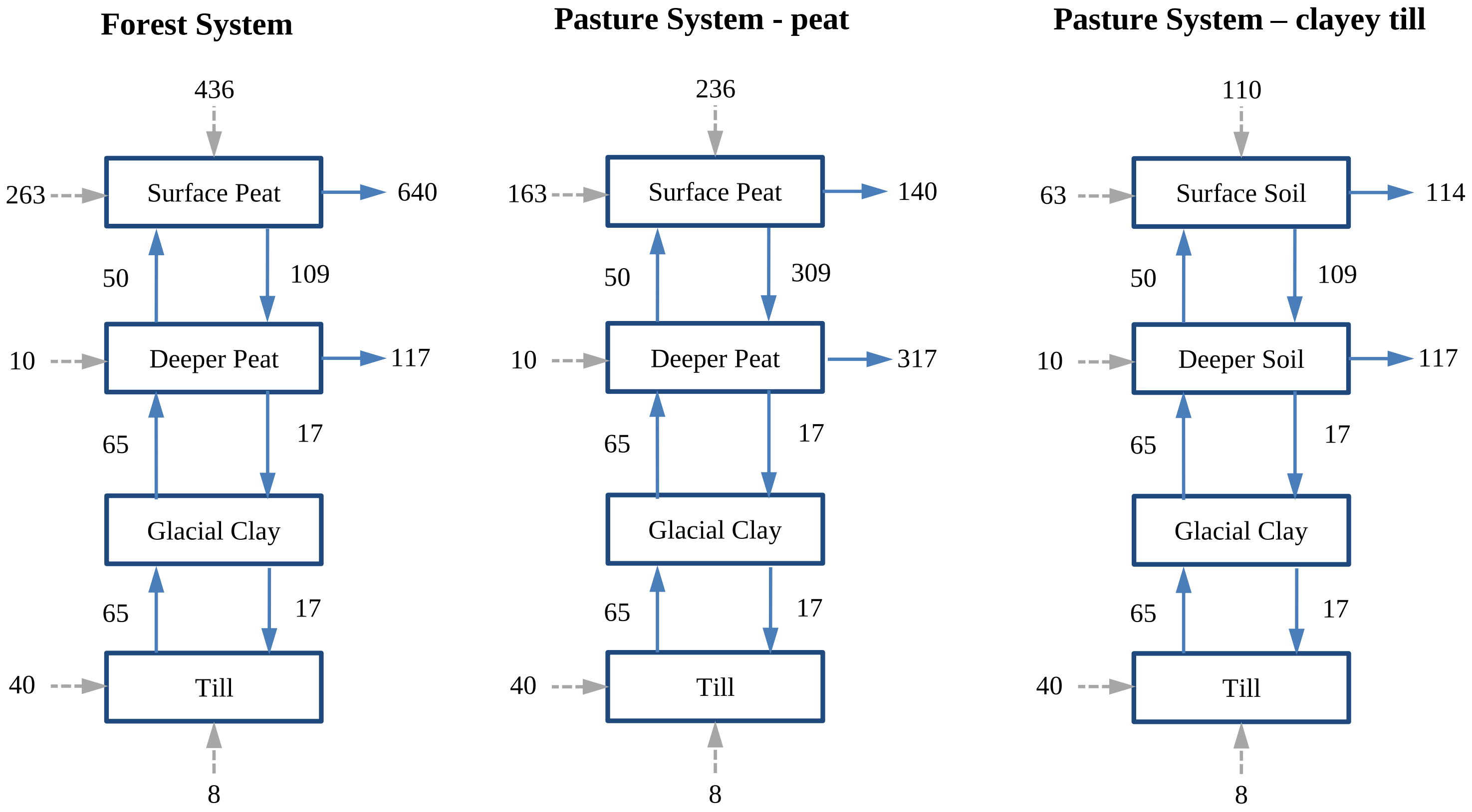


Figure 19: Water balances for forest and pasture systems, mm y^{-1}.

7.4. Other Transfer Processes

Parameter values are needed to characterise other transfer processes in the biosphere models. Surface water exchange/turnover rates are described in Section 7.4.1. Sedimentation and resuspension of aquatic sediments in the water column are described in Section 7.4.2. Bioturbation between surface sediment/soil layers is described in Section 7.4.3. Parameters relating to volatilisation from soil are presented in Section 7.4.5.

7.4.1. Surface Water Exchanges/Turn-over

In SR-Site, marine water exchanges are based on detailed hydrodynamic modelling and reflected in the average residence time of water. Residence times for marine systems that are within a few kilometres of the coast at 2020 AD are about 27 days (based on 'basins' 117, 118, 121 and 126 in Table 10-20 of Aquilonius (2010). In SR-Site, the reciprocal of this value is used as the transfer rate from marine water.

In SR-Site, flow rates through lakes are calculated based on time-dependent watershed areas and runoff. In this case, the mean residence time of lakes in the Forsmark area of 76 days is used (Table 3-8 of Andersson, 2010).

7.4.2. Sedimentation and Resuspension

Sedimentation and resuspension rates are calculated in SR-Site to reflect the evolving nature of the system, in-filling of lakes in particular. The simple systems represented in this assessment do not evolve, therefore net sedimentation is taken to be zero. However, gross sedimentation and resuspension rates are required for the marine and lake systems, to reflect a turnover of sediment throughout the year.

The change in calculated bed sediment volumes over time is used to derive the sedimentation and resuspension rates considered in SR-Site (see Section 7.7.4 of Lindborg, 2010). However, the long-term changes in sediment volumes will reflect only net sedimentation/resuspension, whereas to model the exchange between the water column and bed sediment appropriately, the gross sedimentation and resuspension rates should be used. The SR-Site approach and data are therefore not used directly.

A gross sedimentation rate of 0.2 kg m^{-2} y^{-1} is adopted here for the marine system, based on the value for open coasts in Table 3-12 of Bergström et al. (1999). The same value is used for the resuspension rate, maintaining a sediment balance.

A gross sedimentation rate of 1 kg m^{-2} y^{-1} is used for the lake system, based on the value for oligotrophic lakes in Table 3-6 of Bergström et al. (1999). The same value is used for the resuspension rate, maintaining a sediment balance.

7.4.3. Erosion

Soil erosion is taken to occur in the arable and pasture systems. The rate of erosion is higher in the arable system, due to more exposed nature of the soils. A rate of 1 mm y^{-1} is adopted for the arable system and 0.2 mm y^{-1} for the pasture system, based on consideration of the range discussed for non-sloping farm land on p338 of IAEA (2003), which is referenced to Jones (1987).

7.4.4. Bioturbation

Bioturbation reflects mixing of surface sediments due to the action of organisms including earthworms and ants in soils and polychaete worms in the marine system. Bioturbation rates are given in Table 16.

Table 16: Bioturbation rates between surface soil/sediment layers, kg m^{-2} y^{-1}.

System	Bioturbation rate	Notes
Marine	1	1
Lake	0.25	2
Mire	0	3
Forest	0.5	4
Pasture	1	5
Arable	2	6

Notes for Table 16:

1 Bioturbation is taken to occur in the marine system, reflecting, for example, polychaete worms; a nominal value is used in the absence of specific data.

2 A low rate of bioturbation is taken to occur in the lake to reflect, for example, freshwater crustaceans.

3 No bioturbation taken to occur between the two peat layers.

4 Taken to be half the rate is pasture soils, to reflect greater degree of saturation.

5 Low value adopted to reflect poor and relatively saturated soils, based on Table 5-1 of Karlsson, et al. (2001).

6 Best estimate for agricultural land in Table 5-1 of Karlsson, et al. (2001).

7.4.5. Volatilisation and Atmosphere

Volatilisation from soils and sediments is of potential relevance for Se-79 and I-129. Volatilisation rates are given in Table 17.

Table 17: Volatilisation rates.

System	Volatilisation rate	Notes
Se-79 (soils)	0.03 y^{-1}	1
Se-79 (sediments)	0.06 y^{-1}	1
I-129	0.02 y^{-1}	2

Notes for Table 17:

1 Based on Section 4.3 of Limer and Thorne (2010).

2 Based on Clause 6.3.5.1 of CSA (2008).

A wind velocity of 1.93 m s^{-1} is used, based on the mean wind speed in Table 13-8 of Löfgren (2010) and a conservative mixing height of 2 m is adopted.

7.5. Exposure Group Assumptions

Characteristics are required for potentially exposed groups, including occupancies of contaminated areas and rates of ingestion of contaminated food stuffs.

The assumptions concerning the size of the biosphere systems being modelled differ between this assessment and SR-Site. It is, therefore, not appropriate to adopt the SR-Site occupancies and they are instead defined below based on consideration of potential exposure group behaviours.

Ingestion rates of food in SR-Site are based solely on consideration of total carbon intake (Section 6.4.2 of Nordén at al., 2010). The value of 110 kgC y^{-1} is based on male ingestion rates of protein, carbohydrate and fat from p351 of ICRP (1975), which draw on surveys reported between 1936 and 1969. The intake is arbitrarily apportioned to different foodstuffs within the mathematical model reported in Appendix A of Avila et al. (2010).

Instead of adopting the SR-Site approach, ingestion rates are simply specified for each food group modelled and are given in the sub-sections below.

7.5.1. Marine System

Exposure group assumptions for the marine system are given in Table 18, based on recreational use and collection of food stuffs.

Table 18: Exposure group parameters for the marine system.

Item	**Units**	**Age Group**			**Notes**
		Adult	**Child**	**Infant**	
Shoreline occupancy	hrs y^{-1}	168	84	42	1
Swimming occupancy	hrs y^{-1}	14	7	0	2
Incidental ingestion of water	m^3 hr^{-1}	2.E-5	2.E-5	2.E-5	3
Dust concentration on shoreline	kg dw m^{-3}	1E-7	1E-7	1E-7	4
Concentration of spray on shoreline	m^3 m^{-3}	1E-11	1E-11	1E-11	5
Inhalation rate on shoreline	m^3 hr^{-1}	1.375	1.12	0.22	6
Ingestion rates					
Fish	kg fw y^{-1}	30	15	10	7
Crustaceans	kg fw y^{-1}	5	3	1	8
Molluscs	kg fw y^{-1}	5	3	1	8
Algae	kg fw y^{-1}	2	1.5	0.5	9
Inadvertent ingestion of sediment	mg dw hr^{-1}	5	10	50	10

Notes to Table 18:

1 Adult based on an average of 2 hours per day for three months of the year; child and infant half of this rate.

2 Adult based on an average 0.5 hour per day for one month of the year; child half this rate; infant taken not to swim in the sea.

3 Note that this rate is applicable whilst swimming (i.e. it needs to be multiplied by the duration of swimming to give an annual rate). Value based on an inadvertent ingestion rate of one or two mouthfuls (~0.02 L) per hour, from consideration of Section 7.9.6 of Walke et al. (2013b).

4 Typical value considered in assessments Wasiolek et al. (2005).

5 Based on Section 7.9.3 of Walke et al. (2013b).

6 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

7 Adult value based on Table 9-3 of Karlsson et al. (2001), which refers to Bergström and Nordlinder (1990) and matches the 95th percentile of consumers in Table 2 of Smith and

Jones (2003); values for children and infants based on 95th percentile of consumers in Tables 4 and 5 of Smith and Jones (2003).

8 Adult and child values based on consideration of the high consumption rates for consumers of shellfish in Smith and Jones (2003) and split equally between crustaceans and molluscs; value for infants based on consideration of values for adults and children.

9 Value for adults based on Table B-2 of Bergström et al. (1999); values for children and infants based on consideration of the value for adults.

10 Based on the hourly rates in Table 11 of Smith and Jones (2003).

7.5.2. Lake System

Exposure group assumptions for the lake system are given in Table 19, based on recreational use and collection of food stuffs.

Table 19: Exposure group parameters for the lake system.

Item	Units	Age Group			Notes
		Adult	Child	Infant	
Shoreline occupancy	hrs y^{-1}	168	84	42	1
Swimming occupancy	hrs y^{-1}	14	7	0	2
Incidental ingestion of water	m^3 hr^{-1}	2.E-5	2.E-5	2.E-5	3
Dust concentration on shoreline	kg dw m^{-3}	1E-7	1E-7	1E-7	4
Inhalation rate on shoreline	m^3 hr^{-1}	1.375	1.12	0.22	5
Ingestion rates					
Wild fowl	kg fw y^{-1}	10	7.5	4	6
Fish	kg fw y^{-1}	30	15	10	7
Crustaceans	kg fw y^{-1}	9	5	2	8
Inadvertent ingestion of sediment	mg dw hr^{-1}	5	10	50	9

Notes to Table 19:

1 Adult based on an average of 2 hours per day for three months of the year; child and infant half of this rate.

2 Adult based on an average 0.5 hour per day for one month of the year; child half this rate; infant taken not to swim in the sea.

3 Note that this rate is applicable whilst swimming (i.e. it needs to be multiplied by the duration of swimming to give an annual rate). Value based on an inadvertent ingestion rate of one or two mouthfuls (~0.02 L) per hour, from consideration of Section 7.9.6 of Walke et al. (2013b).

4 Typical value considered in assessment, as discussed in Section 7.9.2 of Walke et al. (2013b).

5 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

6 Adult and child values based on 95th percentile of consumers in Smith and Jones (2003); value for infants based on consideration of value for adults and children

7 Adult value based on Table 9-3 of Karlsson et al. (2001), which refers to Bergström and Nordlinder (1990) and matches the 95th percentile of consumers in Table 2 of Smith and Jones (2003); values for children and infants based on 95th percentile of consumers in Tables 4 and 5 of Smith and Jones (2003).

8 Adult and child values based on consideration of the high consumption rates for consumers of shellfish in Smith and Jones (2003); value for infants based on consideration of values for adults and children.

9 Based on the hourly rates in Table 11 of Smith and Jones (2003).

7.5.3. Mire System

Exposure group assumptions for the mire system are given in Table 20, based on recreational use and collection of food stuffs and use of peat as fuel. Parameters associated with calculating the radionuclide concentration in smoke generated from the burning of peat as fuel are given in Table 21. The model for inhaling smoke from burning peat is sensitive to the relative concentration that is used, which reflects dispersion. The value included in Table 21 is drawn from a previous SKB assessment and is used without review.

Table 20: Exposure group parameters for the mire system.

Item	Units	Age Group			Notes
		Adult	Child	Infant	
Occupancy of mire	hrs y^{-1}	42	0	0	1
Occupancy near burning of peat	hrs y^{-1}	8000	8000	8000	2
Dust concentration	kg dw m^{-3}	1E-9	1E-9	1E-9	3
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	4
Ingestion rate of wild fowl	kg fw y^{-1}	10	7.5	4	5
Inadvertent ingestion rate of sediment	mg dw hr^{-1}	5	0	0	6

Notes to Table 20:

1 Adult based on an average of 0.5 hour per day for three months of the year; children and infants taken not to occupy the mire system.

2 Based on best estimate in Table 9-4 of Karlsson et al. (2001)

3 Low value used to reflect wet and vegetated nature of mire sediments, based on consideration of Section 7.9.2 of Walke et al. (2013b).

4 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

5 Adult and child values based on 95th percentile of consumers in Smith and Jones (2003); value for infants based on consideration of value for adults and children.

6 Based on average annual rate for adults in Table 11 of Smith and Jones (2003) to reflect handling of peat fuel; no inadvertent ingestion of peat is considered for children and infants.

Table 21: Parameters for use of peat as fuel.

Parameter	Value
Fuel load, kg dw s^{-1}	1.E-4
Relative concentration, s m^{-3}	1.E-5
Fraction in exhaust gases, unitless	1

Note to Table 21: Based on best estimates in Table 9-4 of Karlsson et al. (2001).

7.5.4. Forest System

Exposure group assumptions for the forest system are given in Table 22, based on recreational use and collection of food stuffs.

Table 22: Exposure group data for the forest system.

Item	Units	Age Group			Notes
		Adult	Child	Infant	
Occupancy	hrs y^{-1}	42	21	0	1
Dust concentration	kg dw m^{-3}	1E-8	1E-8	1E-8	2
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	3
Ingestion rates					
Berries	kg fw y^{-1}	5	4	2	4
Game	kg fw y^{-1}	10	7.5	4	5
Mushrooms	kg fw y^{-1}	8	3.5	1.5	6
Inadvertent ingestion of sediment	mg dw hr^{-1}	5	10	0	7

Notes to Table 22:

1 Adult based on an average of 0.5 hour per day for three months of the year; children taken to be half of this rate and infants taken not to occupy the forest system.

2 Intermediate dust concentration used to reflect relatively damp and vegetated nature of forest sediments, based on consideration of Section 7.9.2 of Walke et al. (2013b).

3 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

4 Based on about a quarter of the mean rate of consumers for domestic fruit in Smith and Jones (2003), which is taken to reflect a relatively high consumption rate for wild berries.

5 Adult and child values based on 95th percentile of consumers in Smith and Jones (2003); value for infants based on consideration of values for adults and children.

6 Based on 95th percentile of consumers in Smith and Jones (2003).

7 Based on the hourly rate in Table 11 of Smith and Jones (2003), although zero rate used for infant because they are not taken to occupy the forest.

7.5.5. Pasture System

Exposure group assumptions for the pasture system are given in Table 23. These are based on grazing of animals and the use of the land to grow hay. Some recreational use is also considered.

Table 23: Exposure group data for the pasture system.

Item	Units	Age Group			Notes
		Adult	Child[1]	Infant[1]	
Occupancy	hrs y^{-1}	730	180	90	2
Dust concentration	kg dw m^{-3}	1E-7	1E-7	1E-7	3
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	4
Ingestion rates					
Cows' milk	L y^{-1}	100	105	140	5
Cows' milk produce	kg fw y^{-1}	10	7.5	7.5	6
Goats' milk	L y^{-1}	100	105	140	5
Goats' milk produce	kg fw y^{-1}	10	7.5	7.5	6
Beef	kg fw y^{-1}	40	40	8	7
Beef offal	kg fw y^{-1}	5	3	1	8
Sheep meat	kg fw y^{-1}	30	15	3	7
Sheep offal	kg fw y^{-1}	5	3	1	8
Inadvertent ingestion of sediment	mg dw hr^{-1}	5	10	50	9

Notes to Table 23:

1 Values for food intakes for children and infants are scaled to the adult ingestion rates based on ratios calculated from Smith and Jones (2003); 95th percentile rates were used for milk because the value matched best for adult consumption.

2 Adult based on about four hours per day for six months of the year (when average temperature is above about 5 degrees and pasture will be growing); child and infant values based on a quarter and an eighth of the adult values.

3 Typical value considered in assessment, as discussed in Section 7.9.2 of Walke et al. (2013b).

4 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

5 Adult value based on the Table C.4 of Bergström and Nordlinder (1990) value for milk, which does not include the contribution from milk produce. The value is split evenly

between cows' and goats' milk. Note that 1 L of milk is taken to be equivalent to 1 kg milk in the exposure model.

6 Adult value based on consideration of total cheese in Table 10 of Jordbruks Verket (2009b) and split equally between cows' and goats' milk produce.

7 Adult value based on a total meat consumption of 70 kg y^{-1} from Table 9-3 of Karlsson et al. (2001), which reflects data from the Swedish Board of Agriculture. This is distributed between beef and sheep, assuming that consumption of sheep meat is lower than for beef.

8 Adult value based on consideration of Smith and Jones (2003).

9 Based on the hourly rates in Table 11 of Smith and Jones (2003).

7.5.6. Arable System

Exposure group assumptions for the arable system are given in Table 24. These are based on growing crops in the arable area, which is also used for recreation.

Table 24: Exposure group data for the arable system.

Item	**Units**	**Age Group**			**Notes**
		Adult	**Child** [1]	**Infant** [1]	
Occupancy outdoors	hrs y^{-1}	1090	270	140	2
Occupancy bathing	hrs y^{-1}	61	61	61	3
Dust concentration	kg dw m^{-3}	5E-6	1E-7	1E-7	4
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	5
Ingestion rates					
Drinking water	L y^{-1}	600	350	260	6
Vegetables	kg fw y^{-1}	60	30	15	7
Root vegetables	kg fw y^{-1}	70	60	20	7
Cereals	kg fw y^{-1}	80	60	25	8
Pork	kg fw y^{-1}	35	20	4	9
Poultry meat	kg fw y^{-1}	35	21	7	9
Eggs	kg fw y^{-1}	10	8	6	10
Inadvertent ingestion of sediment	kg dw y^{-1}	0.0083	0.018	0.044	11

Notes to Table 24:

1 Values for food intakes for children and infants are scaled to the adult ingestion rates based on ratios calculated from Smith and Jones (2003); 95th percentile rates were used for poultry and cereals because these values matched best for adult consumptions.

2 Adult based on about six hours per day for six months of the year (when average temperature is above about 5 degrees and pasture will be growing); child and infant values based on a quarter and an eighth of the adult values.

3 Based on an average of ten minutes bathing per day (i.e. twenty minutes every two days).

4 Adult value from p349 of Löfgren (2010), typical assessment values adopted for children and infants, based on consideration of Section 7.9.2 of Walke et al. (2013b).

5 Values representative of light exercise for adults and children and for sitting awake for infants, based on Section 7.9.2 of Walke et al. (2013b).

6 Adult based on Section 6.4.1 of Nordén et al. (2010), child and infant values based on Table 10 of Smith and Jones (2003).

7 Adult value based on Table 9-3 of Karlsson et al. (2001), which reflects data from the Swedish Board of Agriculture.

8 Adult value based on Table 9-3 of Karlsson et al. (2001), which refers to Bergström and Nordlinder (1990).

9 Adult value based on a total meat consumption of 70 kg y^{-1} from Table 9-3 of Karlsson et al. (2001), which reflects data from the Swedish Board of Agriculture. This is distributed equally between poultry and pork.

10 Adult value based on Table 10 of Jordbruks Verket (2009b).

11 Based on the critical annual rates in Table 11 of Smith and Jones (2003).

7.6. Radionuclides and Decays Chains

The radionuclides considered are given in Table 25, together with their associated half-lives.

- It is noted that the half-lives for Ac-227 and Mo-93 differ between Table 2 1 of Avila et al. (2010) and Table 6-1 of Nordén et al. (2010). The SR-Site values that match closest with ICRP (2008) are adopted here.
- This assessment includes Nb-93m, Ra-228 and Th-228, which were not explicitly included in Avila et al. (2010).

The decay chains that are explicitly modelled are shown in Table 26. Some discrepancies between the modelled decay chains and those represented in the SR-Site biosphere modelling are noted.

- Decay of both Zr-93 and Mo-93 to Nb-93m is explicitly modelled herein.
- No decay from Pa-231 to Ac-227 is indicated in Table 2-1 of Avila et al. (2010), although it is represented here, consistent with ICRP (2008).

Assumptions concerning secular equilibrium are reproduced in Table 27 based on ICRP (2008) and including branching ratios. These assumptions are not explicitly described in the SR-Site documentation and it is unclear if they have been appropriately taken into account in the calculation of dose coefficients for parent radionuclides, as discussed in Section 7.13.

Table 25: Explicitly modelled radionuclides and associated half-lives.

Radionuclide	Half-life (y)	Radionuclide	Half-life (y)
Ac-227[1]	2.180E+1	Pd-107	6.500E+6
Ag-108m	4.180E+2	Po-210	4.000E-1
Am-241	4.322E+2	Pu-239	2.411E+4
Am-243	7.370E+3	Pu-240	6.563E+3
C-14[2]	5.730E+3	Pu-242	3.730E+5
Ca-41	1.030E+5	Ra-226	1.600E+3
Cd-113m	1.410E+1	Ra-228[4]	5.750E+0
Cl-36	3.010E+5	Se-79	1.130E+6
Cm-244	1.810E+1	Sm-151	9.000E+1
Cm-245	8.500E+3	Sn-126	1.000E+5
Cm-246	4.730E+3	Sr-90	2.880E+1
Cs-135	2.300E+6	Tc-99	2.110E+5
Cs-137	3.010E+1	Th-228[4]	1.912E+0
Ho-166m	1.200E+3	Th-229	7.340E+3
I-129	1.570E+7	Th-230	7.538E+4
Mo-93[3]	3.999E+3*	Th-232	1.410E+10
Nb-93m[4]	1.613E+1	U-233	1.590E+5
Nb-94	2.030E+4	U-234	2.460E+5
Ni-59	7.600E+4	U-235	7.040E+8
Ni-63	1.001E+2	U-236	2.340E+7
Np-237	2.140E+6	U-238	4.470E+9
Pa-231	3.276E+4	Zr-93	1.530E+6
Pb-210	2.230E+1		

Notes for Table 25: Primarily based on from Table 2-1 of Avila et al. (2010).

1 Based on Table 6-1 of Nordén et al. (2010), which is more consistent with the value of 21.772 y in ICRP (2008).

2 Note that the biosphere transport and accumulation of C-14 requires special consideration; it has been excluded from the simple biosphere models presented here.

3 It is noted that this differs from the value of 781.4 y in Table 6-1 of Nordén et al. (2010), but is retains because it is more consistent with the value of 4000 y in ICRP (2008).

4 Not explicitly modelled in Avila et al. (2010), but explicitly modelled here with half-lives based on ICRP (2008).

Table 26: Explicitly modelled decay chains.

Chains
Zr-93 [1] → (0.975) Nb-93m
Mo-93 [1] → (0.88) Nb-93m
Am-243 → Pu-239 → U-235 → Pa-231 → Ac-227 [2]
Cm-244 → Pu-240 → U-236 → Th-232 → Ra-228 → Th-228 [3]
Cm-245 → Am-241 → Np-237 → U-233 → Th-229
Cm-246 → Pu-242 → U-238 → U-234 → Th-230 → Ra-226 → Pb-210 → Po-210

Notes for Table 26: Based on Table 2-1 of Avila et al (2010).

1 No decay chains are shown for Zr-93 or Mo-93 in Table 2-1 of Avila et al (2010), decay chains are included here, based on ICRP (2008).

2 No decay from Pa-231 to Ac-227 is indicated in Table 2-1 of Avila et al. (2010), although it is represented here, consistent with ICRP (2008).

3 Note that Th-232 decay to Ra-228 and Th-228 is not represented in Avila et al. (2010), but is explicitly included here.

Table 27: Short-lived daughters taken to be present in secular equilibrium with their parent.

Parent	Short-lived Daughters (and branching ratio, where applicable)
Sr-90	Y-90
Ag-108m	(0.087) Ag-108
Cs-137	(0.944) Ba-137
Pb-210	Bi-210
Ra-226	Rn-222, Po-218, (0.9998) Pb-214, Bi-214, (0.9998), Po-214, (0.0002) At-218, (0.0002) Tl-210
Ra-228	Ac-228
Ac-227	(0.9862) Th-227, (0.0138) Fr-223, Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (0.9972) Tl-207, (0.0028) Po-211
Th-228	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (0.6406) Po-212, (0.3594) Tl-208,
Th-229	Ra-225, Ac-225, Fr-221, At-217, (0.9999) Bi-213, (0.9791) Po-213, (0.0209) Tl-209, Pb-209
U-235	Th-231
U-238	Th-234, Pa-234m, (0.0015) Pa-234
Np-237	Pa-233
Am-243	Np-239

Notes: Based on ICRP (2008).

7.7. Sorption

Distinct equilibrium sorption coefficients (K_d) are used in SR-Site for four types of media:

- inorganic deposits;
- organic deposits;
- suspended matter in marine systems; and
- suspended matter in lake systems.

Sorption coefficients for these media used in SR-Site are given in Table 28 to Table 31. The discussion, together with Figure 3-1, in Section 3.1.1 of Nordén et al.

(2010) implies that the values for inorganic deposit were used to represent the till, whilst the organic deposit values were used to represent organic soils, bed sediments and glacial clays. However, the glacial clay is an inorganic media (e.g. see the third paragraph of Appendix B in Nordén et al., 2010), the values for inorganic deposits are used to represent glacial clays as well as till in this study.

In addition to organic soils, potential for agriculture on clayey silty tills is included in this study, so an associated data set is needed and is given in Table 32. The data are preferentially taken from Sheppard et al. (2009) and based on recommended data following analysis of a compilation of data sets and specifically including consideration of the properties of the clayey silty tills of the Forsmark area.

Parameter values for many of the element-dependent parameter values used in the SR-Site study (sorption coefficients, concentration ratios and transfer factors) are given to two significant figures. Significant uncertainty surrounds many of these parameters, such that presentation of data to one significant figure is more appropriate, to avoid the undue implication of precision. However, for consistency with SR-Site, two significant figures are used here.

Table 28: Sorption coefficients for inorganic till, m^3 kg^{-1} dry weight

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.2E+0	1.2E+0	2
Ag	1.4E-1	1.4E-1	3
Am	2.6E+0	2.6E+0	6
Ca	3.4E-2	3.4E-2	1.7
Cd	2.4E-1	2.4E-1	8.4
Cl	4.4E-4	4.4E-4	4.7
Cm	9.3E+0	9.3E+0	4
Cs	3.6E+1	3.6E+1	4.1
Ho	5.2E+0	5.2E+0	9.7
I	7.1E-3	7.1E-3	5.1
Mo	1.5E-1	1.5E-1	3.3
Nb	1.9E+0	1.9E+0	5.3
Ni	3.1E-1	1.8E+0	4
Np	2.0E-2	2.0E-2	4
Pa	1.4E+0	1.4E+0	2
Pb	7.7E+0	7.7E+0	5.4
Pd	1.4E-1	1.4E-1	2
Po	2.1E-1	1.9E-1	5
Pu	7.4E-1	7.4E-1	4
Ra	7.3E+0	7.3E+0	2.2
Se	2.2E-2	2.2E-2	2.6
Sm	5.0E+0	5.0E+0	13
Sn	2.9E-1	2.9E-1	2
Sr	3.2E-1	3.2E-1	2.9
Tc	6.0E-5	6.0E-5	4
Th	3.2E+1	3.2E+1	15
U	1.5E+0	1.5E+0	3.3
Zr	4.7E-1	4.7E-1	1.6

Drawn from Table 3-1 of Nordén et al. (2010).

Table 29: Sorption coefficients for organic sediments, $m^3\ kg^{-1}$ dry weight

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.7E+0	1.7E+0	3
Ag	6.2E+1	5.2E+1	3.5
Am	2.5E+0	2.5E+0	5
Ca	6.3E-2	1.5E-2	5
Cd	4.3E+0	2.4E+0	19
Cl	1.0E-2	1.1E-2	3.5
Cm	9.3E+0	9.3E+0	4
Cs	2.6E+1	2.6E+1	2.2
Ho	1.2E+1	8.2E+0	4.7
I	7.1E-1	2.4E-1	7.6
Mo	1.1E+0	4.8E-1	8.8
Nb	4.0E+1	4.0E+1	3.8
Ni	3.0E+0	1.9E+0	4.3
Np	8.1E-1	8.1E-1	1.3
Pa	2.0E+0	2.0E+0	3
Pb	4.3E+1	2.8E+1	5.8
Pd	1.8E-1	1.8E-1	2
Po	6.6E+0	6.6E+0	5
Pu	7.4E-1	7.4E-1	4
Ra	2.3E+0	2.3E+0	2.1
Se	5.3E-1	2.3E-1	3.8
Sm	1.1E+1	7.8E+0	5.3
Sn	8.0E+0	8.0E+0	3.6
Sr	1.2E-1	1.2E-1	2.7
Tc	3.0E-3	3.0E-3	3
Th	4.2E+1	4.2E+1	3.7
U	6.5E+0	6.3E+0	3.4
Zr	5.6E+0	5.6E+0	16

Drawn from Table 3-2 of Nordén et al. (2010).

Table 30: Sorption coefficients for suspended marine sediments, $m^3 kg^{-1}$ dry weight

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.0E+1	1.0E+1	3.2
Ag	1.0E+1	1.0E+1	2.3
Am	2.0E+3	2.0E+3	5.7
Ca	2.7E-1	2.7E-1	8.6
Cd	7.7E+1	7.7E+1	11
Cl	1.0E-3	1.0E-3	25
Cm	2.0E+3	2.0E+3	9.6
Cs	1.1E+1	1.1E+1	6.7
Ho	4.6E+1	4.6E+1	5.1
I	3.3E+0	3.3E+0	2.1
Mo	1.6E-1	1.6E-1	17
Nb	2.0E+2	2.0E+2	4.7
Ni	1.4E+1	1.4E+1	1.4
Np	1.0E+0	1.0E+0	4.9
Pa	1.1E+3	1.1E+3	3.2
Pb	2.5E+2	2.5E+2	2.7
Pd	1.0E+1	1.0E+1	3.2
Po	2.0E+4	2.0E+4	3.2
Pu	1.2E+3	1.2E+3	25
Ra	4.0E+0	4.0E+0	3.1
Se	3.4E+0	3.4E+0	16
Sm	4.2E+2	4.2E+2	2.2
Sn	4.7E+1	4.7E+1	2.6
Sr	1.9E-2	1.9E-2	21
Tc	1.0E-1	1.0E-1	4.6
Th	1.0E+3	1.0E+3	4.9
U	1.2E+0	1.2E+0	2.7
Zr	2.6E+2	2.6E+2	4.3

Drawn from Table 3-3 of Nordén et al. (2010).

Table 31: Sorption coefficients for suspended lake sediments, $m^3 kg^{-1}$ dry weight

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.0E+1	1.0E+1	3.2
Ag	9.3E+1	9.3E+1	2.3
Am	1.2E+2	1.2E+2	5.7
Ca	7.0E-1	7.0E-1	3.2
Cd	8.6E+1	8.6E+1	4
Cl	9.8E-2	9.8E-2	25
Cm	5.0E+0	5.0E+0	9.6
Cs	9.7E+1	9.7E+1	3.2
Ho	1.6E+2	1.6E+2	2.2
I	1.0E+1	1.0E+1	3.7
Mo	6.8E+0	6.8E+0	5.3
Nb	2.3E+2	2.3E+2	3.2
Ni	2.6E+1	2.6E+1	2.3
Np	1.0E-2	1.0E-2	4.9
Pa	1.0E+2	1.0E+2	3.2
Pb	5.4E+2	5.4E+2	2.9
Pd	2.0E+0	2.0E+0	3.2
Po	1.0E+1	1.0E+1	3.2
Pu	2.4E+2	2.4E+2	6.6
Ra	7.4E+0	7.4E+0	3.1
Se	8.4E+0	8.4E+0	2.1
Sm	1.4E+2	1.4E+2	3.6
Sn	5.0E+1	3.2E+1	1.8
Sr	1.1E+0	1.1E+0	3
Tc	5.0E-3	5.0E-3	4.6
Th	3.0E+2	3.0E+2	4.6
U	6.3E+0	6.3E+0	9.3
Zr	5.7E+1	5.7E+1	4.4

Drawn from Table 3-4 of Nordén et al. (2010).

Table 32: Sorption coefficients for clayey silty till, $m^3 kg^{-1}$ dry soil

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation	Notes
Ac	1.7E+00	1.7E+00	2.8	1
Ag	3.8E-01	3.8E-01	7.1	1
Am	2.6E+00	2.6E+00	6.1	2
Ca	7.0E-03	7.0E-03	3.2	3
Cd	4.0E-02	4.0E-02	1.6	4
Cl	1.4E-03	1.4E-03	10	5
Cm	9.3E+00	9.3E+00	3.8	6
Cs	5.4E+00	5.4E+00	7.4	7
Ho	1.4E+01	1.4E+01	3.1	7
I	1.6E+02	1.6E+02	9.3	7
Mo	7.3E-02	7.3E-02	3.3	7
Nb	3.5E+01	3.5E+01	4.7	7
Ni	1.4E-01	1.4E-01	4.2	7
Np	6.3E-03	6.3E-03	6.8	7
Pa	2.0E+00	2.0E+00	2.8	9
Pb	5.0E+00	5.0E+00	7.7	7
Pd	1.8E-01	1.8E-01	2.3	1
Po	1.9E-01	1.9E-01	5.1	3
Pu	8.6E-01	8.6E-01	6.6	7
Ra	7.3E+00	7.3E+00	2.2	10
Se	3.3E-01	3.3E-01	3.4	7
Sm	2.8E+01	2.8E+01	3.3	7
Sn	3.3E+00	3.3E+00	2.7	7
Sr	4.6E-02	4.6E-02	7.4	7
Tc	3.1E-03	3.1E-03	5.8	11
Th	1.0E+01	1.0E+01	11	7
U	2.8E+00	2.8E+00	6.6	7
Zr	4.1E-01	4.1E-01	21	1

Notes for Table 32.

1 Based on value for all soils in Table 14 of IAEA (2010), given small overall number of samples.

2 Based on value for all soils in Table 14 of IAEA (2010), given lack of distinction between soil textures.

3 Based on value for mineral soils in Table 14 of IAEA (2010).

4 Based on value for silt soil in Table 5 of Thibault et al. (1990); silty soil is used because it is taken to best reflect the properties of the clayey silty tills of the Forsmark area described in Table 3-3 of Sheppard et al. (2009).

5 Recommendation for mineral soils in Section 5.3 of Sheppard et al. (2009).

6 Based on the value for all soils in Table 14 of IAEA (2010) in the absence of recommendations for specific soil types.

7 Average of recommended values for Forsmark clayey silty till in Section 5.3 of Sheppard et al. (2009).

8 Average of values for Ho and Sm, in the absence of other data and for consistency amongst lanthanides.

9 Consistent with Section 5.3.17 of R-09-27, based on Table 14 of IAEA (2010) value for all soils.

10 Based on value for inorganic deposits in Table B-2 of TR-10-07, which draws on site-specific samples of clayey till and glacial clay.

11 Value recommended for aerated soils in Section 5.3.26 of Sheppard et al. (2009).

7.8. Diffusivity

The free pore water diffusion coefficients for each element are given in Table 33, based on the data used in SR-Site.

Table 33: Free pore water diffusion coefficients, $m^2\ y^{-1}$

Element	Value	Notes
Ac	3.2E-2	1
Ag	5.4E-2	1
Am	3.2E-2	1
Ca	3.2E-2	1
Cd	2.3E-2	2
Cl	6.3E-2	1
Cm	3.2E-2	1
Cs	6.6E-2	1
Ho	3.2E-2	1
I	2.6E-2	1
Mo	3.2E-2	2
Nb	3.2E-2	1
Ni	2.1E-2	1
Np	3.2E-2	1
Pa	3.2E-2	1
Pb	3.2E-2	1
Pd	3.2E-2	1
Po	3.2E-2	1
Pu	3.2E-2	1
Ra	2.8E-2	1
Se	3.2E-2	1
Sm	3.2E-2	1
Sn	3.2E-2	1
Sr	2.5E-2	1
Tc	3.2E-2	1
Th	4.7E-3	1
U	3.2E-2	1
Zr	3.2E-2	1

Notes for Table 33:

1 Based on Table 6-3 of Nordén et al. (2010).

2 Based on Table 5-11 of Liu et al. (2006), which represents the source for Table 6-3 of Nordén et al. (2010).

7.9. Sea-Spray Enhancement

Enrichment/enhancement factors for element concentrations in sea-spray relative to the concentration in sea water are given in Table 34, based on consideration of Walke et al (2013b).

Table 34: Enrichment factor for sea-spray, unitless

Element	Value	Range
Ac	100	10, 1000
Ag	10	1, 100
Am	100	10, 1000
Ca	10	1, 100
Cd	10	1, 100
Cl	1	-
Cm	100	10, 1000
Cs	3	1, 10
Ho	100	10, 1000
I	1	-
Mo	10	1, 100
Nb	10	1, 100
Ni	10	1, 100
Np	100	10, 1000
Pa	100	10, 1000
Pb	10	1, 100
Pd	10	1, 100
Po	10	1, 100
Pu	100	10, 1000
Ra	10	1, 100
Se	1	-
Sm	100	10, 1000
Sn	10	1, 100
Sr	10	1, 100
Tc	1	-
Th	100	10, 1000
U	100	10, 1000
Zr	10	1, 100

Note for Table 34: Based on consideration of Table 8 of Walke et al. (2013b).

7.10. Data for Plants

Element-independent data for plants are given in Table 35. The fraction of external intercepted contamination that is absorbed to internal plants and the subsequent degree of translocation depend on whether elements are actively transported by plants or not and are given in Table 36 and Table 37.

Table 35: Element independent data for plants.

Parameter		**Crop type**		**Notes**
	Root crops	**Vegetables**	**Cereals**	
Interception coefficient, m^2 kg^{-1} dw	3	3	3	1
Standing biomass, kg dw m^{-2}	0.5	0.5	0.5	2
Yield of the edible component, kg fw m^{-2} y^{-1}	2	0.5	0.3	3
Time between irrigation and harvest, y	0.04	0.04	0.04	4
Weathering rate, y^{-1}	12.6	12.6	12.6	5
Fraction of external contamination associated with edible part of the plant, unitless	0	1	0.25	6

Notes for Table 35:

1 Based on discussion associated with wet deposition in Section 3.6.1 of Walke et al. (2012b).

2 Based on consideration of above-ground standing biomass for cereals in a Swedish context on p355 of Löfrgen (2010) and on discussion of crop growth in a UK context in Section 3.4.2 of Walke et al. (2012b) and taken to be representative of plants approaching maturity.

3 Based on SR-Site values for present-day climate given on p355-356 of Löfgren (2010).

4 Taken to be two weeks.

5 Based on a weathering half-life of 20 days, consistent with the discussion in Section 3.6.3 of Walke et al. (2012b).

6 Value for cereals combines reflects the fraction of interception deposited to grain in plants approaching maturity and a food processing factor. The former uses a harvest index of 0.5 (Kemanian et al., 2007). A food processing factor of 0.5 is used, based on the range given in Table 71 of IAEA (2010) for milling to flour and bran.

Table 36: Fraction of external intercepted contamination that is absorbed to the internal plant, unitless.

Group	Elements	Value	Notes
Elements that are actively transported in plants	*Ca*, Cd, *Cl*, Cs, I, *Mo*, Ni, Pd, Po, Ra, Se, Tc	0.5	Based on Section 3.8.3 of Walke et al., (2012b).
Elements that are not actively transported in plants (bioexcluded)	*Ac*, *Ag*, Am, Cm, Ho, Nb, Np, *Pa*, Pb, Pu, Sm, *Sn*, Sr, Th, U, Zr	0.01	Based on Section 3.8.2 of Walke et al., (2012b).

Note to Table 36: Distinction between elements that are actively transported by plants and those that are not is based on Section 3.8.1 of Walke et al. (2012b) and assumptions on the bioavailability of those elements not included in that reference (highlighted in *italics*).

Table 37: Fraction of contamination absorbed from external contamination that is present in or translocated to the edible plant tissue, unitless.

Group	Crop type			Notes
	Root crops	Vegetables	Cereals	
Elements that are actively transported in plants	0.5	0.8	0.4	1
Elements that are not actively transported in plants	0.01	1	0.5	2

Notes for Table 37: Distinction between elements that are actively transported by plants and those that are not is given in Table 37. Conservatively, no loss of internal contamination due to food processing is considered.

1 A uniform distribution throughout the plants is assumed. For root vegetables, about half of the total biomass is taken to be associated with edible tubers/roots. For vegetables, only the fraction translocated to roots is not consumed and a root:shoot ratio of about 0.2 is adopted (p27 of Walke et al., 2012b). For cereals, a harvest index of 0.5 (Kemanian et al., 2007) and a root:shoot ratio of 0.2 (p23 of Walke et al., 2012b) are used.

2 A small fraction is taken to be translocated from the above-ground plant to the roots for root vegetables. For vegetables, interception is taken to be dominantly to leaves and the leaves are taken to be the primarily part consumed (i.e. the small fraction that might be translocated elsewhere is conservatively ignored). The value for cereals reflects a harvest index of about 0.5 and the small fraction that might be translocated elsewhere is conservatively ignored.

Equilibrium soil-to-plant concentration ratios are needed. These are typically presented in the literature as the ratio of concentrations in fresh or dry weight plant tissues to concentrations in dry soil. In SR-Site these are normalised to the carbon content of the plant tissue (described in Section 4.1 of Nordén et al., 2010). Concentration ratios are not normalised to the carbon content of plant tissues herein, so the SR-Site values are adjusted using the carbon content in fresh plant tissues, given in Table 38.

Table 38: Carbon content in plant and mushroom tissues, kgC kg^{-1} fresh weight

Tissue type	Carbon content		Dry matter	Notes
	kgC kg^{-1} dw	kgC kg^{-1} fw	(fraction)	
Cereals	0.45	0.39	0.87	1
Root crops	0.48	0.1	0.21	1
Vegetables	0.39	0.03	0.0885	1
Primary producers	0.51	0.1	0.2	2
Mushrooms	0.46	0.05	0.1	3

Notes to Table 38:

1 Table 4-1 of Nordén et al. (2010).

2 Dry carbon content from Table 4-1 of Nordén et al. (2010), dry matter content estimated based on Appendix I of IAEA (2010).

3 Dry carbon content from Table 4-1 of Nordén et al. (2010), dry matter content of mushrooms from Section 7.2 of IAEA (2010).

Equilibrium soil-to-plant concentration ratios, expressed on a fresh weight plant, dry weight soil basis, are given for primary producers (representative of field and shrub layers together with green parts of trees), cereal grain, root crops, vegetables and mushrooms in Table 39 to Table 43.

Table 39: Equilibrium soil-to-plant concentration ratios for primary producers, (Bq kg^{-1} fresh plant)/(Bq kg^{-1} dry soil)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.0E-04	1.0E-04	4
Ag	1.1E-01	9.8E-02	3.1
Am	2.9E-04	2.9E-04	4.1
Ca	2.0E-01	2.0E-01	3
Cd	7.9E-02	7.9E-02	3.4
Cl	3.4E+00	4.7E+00	3.8
Cm	2.0E-04	2.0E-04	2.4
Cs	1.9E-02	1.9E-02	4.2
Ho	2.9E-04	2.9E-04	2.5
I	5.6E-02	8.6E-02	4.8
Mo	1.9E-02	1.9E-02	3.4
Nb	4.0E-04	4.0E-04	3.5
Ni	1.8E-02	1.8E-02	2.7
Np	1.2E-02	1.2E-02	2.7
Pa	6.6E-04	6.6E-04	3.2
Pb	2.1E-03	2.1E-03	2.4
Pd	4.4E-02	4.4E-02	3.2
Po	2.4E-02	2.4E-02	4.2
Pu	1.1E-04	1.1E-04	3
Ra	1.4E-02	1.4E-02	4.6
Se	4.4E+00	1.2E+00	2.4
Sm	2.6E-04	2.6E-04	4.5
Sn	5.0E-03	5.0E-03	2.1
Sr	5.5E-02	2.1E-01	2.6
Tc	1.5E+01	1.5E+01	3
Th	1.9E-02	1.9E-02	5.5
U	1.7E-04	1.7E-04	4.1
Zr	3.0E-04	5.8E-05	3.3

Note: Based on Table 4-2 of Nordén et al. (2010) and adjusted to a fresh weight plant basis using the carbon content of plant tissues given in Table 38.

Table 40: Equilibrium soil-to-plant concentration ratios for cereal grain, (Bq kg^{-1} fresh plant)/(Bq kg^{-1} dry soil)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	3.9E-04	1.0E-04	3.2
Ag	3.9E-01	3.5E-01	3
Am	1.9E-05	1.9E-05	11
Ca	9.8E-02	9.8E-02	2.7
Cd	7.8E-01	7.8E-01	2.7
Cl	3.1E+01	3.1E+01	1.6
Cm	2.0E-05	2.0E-05	3.3
Cs	2.7E-02	2.7E-02	4.1
Ho	1.0E-04	1.0E-04	3.2
I	1.0E-01	1.0E-01	3.2
Mo	7.0E-01	7.0E-01	14
Nb	1.2E-02	6.2E-03	1.9
Ni	2.3E-02	2.3E-02	2.7
Np	2.5E-03	2.5E-03	5
Pa	3.0E-03	3.0E-03	3.2
Pb	9.8E-03	9.8E-03	3.6
Pd	3.0E-02	3.0E-02	3.2
Po	2.1E-04	2.1E-04	1
Pu	8.2E-06	8.2E-06	6.7
Ra	1.5E-02	1.5E-02	12
Se	2.0E+01	5.1E+00	2.4
Sm	1.0E-04	1.0E-04	3.2
Sn	3.9E-01	1.0E-01	3.2
Sr	9.8E-02	9.8E-02	2.7
Tc	1.1E+00	1.1E+00	3.6
Th	1.8E-03	1.8E-03	3.4
U	5.5E-03	5.5E-03	7.7
Zr	8.6E-04	8.6E-04	14

Note: Based on Table 4-3 of Nordén et al. (2010) and adjusted to a fresh weight plant basis using the carbon content of plant tissues given in Table 38.

Table 41: Equilibrium soil-to-plant concentration ratios for root crops, (Bq kg^{-1} fresh plant)/(Bq kg^{-1} dry soil)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	4.9E-05	4.3E-04	4.9
Ag	1.9E-01	1.4E-01	2.7
Am	4.3E-05	4.3E-05	6
Ca	3.3E-02	3.3E-02	3
Cd	3.1E-01	3.1E-01	14
Cl	5.8E+00	6.1E+00	1.8
Cm	3.1E-05	3.1E-05	3.7
Cs	1.1E-02	1.1E-02	3
Ho	8.7E-05	8.7E-05	3.2
I	2.0E-02	2.0E-02	14
Mo	1.9E-01	1.9E-01	3.2
Nb	8.2E-04	8.2E-04	14
Ni	3.9E-02	3.9E-02	3.2
Np	1.2E-03	1.2E-03	2.5
Pa	5.8E-04	5.8E-04	3.2
Pb	3.1E-04	3.1E-04	7.4
Pd	3.9E-02	3.9E-02	3.2
Po	5.5E-04	5.5E-04	5.8
Pu	2.2E-05	2.2E-05	5.5
Ra	2.0E-03	2.0E-03	6.8
Se	3.9E+00	1.1E+00	2.4
Sm	3.9E-05	3.9E-05	3.2
Sn	5.8E-02	9.7E-02	3.2
Sr	3.3E-02	3.3E-02	3
Tc	4.7E-02	4.7E-02	3.7
Th	4.1E-05	4.1E-05	9.9
U	1.0E-03	1.0E-03	6.4
Zr	4.1E-04	4.1E-04	14

Note: Based on Table 4-4 of Nordén et al. (2010) and adjusted to a fresh weight plant basis using the carbon content of plant tissues given in Table 38.

Table 42: Equilibrium soil-to-plant concentration ratios for vegetables, (Bq kg^{-1} fresh plant)/(Bq kg^{-1} dry soil)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	3.9E-03	3.9E-03	4.6
Ag	1.6E-05	1.6E-05	3.3
Am	2.4E-05	2.4E-05	3.3
Ca	6.6E-02	6.6E-02	6
Cd	5.1E-01	5.1E-01	3.2
Cl	2.3E+00	2.3E+00	1.7
Cm	1.2E-04	1.2E-04	4.5
Cs	5.4E-03	5.4E-03	6
Ho	3.0E-03	3.0E-03	3.2
I	1.8E-02	1.8E-02	3.7
Mo	4.2E-02	4.2E-02	1.2
Nb	1.3E-03	1.3E-03	1.3
Ni	2.0E-02	2.0E-02	3.2
Np	2.4E-03	2.4E-03	3
Pa	3.0E-04	3.0E-04	3.2
Pb	7.2E-03	7.2E-03	13
Pd	2.0E-02	2.0E-02	3.2
Po	6.6E-04	6.6E-04	6.9
Pu	7.2E-06	7.2E-06	2.7
Ra	8.1E-03	8.1E-03	6.7
Se	2.0E+00	5.4E-01	2.4
Sm	3.0E-03	3.0E-03	3.2
Sn	5.1E-02	9.9E-02	3.2
Sr	6.6E-02	6.6E-02	6
Tc	1.6E+01	1.6E+01	14
Th	1.1E-04	1.1E-04	6
U	1.8E-03	1.8E-03	14
Zr	3.6E-04	3.6E-04	14

Note: Based on Table 4-5 of Nordén et al. (2010) and adjusted to a fresh weight plant basis using the carbon content of plant tissues given in Table 38.

Table 43: Equilibrium soil-to-plant concentration ratios for mushrooms, (Bq kg^{-1} fresh plant)/(Bq kg^{-1} dry soil)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	5.0E-05	5.0E-05	4
Ag	5.5E-02	4.9E-02	3.1
Am	1.5E-04	1.5E-04	4.1
Ca	3.0E-03	3.0E-03	3.2
Cd	4.0E-02	4.0E-02	3.4
Cl	2.0E+00	2.4E+00	3.8
Cm	1.0E-04	1.0E-04	2.4
Cs	1.5E+00	1.5E+00	6.5
Ho	1.5E-04	1.5E-04	2.5
I	3.4E-03	3.4E-03	2.3
Mo	9.5E-03	9.5E-03	3.4
Nb	2.0E-04	2.0E-04	3.5
Ni	1.6E-02	1.6E-02	2.4
Np	7.5E-03	7.5E-03	2.7
Pa	3.3E-04	3.3E-04	3.2
Pb	1.3E-03	1.3E-03	2.4
Pd	2.2E-02	2.2E-02	3.2
Po	1.2E-02	1.2E-02	4.2
Pu	2.2E-04	2.2E-04	3
Ra	3.0E-01	3.0E-01	4.6
Se	2.2E+00	6.0E-01	2.4
Sm	1.3E-04	1.3E-04	4.5
Sn	2.5E-03	2.5E-03	2.1
Sr	4.6E-03	4.6E-03	3.4
Tc	1.1E-01	1.1E-01	3
Th	4.1E-04	4.1E-04	3.1
U	6.5E-04	6.5E-04	9.1
Zr	1.3E-04	2.9E-05	3.3

Note: Based on Table 4-6 of Nordén et al. (2010) and adjusted to a fresh weight plant basis using the carbon content of plant tissues given in Table 38.

7.11. Data for Terrestrial Animals

Data are required for the following terrestrial animals and animal produce:

- beef cattle (meat and offal);
- dairy cattle (milk);
- mutton/lamb (meat and offal);
- goats (milk);
- pigs (pork);
- chicken (meat and eggs);
- wild fowl (meat); and
- game (meat).

Element-independent parameters for animals are given in Table 44 to Table 46.

Table 44: Element-independent parameters for cattle.

Parameter	Dairy cattle	Beef cattle	Notes
Ingestion rate of water, m^3 day^{-1}	0.07	0.04	1
Ingestion rate of fodder, kg fw day^{-1}	70	40	2
Ingestion rate of soil, kg dw day^{-1}	0.3	0.3	3
Processing efficiency (unitless)	1 (milk) 0.08 (milk produce)	1	4

Notes to Table 44:

1 From Table 6-7 of Nordén et al. (2010).

2 Based on Table 6-7 of Nordén et al. (2010) and converted to fresh weight basis using a dry matter content of 20% (Table 84 of IAEA, 2010) and a dry weight carbon content for pasture of 0.51 from Table 4-1 of Nordén et al. (2010).

3 From Table 6-7 of Nordén et al. (2010).

4 There is taken to be no loss in weight during food processing for meat, offal or milk. The processing efficiency for milk produce is taken to be 8%, based on consideration of butter, cheese and cream in Table 75 of IAEA (2010).

Table 45: Element-independent parameters for sheep and goats.

Parameter	Dairy goats	Sheep	Notes
Ingestion rate of water, m^3 day^{-1}	0.008	0.004	1
Ingestion rate of fodder, kg fw day^{-1}	10	5	2
Ingestion rate of soil, kg dw day^{-1}	0.2	0.1	3
Processing efficiency (unitless)	1 (milk) 0.08 (milk produce)	1	4

Notes to Table 45:

1 Average of the range quoted in Table XI of IAEA (1994) rounded to one significant figure.

2 Based on Figure 4-3 of Walke et al. (2012b) with a dry matter content of 20%, consistent with cattle pasture in Table 44.

3 Based on ratio to dry weight feed intake of 0.1, from consideration of Section 4.3.3 of Walke et al. (2012b).

4 There is taken to be no loss in weight during food processing for meat, offal or milk. The processing efficiency for milk produce is taken to be 8%, based on consideration of butter, cheese and cream in Table 75 of IAEA (2010).

Table 46: Element-independent parameters for pigs and hens.

Parameter	Pigs	Hens	Notes
Ingestion rate of water, m^3 day^{-1}	0.008	0.0002	1
Ingestion rate of water, m^3 day^{-1}	0.008	0.0002	2
Ingestion rate of fodder, kg fw day^{-1}	1.7 (grain) 7.1 (root veg.)	0.09 (grain) 0.23 (vegetables)	3
Ingestion rate of soil, kg dw day^{-1}	0.3	0.01	4
Processing efficiency (unitless)	1	1	5

Notes to Table 46:

1 Average of the range quoted in Table XI of IAEA (1994) rounded to one significant figure.

2 Average of the range quoted in Table XI of IAEA (1994) rounded to one significant figure.

3 Based on Figure 4-3 of Walke et al. (2012b) with dry matter contents from Table 4-1 of Nordén et al. (2010).

4 Based on ratio to dry weight feed intake of 0.1, from consideration of Section 4.3.3 of Walke et al. (2012b).

5 There is taken to be no loss in weight during food processing for meat and eggs.

Table 47: Element-independent parameters for wild fowl and game.

Parameter	Wild fowl	Game	Notes
Fractional occupancy of contaminated region	0.1	0.05	1
Ingestion rate of fodder, kg fw day^{-1}	0.5	n/a	2
Ingestion rate of sediment/soil, kg dw day^{-1}	0.01	n/a	3
Processing efficiency (unitless)	1	1	4

Notes to Table 46:

1 Assumed value adopted for wild fowl. For game, the value is based on three roe deer per year (the most common species) to provide enough meat for a small family, the felling rate of roe deer in the Forsmark area (about 2 km^{-1} y^{-1} based on Table 4-61 of Löfgren, 2010) and the contaminated area of forest (see Section 7.1.1).

2 Value for wild fowl based on 0.1 kg dry matter per day (based on that used for chickens) and a dry matter content of 0.2, based on consideration of Appendix I of IAEA (2010). Not applicable to game, which use a concentration ratio model in relation to the vegetation that they consume.

3 Value for wild fowl based on ratio to dry weight feed intake of 0.1, consistent with chickens. Not applicable to game.

4 There is taken to be no loss in weight during food processing for wild fowl and game.

SR-Site includes equilibrium transfer factors for beef meat and cows' milk, which are used here and given in Table 48 and Table 49. Additional data is needed for the other animal food stuffs, these are given in Table 50 to Table 55.

In the case of wild fowl, the transfer factors for chickens are used in the absence of other readily available data.

Table 48: Equilibrium transfer factors from ingestion to beef meat, (Bq kg^{-1} fresh meat)/(Bq day^{-1})

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	2.0E-05	2.0E-05	3.2
Ag	3.0E-03	3.5E-03	1.3
Am	5.0E-04	5.0E-04	7.9
Ca	1.3E-02	1.3E-02	5.1
Cd	4.0E-04	4.0E-04	3.2
Cl	1.7E-02	1.7E-02	7.9
Cm	2.0E-05	2.0E-05	3.2
Cs	2.2E-02	2.2E-02	2.2
Ho	5.0E-03	5.0E-03	3.2
I	6.7E-03	6.7E-03	2.1
Mo	1.0E-03	1.0E-03	3.2
Nb	2.6E-07	2.6E-07	7.9
Ni	5.0E-03	5.0E-03	3.2
Np	1.0E-03	1.0E-03	3.2
Pa	1.0E-05	1.0E-05	3.2
Pb	7.0E-04	7.0E-04	1.7
Pd	1.0E-03	1.0E-03	3.2
Po	5.0E-03	1.7E-03	1.7
Pu	1.1E-06	1.1E-06	7.9
Ra	1.7E-03	1.7E-03	7.9
Se	1.5E-02	1.4E-03	3.9
Sm	5.0E-03	5.0E-03	3.2
Sn	1.0E-02	1.0E-02	3.2
Sr	1.3E-03	1.3E-03	2.7
Tc	1.0E-04	1.0E-04	3.2
Th	2.3E-04	2.3E-04	2.2
U	3.9E-04	3.9E-04	1.3
Zr	1.2E-06	1.2E-06	7.9

Note: Drawn from Table 4-8 of Nordén et al. (2010).

Table 49: Equilibrium transfer factors from ingestion to cows' milk, (Bq L^{-1} milk)/(Bq day^{-1})

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	2.0E-06	2.0E-06	3.2
Ag	5.0E-05	5.0E-05	3.2
Am	4.2E-07	4.2E-07	5.8
Ca	1.0E-02	1.0E-02	1.6
Cd	1.0E-04	1.0E-04	3.2
Cl	1.7E-02	1.1E-02	1.1
Cm	2.0E-05	2.0E-05	3.2
Cs	4.6E-03	4.6E-03	3.3
Ho	2.5E-06	3.0E-06	3.2
I	5.4E-03	5.4E-03	2.9
Mo	2.0E-03	2.0E-03	3.2
Nb	4.1E-07	4.1E-07	5.8
Ni	9.5E-04	9.5E-04	5.8
Np	5.0E-06	5.0E-06	3.2
Pa	5.0E-05	1.0E-05	3.2
Pb	1.9E-04	1.9E-04	3.7
Pd	1.0E-03	1.0E-03	3.2
Po	2.1E-04	2.1E-04	1.4
Pu	1.0E-05	1.0E-05	5.8
Ra	3.8E-04	3.8E-04	2
Se	4.0E-03	4.0E-03	1.8
Sm	2.0E-05	2.0E-05	3.2
Sn	1.0E-03	1.0E-03	3.2
Sr	1.3E-03	1.3E-03	1.9
Tc	2.0E-05	1.0E-04	3.2
Th	5.0E-06	3.1E-06	5.8
U	1.8E-03	1.8E-03	1.9
Zr	3.6E-06	3.6E-06	2.4

Note: Drawn from Table 4-7 of Nordén et al. (2010).

Table 50: Equilibrium transfer factors from ingestion to offal from cattle, (Bq kg^{-1} fresh weight)/(Bq day^{-1})

Element	Best estimate	Notes
Ac	2.E-02	1
Ag	8.E-03	2
Am	2.E-02	1
Ca	2.E-01	1
Cd	4.E-04	3
Cl	2.E-02	1
Cm	2.E-02	1
Cs	4.E-02	1
Ho	8.E-02	2
I	4.E-03	1
Mo	1.E-01	1
Nb	2.E-04	1
Ni	1.E-02	1
Np	1.E-02	1
Pa	1.E-02	1
Pb	5.E-01	1
Pd	1.E-03	2
Po	1.E-01	2
Pu	4.E-03	1
Ra	1.E-02	1
Se	3.E-01	2
Sm	8.E-02	2
Sn	2.E-03	2
Sr	2.E-02	1
Tc	8.E-04	1
Th	3.E-03	1
U	2.E-04	1
Zr	2.E-04	1

Notes for Table 50:

1 Based on Table 3.3 of Thorne (2008).

2 Based on Table 20 of Walke et al. (2013a).

3 Taken to be the same as for meat, in the absence of specific data.

Table 51: Equilibrium transfer factors from ingestion to sheep meat and offal, (Bq kg^{-1} fresh weight)/(Bq day^{-1}).

Element	Best estimate for		Notes
	Sheep meat	Sheep offal	
Ac	5.E-05	2.E-02	1
Ag	5.E-04	5.E-04	2
Am	5.E-05	2.E-02	1
Ca	2.E-01	2.E-01	1
Cd	1.E-03	1.E-03	3
Cl	2.E-01	2.E-01	1
Cm	5.E-05	2.E-02	1
Cs	5.E-01	2.E-01	1
Ho	3.E-04	3.E-04	4
I	4.E-02	4.E-02	1
Mo	8.E-01	8.E-01	1
Nb	1.E-03	1.E-03	1
Ni	2.E-02	2.E-02	1
Np	1.E-03	7.E-02	1
Pa	1.E-03	1.E-02	1
Pb	5.E-03	5.E-01	1
Pd	1.E-02	1.E-02	5
Po	5.E-02	1.E+00	5
Pu	1.E-05	4.E-03	1
Ra	4.E-04	1.E-02	1
Se	2.E-01	3.E+0	5
Sm	3.E-04	3.E-04	4
Sn	1.E-01	2.E-02	5
Sr	2.E-02	2.E-02	1
Tc	8.E-03	8.E-03	1
Th	1.E-03	1.E-02	1
U	1.E-03	1.E-03	1
Zr	2.E-04	2.E-04	1

Notes for Table 51:

1 Based on Table 3.3 of Thorne (2008).

2 Value for mutton based on Table 31 of IAEA (2010), with the value for sheep offal taken to be the same.

3 Based on Table 31 of IAEA (2010), with the value for sheep offal taken to be the same.

4 Based on Ce from Table 31 of IAEA (2010) , with the value for sheep offal taken to be the same.

5 Taken to be an order of magnitude greater than the values for beef meat and offal in the absence of specific data and rounded to one significant figure.

Table 52: Equilibrium transfer factors from ingestion to goats' milk, (Bq L^{-1} milk)/(Bq day^{-1}).

Element	Best estimate	Notes
Ac	7.E-06	1
Ag	8.E-06	2
Am	7.E-06	3
Ca	7.E-02	3
Cd	2.E-02	3
Cl	2.E-01	4
Cm	7.E-06	1
Cs	1.E-01	3
Ho	3.E-05	5
I	2.E-01	3
Mo	8.E-03	3
Nb	1.E-03	4
Ni	1.E-01	6
Np	5.E-05	3
Pa	1.E-03	4
Pb	6.E-03	3
Pd	1.E-02	4
Po	2.E-03	3
Pu	1.E-04	7
Ra	4.E-04	4
Se	7.E-02	3
Sm	3.E-05	5
Sn	1.E-02	2
Sr	2.E-02	3
Tc	8.E-03	4
Th	2.E-05	2
U	1.E-03	3
Zr	6.E-06	3

Notes for Table 52:

1 Based on the value for Am, consistent with the approach in Thorne (2008).

2 Adopts the same ratio to meat as that for cattle, in the absence of other data and given the large difference between the transfer factor to meat and milk in cattle.

3 Based on Table 27 of IAEA (2010).

4 Adopts the same value as sheep meat, given the similarity of values for beef and cows' milk.

5 Based on the average of values for Ce and Pm from Tables 27 of IAEA (2010).

6 Average of the three values for Ni reported in Tables 27 and 28 of IAEA (2010).

7 Based on the value for sheep's milk in Table 28 of IAEA (2010).

Table 53: Equilibrium transfer factors from ingestion to poultry meat and eggs, (Bq kg^{-1} fresh weight)/(Bq day^{-1}).

Element	Best estimate for		Notes
	Poultry meat [1]	Eggs	
Ac	5.E-03	5.E-03	2
Ag	8.E-02	8.E-02	3
Am	5.E-03	5.E-03	2
Ca	2.E+00	2.E+00	2
Cd	2.E+00	2.E+00	4
Cl	2.E+00	2.E+00	2
Cm	5.E-03	5.E-03	2
Cs	2.E+00	2.E-01	2
Ho	3.E-03	3.E-03	3
I	1.E-01	3.E+00	2
Mo	1.E+01	1.E+01	2
Nb	2.E-02	2.E-02	2
Ni	1.E+00	1.E+00	2
Np	1.E-02	1.E-02	2
Pa	1.E-01	1.E-01	2
Pb	1.E+00	1.E+00	2
Pd	1.E-02	1.E-02	3
Po	3.E+00	3.E+00	3
Pu	1.E-03	1.E-03	2
Ra	4.E-02	4.E-02	2
Se	1.E+01	2.E+01	3
Sm	3.E-03	3.E-03	3
Sn	2.E-03	2.E-03	3
Sr	2.E-01	2.E-01	2
Tc	1.E-01	1.E-01	2
Th	3.E-02	3.E-02	2
U	1.E+00	1.E+00	2
Zr	2.E-02	2.E-02	2

Notes for Table 53:

1 These values are also used for wild fowl.

2 Based on Table 3.3 of Thorne (2008).

3 Based on Table 20 of Walke et al. (2013a).

4 Based on Table 34 of IAEA (2010), with the value for eggs taken to be the same as that for meat.

Table 54: Equilibrium transfer factors from ingestion to pork, (Bq kg^{-1} fresh weight)/(Bq day^{-1}).

Element	Best estimate	Notes
Ac	5.E-05	1
Ag	5.E-04	1
Am	5.E-05	1
Ca	2.E-03	2
Cd	2.E-02	3
Cl	2.E-01	1
Cm	5.E-05	1
Cs	2.E-01	2
Ho	3.E-04	1
I	4.E-02	2
Mo	8.E-01	1
Nb	1.E-03	1
Ni	2.E-02	1
Np	1.E-03	1
Pa	1.E-03	1
Pb	5.E-03	1
Pd	1.E-02	1
Po	5.E-02	1
Pu	1.E-05	1
Ra	4.E-04	1
Se	3.E-01	2
Sm	3.E-04	1
Sn	1.E-01	1
Sr	3.E-03	2
Tc	8.E-03	1
Th	1.E-03	1
U	4.E-02	2
Zr	2.E-04	1

Notes for Table 54:

1 Based on sheep meat, given the closer similarity of values for Cs and Sr (for which a reasonable number of sales is available for pork in Table 33 of IAEA, 2010) in comparison to cattle.

2 Based on Table 33 of IAEA (2010).

3 Based on Table XVIII of IAEA (1994).

Table 55: Concentration ratios for wild game relative to their feed, (Bq kg^{-1} fw meat) per (Bq kg^{-1} fw feed)

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	6.2E-02		
Ag	7.0E+00		
Am	1.0E-02	8.8E-03	1.4
Ca	2.2E-01	2.2E-01	3
Cd	2.5E-01	2.5E-01	3.3
Cl	1.7E+00	1.7E+00	3.5
Cm	3.8E-02	2.8E-02	1.4
Cs	3.0E+00	3.0E+00	4.1
Ho	9.0E-01	9.0E-01	5.5
I	3.3E+00	2.2E+00	1.3
Mo	5.0E-01	5.0E-01	3.1
Nb	7.0E-01	7.0E-01	3.4
Ni	1.7E-01	1.7E-01	3.6
Np	6.3E-02	5.0E-02	1.4
Pa	3.8E-02	2.8E-02	1.4
Pb	1.2E-01	1.2E-01	5.5
Pd	6.3E-01		
Po	6.3E+01		
Pu	6.2E-03	4.9E-03	1.5
Ra	1.3E+00	1.2E+00	1.1
Se	6.6E+01	6.3E+01	1.2
Sm	1.5E-01	1.5E-01	4.9
Sn	3.2E+00	3.2E+00	3.9
Sr	3.3E-02	3.3E-02	3
Tc	2.9E-01	1.5E-01	1.8
Th	9.5E-01	9.5E-01	2.7
U	4.4E-01	4.4E-01	3.5
Zr	2.1E+00	2.1E+00	3.9

Note: Based on Table 4-10 of Nordén et al. (2010) and converted to fresh weight meat/fresh weigh vegetation on the basis of carbon contents of 0.132 for fresh meat and 0.1 for vegetation.

7.12. Data for Aquatic Organisms

Equilibrium concentration ratios for freshwater plants, freshwater crustaceans, freshwater fish, seaweed and marine fish are provided in Table 56 to Table 60 based on data presented in Nordén et al. (2010). Concentration ratios are also needed for marine molluscs and marine crustaceans; these are given in Table 61 based on other sources.

Table 56: Equilibrium concentration ratios for freshwater plants, m^3 kg^{-1} fresh weight.

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	2.7E+00	5.4E-01	3.2
Ag	2.6E-01	2.6E-01	1.1
Am	1.7E+00	1.7E+00	8.3
Ca	2.9E-01	2.9E-01	3.7
Cd	2.1E+00	2.1E+00	6.6
Cl	4.4E-02	4.4E-02	7.2
Cm	5.4E-02	5.4E-02	2.6
Cs	4.1E-01	4.1E-01	5.3
Ho	2.9E-01	2.9E-01	5.3
I	1.0E-01	1.0E-01	3.4
Mo	1.5E-01	1.5E-01	3.4
Nb	9.2E-01	9.2E-01	3.4
Ni	2.4E-01	1.9E-01	3
Np	3.4E+00	3.4E+00	1.1
Pa	3.4E-03	3.4E-03	3.2
Pb	1.1E+00	1.3E+00	5.3
Pd	1.1E+00	7.5E-01	2.7
Po	1.1E+00	1.1E+00	2.7
Pu	1.2E+01	1.2E+01	14
Ra	8.8E-01	8.8E-01	4.9
Se	2.3E-01	2.3E-01	1.5
Sm	6.8E-01	6.8E-01	6.6
Sn	5.4E-02	5.4E-02	3.2
Sr	1.4E-01	1.4E-01	3.8
Tc	6.1E-01	6.1E-01	4.9
Th	3.7E-01	3.7E-01	4.9
U	9.2E-02	9.2E-02	3
Zr	2.6E-01	2.6E-01	3.8

Note to Table 56: Based on Table 5-4 of Nordén et al. (2010) and converted from m^3 kgC^{-1} to m^3 kg^{-1} based on carbon content of 0.34 kgC/kg dw (Table 5-1 of Nordén et al., 2010) and a dry matter content of freshwater plants of 0.1.

Table 57: Equilibrium concentration ratios for freshwater crustacean flesh, $m^3\ kg^{-1}$ fresh weight.

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.3E+00	1.3E+00	3.2
Ag	2.6E+00	2.6E+00	23
Am	3.2E+00	3.2E+00	7
Ca	2.8E-01	2.8E-01	6.8
Cd	1.2E+02	1.2E+02	2.6
Cl	8.9E-02	8.9E-02	6.1
Cm	1.3E+01	1.3E+01	1.1
Cs	6.5E-01	6.5E-01	4.7
Ho	7.9E-01	7.9E-01	5.8
I	1.9E-01	1.9E-01	3.5
Mo	3.0E-01	3.0E-01	3.8
Nb	8.4E-01	8.4E-01	2.3
Ni	3.7E-01	3.7E-01	2.4
Np	1.5E+00	1.5E+00	1
Pa	1.3E-01	1.3E-01	3.2
Pb	5.0E+00	5.0E+00	4.6
Pd	4.0E-01	4.0E-01	3.2
Po	1.3E+01	1.3E+01	1.2
Pu	1.4E+00	1.4E+00	1.5
Ra	2.6E-02	1.3E+00	1.5
Se	5.0E+00	5.0E+00	1.2
Sm	2.1E+00	2.1E+00	11
Sn	7.3E-01	7.3E-01	1.2
Sr	4.2E-01	4.2E-01	3.3
Tc	3.5E-02	3.5E-02	9.8
Th	1.3E+00	1.3E+00	5.2
U	2.1E-01	1.7E-01	4.6
Zr	1.8E-01	1.8E-01	4.1

Note to Table 57: Based on Table 5-5 of Nordén et al. (2010) and converted from $m^3\ kgC^{-1}$ to $m^3\ kg^{-1}$ based on carbon content of 0.36 kgC/kg dw (Table 5-1 of Nordén et al., 2010) and a dry matter content of meat of 0.3.

Table 58: Equilibrium concentration ratios for freshwater fish meat, $m^3\ kg^{-1}$ fresh weight.

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.5E-01	6.5E-02	2.1
Ag	1.6E-01	1.6E-01	7.3
Am	2.5E-01	2.5E-01	7.3
Ca	1.8E-02	1.8E-02	2.6
Cd	1.5E-01	1.5E-01	7.3
Cl	4.2E-02	4.2E-02	4.1
Cm	1.6E-01	1.6E-01	7.3
Cs	3.4E+00	3.4E+00	2.6
Ho	4.4E-02	4.4E-02	3.2
I	4.0E-02	4.0E-02	2.8
Mo	3.2E-03	3.2E-03	2.4
Nb	2.9E-02	2.9E-02	7.3
Ni	3.0E-02	3.0E-02	1.9
Np	1.6E-01	1.6E-01	7.3
Pa	1.5E-02	1.5E-02	3.2
Pb	3.6E-02	3.6E-02	2.9
Pd	1.5E-01	1.5E-01	3.2
Po	2.6E-01	2.6E-01	2.1
Pu	3.7E-02	3.7E-02	3.7
Ra	7.7E-03	2.5E-02	5.5
Se	4.5E+00	4.5E+00	2.9
Sm	4.4E-02	4.4E-02	3.2
Sn	4.4E+00	4.4E+00	3.2
Sr	4.4E-03	4.4E-03	4.3
Tc	4.4E-02	4.4E-02	7.3
Th	1.1E-01	1.1E-01	2.3
U	6.1E-04	2.8E-04	6.3
Zr	1.8E-02	1.8E-02	3.6

Note to Table 58: Based on Table 5-6 of Nordén et al. (2010) and converted from $m^3\ kgC^{-1}$ to $m^3\ kg^{-1}$ based on carbon content of 0.44 kgC/kg dw (Table 5-1 of Nordén et al., 2010) and a dry matter content of meat of 0.3.

Table 59: Equilibrium concentration ratios for seaweed, $m^3\ kg^{-1}$ fresh weight.

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	2.6E+00	5.3E-01	3.2
Ag	5.0E-01	5.0E-01	2.3
Am	2.6E-01	2.6E-01	2.7
Ca	2.7E-02	2.7E-02	3.3
Cd	3.3E+00	4.3E-01	3.4
Cl	9.9E-04	9.9E-04	1.8
Cm	4.3E+00	4.3E+00	2.3
Cs	1.6E-01	1.6E-01	4.3
Ho	1.9E-01	1.9E-01	9.8
I	4.0E-01	4.0E-01	2.1
Mo	2.1E-02	2.1E-02	2.4
Nb	3.6E-01	3.6E-01	3.3
Ni	5.6E-01	5.6E-01	2.1
Np	2.4E-02	2.4E-02	1.8
Pa	3.1E-03	3.1E-03	3.2
Pb	6.3E-01	3.3E-01	3.8
Pd	1.1E+00	7.3E-01	2.7
Po	4.3E-01	4.3E-01	2
Pu	9.6E-01	9.6E-01	3.5
Ra	4.0E-02	4.0E-02	1.7
Se	4.0E-01	4.0E-01	2.1
Sm	2.5E+00	2.5E+00	4.6
Sn	4.3E-01	4.3E-01	3.7
Sr	1.6E-02	1.6E-02	2.6
Tc	1.3E+01	1.3E+01	1.9
Th	4.0E+00	1.9E+00	6.9
U	7.9E-02	7.9E-02	2.1
Zr	3.0E+00	7.6E-01	3.5

Note to Table 59: Based on Table 5-9 of Nordén et al. (2010) and converted from $m^3\ kgC^{-1}$ to $m^3\ kg^{-1}$ based on carbon content of 0.33 kgC/kg dw (Table 5-1 of Nordén et al., 2010) and a dry matter content of seaweed of 0.1.

Table 60: Equilibrium concentration ratios for marine fish meat, $m^3\ kg^{-1}$ fresh weight.

Element	Best Estimate	Geometric Mean	Geometric Standard Deviation
Ac	1.4E-01	6.1E-02	2.1
Ag	2.3E+00	2.3E+00	2.9
Am	5.0E-02	5.0E-02	2.6
Ca	3.1E-02	3.1E-02	3
Cd	9.0E-02	2.3E-01	6.5
Cl	1.9E-04	1.9E-04	1.9
Cm	1.4E-01	1.4E-01	6.1
Cs	2.8E-01	2.8E-01	2
Ho	4.1E-02	4.1E-02	3.2
I	1.5E-02	1.5E-02	2.1
Mo	3.1E-03	3.1E-03	2
Nb	2.3E-02	2.3E-02	2.1
Ni	1.3E-02	3.5E-02	4.9
Np	1.4E-03	1.4E-03	6.1
Pa	1.4E-02	1.4E-02	3.2
Pb	6.3E-02	6.3E-02	6.1
Pd	1.4E-02	1.4E-02	3.2
Po	2.6E+00	2.6E+00	2
Pu	6.8E-02	6.8E-02	3.7
Ra	9.9E-02	9.9E-02	3.1
Se	6.5E+00	6.5E+00	1.9
Sm	2.7E-02	2.7E-02	3.5
Sn	5.3E-01	5.3E-01	2.5
Sr	9.6E-04	9.6E-04	3.3
Tc	2.0E-02	2.0E-02	3.3
Th	1.5E-01	1.5E-01	3.3
U	2.6E-04	2.6E-04	2.1
Zr	5.5E-02	6.9E-02	4.8

Note to Table 60: Based on Table 5-10 of Nordén et al. (2010) and converted from $m^3\ kgC^{-1}$ to $m^3\ kg^{-1}$ based on carbon content of 0.45 kgC/kg dw (Table 5-1 of Nordén et al., 2010) and a dry matter content of meat of 0.3.

Table 61: Equilibrium concentration ratios for marine mollusc and crustacean flesh, $m^3\ kg^{-1}$ fresh weight.

Element	Molluscs	Crustaceans	Notes
Ac	1.E+00	1.E+00	1
Ag	6.E+01	2.E+02	1
Am	1.E+00	1.E+00	1
Ca	3.E-03	5.E-03	2
Cd	8.E+01	8.E+01	3
Cl	6.E-05	6.E-05	1
Cm	1.E+00	1.E+00	1
Cs	3.E-02	3.E-02	1
Ho	7.E+00	4.E+00	1
I	5.E-02	5.E-02	1
Mo	1.E-02	1.E-02	1
Nb	1.E+00	1.E+00	1
Ni	1.E+00	1.E+00	1
Np	1.E-01	1.E-01	1
Pa	1.E-01	1.E-01	1
Pb	1.E+01	1.E+01	1
Pd	3.E-01	3.E-01	1
Po	2.E+01	2.E+01	1
Pu	1.E+00	1.E+00	1
Ra	1.E-01	1.E-01	1
Se	1.E+00	1.E+01	1
Sm	7.E+00	4.E+00	1
Sn	5.E+02	5.E+02	1
Sr	1.E-02	5.E-03	1
Tc	1.E+00	1.E+00	1
Th	1.E+00	1.E+00	1
U	3.E-02	1.E-02	1
Zr	1.E+00	1.E+00	1

Notes to Table 61:

1 Based on Table 11 of Walke et al. (2013b) and converted from $L\ kg^{-1}$ to $m^3\ kg^{-1}$.

2 Based on Table 3.5 of Thorne (2008) and converted from $L\ kg^{-1}$ to $m^3\ kg^{-1}$.

3 Based on Tables V and IV of IAEA (2004) and converted from $L\ kg^{-1}$ to $m^3\ kg^{-1}$.

7.13. Dose Coefficients

Dose coefficients are given in the tables below. Note that in each case, the contribution from short-lived daughters is explicitly given, together with the associated branching ratios.

Ingestion dose coefficients are included in Table 62; these are primarily based on EU (1996) and include contributions from short-lived daughters. The table includes the dose coefficients from Nordén et al. (2010), which quotes the same sources.

- Discrepancies are evident for some radionuclides (Ac-227, Sr-90, Th-229 and U-238) indicate that contributions from short-lived daughters are not properly accounted for in Nordén et al. (2010).
- A difference is also evident for Nb-93m, which would seem to be a transcription error in Nordén et al. (2010).

Dose coefficients for inhalation of particulates are given in Table 63; the values are based on EU (1996), consistent with Nordén et al (2010) and use the highest dose factor amongst the inhalation classes presented.

- Discrepancies for some radionuclides (Ac-227, Pb-210, Th-229), again suggest that short-lived daughters are not properly taken into account in Nordén et al. (2010).
- For Cd-113m, the value of 5.2E-8 Sv Bq^{-1} given in Table 6-2 of Nordén et al. (2010) represents that for a medium rate of absorption from the lung, but is not the highest available value, which is 1.1E-7 Sv Bq^{-1} for fast lung absorption.
- For I-129, a footnote to Table 6-2 in Nordén et al. (2010) states that the value used represents the soluble gas form. However, the value of 9.8E-9 Sv Bq^{-1} does not match the value of 9.6E-8 Sv Bq^{-1} given for I-129 vapour in Annex III, Table C.2 of EU (1996). Gases and particulates are treated separately in the model documented here.

Dose coefficients for inhalation of gases are given in Table 64. In the absence of other data, the dose coefficients for inhalation of particulates are also used for inhalation of spray.

Dose coefficients for external irradiation from the ground are given in Table 65. Consistent with Table 6-2 of Nordén et al. (2010), the values are based on Eckerman and Leggett (1996)[6], using the values based on ICRP 60 (1991). The source reference provides values appropriate for adults, whilst values for children and infants are also needed. Consistent with CSA (2008)[7] children are taken to have the same dose coefficient as adults and a factor of 1.3 is applied to calculated dose coefficients for infants, although in this case the factor is conservatively applied to all radionuclides.

- Discrepancies for some radionuclides (Am-243, Cs-137, Np-237, Pb-210, Ra-226, Sr-90, Th-229, U-238), again suggest that short-lived daughters are not properly taken into account in Nordén et al. (2010). Either due to the contribution from short-lived daughters not being represented at all, or due to inappropriate treatment of branching ratios.

---

[6] Eckerman and Leggett (1996) refers to the DCFPAK software, Version 1.0 (3/29/2000) was used herein.

[7] See clause 6.14.2 of CSA (2008), which does not apply the factor of 1.3 to essentially pure beta emitters, but which is conservatively applied in all cases here.

- For Ac-227, Mo-93, Nb-93m, Se-79, Sn-126, it is unclear why the reported values do not match those given in the source reference. It is noted that the external dose coefficients are based on a software database and that there is potential for some of the discrepancies to be due to different versions being used.

Table 62: Ingestion dose coefficients

Radionuclide Modelled	Contribution	Ratio	Dose Coefficient (Sv Bq^{-1}) Infant	Child	Adult	Total Dose Coefficient for Parent (Sv Bq^{-1}) Infant	Child	Adult	SR-Site Adult
Ac-227	Ac-227	1	3.1E-06	1.5E-06	1.1E-06	4.3E-06	2.0E-06	1.2E-06	1.1E-06
	Th-227	0.9862	7.0E-08	2.3E-08	8.8E-09				
	Fr-223	0.0138	1.7E-08	5.0E-09	2.4E-09				
	Ra-223	1	1.1E-06	4.5E-07	1.0E-07				
	Rn-219	1	-	-	-				
	Po-215	1	-	-	-				
	Pb-211	1	1.4E-09	4.1E-10	1.8E-10				
	Bi-211	1	-	-	-				
	Tl-207	0.9972	-	-	-				
	Po-211	0.0028	-	-	-				
Ag-108m	Ag-108m	1	1.1E-08	4.3E-09	2.3E-09	1.1E-08	4.3E-09	2.3E-09	2.3E-09
	Ag-108	0.087	-	-	-				
Am-241	Am-241	1	3.7E-07	2.2E-07	2.0E-07	3.7E-07	2.2E-07	2.0E-07	2.0E-07
Am-243	Am-243	1	3.7E-07	2.2E-07	2.0E-07	3.8E-07	2.2E-07	2.0E-07	2.0E-07
	Np-239	1	5.7E-09	1.7E-09	8.0E-10				
Ca-41	Ca-41	1	5.2E-10	4.8E-10	1.9E-10	5.2E-10	4.8E-10	1.9E-10	1.9E-10
Cd-113m	Cd-113m	1	5.6E-08	2.9E-08	2.3E-08	5.6E-08	2.9E-08	2.3E-08	2.3E-08

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
Cl-36	Cl-36	1	6.3E-09	1.9E-09	9.3E-10	6.3E-09	1.9E-09	9.3E-10	9.3E-10
Cm-244	Cm-244	1	2.9E-07	1.4E-07	1.2E-07	2.9E-07	1.4E-07	1.2E-07	1.2E-07
Cm-245	Cm-245	1	3.7E-07	2.3E-07	2.1E-07	3.7E-07	2.3E-07	2.1E-07	2.1E-07
Cm-246	Cm-246	1	3.7E-07	2.2E-07	2.1E-07	3.7E-07	2.2E-07	2.1E-07	2.1E-07
Cs-135	Cs-135	1	2.3E-09	1.7E-09	2.0E-09	2.3E-09	1.7E-09	2.0E-09	2.0E-09
Cs-137	Cs-137	1	1.2E-08	1.0E-08	1.3E-08	1.2E-08	1.0E-08	1.3E-08	1.3E-08
	Ba-137m	0.944	-	-	-				
Ho-166m	Ho-166m	1	9.3E-09	3.5E-09	2.0E-09	9.3E-09	3.5E-09	2.0E-09	2.0E-09
I-129	I-129	1	2.2E-07	1.9E-07	1.1E-07	2.2E-07	1.9E-07	1.1E-07	1.1E-07
Mo-93	Mo-93	1	6.9E-09	4.0E-09	3.1E-09	6.9E-09	4.0E-09	3.1E-09	3.1E-09
Nb-93m	Nb-93m	1	9.1E-10	2.7E-10	1.2E-10	9.1E-10	2.7E-10	1.2E-10	1.1E-10
Nb-94	Nb-94	1	9.7E-09	3.4E-09	1.7E-09	9.7E-09	3.4E-09	1.7E-09	1.7E-09
Ni-59	Ni-59	1	3.4E-10	1.1E-10	6.3E-11	3.4E-10	1.1E-10	6.3E-11	6.3E-11
Ni-63	Ni-63	1	8.4E-10	2.8E-10	1.5E-10	8.4E-10	2.8E-10	1.5E-10	1.5E-10
Np-237	Np-237	1	2.1E-07	1.1E-07	1.1E-07	2.2E-07	1.1E-07	1.1E-07	1.1E-07
	Pa-233	1	6.2E-09	1.9E-09	8.7E-10				
Pa-231	Pa-231	1	1.3E-06	9.2E-07	7.1E-07	1.3E-06	9.2E-07	7.1E-07	7.1E-07
Pb-210	Pb-210	1	3.6E-06	1.9E-06	6.9E-07	3.6E-06	1.9E-06	6.9E-07	6.9E-07

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Bi-210	1	9.7E-09	2.9E-09	1.3E-09				
Pd-107	Pd-107	1	2.8E-10	8.1E-11	3.7E-11	2.8E-10	8.1E-11	3.7E-11	3.7E-11
Po-210	Po-210	1	8.8E-06	2.6E-06	1.2E-06	8.8E-06	2.6E-06	1.2E-06	1.2E-06
Pu-239	Pu-239	1	4.2E-07	2.7E-07	2.5E-07	4.2E-07	2.7E-07	2.5E-07	2.5E-07
	U-235m	1	-	-	-				
Pu-240	Pu-240	1	4.2E-07	2.7E-07	2.5E-07	4.2E-07	2.7E-07	2.5E-07	2.5E-07
Pu-242	Pu-242	1	4.0E-07	2.6E-07	2.4E-07	4.0E-07	2.6E-07	2.4E-07	2.4E-07
Ra-226	Ra-226	1	9.6E-07	8.0E-07	2.8E-07	9.6E-07	8.0E-07	2.8E-07	2.8E-07
	Rn-222	1	-	-	-				
	Po-218	1	-	-	-				
	Pb-214	0.9998	1.0E-09	3.1E-10	1.4E-10				
	Bi-214	1	7.4E-10	2.1E-10	1.1E-10				
	Po-214	0.9998	-	-	-				
	At-218	0.0002	-	-	-				
	Tl-210	0.0002	-	-	-				
Ra-228	Ra-228	1	5.7E-06	3.9E-06	6.9E-07	5.7E-06	3.9E-06	6.9E-07	-
	Ac-228	1	2.8E-09	8.7E-10	4.3E-10				
Se-79	Se-79	1	2.8E-08	1.4E-08	2.9E-09	2.8E-08	1.4E-08	2.9E-09	2.9E-09

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
Sm-151	Sm-151	1	6.4E-10	2.0E-10	9.8E-11	6.4E-10	2.0E-10	9.8E-11	9.8E-11
Sn-126	Sn-126	1	3.0E-08	9.8E-09	4.7E-09	3.0E-08	9.8E-09	4.7E-09	4.7E-09
Sr-90	Sr-90	1	7.3E-08	6.0E-08	2.8E-08	9.3E-08	6.6E-08	3.1E-08	2.8E-08
	Y-90	1	2.0E-08	5.9E-09	2.7E-09				
Tc-99	Tc-99	1	4.8E-09	1.3E-09	6.4E-10	4.8E-09	1.3E-09	6.4E-10	6.4E-10
Th-228	Th-228	1	3.7E-07	1.5E-07	7.2E-08	1.1E-06	4.3E-07	1.4E-07	-
	Ra-224	1	6.6E-07	2.6E-07	6.5E-08				
	Rn-220	1	-	-	-				
	Po-216	1	-	-	-				
	Pb-212	1	6.3E-08	2.0E-08	6.0E-09				
	Bi-212	1	1.8E-09	5.0E-10	2.6E-10				
	Po-212	0.6406	-	-	-				
	Tl-208	0.3594	-	-	-				
Th-229	Th-229	1	1.0E-06	6.2E-07	4.9E-07	2.4E-06	1.2E-06	6.1E-07	4.9E-07
	Ra-225	1	1.2E-06	5.0E-07	9.9E-08				
	Ac-225	1	1.8E-07	5.4E-08	2.4E-08				
	Fr-221	1	-	-	-				
	At-217	1	-	-	-				

Radionuclide Modelled	Contribution	Ratio	Dose Coefficient (Sv Bq^{-1}) Infant	Child	Adult	Total Dose Coefficient for Parent (Sv Bq^{-1}) Infant	Child	Adult	SR-Site Adult
	Bi-213	0.9999	1.4E-09	3.9E-10	2.0E-10				
	Po-213	0.9791	-	-	-				
	Tl-209	0.0209	-	-	-				
	Pb-209	1	3.8E-10	1.1E-10	5.7E-11				
Th-230	Th-230	1	4.1E-07	2.4E-07	2.1E-07	4.1E-07	2.4E-07	2.1E-07	2.1E-07
Th-232	Th-232	1	4.5E-07	2.9E-07	2.3E-07	4.5E-07	2.9E-07	2.3E-07	2.3E-07
U-233	U-233	1	1.4E-07	7.8E-08	5.1E-08	1.4E-07	7.8E-08	5.1E-08	5.1E-08
U-234	U-234	1	1.3E-07	7.4E-08	4.9E-08	1.3E-07	7.4E-08	4.9E-08	4.9E-08
U-235	U-235	1	1.3E-07	7.1E-08	4.7E-08	1.3E-07	7.2E-08	4.7E-08	4.7E-08
	Th-231	1	2.5E-09	7.4E-10	3.4E-10				
U-236	U-236	1	1.3E-07	7.0E-08	4.7E-08	1.3E-07	7.0E-08	4.7E-08	4.7E-08
U-238	U-238	1	1.2E-07	6.8E-08	4.5E-08	1.5E-07	7.5E-08	4.8E-08	4.5E-08
	Th-234	1	2.5E-08	7.4E-09	3.4E-09				
	Pa-234m	1	-	-	-				
	Pa-234	0.0015	3.2E-09	1.0E-09	5.1E-10				
Zr-93	Zr-93	1	7.6E-10	5.8E-10	1.1E-09	7.6E-10	5.8E-10	1.1E-09	1.1E-09

Notes: Based on Annex III Table A of EU (1996). SR-Site value from Table 6-2 of Nordén et al (2010). Discrepancies between the two data sets are highlighted in blue cells. '-' indicates no value available.

Table 63: Inhalation dose coefficients for particulates.

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
Ac-227	Ac-227	1	1.6E-03	7.2E-04	5.5E-04	1.7E-03	7.4E-04	5.7E-04	5.5E-04
	Th-227	0.9862	3.0E-05	1.4E-05	1.0E-05				
	Fr-223	0.0138	7.3E-09	1.9E-09	8.9E-10				
	Ra-223	1	2.4E-05	1.1E-05	8.7E-06				
	Rn-219	1	-	-	-				
	Po-215	1	-	-	-				
	Pb-211	1	4.8E-08	2.0E-08	1.2E-08				
	Bi-211	1	-	-	-				
	Tl-207	0.9972	-	-	-				
	Po-211	0.0028	-	-	-				
Ag-108m	Ag-108m	1	8.7E-08	4.4E-08	3.7E-08	8.7E-08	4.4E-08	3.7E-08	3.7E-08
	Ag-108	0.087	-	-	-				
Am-241	Am-241	1	1.8E-04	1.0E-04	9.6E-05	1.8E-04	1.0E-04	9.6E-05	9.6E-05

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**	
Am-243	Am-243	1	1.7E-04	1.0E-04	9.6E-05	1.7E-04	1.0E-04	9.6E-05	9.6E-05
	Np-239	1	4.2E-09	1.6E-09	1.0E-09				
Ca-41	Ca-41	1	6.0E-10	3.3E-10	1.8E-10	6.0E-10	3.3E-10	1.8E-10	1.8E-10
Cd-113m	Cd-113m	1	2.7E-07	1.3E-07	1.1E-07	2.7E-07	1.3E-07	1.1E-07	5.2E-08
Cl-36	Cl-36	1	2.6E-08	1.0E-08	7.3E-09	2.6E-08	1.0E-08	7.3E-09	7.3E-09
Cm-244	Cm-244	1	1.3E-04	6.1E-05	5.7E-05	1.3E-04	6.1E-05	5.7E-05	5.7E-05
Cm-245	Cm-245	1	1.8E-04	1.0E-04	9.9E-05	1.8E-04	1.0E-04	9.9E-05	9.9E-05
Cm-246	Cm-246	1	1.8E-04	1.0E-04	9.8E-05	1.8E-04	1.0E-04	9.8E-05	9.8E-05
Cs-135	Cs-135	1	2.4E-08	1.1E-08	8.6E-09	2.4E-08	1.1E-08	8.6E-09	8.6E-09
Cs-137	Cs-137	1	1.0E-07	4.8E-08	3.9E-08	1.0E-07	4.8E-08	3.9E-08	3.9E-08
	Ba-137m	0.944	-	-	-				
Ho-166m	Ho-166m	1	2.5E-07	1.3E-07	1.2E-07	2.5E-07	1.3E-07	1.2E-07	1.2E-07
I-129	I-129	1	8.6E-08	6.7E-08	3.6E-08	8.6E-08	6.7E-08	3.6E-08	9.8E-09
Mo-93	Mo-93	1	5.8E-09	2.8E-09	2.3E-09	5.8E-09	2.8E-09	2.3E-09	2.3E-09
Nb-93m	Nb-93m	1	6.5E-09	2.5E-09	1.8E-09	6.5E-09	2.5E-09	1.8E-09	1.8E-09
Nb-94	Nb-94	1	1.2E-07	5.8E-08	4.9E-08	1.2E-07	5.8E-08	4.9E-08	4.9E-08
Ni-59	Ni-59	1	1.5E-09	5.9E-10	4.4E-10	1.5E-09	5.9E-10	4.4E-10	4.4E-10
Ni-63	Ni-63	1	4.3E-10	1.7E-09	1.3E-09	4.3E-10	1.7E-09	1.3E-09	1.3E-09

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
Np-237	Np-237	1	9.3E-05	5.0E-05	5.0E-05	9.3E-05	5.0E-05	5.0E-05	5.0E-05
	Pa-233	1	1.3E-08	5.5E-09	3.9E-09				
Pa-231	Pa-231	1	2.3E-04	1.5E-04	1.4E-04	2.3E-04	1.5E-04	1.4E-04	1.4E-04
Pb-210	Pb-210	1	1.8E-05	7.2E-06	5.6E-06	1.8E-05	7.3E-06	5.7E-06	5.6E-06
	Bi-210	1	3.0E-07	1.3E-07	9.3E-08				
Pd-107	Pd-107	1	2.0E-09	7.8E-10	5.9E-10	2.0E-09	7.8E-10	5.9E-10	5.9E-10
Po-210	Po-210	1	1.4E-05	5.9E-06	4.3E-06	1.4E-05	5.9E-06	4.3E-06	4.3E-06
Pu-239	Pu-239	1	2.0E-04	1.2E-04	1.2E-04	2.0E-04	1.2E-04	1.2E-04	1.2E-04
	U-235m	1	-	-	-				
Pu-240	Pu-240	1	2.0E-04	1.2E-04	1.2E-04	2.0E-04	1.2E-04	1.2E-04	1.2E-04
Pu-242	Pu-242	1	1.9E-04	1.2E-04	1.1E-04	1.9E-04	1.2E-04	1.1E-04	1.1E-04
Ra-226	Ra-226	1	2.9E-05	1.2E-05	9.5E-06	2.9E-05	1.2E-05	9.5E-06	9.5E-06
	Rn-222	1	-	-	-				
	Po-218	1	-	-	-				
	Pb-214	0.9998	5.0E-08	2.1E-08	1.5E-08				
	Bi-214	1	6.1E-08	2.2E-08	1.4E-08				
	Po-214	0.9998	-	-	-				
	At-218	0.0002	-	-	-				

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Tl-210	0.0002	-	-	-				
Ra-228	Ra-228	1	4.8E-05	2.0E-05	1.6E-05	4.8E-05	2.0E-05	1.6E-05	-
	Ac-228	1	1.6E-07	5.7E-08	2.5E-08				
Se-79	Se-79	1	2.0E-08	8.7E-09	6.8E-09	2.0E-08	8.7E-09	6.8E-09	6.8E-09
Sm-151	Sm-151	1	1.0E-08	4.5E-09	4.0E-09	1.0E-08	4.5E-09	4.0E-09	4.0E-09
Sn-126	Sn-126	1	1.0E-07	4.1E-08	2.8E-08	1.0E-07	4.1E-08	2.8E-08	2.8E-08
Sr-90	Sr-90	1	4.0E-07	1.8E-07	1.6E-07	4.1E-07	1.8E-07	1.6E-07	1.6E-07
	Y-90	1	8.8E-09	2.7E-09	1.5E-09				
Tc-99	Tc-99	1	3.7E-08	1.7E-08	1.3E-08	3.7E-08	1.7E-08	1.3E-08	1.3E-08
Th-228	Th-228	1	1.5E-04	5.5E-05	4.0E-05	1.6E-04	6.0E-05	4.4E-05	-
	Ra-224	1	9.2E-06	4.4E-06	3.4E-06				
	Rn-220	1	-	-	-				
	Po-216	1	-	-	-				
	Pb-212	1	5.0E-07	2.5E-07	1.9E-07				
	Bi-212	1	1.1E-07	4.4E-08	3.1E-08				
	Po-212	0.6406	-	-	-				
	Tl-208	0.3594	-	-	-				
Th-229	Th-229	1	5.1E-04	2.9E-04	2.4E-04	5.6E-04	3.1E-04	2.6E-04	2.4E-04

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Ra-225	1	2.2E-05	1.0E-05	7.7E-06				
	Ac-225	1	2.3E-05	1.1E-05	8.5E-06				
	Fr-221	1	-	-	-				
	At-217	1	-	-	-				
	Bi-213	0.9999	1.2E-07	4.4E-08	3.0E-08				
	Po-213	0.9791	-	-	-				
	Tl-209	0.0209	-	-	-				
	Pb-209	1	2.9E-10	9.9E-11	6.1E-11				
Th-230	Th-230	1	2.0E-04	1.1E-04	1.0E-04	2.0E-04	1.1E-04	1.0E-04	1.0E-04
Th-232	Th-232	1	2.2E-04	1.3E-04	1.1E-04	2.2E-04	1.3E-04	1.1E-04	1.1E-04
U-233	U-233	1	3.0E-05	1.2E-05	9.6E-06	3.0E-05	1.2E-05	9.6E-06	9.6E-06
U-234	U-234	1	2.9E-05	1.2E-05	9.4E-06	2.9E-05	1.2E-05	9.4E-06	9.4E-06
U-235	U-235	1	2.6E-05	1.1E-05	8.5E-06	2.6E-05	1.1E-05	8.5E-06	8.5E-06
	Th-231	1	1.7E-09	5.2E-10	3.3E-10				
U-236	U-236	1	2.7E-05	1.1E-05	8.7E-06	2.7E-05	1.1E-05	8.7E-06	8.7E-06
U-238	U-238	1	2.5E-05	1.0E-05	8.0E-06	2.5E-05	1.0E-05	8.0E-06	8.0E-06
	Th-234	1	3.1E-08	1.1E-08	7.7E-09				
	Pa-234m	1	-	-	-				

Radionuclide			Dose Coefficient (Sv Bq^{-1})			Total Dose Coefficient for Parent (Sv Bq^{-1})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Pa-234	0.0015	2.1E-09	7.1E-10	4.0E-10				
Zr-93	Zr-93	1	6.4E-09	9.7E-09	2.5E-08	6.4E-09	9.7E-09	2.5E-08	2.5E-08

Notes: Based on Annex III Table B of EU (1996). SR-Site value from Table 6-2 of Nordén et al (2010). Discrepancies between the two data sets are highlighted in blue cells. '-' indicates no value available.

Table 64: Dose coefficients for inhalation of gases, Sv Bq^{-1}.

Radionuclide	Infant	Child	Adult	Notes
I-129	2.0E-07	1.7E-07	9.6E-08	Based on elemental iodine, which has the highest value
Se-79	2.0E-08	8.7E-09	6.8E-09	Based on particulate value for fast lung absorption, in the absence of other data

Additional notes: I-129 values based on Table A.3 of ICRP (1996), which are consistent with Annex III Table C.2 of EU (1996). Values for Se-79 are based on the value for fast lung absorption of particulates in Annex III Table B of EU (1996).

Table 65: Dose coefficients for external irradiation from soil contaminated to an infinite thickness.

Radionuclide			**Dose Coefficient (Sv s^{-1})/(Bq m^{-3})**			**Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})**			**SR-Site Adult**
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**	
Ac-227	Ac-227	1	3.11E-21	2.39E-21	2.39E-21	4.7E-14	3.6E-14	3.6E-14	0
	Th-227	0.9862	3.34E-18	2.57E-18	2.57E-18				
	Fr-223	0.0138	1.26E-18	9.70E-19	9.70E-19				
	Ra-223	1	3.85E-18	2.96E-18	2.96E-18				
	Rn-219	1	1.99E-18	1.53E-18	1.53E-18				
	Po-215	1	6.58E-21	5.06E-21	5.06E-21				
	Pb-211	1	2.03E-18	1.56E-18	1.56E-18				
	Bi-211	1	1.65E-18	1.27E-18	1.27E-18				
	Tl-207	0.9972	1.60E-19	1.23E-19	1.23E-19				
	Po-211	0.0028	3.12E-19	2.40E-19	2.40E-19				
Ag-108m	Ag-108m	1	6.28E-17	4.83E-17	4.83E-17	2.3E-13	1.7E-13	1.7E-13	1.7E-13
	Ag-108	0.087	7.97E-19	6.13E-19	6.13E-19				
Am-241	Am-241	1	2.59E-19	1.99E-19	1.99E-19	9.3E-16	7.2E-16	7.2E-16	7.2E-16
Am-243	Am-243	1	8.65E-19	6.65E-19	6.65E-19	2.0E-14	1.6E-14	1.6E-14	2.4E-15
	Np-239	1	4.80E-18	3.69E-18	3.69E-18				
Ca-41	Ca-41	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00	0
Cd-113m	Cd-113m	1	4.19E-21	3.22E-21	3.22E-21	1.5E-17	1.2E-17	1.2E-17	1.2E-17

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
Cl-36	Cl-36	1	1.73E-20	1.33E-20	1.33E-20	6.2E-17	4.8E-17	4.8E-17	4.8E-17
Cm-244	Cm-244	1	6.23E-22	4.79E-22	4.79E-22	2.2E-18	1.7E-18	1.7E-18	1.7E-18
Cm-245	Cm-245	1	2.13E-18	1.64E-18	1.64E-18	7.7E-15	5.9E-15	5.9E-15	5.9E-15
Cm-246	Cm-246	1	5.77E-22	4.44E-22	4.44E-22	2.1E-18	1.6E-18	1.6E-18	1.6E-18
Cs-135	Cs-135	1	2.24E-22	1.72E-22	1.72E-22	8.0E-19	6.2E-19	6.2E-19	6.2E-19
Cs-137	Cs-137	1	5.81E-21	4.47E-21	4.47E-21	8.0E-14	6.2E-14	6.2E-14	6.5E-14
	Ba-137m	0.944	2.35E-17	1.81E-17	1.81E-17				
Ho-166m	Ho-166m	1	6.72E-17	5.17E-17	5.17E-17	2.4E-13	1.9E-13	1.9E-13	1.9E-13
I-129	I-129	1	6.64E-20	5.11E-20	5.11E-20	2.4E-16	1.8E-16	1.8E-16	1.8E-16
Mo-93	Mo-93	1	2.90E-21	2.23E-21	2.23E-21	1.0E-17	8.0E-18	8.0E-18	8.9E-18
Nb-93m	Nb-93m	1	5.12E-22	3.94E-22	3.94E-22	1.8E-18	1.4E-18	1.4E-18	1.3E-18
Nb-94	Nb-94	1	6.34E-17	4.88E-17	4.88E-17	2.3E-13	1.8E-13	1.8E-13	1.8E-13
Ni-59	Ni-59	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00	0
Ni-63	Ni-63	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00	0
Np-237	Np-237	1	4.84E-19	3.72E-19	3.72E-19	2.5E-14	1.9E-14	1.9E-14	1.3E-15
	Pa-233	1	6.55E-18	5.04E-18	5.04E-18				
Pa-231	Pa-231	1	1.23E-18	9.44E-19	9.44E-19	4.4E-15	3.4E-15	3.4E-15	3.4E-15
Pb-210	Pb-210	1	1.38E-20	1.06E-20	1.06E-20	1.9E-16	1.4E-16	1.4E-16	3.8E-17

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Bi-210	1	3.80E-20	2.92E-20	2.92E-20				
Pd-107	Pd-107	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00	0
Po-210	Po-210	1	3.43E-22	2.64E-22	2.64E-22	1.2E-18	9.5E-19	9.5E-19	9.5E-19
Pu-239	Pu-239	1	1.83E-21	1.41E-21	1.41E-21	6.6E-18	5.1E-18	5.1E-18	5.1E-18
	U-235m	1	-	-	-				
Pu-240	Pu-240	1	7.83E-22	6.02E-22	6.02E-22	2.8E-18	2.2E-18	2.2E-18	2.2E-18
Pu-242	Pu-242	1	6.90E-22	5.31E-22	5.31E-22	2.5E-18	1.9E-18	1.9E-18	1.9E-18
Ra-226	Ra-226	1	2.03E-19	1.56E-19	1.56E-19	2.7E-13	2.0E-13	2.0E-13	5.6E-16
	Rn-222	1	1.52E-20	1.17E-20	1.17E-20				
	Po-218	1	3.71E-22	2.85E-22	2.85E-22				
	Pb-214	0.9998	8.65E-18	6.65E-18	6.65E-18				
	Bi-214	1	6.50E-17	5.00E-17	5.00E-17				
	Po-214	0.9998	3.37E-21	2.59E-21	2.59E-21				
	At-218	0.0002	3.39E-20	2.61E-20	2.61E-20				
	Tl-210	0.0002	-	-	-				
Ra-228	Ra-228	1	0.00E+00	0.00E+00	0.00E+00	1.4E-13	1.1E-13	1.1E-13	-
	Ac-228	1	3.94E-17	3.03E-17	3.03E-17				
Se-79	Se-79	1	1.06E-22	8.19E-23	8.19E-23	3.8E-19	2.9E-19	2.9E-19	3.0E-19

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})			SR-Site Adult
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**	
Sm-151	Sm-151	1	4.71E-24	3.62E-24	3.62E-24	1.7E-20	1.3E-20	1.3E-20	1.3E-20
Sn-126	Sn-126	1	9.05E-19	6.96E-19	6.96E-19	3.3E-15	2.5E-15	2.5E-15	2.3E-13
Sr-90	Sr-90	1	4.50E-21	3.46E-21	3.46E-21	1.0E-15	7.9E-16	7.9E-16	1.2E-17
	Y-90	1	2.80E-19	2.15E-19	2.15E-19				
Tc-99	Tc-99	1	7.54E-22	5.80E-22	5.80E-22	2.7E-18	2.1E-18	2.1E-18	2.1E-18
Th-228	Th-228	1	4.99E-20	3.84E-20	3.84E-20	2.4E-13	1.9E-13	1.9E-13	-
	Ra-224	1	3.29E-19	2.53E-19	2.53E-19				
	Rn-220	1	1.50E-20	1.15E-20	1.15E-20				
	Po-216	1	6.84E-22	5.26E-22	5.26E-22				
	Pb-212	1	4.50E-18	3.46E-18	3.46E-18				
	Bi-212	1	7.75E-18	5.96E-18	5.96E-18				
	Po-212	0.6406	0.00E+00	0.00E+00	0.00E+00				
	Tl-208	0.3594	1.52E-16	1.17E-16	1.17E-16				
Th-229	Th-229	1	2.02E-18	1.55E-18	1.55E-18	3.7E-14	2.8E-14	2.8E-14	5.6E-15
	Ra-225	1	5.99E-20	4.61E-20	4.61E-20				
	Ac-225	1	4.02E-19	3.09E-19	3.09E-19				
	Fr-221	1	9.83E-19	7.56E-19	7.56E-19				
	At-217	1	1.15E-20	8.86E-21	8.86E-21				

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})			SR-Site Adult
Modelled	Contribution	Ratio	Infant	Child	Adult	Infant	Child	Adult	
	Bi-213	0.9999	4.99E-18	3.84E-18	3.84E-18				
	Po-213	0.9791	0.00E+00	0.00E+00	0.00E+00				
	Tl-209	0.0209	8.53E-17	6.56E-17	6.56E-17				
	Pb-209	1	5.24E-21	4.03E-21	4.03E-21				
Th-230	Th-230	1	7.45E-21	5.73E-21	5.73E-21	2.7E-17	2.1E-17	2.1E-17	2.1E-17
Th-232	Th-232	1	3.17E-21	2.44E-21	2.44E-21	1.1E-17	8.8E-18	8.8E-18	8.8E-18
U-233	U-233	1	8.80E-21	6.77E-21	6.77E-21	3.2E-17	2.4E-17	2.4E-17	2.4E-17
U-234	U-234	1	2.39E-21	1.84E-21	1.84E-21	8.6E-18	6.6E-18	6.6E-18	6.6E-18
U-235	U-235	1	4.59E-18	3.53E-18	3.53E-18	1.7E-14	1.3E-14	1.3E-14	1.3E-14
	Th-231	1	2.24E-19	1.72E-19	1.72E-19				
U-236	U-236	1	1.24E-21	9.51E-22	9.51E-22	4.5E-18	3.4E-18	3.4E-18	3.4E-18
U-238	U-238	1	5.54E-22	4.26E-22	4.26E-22	3.4E-15	2.6E-15	2.6E-15	1.5E-18
	Th-234	1	1.48E-19	1.14E-19	1.14E-19				
	Pa-234m	1	6.86E-19	5.28E-19	5.28E-19				
	Pa-234	0.0015	7.58E-17	5.83E-17	5.83E-17				
Zr-93	Zr-93	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00	0

Notes: Based on DCFPAK Version 1.0 (Ekerman and Leggett, 1996) values for soil contaminated to an infinite thickness, using the ‘E’ values based on ICRP 60 (1991). SR-Site value from Table 6-2 of Nordén et al (2010). Discrepancies between the two data sets are highlighted in blue cells. ‘-‘ indicates no value available.

Table 66: Dose coefficients for external irradiation resulting from immersion in water.

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})		
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**
Ac-227	Ac-227	1	1.48E-20	1.14E-20	1.14E-20	1.8E-13	1.3E-13	1.3E-13
	Th-227	0.9862	1.26E-17	9.71E-18	9.71E-18			
	Fr-223	0.0138	6.07E-18	4.67E-18	4.67E-18			
	Ra-223	1	1.56E-17	1.20E-17	1.20E-17			
	Rn-219	1	6.97E-18	5.36E-18	5.36E-18			
	Po-215	1	2.20E-20	1.69E-20	1.69E-20			
	Pb-211	1	6.90E-18	5.31E-18	5.31E-18			
	Bi-211	1	5.79E-18	4.45E-18	4.45E-18			
	Tl-207	0.9972	8.23E-19	6.33E-19	6.33E-19			
	Po-211	0.0028	1.00E-18	7.71E-19	7.71E-19			
Ag-108m	Ag-108m	1	2.04E-16	1.57E-16	1.57E-16	7.4E-13	5.7E-13	5.7E-13
	Ag-108	0.087	2.94E-18	2.26E-18	2.26E-18			
Am-241	Am-241	1	2.00E-18	1.54E-18	1.54E-18	7.2E-15	5.5E-15	5.5E-15
Am-243	Am-243	1	5.45E-18	4.19E-18	4.19E-18	9.1E-14	7.0E-14	7.0E-14
	Np-239	1	1.99E-17	1.53E-17	1.53E-17			

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})		
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**
Ca-41	Ca-41	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00
Cd-113m	Cd-113m	1	1.31E-19	1.01E-19	1.01E-19	4.7E-16	3.6E-16	3.6E-16
Cl-36	Cl-36	1	2.54E-19	1.95E-19	1.95E-19	9.1E-16	7.0E-16	7.0E-16
Cm-244	Cm-244	1	1.04E-20	7.97E-21	7.97E-21	3.7E-17	2.9E-17	2.9E-17
Cm-245	Cm-245	1	1.01E-17	7.76E-18	7.76E-18	3.6E-14	2.8E-14	2.8E-14
Cm-246	Cm-246	1	9.43E-21	7.25E-21	7.25E-21	3.4E-17	2.6E-17	2.6E-17
Cs-135	Cs-135	1	1.35E-20	1.04E-20	1.04E-20	4.9E-17	3.7E-17	3.7E-17
Cs-137	Cs-137	1	1.35E-19	1.04E-19	1.04E-19	2.6E-13	2.0E-13	2.0E-13
	Ba-137m	0.944	7.58E-17	5.83E-17	5.83E-17			
Ho-166m	Ho-166m	1	2.22E-16	1.71E-16	1.71E-16	8.0E-13	6.2E-13	6.2E-13
I-129	I-129	1	8.54E-19	6.57E-19	6.57E-19	3.1E-15	2.4E-15	2.4E-15
Mo-93	Mo-93	1	5.28E-20	4.06E-20	4.06E-20	1.9E-16	1.5E-16	1.5E-16
Nb-93m	Nb-93m	1	9.30E-21	7.15E-21	7.15E-21	3.3E-17	2.6E-17	2.6E-17
Nb-94	Nb-94	1	2.03E-16	1.56E-16	1.56E-16	7.3E-13	5.6E-13	5.6E-13
Ni-59	Ni-59	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00
Ni-63	Ni-63	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00
Np-237	Np-237	1	2.59E-18	1.99E-18	1.99E-18	9.7E-14	7.4E-14	7.4E-14
	Pa-233	1	2.43E-17	1.87E-17	1.87E-17			

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})		
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**
Pa-231	Pa-231	1	4.46E-18	3.43E-18	3.43E-18	1.6E-14	1.2E-14	1.2E-14
Pb-210	Pb-210	1	1.35E-19	1.04E-19	1.04E-19	1.9E-15	1.4E-15	1.4E-15
	Bi-210	1	3.87E-19	2.98E-19	2.98E-19			
Pd-107	Pd-107	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00
Po-210	Po-210	1	1.10E-21	8.43E-22	8.43E-22	3.9E-18	3.0E-18	3.0E-18
Pu-239	Pu-239	1	1.02E-20	7.83E-21	7.83E-21	3.7E-17	2.8E-17	2.8E-17
	U-235m	1	-	-	-			
Pu-240	Pu-240	1	1.04E-20	7.97E-21	7.97E-21	3.7E-17	2.9E-17	2.9E-17
Pu-242	Pu-242	1	8.78E-21	6.75E-21	6.75E-21	3.2E-17	2.4E-17	2.4E-17
Ra-226	Ra-226	1	8.11E-19	6.24E-19	6.24E-19	8.5E-13	6.5E-13	6.5E-13
	Rn-222	1	5.02E-20	3.86E-20	3.86E-20			
	Po-218	1	1.18E-21	9.10E-22	9.10E-22			
	Pb-214	0.9998	3.09E-17	2.38E-17	2.38E-17			
	Bi-214	1	2.04E-16	1.57E-16	1.57E-16			
	Po-214	0.9998	1.07E-20	8.26E-21	8.26E-21			
	At-218	0.0002	2.90E-19	2.23E-19	2.23E-19			
	Tl-210	0.0002	-	-	-			
Ra-228	Ra-228	1	0.00E+00	0.00E+00	0.00E+00	4.5E-13	3.5E-13	3.5E-13

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})		
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**
	Ac-228	1	1.26E-16	9.70E-17	9.70E-17			
Se-79	Se-79	1	5.66E-21	4.35E-21	4.35E-21	2.0E-17	1.6E-17	1.6E-17
Sm-151	Sm-151	1	7.49E-23	5.76E-23	5.76E-23	2.7E-19	2.1E-19	2.1E-19
Sn-126	Sn-126	1	5.33E-18	4.10E-18	4.10E-18	1.9E-14	1.5E-14	1.5E-14
Sr-90	Sr-90	1	1.42E-19	1.09E-19	1.09E-19	5.1E-15	3.9E-15	3.9E-15
	Y-90	1	1.28E-18	9.87E-19	9.87E-19			
Tc-99	Tc-99	1	4.07E-20	3.13E-20	3.13E-20	1.5E-16	1.1E-16	1.1E-16
Th-228	Th-228	1	2.34E-19	1.80E-19	1.80E-19	7.7E-13	5.9E-13	5.9E-13
	Ra-224	1	1.22E-18	9.38E-19	9.38E-19			
	Rn-220	1	4.86E-20	3.74E-20	3.74E-20			
	Po-216	1	2.18E-21	1.68E-21	1.68E-21			
	Pb-212	1	1.78E-17	1.37E-17	1.37E-17			
	Bi-212	1	2.47E-17	1.90E-17	1.90E-17			
	Po-212	0.6406	0.00E+00	0.00E+00	0.00E+00			
	Tl-208	0.3594	4.75E-16	3.65E-16	3.65E-16			
Th-229	Th-229	1	9.74E-18	7.49E-18	7.49E-18	1.4E-13	1.1E-13	1.1E-13
	Ra-225	1	6.84E-19	5.26E-19	5.26E-19			
	Ac-225	1	1.83E-18	1.41E-18	1.41E-18			

Radionuclide			Dose Coefficient (Sv s^{-1})/(Bq m^{-3})			Total Dose Coefficient for Parent (Sv h^{-1})/(Bq m^{-3})		
Modelled	**Contribution**	**Ratio**	**Infant**	**Child**	**Adult**	**Infant**	**Child**	**Adult**
	Fr-221	1	3.77E-18	2.90E-18	2.90E-18			
	At-217	1	3.86E-20	2.97E-20	2.97E-20			
	Bi-213	0.9999	1.70E-17	1.31E-17	1.31E-17			
	Po-213	0.9791	0.00E+00	0.00E+00	0.00E+00			
	Tl-209	0.0209	2.72E-16	2.09E-16	2.09E-16			
	Pb-209	1	1.46E-19	1.12E-19	1.12E-19			
Th-230	Th-230	1	4.34E-20	3.34E-20	3.34E-20	1.6E-16	1.2E-16	1.2E-16
Th-232	Th-232	1	2.13E-20	1.64E-20	1.64E-20	7.7E-17	5.9E-17	5.9E-17
U-233	U-233	1	4.10E-20	3.15E-20	3.15E-20	1.5E-16	1.1E-16	1.1E-16
U-234	U-234	1	1.81E-20	1.39E-20	1.39E-20	6.5E-17	5.0E-17	5.0E-17
U-235	U-235	1	1.86E-17	1.43E-17	1.43E-17	7.2E-14	5.5E-14	5.5E-14
	Th-231	1	1.31E-18	1.01E-18	1.01E-18			
U-236	U-236	1	1.16E-20	8.89E-21	8.89E-21	4.2E-17	3.2E-17	3.2E-17
U-238	U-238	1	7.61E-21	5.85E-21	5.85E-21	1.4E-14	1.1E-14	1.1E-14
	Th-234	1	8.54E-19	6.57E-19	6.57E-19			
	Pa-234m	1	2.57E-18	1.98E-18	1.98E-18			
	Pa-234	0.0015	2.46E-16	1.89E-16	1.89E-16			
Zr-93	Zr-93	1	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00

Notes: Based on DCFPAK Version 1.0 (Ekerman and Leggett, 1996) values for immersion in water, using the ‘E’ values based on ICRP 60 (1991). ‘-‘ indicates no value available.

8. Implementation

The models and data described in Sections 6 and 7 are implemented in the AMBER generic compartment modelling code (Quintessa, 2012). AMBER is specifically designed for modelling radionuclide migration and potential exposures and is fully independent from Pandora[8], the MATLAB/Simulink based code used by SKB in SR-Site (Ekström, 2010).

All six biosphere systems, together with associated options for variant calculations, are included within a single AMBER ‘case file’. This approach enables the large amount of data and expressions that are shared between the calculation cases to be managed most efficiently without duplication.

This section provides a summary of the implementation.

8.1. Contaminants

The aim of the calculations is to provide effective dose rates to the potentially exposed groups for a unit source term of each of the radionuclides to the each of the six biosphere systems. The unit flux to dose conversion factors can then be compared against the SR-Site LDFs.

The effective dose for each radionuclide entering the biosphere includes any contributions from radioactive progeny, in addition to any dose calculated for the radionuclide itself. Short-lived daughters with half-lives shorter than a few tens of days are considered to be in secular equilibrium with their parents (see Table 27) and their contribution is taken into account in the dose coefficients used (see Table 62 to Table 66).

To enable contributions from explicitly modelled progeny to be included in the calculations, radioactive decay is explicitly tracked within the case file. The individual contaminant names within the case file comprise of two parts, the first being the radionuclide that it represents and the second part being its associated decay chain (see Table 67). The dose conversion factor for any radionuclide is then simply calculated in the case file as the sum of the calculated effective dose from each Contaminant within each specific decay chain.

---

[8] It is noted that Pandora is benchmarked against AMBER calculations in Section 7 of Ekström (2010).

Table 67: Example of the nomenclature used to tracking radioactive decay within the AMBER case file.

Contaminant	Radionuclide represented by the Contaminant	Associated decay chain
I129_I129	I-129	I-129
Ra226_Ra226	Ra-226	Ra-226
Pb210_Ra226	Pb-210	Ra-226
Po210_Ra226	Po-210	Ra-226
Pb210_Pb210	Pb-210	Pb-210
Po210_Pb210	Po-210	Pb-210
Po210_Po210	Po-210	Po-210

8.2. Discretisation

Consistent with Section 6.2, five compartments are used to represent the till and glacial clay. This approach ensures that the time-dependency of contaminant transport within the lower regolith is appropriately represented for an advective pathway. Above the glacial clay, the soils/sediments are represented with three compartments, one representing the surface soil/sediment, one representing deeper soil/sediment and another representing post-glacial deposits. The heights/ thicknesses of the compartments are given in Table 68, consistent with Table 5 to Table 10. The resulting discretisation enables each of the different materials/media to be represented with distinct compartments.

The groundwater flow rates given in Figure 18 and Figure 19 are assigned to the associated transfers between compartment. Where more than one compartment is used to represent a box shown in the water balance, then the flows are distributed evenly between them, such that a water balance is maintained.

Table 68: Height/thickness of each compartment in each of the biosphere systems (m).

Media	Marine		Lake		Mire		Forest		Pasture		Arable	
	Total	Each comp.	Total	Each comp.	Total	Each comp.	Total	Each comp.	Total	Each comp.	Total	Each comp.
Water column	7.5	7.5	0.7	0.7								
Surface soil/sediment	0.1	0.1	0.05	0.05	0.2	0.2	0.2	0.2	0.1	0.1	0.25	0.25
Deep soil/sediment [1]	1.3	0.65	0.95	0.45	1.5	0.75	1	0.5	1.1	0.55	0.75	0.25
		0.65		0.5		0.75		0.5		0.55		0.5
Glacial clay	0.7	0.7	1.7	0.7	1.7	0.7	0.5	0.5	0.5	0.5		
				1		1						
Till	3.9	0.9	4.7	1	4.7	1	2.3	0.5	2.3	0.5	4	4
		1		1.7		1.7		0.6		0.6		
		1		2		2		0.6		0.6		
		1						0.6		0.6		

Notes: The top ‘deep soil’ compartment is represented as soil/sediment, the lower ‘deep soil’ compartment is represented as post-glacial sediment.

8.3. Layout

Each of the six biosphere systems is represented with its own set of compartments within the AMBER case file. The layout of the compartments is managed by using a separate sub-model for each biosphere system (see Figure 20 and Figure 21).

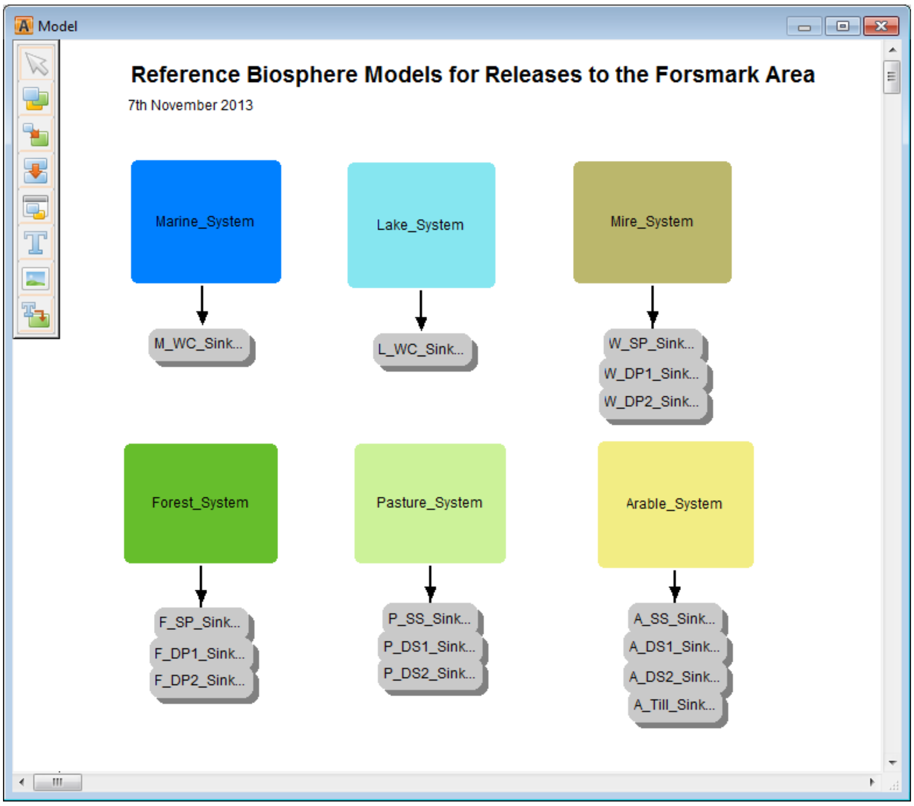


Figure 20: Screenshot of the top-level AMBER model showing sub-models for each of the six biosphere systems.

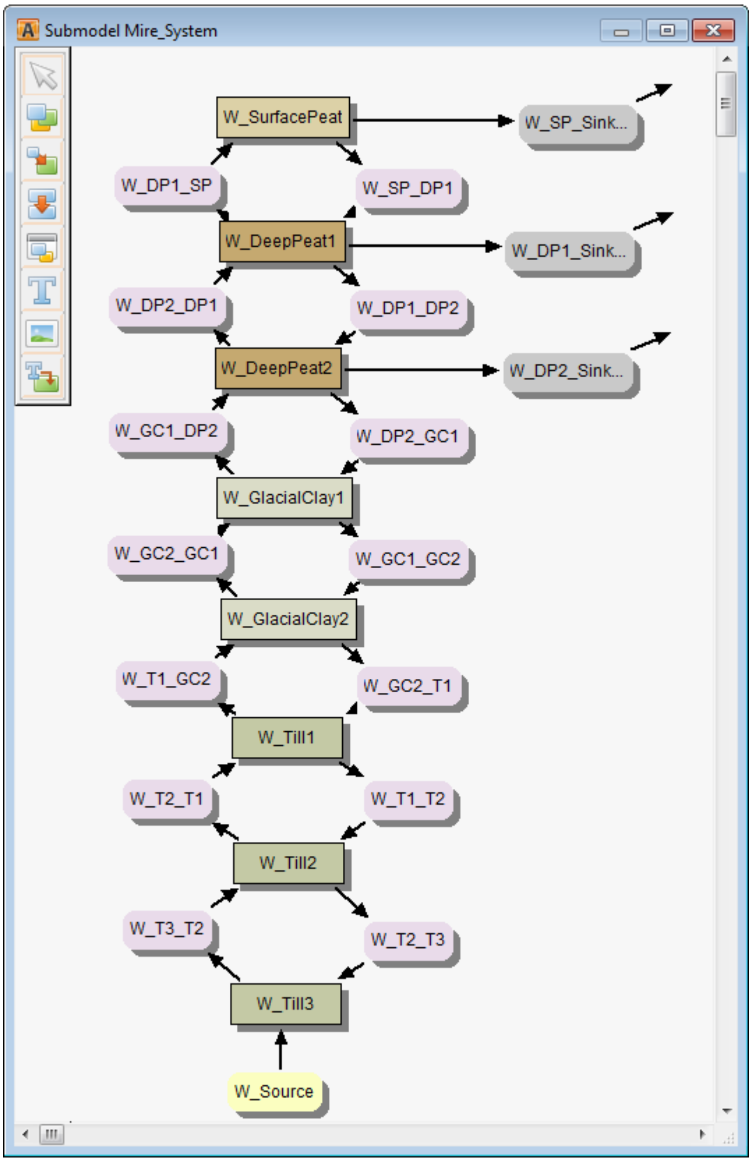
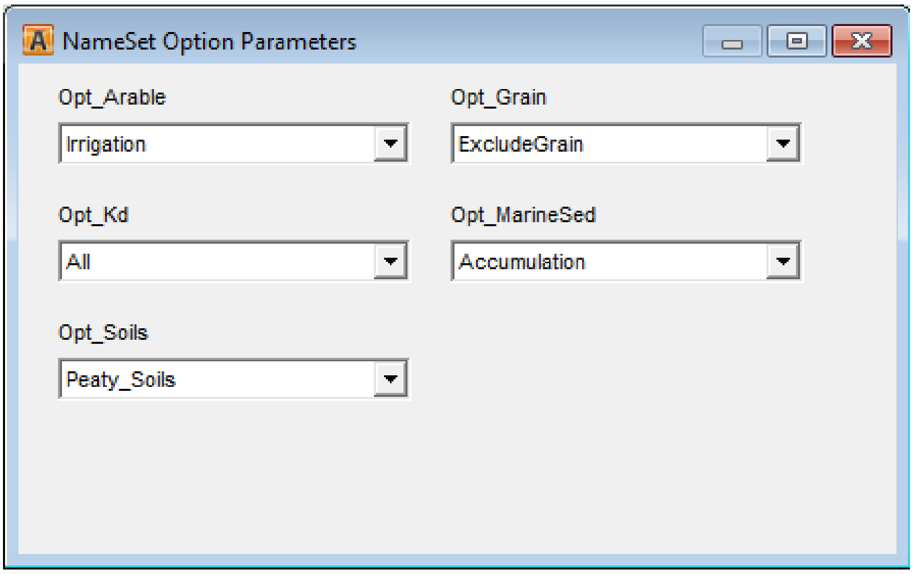


Figure 21: Screenshot of the sub-model for the mire system, showing the individual compartments and associated transfers. The yellow box represents the unit source flux.

8.4. Variant Cases

The AMBER model includes the capability to run different variant calculation cases. The calculation to be run is controlled via ‘nameset option’ parameters, which provide drop-down lists of the different options. The nameset option parameters can be accessed either via:

- the Parameters window (the parameter names all start with ‘Opt_’ and are listed together), where each option includes associated descriptive text; or
- the NameSet Option Parameters window, which collates all of the options together in a single ‘control panel’ (see Figure 22).



NameSet Option Parameters

Opt_Arable: Irrigation

Opt_Grain: ExcludeGrain

Opt_Kd: All

Opt_MarineSed: Accumulation

Opt_Soils: Peaty_Soils

Figure 22: NameSet Option Parameters window showing the calculation choices.

The different calculation options are described in Table 69.

Table 69: Calculation options available.

Option	Choice	Description
Opt_Arable	Irrigation	Arable system is contaminated by use of irrigation water, with no direct discharge of contaminated groundwater.
	Groundwater	Arable system is contaminated by release of contaminated groundwater and there is no irrigation. Note that in this case, the area of release is taken to be the same as that used for pasture (i.e. 10 ha), so that only a fraction of the release is represented as discharging to the area within that which is used for growing crops.
Opt_Grain	ExcludeGrain	Arable system *excludes* contamination of grain.
	IncludeGrain	Arable system *includes* contamination of grain.
Opt_Kd	All	Sorption represented on all modelled media.
	SurfaceOnly	No sorption is represented on the till, glacial clay or post-glacial sediment. Sorption is therefore only represented on soil/sediment in the top two compartments as well as in the water column.
Opt_MarineSed	Accumulation	Marine sediments use properties of accumulation sediments and are represented with organic Kds.
	Erosion	Marine sediments use properties of erosion sediments and are represented with inorganic Kds.
Opt_Soils	Peaty_Soils	Peat soils represented within the pasture and arable systems.
	Clayey_Soils	Clayey sandy till soills represented within the pasture and arable systems.

8.5. Calculation

The implemented model aims to calculate biosphere dose factors for unit releases of radionuclides into static, non-evolving biosphere systems. It therefore aims to calculate the dose factors that are achieved when equilibrium is reached between a constant source flux to the biosphere and the resulting effective dose rate. To help ensure that this is achieved, the models are solved on a one million year timescale, although it is emphasised that:

- the biosphere will not stay constant on anything like such timescales; and
- that the resulting dose factors should be examined to check whether equilibrium has been reached.

The AMBER case file can be solved for the options defined (see Section 8.4) by clicking on the ‘calculate’ button on the top toolbar (see right) and by clicking ‘OK’ on the resulting Calculate dialogue.

8.6. Results

AMBER models are fully transparent. Input data and expressions are all managed as ‘parameters’ and they can all be accessed via the Parameters window.

The AMBER model is set up to calculate biosphere dose conversion factors for each of the originating radionuclides for comparison against the LDFs used in the SR-Site assessment. The highest calculated effective doses (which either represent the dose factor at equilibrium or after a million years, if equilibrium has not been reached), for each originating radionuclide are provided for each biosphere system and age group in a series of parameters whose names begin with ‘LDF_’. The times of the highest calculated effective doses are given in parameters beginning with ‘LDF_Time_’.

The dose conversion factors can be broken down by contributing radionuclide and by exposure pathway via a range of intermediate parameters. Potential output parameters of interest are summarised in Table 70.

A lot of the detail within models implemented in AMBER is found within the parameters; they include the input data, the mathematical expressions for calculating transfers as well as those for calculating results. There are some tools in AMBER that can help users to explore parameters, some of which are highlighted below.

- Users can explore where a selected parameter is used in other expression, or which parameters depend on a selected parameter by clicking on the ‘Param Used By’ and ‘Param Uses’ buttons on the Parameters Window.
- For time-independent parameters, users can see the values that are calculated for expressions by right-clicking over the description for a parameter in the Parameters window and selecting the ‘Show Values’ option from the resulting context-sensitive menu.
- For time-dependent outputs, users can right-click over the description for a parameter in the Parameters window and select ‘Chart’, which will bring up the charting dialogue with the selected parameter already chosen. Charting includes the option of exporting results directly to Microsoft Excel.
- Note that ‘observer’ parameters that depend on the amount of contaminants in each compartment (like concentration and doses) are only available after

a case has been calculated. Users can tell if a case has been calculated by ‘(calculated)’ being present in the banner; an ‘AMBER data file’ (.adf) will also be present in same directory as the case file (.cse).

Table 70: AMBER output parameters of potential interest.

Parameter name	Units	Indexing[†]	Note
ER_food_*	Sv/y	Radionuclides, foods	Gives the contribution of each type of food to the total effective dose summed for each originating radionuclide. Separate parameters for each system and age group.
ER_path_*	Sv/y	Radionuclides, exposure pathways	Gives the contribution of each exposure pathway to the total effective dose summed for each originating radionuclide. Separate parameters for each system and age group.
ER_tot_*	Sv/y	Radionuclides, age groups	Gives the total effective dose summed for each originating radionuclide. Separate parameter for each biosphere system.
E_food_*	Sv/y	Contaminants, foods	Gives the contribution of each type of food to the total effective dose summed for each contaminant (i.e. not summed for each decay chain). Separate parameters for each system and age group.
E_path_*	Sv/y	Contaminants, exposure pathways	Gives the contribution of each exposure pathway to the total effective dose summed for each contaminant (i.e. not summed for each decay chain). Separate parameters for each system and age group.
LDF_*	Sv/Bq	Radionuclides, age groups	Maximum dose conversion factor summed for each originating radionuclide. Separate parameter for each biosphere system.
LDF_Time90_*	y	Radionuclides, age groups	Time to reach 90% of the maximum dose conversion factor summed for each originating radionuclide. Separate parameter for each biosphere system.
LDF_path_*	Sv/y	Radionuclides, exposure pathways	Contribution of exposure pathways to the maximum dose conversion factor summed for each originating radionuclide. Calculated for adults with separate parameter for each biosphere system.
LDF_foods_*	Sv/y	Radionuclides, foods	Contribution of individual foods to the maximum dose conversion factor summed for each originating radionuclide. Calculated for adults with separate parameter for each biosphere system.

Note:. [†] The 'Radionuclides' index is a list of each originating radionuclide that is released to the biosphere, so effective doses indexed over Radionuclides include contributions from all progeny resulting from radioactive decay within the biosphere. The 'Contaminants' index is a list of all radionuclides that distinguishes those that have in-grown from different originating radionuclides (see Section 8.1).

9. Results

The results are discussed below, with the model outputs first being explored independently of the SR-Site LDFs in Section 9.1 and then comparisons being made against the SR-Site LDFs in Section 9.2. A full set of dose factors generated by the model is included in Appendix 2.

For context, SKB (2011)[9] identify C-14, Ni-59, Se-79, Nb-94, I-129, Ra-226 and Np-237 as key radionuclides when combining LDFs with geosphere fluxes for the canister failure scenarios.

9.1. Dose Factors for the Different Biosphere Systems

Biosphere dose factors for reference assumptions associated with the six biosphere systems considered are illustrated in Figure 23, with the values being given in Table 71. The values presented are for adults, dose factors for children and infants are discussed below.

- The dose factors associated with the use of well water for domestic and agricultural purposes provide the highest dose conversion factors.
- In many cases (for 20 out of 44 radionuclides), the dose factors associated with groundwater discharge to pasture areas are the next highest, although those associated with releases to the lake (14) and forest (10) systems are important for some radionuclides.
- In many cases (for at least 12 out of 44 radionuclides), full equilibrium between the unit source fluxes and the calculated doses is not reached, even after the one million year time period assessed.

The time at which the maximum calculated dose factor is achieved in each system is given in Table 72. The table shows that 17 out of 44 radionuclides take longer than 20,000 years to reach 90% of the maximum calculated dose factor. The time-dependency of the calculated dose factors is illustrated for a selection of radionuclides in Figure 24 for the arable system.

The long time to equilibrium for many radionuclides reflects the relative thickness of the strata included in the biosphere (which include the tills, glacial clays and post-glacial deposits in addition to surface soils and sediments), coupled with the degree of retention and long-lived nature of some of the radionuclides (e.g. compare Cs-135, whose half-life is 2.6 million years, with Cs-137, whose half-life is 30.1 years). The systems are also modelled as being non-evolving, without net sedimentation or net erosion.

Contributing Exposure Pathways

The contribution of different exposure pathways to the maximum dose factor is presented in Figure 25 and Figure 26 for the arable and pasture systems, respectively. The figures are reproduced in the appendix, together with those for the other four biosphere systems.

---

[9] Sections 13.5 and 13.6.

- Figure 25 shows that consumption of irrigated crops dominates the potential exposures in most cases with an irrigation source term to the arable system. External irradiation is important for three radionuclides, notably Nb-94, and ingestion of animal produce important for several, notably Se-79.
- In the arable system, ingestion of drinking water from the well contributes no greater than 10% of the maximum dose factor.
- For the pasture system, contaminated via groundwater discharge, Figure 26 shows that ingestion of animal produce dominates in most cases, although external irradiation dominates for four radionuclides and inhalation is important for several.

Comparison of Results for Different Age Groups

Ratios of the maximum calculated dose factor for children and infants to that of adults for each system are given in Table 73.

- For many radionuclides, the dose factors for children and infants are lower than those for adults, principally due to lower occupancies of potentially contaminated areas (see the habit assumptions given in Table 18 to Table 24).
- For the arable, forest, mire and lake systems, an increase by up to about a factor of four is observed for Se-79.
- For the pasture system, an increase by up to about a factor of seven is observed for some radionuclides (including Cl-36, Se-79 and Tc-99) due to an increased intake of milk, especially in infants, and higher radiosensitivity.
- For the marine system, an increase of up to about a factor of seven is observed for Cl-36.

These results support a focus on adults. However, potential for increased doses to children and infants by up to about a factor of seven should be considered in some cases when interpreting results.

Potential for Clayey Silty Till Soils

The description of the Forsmark area, both today and as it evolves into the future, notes the presence of areas of clayey silty till soils and their greater suitability for agriculture. Variant calculations for the arable and pasture systems were included that used properties for clayey silty till soils instead of peaty/organic soils. The properties, including sorption coefficients, used for the clayey silty tills are based on data from the Forsmark area.

The dose conversion factors for arable and pasture systems based on clayey silty till soils are shown in Table 74 and compared against those calculated for peaty soils.

- For the arable system, the results for clayey silty till soils are typically slightly lower or the same as those calculated with peaty/organic soils.
- For the pasture system, there is the calculated dose factor for 14 out of 44 radionuclides is increased when clayey silty tills are considered (notably for Se-79 and Tc-99). Increases are all within a factor of about four.

These results indicate that releases to organic soils do not necessarily result in the highest biosphere dose factors. The SR-Site assessment does not represent releases to clayey silty till soils that are (i) present today and projected to be present in the Forsmark area into the future, and (ii) more suited to long-term agricultural use than the organic soils.

Equilibrium Time-scales

It is highlighted above that the depth of the regolith in the Forsmark area, the groundwater flow rates, the degree of retention on the regolith and soils and the exclusion of some processes, such as net sedimentation and net erosion, mean that environmental concentrations of many radionuclides do not reach an equilibrium with a constant source term from the geosphere within 20,000 years and many don't get close to equilibrium on timescales longer than 100,000 years. This means that the dose conversion factors are sensitive to the duration for which the systems are modelled.

This observation is consistent with the analysis of the LDFs used for SR-Site. For example, Table 4-1 of Avila et al. (2010) shows that the maximum dose factors for most of the radionuclides presented (25 out of 44) occurs at the end of the calculation time frame, meaning that equilibrium with the source flux has not been achieved.

The simplest reference biosphere models typically do not include explicit representation of retardation within the strata above the bed rock but below the surface soils/sediments (e.g. IAEA, 2003; Walke et al., 2013a).

As a means of exploring the effect of retardation in the till, glacial clay and post-glacial deposits below the soils and sediments, as side calculation has been conducted whereby radionuclide sorption in these media is ignored (i.e. sorption is only represented in the soil and sediment). The resulting dose conversion factors and the timescales required to reach 90% of the maximum calculated dose factors are given in Table 75 and the timescales are illustrated for selected radionuclides in Figure 27.

- The dose factors for all radionuclides reach an equilibrium with the constant source flux within the assessed time frame. For some strongly sorbed and longer-lived radionuclides, the time-scale to reach equilibrium is still very long (20,000 years or more), particularly in the mire system.
- For radionuclides with half-lives longer than the timescale to reach equilibrium (e.g. Ni-59, Se-79, I-129), the maximum dose factors are similar with or without retardation in the deeper strata, although the timescales differ significantly.
- For radionuclides with half-lives shorter than the timescale to reach equilibrium (e.g. Ni-63), the maximum dose factor when retention in deeper strata is ignored is significantly overestimated.

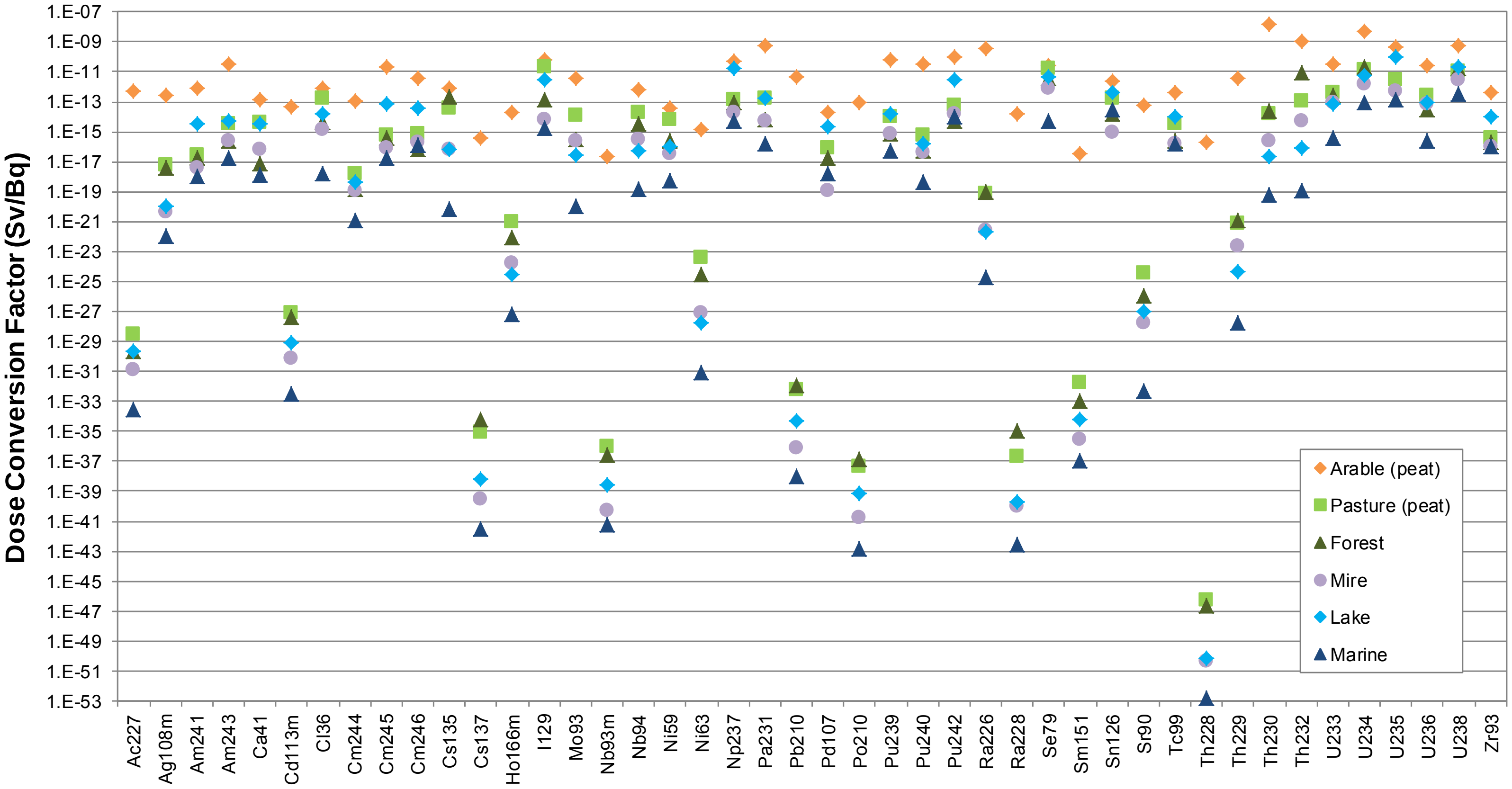


Figure 23: Adult biosphere dose conversion factors for the six different biosphere systems.

Table 71: Adult biosphere dose conversion factors for the six different biosphere systems.

Radio-nuclide	Dose Conversion Factor (Sv/Bq)						Ratio to Arable (peaty soil)				
	Arable (peaty soil)	Pasture (peaty soil)	Forest	Mire	Lake	Marine	Pasture (peat)	Forest	Mire	Lake	Marine
Ac-227	4.7E-13	3.0E-29	2.1E-30	1.3E-31	2.1E-30	2.8E-34	6.2E-17	4.4E-18	2.8E-19	4.4E-18	5.9E-22
Ag-108m	2.7E-13	6.6E-18	3.6E-18	4.5E-21	1.1E-20	1.1E-22	2.5E-05	1.4E-05	1.7E-08	4.0E-08	4.0E-10
Am-241	7.8E-13	3.0E-17	1.8E-17	4.0E-18	3.5E-15	1.0E-18	3.8E-05	2.4E-05	5.1E-06	4.5E-03	1.3E-06
Am-243	3.0E-11	3.1E-15	2.4E-16	2.4E-16	5.4E-15	1.6E-17	1.0E-04	7.9E-06	7.8E-06	1.8E-04	5.3E-07
Ca-41	1.3E-13	4.3E-15	7.1E-18	6.5E-17	3.2E-15	1.2E-18	3.4E-02	5.6E-05	5.2E-04	2.6E-02	9.7E-06
Cd-113m	5.2E-14	8.1E-28	4.7E-28	7.0E-31	7.7E-30	2.8E-33	1.5E-14	9.0E-15	1.3E-17	1.5E-16	5.5E-20
Cl-36	8.6E-13	1.7E-13	4.7E-15	1.5E-15	1.7E-14	1.7E-18	2.0E-01	5.4E-03	1.8E-03	1.9E-02	2.0E-06
Cm-244	1.0E-13	1.7E-18	1.4E-19	1.2E-19	4.6E-19	1.1E-21	1.7E-05	1.3E-06	1.2E-06	4.5E-06	1.1E-08
Cm-245	1.9E-11	5.9E-16	3.6E-16	7.8E-17	6.8E-14	2.0E-17	3.0E-05	1.9E-05	4.0E-06	3.5E-03	1.0E-06
Cm-246	3.8E-12	7.9E-16	6.6E-17	1.8E-16	3.9E-14	1.2E-16	2.1E-04	1.7E-05	4.8E-05	1.0E-02	3.2E-05
Cs-135	8.5E-13	3.4E-14	2.1E-13	7.3E-17	6.1E-17	6.2E-21	4.0E-02	2.5E-01	8.6E-05	7.2E-05	7.3E-09
Cs-137	3.9E-16	9.2E-36	6.2E-35	2.9E-40	6.6E-39	2.8E-42	2.4E-20	1.6E-19	7.6E-25	1.7E-23	7.4E-27
Ho-166m	2.2E-14	9.1E-22	8.0E-23	1.8E-24	3.3E-25	6.3E-28	4.2E-08	3.7E-09	8.2E-11	1.5E-11	2.9E-14
I-129	6.6E-11	2.0E-11	1.4E-13	7.3E-15	2.8E-12	1.8E-15	3.0E-01	2.1E-03	1.1E-04	4.2E-02	2.7E-05
Mo-93	3.9E-12	1.3E-14	3.2E-16	2.3E-16	3.0E-17	9.6E-21	3.2E-03	8.2E-05	6.0E-05	7.7E-06	2.5E-09
Nb-93m	2.2E-17	9.2E-37	2.8E-37	5.1E-41	2.6E-39	5.5E-42	4.2E-20	1.3E-20	2.3E-24	1.2E-22	2.5E-25

Radio-nuclide	Dose Conversion Factor (Sv/Bq)						Ratio to Arable (peaty soil)				
	Arable (peaty soil)	Pasture (peaty soil)	Forest	Mire	Lake	Marine	Pasture (peat)	Forest	Mire	Lake	Marine
Nb-94	7.0E-13	1.8E-14	3.1E-15	3.0E-16	5.5E-17	1.4E-19	2.6E-02	4.4E-03	4.3E-04	8.0E-05	2.0E-07
Ni-59	3.9E-14	6.3E-15	2.6E-16	3.5E-17	9.3E-17	5.9E-19	1.6E-01	6.6E-03	9.1E-04	2.4E-03	1.5E-05
Ni-63	1.5E-15	3.7E-24	3.1E-25	7.6E-28	1.8E-28	8.7E-32	2.4E-09	2.0E-10	5.0E-13	1.2E-13	5.7E-17
Np-237	4.9E-11	1.5E-13	9.1E-14	2.0E-14	1.7E-11	5.0E-15	3.0E-03	1.9E-03	4.0E-04	3.5E-01	1.0E-04
Pa-231	5.2E-10	1.6E-13	6.8E-15	5.7E-15	1.7E-13	1.5E-16	3.1E-04	1.3E-05	1.1E-05	3.2E-04	2.9E-07
Pb-210	5.0E-12	5.5E-33	1.2E-32	7.1E-37	5.5E-35	1.1E-38	1.1E-21	2.4E-21	1.4E-25	1.1E-23	2.2E-27
Pd-107	1.9E-14	8.4E-17	1.7E-17	1.1E-19	2.3E-15	1.5E-18	4.3E-03	8.8E-04	5.9E-06	1.2E-01	8.0E-05
Po-210	8.9E-14	4.2E-38	1.3E-37	1.8E-41	7.3E-40	1.4E-43	4.7E-25	1.4E-24	2.0E-28	8.2E-27	1.6E-30
Pu-239	6.9E-11	9.3E-15	7.1E-16	7.1E-16	1.7E-14	4.9E-17	1.3E-04	1.0E-05	1.0E-05	2.4E-04	7.1E-07
Pu-240	3.5E-11	6.1E-16	4.9E-17	4.3E-17	1.7E-16	4.1E-19	1.8E-05	1.4E-06	1.2E-06	4.8E-06	1.2E-08
Pu-242	1.0E-10	6.2E-14	5.2E-15	1.4E-14	3.1E-12	9.7E-15	6.1E-04	5.1E-05	1.4E-04	3.1E-02	9.6E-05
Ra-226	3.6E-10	7.6E-20	9.0E-20	2.8E-22	2.1E-22	1.8E-25	2.1E-10	2.5E-10	7.8E-13	5.9E-13	5.1E-16
Ra-228	1.5E-14	2.3E-37	1.2E-35	1.1E-40	2.0E-40	2.8E-43	1.5E-23	7.8E-22	7.3E-27	1.3E-26	1.8E-29
Se-79	2.5E-11	1.8E-11	3.7E-12	7.9E-13	4.4E-12	5.1E-15	7.3E-01	1.5E-01	3.2E-02	1.8E-01	2.1E-04
Sm-151	3.8E-17	1.9E-32	9.9E-34	2.7E-36	5.8E-35	1.1E-37	5.1E-16	2.6E-17	7.2E-20	1.5E-18	3.0E-21
Sn-126	2.6E-12	1.7E-13	1.4E-14	9.7E-16	4.7E-13	3.3E-14	6.4E-02	5.5E-03	3.7E-04	1.8E-01	1.3E-02
Sr-90	6.3E-14	3.7E-25	1.0E-26	1.7E-28	1.1E-27	5.1E-33	5.9E-12	1.6E-13	2.6E-15	1.7E-14	8.1E-20

Radio-nuclide	Dose Conversion Factor (Sv/Bq)						Ratio to Arable (peaty soil)				
	Arable (peaty soil)	Pasture (peaty soil)	Forest	Mire	Lake	Marine	Pasture (peat)	Forest	Mire	Lake	Marine
Tc-99	4.0E-13	3.3E-15	2.5E-16	1.5E-16	9.1E-15	1.7E-16	8.4E-03	6.3E-04	3.7E-04	2.3E-02	4.2E-04
Th-228	1.8E-16	5.8E-47	2.2E-47	5.0E-51	7.2E-51	1.5E-53	3.2E-31	1.2E-31	2.8E-35	4.0E-35	8.6E-38
Th-229	3.4E-12	8.4E-22	1.1E-21	2.2E-23	4.6E-25	1.8E-28	2.5E-10	3.3E-10	6.3E-12	1.3E-13	5.3E-17
Th-230	1.5E-08	1.7E-14	2.5E-14	2.6E-16	2.1E-17	5.6E-20	1.1E-06	1.6E-06	1.7E-08	1.4E-09	3.7E-12
Th-232	1.2E-09	1.2E-13	9.3E-12	4.8E-15	8.9E-17	1.1E-19	9.9E-05	7.9E-03	4.1E-06	7.5E-08	9.7E-11
U-233	3.5E-11	3.9E-13	2.5E-13	9.3E-14	7.3E-14	3.5E-16	1.1E-02	7.3E-03	2.7E-03	2.1E-03	1.0E-05
U-234	5.1E-09	1.3E-11	2.1E-11	1.6E-12	5.9E-12	8.9E-14	2.5E-03	4.1E-03	3.2E-04	1.2E-03	1.8E-05
U-235	4.8E-10	3.0E-12	1.5E-13	5.4E-13	1.0E-10	1.3E-13	6.3E-03	3.1E-04	1.1E-03	2.2E-01	2.7E-04
U-236	2.4E-11	2.9E-13	3.1E-14	7.8E-14	9.3E-14	2.4E-16	1.2E-02	1.3E-03	3.2E-03	3.8E-03	9.7E-06
U-238	6.1E-10	1.0E-11	1.6E-11	3.0E-12	2.3E-11	3.4E-13	1.6E-02	2.6E-02	4.8E-03	3.8E-02	5.6E-04
Zr-93	4.6E-13	4.1E-16	1.9E-16	9.6E-17	9.3E-15	1.1E-16	8.9E-04	4.1E-04	2.1E-04	2.0E-02	2.5E-04

Table 72: Time at which 90% of the maximum dose conversion factor is achieved for adults (years).

Radio-nuclide	Biosphere System					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Ac-227	70	300	300	300	300	300
Ag-108m	1,000	4,000	4,000	5,000	5,000	5,000
Am-241	1,000	8,000	8,000	160,000	100,000	50,000
Am-243	30,000	100,000	100,000	140,000	700,000	200,000
Ca-41	2,000	9,000	9,000	20,000	120,000	80,000
Cd-113m	50	200	200	200	200	200
Cl-36	30	100	100	400	2,000	3,000
Cm-244	14,000	100,000	180,000	600,000	500,000	500,000
Cm-245	20,000	30,000	30,000	180,000	120,000	70,000
Cm-246	30,000	180,000	200,000	300,000	800,000	700,000
Cs-135	800,000	900,000	900,000	900,000	900,000	900,000
Cs-137	100	400	400	500	400	400
Ho-166m	4,000	14,000	14,000	16,000	16,000	16,000
I-129	400	2,000	2,000	6,000	40,000	18,000
Mo-93	5,000	16,000	16,000	20,000	20,000	30,000
Nb-93m	50	200	200	200	200	200
Nb-94	40,000	120,000	140,000	160,000	180,000	200,000
Ni-59	18,000	70,000	70,000	140,000	300,000	200,000
Ni-63	300	1,000	1,000	1,000	1,000	1,000
Np-237	1,000	7,000	7,000	160,000	100,000	50,000
Pa-231	40,000	140,000	140,000	180,000	200,000	200,000
Pb-210	70	300	300	300	300	300
Pd-107	8,000	30,000	40,000	90,000	600,000	300,000
Po-210	1	6	6	6	6	6
Pu-239	20,000	90,000	90,000	120,000	700,000	200,000
Pu-240	14,000	100,000	180,000	600,000	500,000	500,000
Pu-242	40,000	180,000	200,000	300,000	800,000	700,000
Ra-226	5,000	18,000	18,000	18,000	18,000	20,000
Ra-228	10	90	90	90	90	90
Se-79	1,000	6,000	6,000	14,000	120,000	50,000
Sm-151	200	1,000	1,000	1,000	1,000	1,000
Sn-126	16,000	70,000	70,000	140,000	300,000	300,000
Sr-90	90	300	300	300	300	400
Tc-99	10	50	60	100	1,000	1,000
Th-228	6	30	30	30	30	30
Th-229	20,000	90,000	90,000	100,000	90,000	90,000

Radio-nuclide	Biosphere System					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Th-230	200,000	600,000	700,000	700,000	700,000	800,000
Th-232	800,000	900,000	900,000	900,000	900,000	900,000
U-233	80,000	300,000	300,000	500,000	700,000	700,000
U-234	200,000	400,000	400,000	600,000	800,000	800,000
U-235	120,000	400,000	400,000	700,000	900,000	900,000
U-236	90,000	400,000	400,000	700,000	900,000	900,000
U-238	300,000	600,000	600,000	800,000	900,000	900,000
Zr-93	20,000	120,000	120,000	300,000	800,000	700,000

Note for Table 72: The calculations ran to one million years, so a time of 1,000,000 years indicates that equilibrium has not been reached within this time frame.

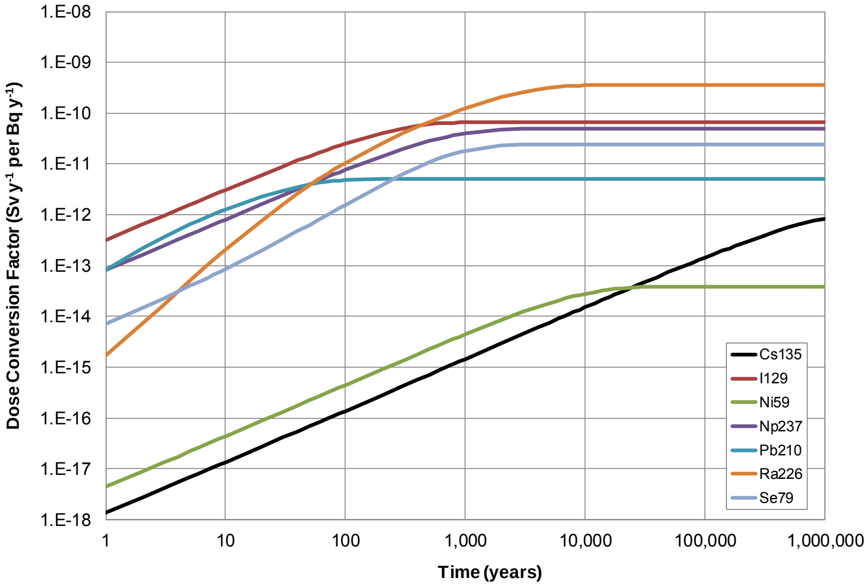


Figure 24: Time-dependency of the calculated dose factors for an adult within the arable system with a peaty soil.

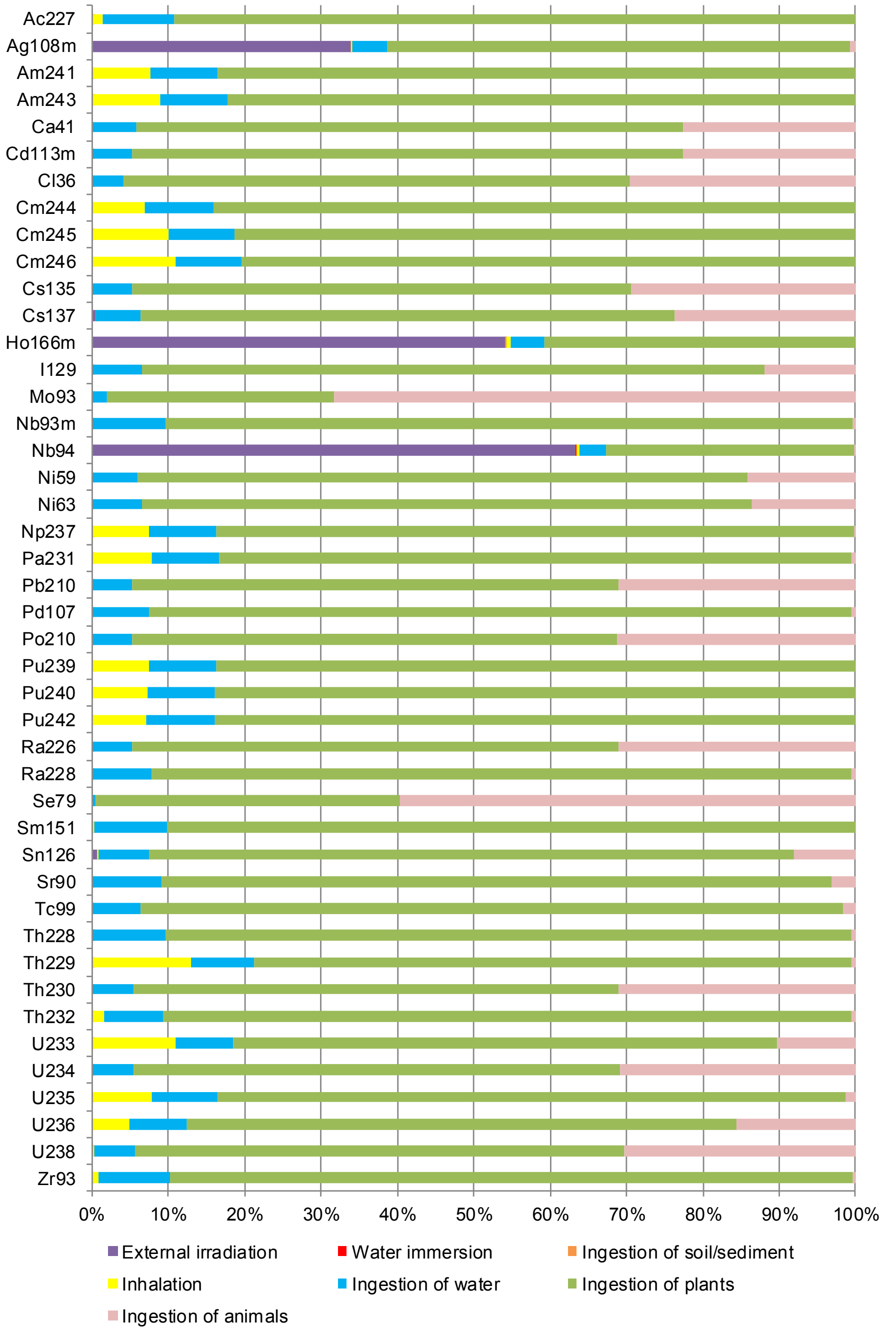


Figure 25: Contribution of different exposure pathways to the maximum dose factor for adults in the arable system for each radionuclide.

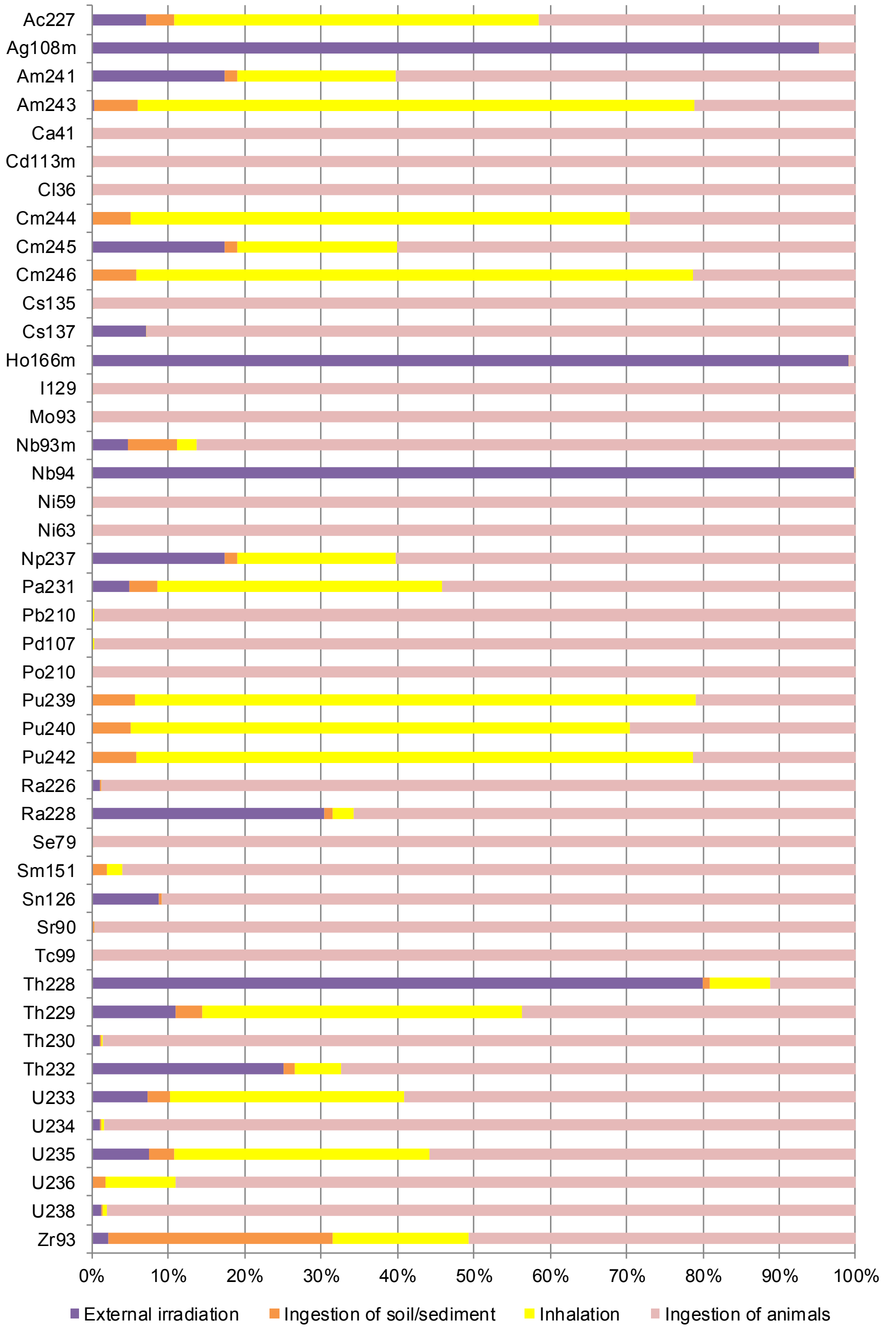


Figure 26: Contribution of different exposure pathways to the maximum dose factor for adults in the pasture system for each radionuclide.

Table 73: Ratio of maximum calculated dose factor for children and infants to that of adults.

	Arable (peaty soil)		Pasture (peaty soil)		Forest		Mire		Lake		Marine	
	Child	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**
Ac-227	0.84	0.95	0.59	0.51	0.85	0.27	0.99	0.46	0.90	0.91	0.95	0.84
Ag-108m	0.83	0.92	0.31	0.22	0.95	1.04	0.03	0.04	0.59	0.49	0.93	0.80
Am-241	0.52	0.46	0.54	0.41	0.49	0.43	0.80	0.37	0.54	0.51	0.52	0.44
Am-243	0.50	0.43	0.34	0.33	0.52	0.25	0.78	0.26	0.65	0.49	0.62	0.41
Ca-41	1.42	0.74	2.10	2.29	1.49	0.79	1.89	1.09	1.42	0.70	1.50	1.86
Cd-113m	0.72	0.66	1.11	2.49	0.56	0.47	0.94	0.97	0.70	0.54	0.76	0.49
Cl-36	1.22	1.72	1.78	6.53	0.99	1.49	1.53	2.71	1.08	1.98	1.14	6.99
Cm-244	0.51	0.43	0.45	0.61	0.57	0.30	0.93	0.63	0.62	0.43	0.61	0.50
Cm-245	0.50	0.44	0.54	0.41	0.49	0.43	0.80	0.37	0.54	0.51	0.52	0.44
Cm-246	0.48	0.41	0.36	0.33	0.56	0.31	0.85	0.28	0.59	0.38	0.60	0.38
Cs-135	0.48	0.28	0.69	0.89	0.37	0.22	0.63	0.46	0.43	0.38	0.45	0.45
Cs-137	0.42	0.23	0.59	0.68	0.34	0.17	0.40	0.26	0.40	0.31	0.48	0.33
Ho-166m	0.54	0.65	0.26	0.16	0.50	0.00	0.00	0.00	0.51	0.34	0.54	0.36
I-129	0.98	0.59	1.52	2.02	1.17	0.70	1.22	0.75	0.92	0.55	1.15	1.04
Mo-93	0.79	0.52	0.77	0.67	0.59	0.44	0.97	0.89	0.80	0.64	1.15	2.82

	Arable (peaty soil)		Pasture (peaty soil)		Forest		Mire		Lake		Marine	
	Child	Infant	Child	Infant	Child	Infant	Child	Infant	Child	Infant	Child	Infant
Nb-93m	1.14	2.03	1.75	6.93	1.15	1.35	0.85	1.15	1.25	2.06	1.37	2.15
Nb-94	0.53	0.66	0.25	0.17	0.50	0.01	0.00	0.00	0.51	0.35	0.51	0.33
Ni-59	1.00	1.45	1.53	5.41	0.77	1.02	1.29	2.13	0.98	1.44	1.08	1.44
Ni-63	1.04	1.51	1.64	5.61	0.83	1.06	1.38	2.20	1.05	1.49	1.16	1.49
Np-237	0.47	0.50	0.54	0.41	0.49	0.43	0.80	0.37	0.54	0.51	0.52	0.44
Pa-231	0.72	0.74	0.68	0.75	0.70	0.29	0.95	0.44	0.90	0.90	0.93	0.83
Pb-210	1.24	1.99	1.52	2.04	1.55	2.74	1.65	2.85	1.21	1.70	1.33	1.63
Pd-107	1.19	2.02	1.90	7.29	1.01	1.53	1.01	1.51	1.15	2.15	1.44	2.45
Po-210	1.23	1.99	1.42	2.07	1.55	2.76	1.62	2.92	1.20	1.70	1.24	1.78
Pu-239	0.51	0.42	0.34	0.33	0.52	0.25	0.78	0.26	0.65	0.50	0.62	0.42
Pu-240	0.51	0.42	0.45	0.61	0.57	0.30	0.93	0.63	0.62	0.43	0.61	0.50
Pu-242	0.51	0.42	0.36	0.33	0.56	0.31	0.85	0.28	0.59	0.38	0.60	0.38
Ra-226	1.24	1.98	1.53	2.02	1.44	2.01	1.64	2.81	1.21	1.70	1.33	1.62
Ra-228	2.99	2.20	3.19	3.68	2.48	1.56	1.17	0.88	2.47	2.19	1.84	2.04
Se-79	3.20	2.47	3.71	6.22	3.46	3.64	3.62	3.86	2.49	2.96	2.51	2.94
Sm-151	1.03	1.74	1.46	1.48	1.08	1.02	0.66	0.37	1.13	1.56	1.25	1.44
Sn-126	1.15	1.63	1.52	3.68	1.07	1.47	0.05	0.05	1.05	2.09	1.25	1.28

	Arable (peaty soil)		Pasture (peaty soil)		Forest		Mire		Lake		Marine	
	Child	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**	**Child**	**Infant**
Sr-90	1.10	0.80	1.82	2.79	0.95	0.57	1.53	1.15	1.18	0.68	1.39	3.46
Tc-99	1.08	1.98	1.74	7.21	1.34	2.54	1.52	3.00	1.05	2.35	1.43	1.82
Th-228	1.56	2.10	0.47	0.44	1.61	1.89	0.57	0.42	1.28	1.51	1.26	1.32
Th-229	0.87	0.92	0.76	0.65	1.30	1.29	0.95	0.45	1.00	0.95	1.09	0.92
Th-230	1.24	1.98	1.52	2.02	1.44	2.00	1.63	2.78	1.21	1.70	1.33	1.62
Th-232	2.82	2.08	3.14	3.60	2.47	1.55	1.08	0.70	2.06	1.78	1.56	1.62
U-233	0.78	0.75	0.92	1.28	1.26	1.24	0.98	0.55	0.98	0.91	1.07	0.94
U-234	1.24	1.98	1.52	2.02	1.44	2.00	1.62	2.74	1.20	1.69	1.33	1.62
U-235	0.73	0.74	0.72	0.90	0.69	0.32	0.97	0.51	0.90	0.90	0.93	0.83
U-236	0.75	0.71	1.20	2.52	0.79	0.55	1.08	0.99	0.84	0.66	0.73	1.13
U-238	1.22	1.93	1.51	2.04	1.44	1.99	1.60	2.69	1.20	1.69	1.33	1.62
Zr-93	0.29	0.23	0.92	3.41	0.41	0.29	0.30	0.19	0.39	0.39	0.41	0.32

Note: Values greater than 3 are highlighted.

Table 74: Maximum dose conversion factors for the arable and pasture systems with clayey silty till soils, with comparison against those with peaty/organic soils.

Radio-nuclide	Arable System			Pasture System		
	Max. Dose Factor (Sv Bq^{-1})	Ratio. to that using peaty/organic soil	Time to 90% of Max. Dose Factor (y)	Max. Dose Factor (Sv Bq^{-1})	Ratio to that using peaty/organic soil	Time to 90% of Max. Dose Factor (y)
Ac-227	4.7E-13	0.99	70	2.5E-30	0.08	300
Ag-108m	2.1E-13	0.81	1,000	3.5E-18	0.52	4,000
Am-241	7.3E-13	0.94	1,000	2.3E-18	0.08	160,000
Am-243	2.8E-11	0.94	30,000	5.7E-15	1.82	100,000
Ca-41	1.2E-13	0.98	2,000	2.0E-15	0.47	9,000
Cd-113m	4.8E-14	0.92	40	6.4E-29	0.08	200
Cl-36	6.7E-13	0.78	30	8.8E-14	0.52	100
Cm-244	9.7E-14	0.95	14,000	2.4E-18	1.40	50,000
Cm-245	1.8E-11	0.92	20,000	4.6E-17	0.08	160,000
Cm-246	3.5E-12	0.91	30,000	1.6E-15	1.99	200,000
Cs-135	7.6E-13	0.90	800,000	9.1E-15	0.27	900,000
Cs-137	3.8E-16	0.99	100	7.6E-37	0.08	400
Ho-166m	2.2E-14	1.03	4,000	1.0E-21	1.13	16,000
I-129	6.4E-11	0.97	400	7.7E-11	3.82	10,000
Mo-93	2.7E-12	0.69	5,000	2.1E-15	0.17	18,000
Nb-93m	2.2E-17	1.00	50	5.6E-38	0.06	200

Radio-nuclide	Arable System			Pasture System		
	Max. Dose Factor ($Sv\ Bq^{-1}$)	**Ratio. to that using peaty/organic soil**	**Time to 90% of Max. Dose Factor (y)**	**Max. Dose Factor ($Sv\ Bq^{-1}$)**	**Ratio to that using peaty/organic soil**	**Time to 90% of Max. Dose Factor (y)**
Nb-94	7.0E-13	1.01	40,000	2.7E-14	1.49	140,000
Ni-59	3.5E-14	0.90	18,000	9.4E-16	0.15	70,000
Ni-63	1.5E-15	0.97	300	3.5E-25	0.09	1,000
Np-237	4.5E-11	0.92	1,000	1.1E-14	0.08	160,000
Pa-231	4.9E-10	0.94	40,000	1.8E-13	1.15	140,000
Pb-210	5.0E-12	1.00	70	3.1E-34	0.06	300
Pd-107	1.9E-14	0.99	8,000	3.1E-16	3.63	40,000
Po-210	8.9E-14	1.00	1	1.8E-39	0.04	6
Pu-239	6.6E-11	0.95	20,000	1.7E-14	1.83	90,000
Pu-240	3.3E-11	0.95	14,000	8.6E-16	1.40	50,000
Pu-242	9.7E-11	0.95	40,000	1.2E-13	1.99	180,000
Ra-226	3.6E-10	1.00	5,000	3.6E-20	0.47	20,000
Ra-228	1.5E-14	1.00	10	2.2E-38	0.10	90
Se-79	1.1E-11	0.44	1,000	3.0E-11	1.64	9,000
Sm-151	3.8E-17	1.00	200	1.9E-33	0.10	1,000
Sn-126	2.0E-12	0.76	16,000	1.0E-13	0.60	80,000
Sr-90	6.2E-14	0.99	90	8.8E-26	0.24	400

Radio-nuclide	Arable System			Pasture System		
	Max. Dose Factor (Sv Bq^{-1})	Ratio. to that using peaty/organic soil	Time to 90% of Max. Dose Factor (y)	Max. Dose Factor (Sv Bq^{-1})	Ratio to that using peaty/organic soil	Time to 90% of Max. Dose Factor (y)
Tc-99	3.7E-13	0.94	10	1.1E-14	3.28	100
Th-228	1.8E-16	1.00	6	9.3E-48	0.16	30
Th-229	3.1E-12	0.89	20,000	2.8E-22	0.33	90,000
Th-230	1.5E-08	1.00	200,000	1.0E-14	0.61	700,000
Th-232	1.2E-09	0.98	800,000	8.3E-14	0.71	900,000
U-233	3.1E-11	0.89	80,000	2.6E-13	0.66	300,000
U-234	5.1E-09	1.00	200,000	9.9E-12	0.77	400,000
U-235	4.5E-10	0.94	120,000	3.7E-12	1.22	400,000
U-236	2.3E-11	0.93	90,000	1.4E-13	0.48	400,000
U-238	6.1E-10	1.00	300,000	7.9E-12	0.79	600,000
Zr-93	4.6E-13	0.99	20,000	1.1E-16	0.26	120,000

Table 75: Maximum calculated adult dose factor and time to reach 90% of the maximum without retention in the deeper sediments, glacial clay and till.

	Maximum Dose Factor (Sv Bq^{-1})						Time to 90% of the Maximum Dose Factors (y)					
	Arable	**Pasture**	**Forest**	**Mire**	**Lake**	**Marine**	**Arable**	**Pasture**	**Forest**	**Mire**	**Lake**	**Marine**
Ac-227	4.6E-10	1.9E-14	1.8E-15	1.2E-15	2.9E-13	5.6E-16	6	100	90	100	100	100
Ag-108m	1.9E-12	4.3E-13	3.0E-13	7.4E-15	4.2E-13	1.3E-14	400	1,000	1,000	1,000	1,000	700
Am-241	8.8E-11	1.2E-13	9.7E-15	2.0E-14	1.0E-11	8.9E-15	9	900	400	1,000	1,000	1,000
Am-243	9.2E-11	3.5E-13	1.6E-14	6.2E-14	5.5E-11	2.8E-14	30	2,000	500	2,000	4,000	2,000
Ca-41	1.3E-13	4.5E-15	7.4E-18	7.1E-17	5.5E-15	1.7E-18	6	100	60	100	600	1,000
Cd-113m	1.5E-11	6.3E-15	5.0E-15	5.2E-17	6.7E-15	5.1E-17	8	70	70	100	100	100
Cl-36	8.6E-13	1.7E-13	4.7E-15	1.5E-15	1.7E-14	1.7E-18	9	40	40	100	400	1,000
Cm-244	4.5E-11	1.6E-15	2.2E-16	8.5E-17	1.6E-13	1.2E-16	5	100	100	700	2,000	1,000
Cm-245	1.0E-10	1.0E-12	5.8E-14	3.1E-13	2.2E-10	6.0E-14	200	4,000	1,000	7,000	1,000	2,000
Cm-246	9.8E-11	5.5E-13	4.0E-14	1.5E-13	2.0E-10	3.9E-14	90	3,000	1,000	6,000	1,000	2,000
Cs-135	1.5E-12	1.9E-12	1.3E-11	4.8E-14	1.9E-12	1.3E-16	60	6,000	4,000	20,000	5,000	1,000
Cs-137	8.2E-12	8.6E-14	7.0E-13	6.8E-17	1.3E-14	4.7E-17	6	100	100	200	200	100
Ho-166m	1.8E-12	7.8E-13	9.0E-14	4.1E-14	1.3E-12	8.2E-15	600	2,000	1,000	3,000	2,000	1,000
I-129	6.6E-11	2.0E-11	1.4E-13	7.3E-15	2.8E-12	1.8E-15	8	800	200	800	900	1,000
Mo-93	6.6E-12	1.6E-13	4.3E-15	1.4E-14	1.0E-13	1.7E-17	300	1,000	300	1,000	800	1,000
Nb-93m	4.4E-14	6.4E-19	2.6E-19	4.2E-22	2.3E-19	8.0E-21	5	80	80	100	100	100
Nb-94	1.9E-12	2.1E-12	4.2E-13	3.7E-13	5.2E-12	1.3E-14	900	6,000	6,000	20,000	10,000	1,000

	Maximum Dose Factor (Sv Bq^{-1})						Time to 90% of the Maximum Dose Factors (y)					
	Arable	Pasture	Forest	Mire	Lake	Marine	Arable	Pasture	Forest	Mire	Lake	Marine
Ni-59	4.2E-14	9.6E-15	3.9E-16	8.2E-17	2.5E-15	5.3E-18	40	2,000	700	3,000	1,000	1,000
Ni-63	9.0E-14	2.0E-15	2.4E-16	8.7E-18	2.0E-16	9.8E-19	7	300	200	400	500	400
Np-237	4.9E-11	1.4E-13	8.6E-14	1.3E-14	1.7E-11	4.8E-15	9	900	200	1,000	700	1,000
Pa-231	4.0E-10	2.5E-12	1.1E-13	4.1E-13	9.1E-10	3.4E-13	200	1,000	500	2,000	3,000	2,000
Pb-210	9.8E-10	7.8E-13	2.2E-12	1.5E-15	1.7E-12	5.1E-15	6	100	100	100	100	100
Pd-107	1.9E-14	8.5E-17	1.7E-17	1.1E-19	2.6E-15	1.6E-18	6	200	100	200	600	1,000
Po-210	1.5E-10	3.3E-20	1.1E-19	3.6E-24	1.8E-22	4.1E-25	1	5	5	6	6	6
Pu-239	1.1E-10	8.1E-14	6.4E-15	2.4E-14	3.0E-11	3.6E-14	9	800	200	800	4,000	2,000
Pu-240	1.1E-10	7.8E-14	6.3E-15	2.3E-14	2.6E-11	3.3E-14	9	800	200	700	3,000	1,000
Pu-242	1.1E-10	7.6E-14	6.1E-15	2.2E-14	3.1E-11	3.5E-14	9	800	200	800	4,000	2,000
Ra-226	2.7E-10	4.8E-11	6.7E-11	3.1E-12	8.2E-10	1.3E-12	100	1,000	500	1,000	1,000	1,000
Ra-228	2.9E-10	1.5E-15	9.6E-14	3.0E-18	2.4E-17	6.6E-19	4	40	40	50	60	60
Se-79	2.5E-11	1.8E-11	3.7E-12	8.0E-13	4.5E-12	5.2E-15	300	600	200	600	800	1,000
Sm-151	3.9E-14	3.1E-17	2.2E-18	1.1E-19	1.3E-16	2.3E-18	6	300	300	400	400	300
Sn-126	2.8E-12	2.3E-13	2.0E-14	1.9E-15	5.5E-12	1.7E-13	400	4,000	1,000	7,000	3,000	1,000
Sr-90	1.2E-11	1.7E-14	6.1E-16	8.5E-17	2.0E-14	8.2E-19	6	80	60	100	100	100
Tc-99	4.0E-13	3.3E-15	2.5E-16	1.5E-16	9.1E-15	1.7E-16	6	40	40	100	600	900
Th-228	2.9E-11	1.7E-18	8.0E-19	1.2E-22	4.0E-22	1.7E-23	3	20	20	20	20	20

	Maximum Dose Factor (Sv Bq^{-1})						Time to 90% of the Maximum Dose Factors (y)					
	Arable	Pasture	Forest	Mire	Lake	Marine	Arable	Pasture	Forest	Mire	Lake	Marine
Th-229	2.9E-10	1.9E-12	3.6E-12	8.9E-13	5.6E-11	1.2E-13	100	5,000	6,000	16,000	9,000	2,000
Th-230	1.1E-10	4.5E-11	8.1E-11	2.9E-11	2.3E-09	6.7E-13	500	7,000	8,000	40,000	12,000	2,000
Th-232	2.2E-10	1.1E-11	9.1E-10	3.7E-12	1.4E-10	1.4E-13	200	6,000	8,000	50,000	14,000	2,000
U-233	2.8E-11	7.5E-13	2.9E-13	3.8E-13	4.6E-12	8.5E-15	200	6,000	6,000	18,000	8,000	2,000
U-234	2.5E-11	1.3E-12	5.9E-13	8.6E-13	1.5E-11	4.4E-15	10	8,000	8,000	40,000	12,000	3,000
U-235	2.5E-11	4.8E-13	3.7E-14	1.2E-13	1.4E-11	6.2E-15	40	4,000	1,000	6,000	3,000	2,000
U-236	2.4E-11	2.9E-13	3.0E-14	8.7E-14	8.4E-13	7.2E-16	10	3,000	1,000	6,000	1,000	1,000
U-238	2.5E-11	3.2E-13	3.2E-14	9.6E-14	8.8E-13	8.3E-16	10	4,000	1,000	8,000	1,000	1,000
Zr-93	4.6E-13	4.3E-16	2.0E-16	1.0E-16	2.4E-14	1.5E-16	6	3,000	1,000	5,000	3,000	1,000

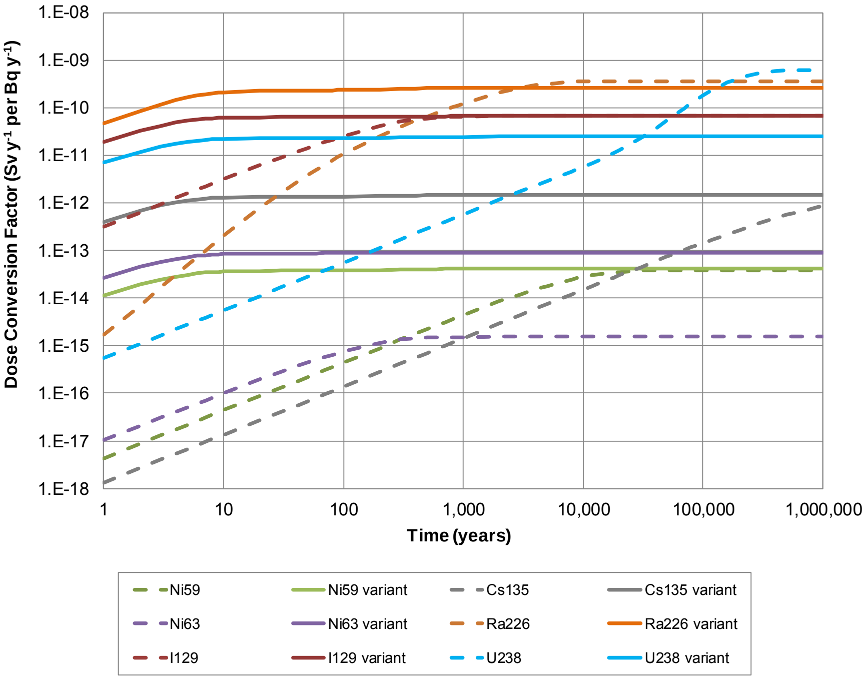


Figure 27: Comparison of adult dose factor timescales for the arable system with and without (variant) retardation in the till, glacial clay and post-glacial sediment beneath the surface soils/sediments.

9.2. Comparison Against the SR-Site LDFs

In SR-Site, the maximum calculated dose factors occur during the interglacial period. The time of the maximum dose factors used as LDFs is given in Table 4-1 of Avila et al. (2010); these occur after the sea has retreated, and in many cases, at the maximum point of terrestrialisation during the interglacial period.

The maximum calculated dose factors calculated with the models described in this report are presented in Table 77 and compared against the interglacial LDFs from the SR-Site assessment[10]. Differences greater than an order of magnitude are highlighted in the table.

- Many of the dose factors are lower than those used within SR-Site across all of the biosphere systems (for 18 out of 39 radionuclides for which comparisons are possible).
- For many radionuclides (21, including Ra-226), the calculated dose factors for the arable system are higher than those used in SR-Site.
- For some radionuclides (e.g. U-234 and U-238), calculated dose factors are higher than those used in SR-Site in some of the other (i.e. non-arable) biosphere systems considered.

It is important to bear in mind differences between the SR-Site biosphere models and those described in this report. Notable differences are summarised in Table 76.

---

[10] It is noted that Table 2-of Avila et al. (2010) states that LDFs are calculated for Mo-93 and Cd-113m, however, results for these radionuclides are not then presented in Sections 4 and 5 of that report.

Table 76: Notable differences between the SR-Site biosphere models and those presented herein.

SR-Site	Models herein
Represents radionuclide releases across entire lake basins (termed biosphere-objects) and exposures calculated to groups of people that can be sustained by the productivity of each object (typically tens of individuals)	Consider potential for more focused radionuclide releases and potential exposure of a small number of individuals (typically self-sufficient in supply of some food groups).
Represents potential accumulation and transition between biosphere systems over an interglacial period of 18,400 years.	Represents non-evolving systems out to a million years, allowing longer for equilibrium to be reached.
Uses three compartments to represent the till, glacial clay, post-glacial deposits and surface soils/sediments.	Uses eight compartments to represent the till, glacial clay, post-glacial deposits and surface soils/sediments.
Only represents contamination of soil via natural groundwater discharge, although groundwater is used in part to provide drinking water for humans and livestock.	Arable system is only contaminated via use of contaminated well water for irrigation. The well water is also used domestically and as drinking water for animals. Less dilution in the well water.

Table 77 demonstrates that dose factors arising from potential use of well water for irrigation can give rise to higher dose factors than considered in SR-Site. Potential use of well water for irrigation is considered in the exploration of uncertainties in Section 5.1.2 of Avila et al. (2010), however:

- only short-term irrigation with a combination of both well and surface water was considered; and
- consideration of long-term irrigation on clay soils only assessed the use of surface water.

Further comparison is made against a variant case that has been set up to resemble the reference assumptions adopted in the SR-Site modelling. The case is based on groundwater releases to an agricultural system that includes both crops and pasture. No irrigation is considered, to reflect the reference SR-Site assumptions. The case is effectively set up to represent crops being grown within the area used for pasture, such that the arable and pasture dose factors can be combined to represent almost complete self-sufficiency in food stuffs. The case includes consumption of groundwater by humans and animals[11], but no irrigation. The resulting comparison is presented in Figure 28 and the values are given in Table 78.

- Maximum dose factors for 16 out of 39 radionuclides are within an order of magnitude of the SR-Site LDFs (including Ni-59, Ra-226 and Np-237), suggesting reasonable agreement for these radionuclides given the uncertainties involved.
- The maximum dose factors for six radionuclides are higher than the SR-Site LDFs by more than an order of magnitude (and by more than two orders of magnitude for U-234 and U-238).

---

[11] In this case, humans and animals are taken to obtain 50% of their drinking water requirements from groundwater, consistent with SR-Site assumptions. The well water concentrations are based on those modelled in the till.

- Maximum dose factors for 17 radionuclides are more than an order of magnitude lower than the SR-Site LDFs (including Se-79, Nb-94 and I-129), with the results for 7 of those being more than two orders of magnitude lower.

The maximum dose factors for the variant case, which is adapted to resemble the assumptions adopted in SR-Site, are broken down by exposure pathway in Figure 29.

- The figure shows that, for these assumptions (i.e. groundwater release to agricultural soils, no irrigation, but including consumption of shallow groundwater by humans and animals), the drinking water pathway dominates for many radionuclides.
- Notable exceptions include Cl-36 and Se-79 (for which ingestion of animal produce is key) and Nb-94 (for which external irradiation is important).

Comparison can be made with the contributions of well water consumption to the baseline LDFs shown in Figure 5-22 of Avila (2010) for 19 radionuclides.

- The comparison shows that there is reasonable agreement in the importance of the drinking water pathway for 7 of the radionuclides (including Cl-36, Se-79 and Ra-226).
- The contribution of the drinking water pathway is higher in the simple biosphere models for 12 radionuclides and significantly higher for five (including Np-237). This partly reflects differences in the way in which the well water concentrations are calculated, with the simple model directly using concentrations in the till, whilst the SR-Site model dilutes the release in an assumed well capacity.

Table 77: Comparison of maximum calculated dose factors against the SR-Site maximum dose factor for the interglacial period.

Radio-nuclide	SR-Site Interglacial	Arable (clay)		Pasture (peat)		Forest		Mire		Lake		Marine	
		Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio
Ac-227	8.0E-12	4.7E-13	5.9E-02	3.0E-29	3.7E-18	2.1E-30	2.6E-19	1.3E-31	1.7E-20	2.1E-30	2.6E-19	2.8E-34	3.5E-23
Ag-108m	7.1E-13	2.1E-13	3.0E-01	6.6E-18	9.3E-06	3.6E-18	5.1E-06	4.5E-21	6.4E-09	1.1E-20	1.5E-08	1.1E-22	1.5E-10
Am-241	1.5E-12	7.3E-13	4.9E-01	3.0E-17	2.0E-05	1.8E-17	1.2E-05	4.0E-18	2.6E-06	3.5E-15	2.3E-03	1.0E-18	6.7E-07
Am-243	1.5E-12	2.8E-11	1.9E+01	3.1E-15	2.1E-03	2.4E-16	1.6E-04	2.4E-16	1.6E-04	5.4E-15	3.6E-03	1.6E-17	1.1E-05
Ca-41	9.9E-14	1.2E-13	1.3E+00	4.3E-15	4.4E-02	7.1E-18	7.2E-05	6.5E-17	6.6E-04	3.2E-15	3.3E-02	1.2E-18	1.2E-05
Cl-36	5.8E-13	6.7E-13	1.2E+00	1.7E-13	2.9E-01	4.7E-15	8.1E-03	1.5E-15	2.7E-03	1.7E-14	2.9E-02	1.7E-18	2.9E-06
Cm-244	8.7E-13	9.7E-14	1.1E-01	1.7E-18	1.9E-06	1.4E-19	1.6E-07	1.2E-19	1.4E-07	4.6E-19	5.3E-07	1.1E-21	1.3E-09
Cm-245	1.6E-12	1.8E-11	1.1E+01	5.9E-16	3.7E-04	3.6E-16	2.3E-04	7.8E-17	4.9E-05	6.8E-14	4.2E-02	2.0E-17	1.2E-05
Cm-246	1.6E-12	3.5E-12	2.2E+00	7.9E-16	4.9E-04	6.6E-17	4.1E-05	1.8E-16	1.1E-04	3.9E-14	2.5E-02	1.2E-16	7.7E-05
Cs-135	4.0E-14	7.6E-13	1.9E+01	3.4E-14	8.5E-01	2.1E-13	5.3E+00	7.3E-17	1.8E-03	6.1E-17	1.5E-03	6.2E-21	1.5E-07
Cs-137	1.2E-13	3.8E-16	3.2E-03	9.2E-36	7.6E-23	6.2E-35	5.2E-22	2.9E-40	2.4E-27	6.6E-39	5.5E-26	2.8E-42	2.4E-29
Ho-166m	5.9E-14	2.2E-14	3.8E-01	9.1E-22	1.5E-08	8.0E-23	1.4E-09	1.8E-24	3.1E-11	3.3E-25	5.6E-12	6.3E-28	1.1E-14
I-129	6.5E-10	6.4E-11	9.9E-02	2.0E-11	3.1E-02	1.4E-13	2.1E-04	7.3E-15	1.1E-05	2.8E-12	4.2E-03	1.8E-15	2.7E-06
Nb-94	4.0E-12	7.0E-13	1.8E-01	1.8E-14	4.5E-03	3.1E-15	7.7E-04	3.0E-16	7.5E-05	5.5E-17	1.4E-05	1.4E-19	3.4E-08
Ni-59	7.4E-14	3.5E-14	4.7E-01	6.3E-15	8.5E-02	2.6E-16	3.5E-03	3.5E-17	4.8E-04	9.3E-17	1.3E-03	5.9E-19	8.0E-06
Ni-63	1.2E-15	1.5E-15	1.2E+00	3.7E-24	3.1E-09	3.1E-25	2.6E-10	7.6E-28	6.3E-13	1.8E-28	1.5E-13	8.7E-32	7.3E-17

Radio-nuclide	SR-Site	Arable (clay)		Pasture (peat)		Forest		Mire		Lake		Marine	
	Interglacial	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio
Np-237	4.8E-11	4.5E-11	9.4E-01	1.5E-13	3.1E-03	9.1E-14	1.9E-03	2.0E-14	4.1E-04	1.7E-11	3.6E-01	5.0E-15	1.0E-04
Pa-231	8.1E-12	4.9E-10	6.0E+01	1.6E-13	2.0E-02	6.8E-15	8.4E-04	5.7E-15	7.1E-04	1.7E-13	2.0E-02	1.5E-16	1.8E-05
Pb-210	5.1E-12	5.0E-12	9.8E-01	5.5E-33	1.1E-21	1.2E-32	2.4E-21	7.1E-37	1.4E-25	5.5E-35	1.1E-23	1.1E-38	2.1E-27
Pd-107	6.7E-15	1.9E-14	2.9E+00	8.4E-17	1.3E-02	1.7E-17	2.5E-03	1.1E-19	1.7E-05	2.3E-15	3.5E-01	1.5E-18	2.3E-04
Po-210	8.9E-12	8.9E-14	1.0E-02	4.2E-38	4.7E-27	1.3E-37	1.4E-26	1.8E-41	2.0E-30	7.3E-40	8.2E-29	1.4E-43	1.6E-32
Pu-239	1.9E-12	6.6E-11	3.5E+01	9.3E-15	4.9E-03	7.1E-16	3.7E-04	7.1E-16	3.7E-04	1.7E-14	8.7E-03	4.9E-17	2.6E-05
Pu-240	1.9E-12	3.3E-11	1.7E+01	6.1E-16	3.2E-04	4.9E-17	2.6E-05	4.3E-17	2.3E-05	1.7E-16	8.7E-05	4.1E-19	2.2E-07
Pu-242	1.9E-12	9.7E-11	5.1E+01	6.2E-14	3.3E-02	5.2E-15	2.7E-03	1.4E-14	7.5E-03	3.1E-12	1.6E+00	9.7E-15	5.1E-03
Ra-226	3.8E-12	3.6E-10	9.4E+01	7.6E-20	2.0E-08	9.0E-20	2.4E-08	2.8E-22	7.4E-11	2.1E-22	5.5E-11	1.8E-25	4.8E-14
Se-79	1.2E-09	1.1E-11	9.1E-03	1.8E-11	1.5E-02	3.7E-12	3.1E-03	7.9E-13	6.6E-04	4.4E-12	3.6E-03	5.1E-15	4.3E-06
Sm-151	7.2E-16	3.8E-17	5.3E-02	1.9E-32	2.7E-17	9.9E-34	1.4E-18	2.7E-36	3.8E-21	5.8E-35	8.1E-20	1.1E-37	1.6E-22
Sn-126	2.5E-11	2.0E-12	7.9E-02	1.7E-13	6.6E-03	1.4E-14	5.8E-04	9.7E-16	3.9E-05	4.7E-13	1.9E-02	3.3E-14	1.3E-03
Sr-90	2.2E-13	6.2E-14	2.8E-01	3.7E-25	1.7E-12	1.0E-26	4.6E-14	1.7E-28	7.5E-16	1.1E-27	4.8E-15	5.1E-33	2.3E-20
Tc-99	9.0E-13	3.7E-13	4.2E-01	3.3E-15	3.7E-03	2.5E-16	2.8E-04	1.5E-16	1.6E-04	9.1E-15	1.0E-02	1.7E-16	1.9E-04
Th-229	3.6E-12	3.1E-12	8.5E-01	8.4E-22	2.3E-10	1.1E-21	3.2E-10	2.2E-23	6.0E-12	4.6E-25	1.3E-13	1.8E-28	5.1E-17
Th-230	1.3E-11	1.5E-08	1.2E+03	1.7E-14	1.3E-03	2.5E-14	1.9E-03	2.6E-16	2.0E-05	2.1E-17	1.6E-06	5.6E-20	4.3E-09
Th-232	1.7E-12	1.2E-09	6.8E+02	1.2E-13	6.9E-02	9.3E-12	5.5E+00	4.8E-15	2.8E-03	8.9E-17	5.2E-05	1.1E-19	6.7E-08
U-233	2.5E-12	3.1E-11	1.2E+01	3.9E-13	1.6E-01	2.5E-13	1.0E-01	9.3E-14	3.7E-02	7.3E-14	2.9E-02	3.5E-16	1.4E-04

Radio-nuclide	SR-Site	Arable (clay)		Pasture (peat)		Forest		Mire		Lake		Marine	
	Interglacial	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio	Dose Factor	Ratio
U-234	3.6E-12	5.1E-09	1.4E+03	1.3E-11	3.5E+00	2.1E-11	5.8E+00	1.6E-12	4.5E-01	5.9E-12	1.6E+00	8.9E-14	2.5E-02
U-235	2.8E-12	4.5E-10	1.6E+02	3.0E-12	1.1E+00	1.5E-13	5.4E-02	5.4E-13	1.9E-01	1.0E-10	3.7E+01	1.3E-13	4.6E-02
U-236	1.9E-12	2.3E-11	1.2E+01	2.9E-13	1.5E-01	3.1E-14	1.7E-02	7.8E-14	4.1E-02	9.3E-14	4.9E-02	2.4E-16	1.2E-04
U-238	1.9E-12	6.1E-10	3.2E+02	1.0E-11	5.3E+00	1.6E-11	8.6E+00	3.0E-12	1.6E+00	2.3E-11	1.2E+01	3.4E-13	1.8E-01
Zr-93	2.8E-14	4.6E-13	1.6E+01	4.1E-16	1.5E-02	1.9E-16	6.7E-03	9.6E-17	3.4E-03	9.3E-15	3.3E-01	1.1E-16	4.1E-03

Notes for Table 77: Differences greater than an order of magnitude are highlighted with red for higher dose factors and blue for lower dose factors.

* The results for a clayey silty till are used for the arable system, as this is more appropriate for long-term arable use than an organic soil.

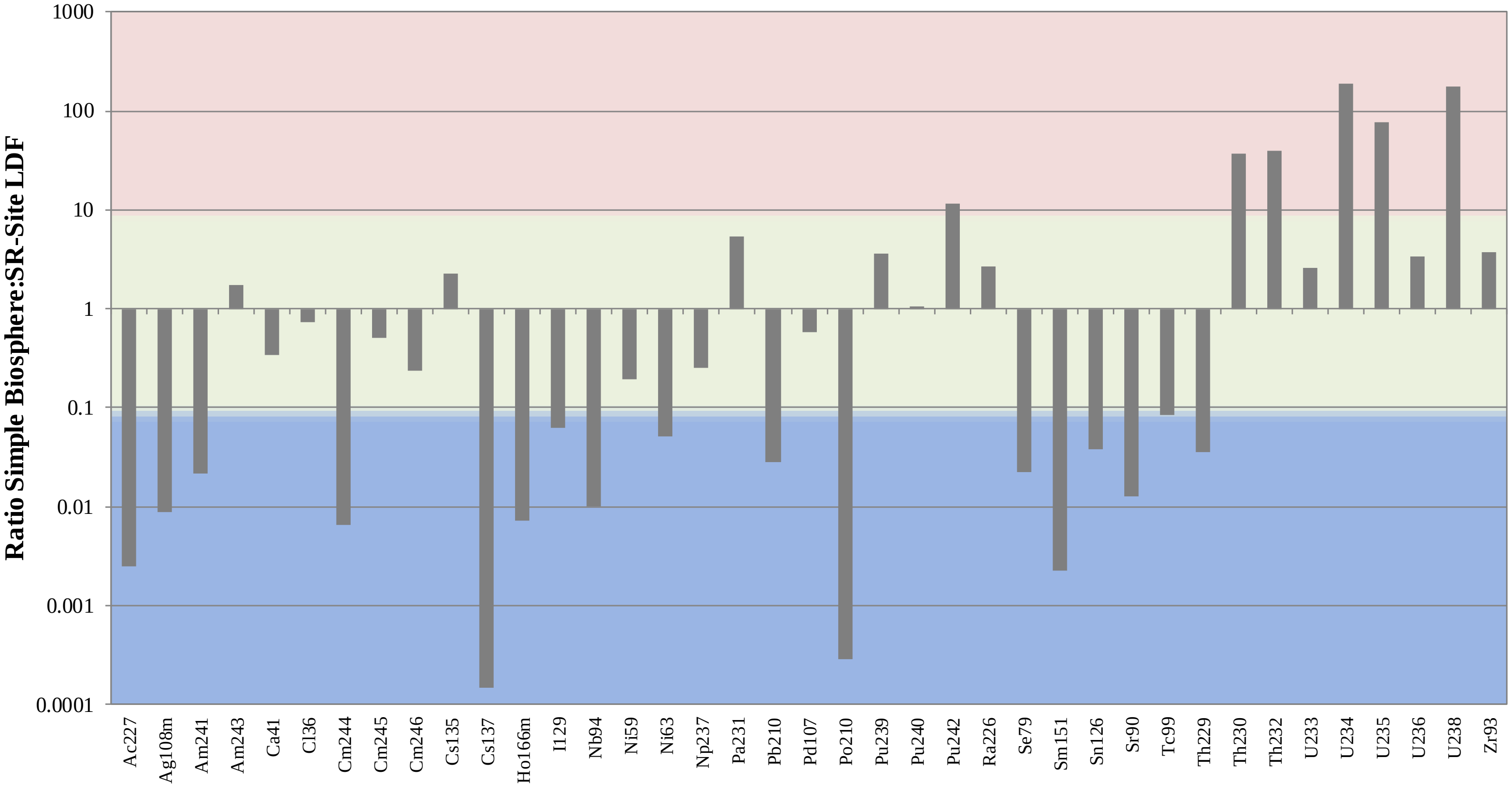


Figure 28: Comparison of maximum dose factors for groundwater release to combined arable and pasture system with SR-Site LDFs.

Table 78: Comparison of maximum dose factors for groundwater release to combined arable and pasture system with SR-Site LDFs.

Radio-nuclide	SR-Site Interglacial LDF Sv Bq^{-1}	Groundwater release to arable and pasture systems Sv Bq^{-1}	Ratio to SR-Site LDF
Ac-227	8.0E-12	2.0E-14	2.4E-03
Ag-108m	7.1E-13	6.2E-15	8.8E-03
Am-241	1.5E-12	3.2E-14	2.2E-02
Am-243	1.5E-12	2.6E-12	1.7E+00
Ca-41	9.9E-14	3.4E-14	3.4E-01
Cl-36	5.8E-13	4.2E-13	7.2E-01
Cm-244	8.7E-13	5.7E-15	6.5E-03
Cm-245	1.6E-12	8.1E-13	5.1E-01
Cm-246	1.6E-12	3.7E-13	2.3E-01
Cs-135	4.0E-14	9.0E-14	2.3E+00
Cs-137	1.2E-13	1.8E-17	1.5E-04
Ho-166m	5.9E-14	4.3E-16	7.3E-03
I-129	6.5E-10	4.0E-11	6.2E-02
Nb-94	4.0E-12	4.0E-14	1.0E-02
Ni-59	7.4E-14	1.4E-14	1.9E-01
Ni-63	1.2E-15	6.0E-17	5.0E-02
Np-237	4.8E-11	1.2E-11	2.5E-01
Pa-231	8.1E-12	4.4E-11	5.4E+00
Pb-210	5.1E-12	1.4E-13	2.8E-02
Pd-107	6.7E-15	3.9E-15	5.8E-01
Po-210	8.9E-12	2.5E-15	2.8E-04
Pu-239	1.9E-12	6.8E-12	3.6E+00
Pu-240	1.9E-12	2.0E-12	1.0E+00
Pu-242	1.9E-12	2.2E-11	1.2E+01
Ra-226	3.8E-12	1.0E-11	2.7E+00
Se-79	1.2E-09	2.7E-11	2.2E-02
Sm-151	7.2E-16	1.6E-18	2.3E-03
Sn-126	2.5E-11	9.5E-13	3.8E-02
Sr-90	2.2E-13	2.8E-15	1.3E-02
Tc-99	9.0E-13	7.5E-14	8.3E-02
Th-229	3.6E-12	1.3E-13	3.5E-02
Th-230	1.3E-11	4.9E-10	3.7E+01
Th-232	1.7E-12	6.7E-11	3.9E+01
U-233	2.5E-12	6.6E-12	2.6E+00

Radio-nuclide	**SR-Site Interglacial LDF Sv Bq^{-1}**	**Groundwater release to arable and pasture systems Sv Bq^{-1}**	**Ratio to SR-Site LDF**
U-234	3.6E-12	6.9E-10	1.9E+02
U-235	2.8E-12	2.2E-10	7.8E+01
U-236	1.9E-12	6.3E-12	3.3E+00
U-238	1.9E-12	3.3E-10	1.7E+02
Zr-93	2.8E-14	1.1E-13	3.8E+00

Note for Table 78: Differences greater than an order of magnitude are highlighted with red for higher dose factors and blue for lower dose factors. Results for both arable and pasture systems are based on organic/peat based soils, for consistency.

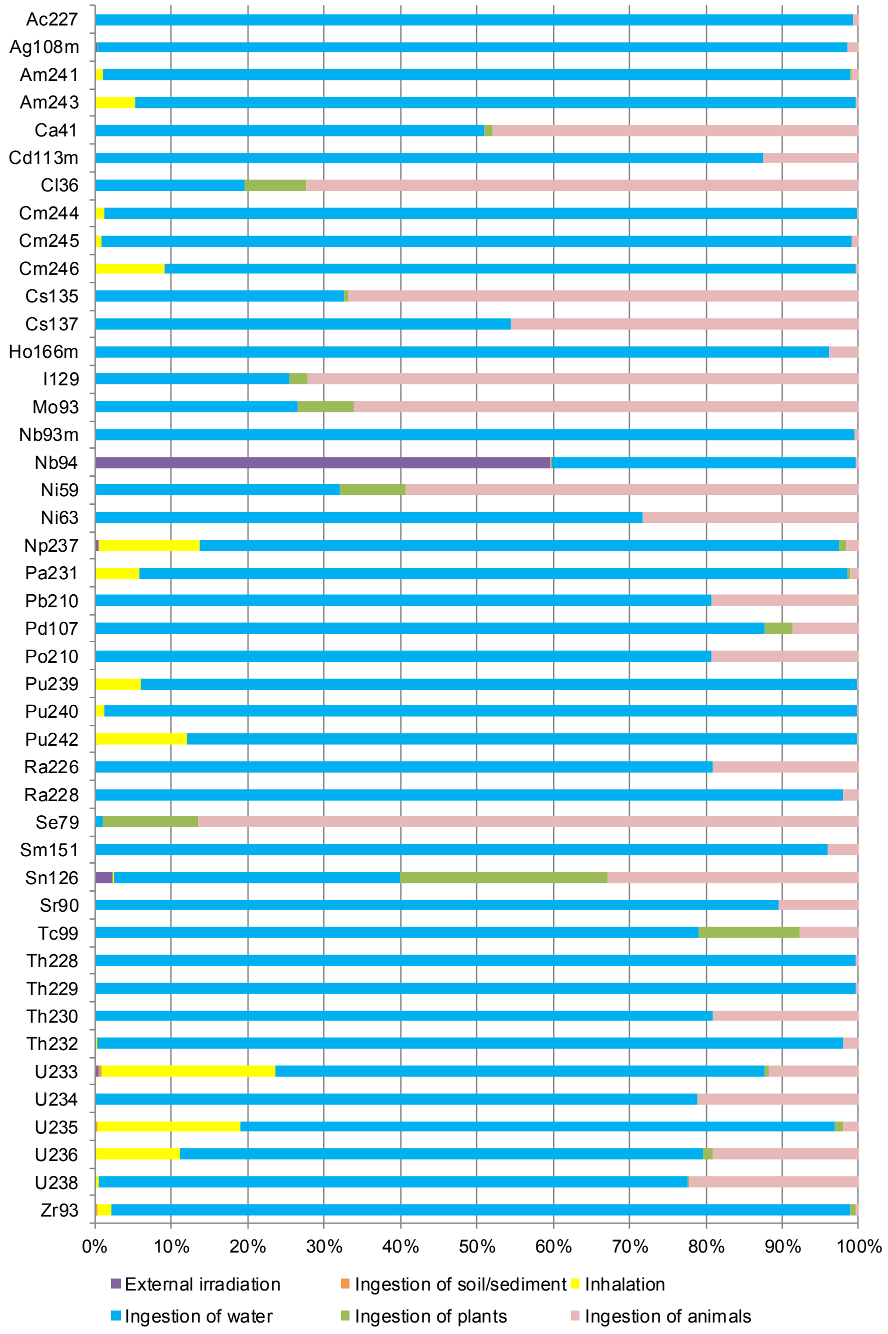


Figure 29: Contribution of different exposure pathways to the maximum dose factor for adults with no irrigation, but combining the arable and pasture exposures for each radionuclide.

10. Conclusions

This report presents results for simple reference biosphere models developed suitable to the context for the proposed geological repository for spent fuel at Forsmark in Sweden. The work contributes to the regulatory review of the SR-Site assessment undertaken by SKB.

The objective of the study was to use the SR-Site data, where appropriate, to support the development of simple biosphere models for comparison against the results of the more complex landscape evolution and biosphere object orientated approach adopted by SKB. In the process, the work would contribute to an understanding and review of the approach adopted by SKB.

Biosphere Modelling Approach Adopted in SR-Site

The SR-Site biosphere models focus on potential radionuclide releases to biosphere ‘objects’, which represent lake basins that arise in the present-day and projected landscape. The LDFs are calculated based on unit releases to each of these biosphere objects, which might typically support several tens of individuals. This approach includes the implicit assumption that radionuclide releases are distributed across each biosphere object/basin.

The SR-Site scenarios are based on consideration of a very small number of canister failures on a one million year timescale. Given the nature of potential groundwater flow via fractures from the repository to the surface, radionuclide releases from such point-sources may be relatively focused. For this reason, the simple models developed in this report focus on a smaller spatial scale than the SR-Site biosphere ‘objects’ and consider potential exposures that might arise to a small family group.

The focus of the SR-Site biosphere modelling solely on systems that evolve from marine, through lake and mire to terrestrial systems with associated organic soils, means that areas of clayey silty till, which are more suited to longer-term agriculture, are only considered in passing. Areas of clayey silty till are present in the landscape today, represent the primary soil type used for agriculture in the system today and are projected to be a non-trivial component of the landscape in future. Potential for groundwater discharge and use of such soils for agriculture is considered within the models developed in this report.

Surveys of wells within the Forsmark area show that some shallow wells are used for irrigation (Ludvigson, 2002). Potential use of well water for irrigation is excluded from the central calculations in SR-Site, although limited consideration is given to the use of well water for irrigation in side calculations. The potential for well water to act as a source of contamination for small scale cultivation is included in the models developed in this report.

The regolith in the SR-Site biosphere model is coarsely discretised, with only three compartments representing the advective/diffusive radionuclide transport pathway from the geosphere releases to the surface soils and sediments. The coarse discretisation means that the dynamics of accumulation in the biosphere are poorly represented in the SR-Site biosphere models, especially in the marine and lake systems where lower groundwater flow rates mean that diffusion becomes important. Although, side calculations show that the coarse discretisation will over-estimate dose factors; it also significantly underestimates the timescale for the system to reach equilibrium. Some consideration is given to discretisation of the lower regolith in Avila et al. (2010)[12], although the effect on time scales in the context of the sensitivity of the dose factors to the assumptions regarding climate evolution is not discussed.

Detailed hydrological and hydrogeological models of six lakes within the present-day Forsmark system is used to support the parameterisation of groundwater flow and discharge in the SR-Site biosphere models. However, the results of the detailed modelling are abstracted to such an extent before being used in the radionuclide transport modelling that confidence in the resulting flow scheme is reduced. In particular,

- the flows are averaged and normalised prior to use within the models, such that the water flow scheme does not appear to balance;
- not all of the flows derived from the detailed modelling appear to be used in the biosphere modelling; and
- net groundwater flow rates appear to be used instead of the modelled exchange in each direction.

The degree of sorption for some many radionuclides, combined with the dynamics of radionuclide transport within the Forsmark environment mean that it can take an extremely long time for an equilibrium to be reached between fluxes of radionuclides from the geosphere and potential exposures. In some cases, both within the SR-Site modelling and within the biosphere models presented in this report, equilibrium is not achieved. In the SR-Site documentation (Section 4.1 of Avila et al., 2010) the lack of an equilibrium is noted, but it is stated that, in most cases, the dose factors are approaching equilibrium on the approximate 20,000 year interglacial timescale considered in the reference calculations. The models described in this report include a more refined representation of the regolith and show that timescales to approach equilibrium will be significantly longer for some radionuclides. It is noted, however, that the modelling of non-evolving system means that some effective losses from surface sediments (e.g. net sedimentation and net erosion) are not represented, which will tend to extend the time required to achieve equilibrium.

A detailed, spatial and time-dependent representation of the biosphere is used in support of the SR-Site assessment. However, the results are used to support a single set of time-independent dose factors that represent the highest dose factors calculated at any time across all biosphere objects. The approach adopted in SR-Site is pessimistic. Exploration of results achieved by using the calculated geosphere fluxes as an input to the dynamic biosphere modelling would inform on how pessimistic the reference approach is. Direct use of a geosphere source term as input to the biosphere calculations would also avoid potential concerns of using the LDF approach in the absence of equilibria within any reasonable timeframes within the biosphere.

---

[12] Section 5.2.1.

Comparison of Landscape Dose Factors

Comparison of the SR-Site LDFs with equivalent factors calculated with the simple biosphere models described in this report indicates that:

- potential impacts are generally not underestimated for important radionuclides in SR-Site for releases to surface soils/sediments via groundwater;
- for some radionuclides, the explicit representation of transitions between marine, lake, mire and terrestrial systems results in dose factors that are more than an order of magnitude greater than those calculated with simple, non-evolving biosphere systems;
- for six radionuclides, the simple biosphere models resulted in dose factors more than an order of magnitude higher than those used in SR-Site when equivalent assumptions were adopted; and
- that a focus on exposure of adults in SR-Site is justified, but that potential for doses to children and infants that are up to about a factor of seven for certain radionuclides should be borne in mind.

Potential exposures arising from the use of shallow wells for small-scale horticulture in addition to domestic and other agricultural uses results in dose factors that are higher than those considered in SR-Site for 21 out of 39 radionuclides for which comparisons were possible.

Commentary on SR-Site Biosphere Reporting

The SR-Site reports demonstrate a thorough understanding of the present-day site and the way in which it will evolve into the future. The approach to representation of the biosphere in the post-closure safety assessment is complicated and is not aided by the description of the models and their parameterisation being distributed across five reports. The lack of a stand-alone full description of the quantitative assessment model means that it is difficult to get a clear understanding of what was done. In addition:

- some modelling assumptions are not explicitly discussed (e.g. the assumption that each crop takes up one fifth of terrestrial area of each object), but can be deduced from reference to the detailed mathematical functions presented as an appendix to Avila et al. (2010);
- the evolving nature of the biosphere objects means that many time-dependent parameters are not calculated but imposed as time-dependent input values based on supporting landscape development modelling, the values for which can be explored with access to the supporting data sets held in Microsoft Excel; and
- resource usage is based on consideration of a carbon model to help ensure internal consistency, however, there is little subsequent discussion of the results such that it is unclear (i) what exposure assumptions are ultimately represented in the models and (ii) if those behaviours are feasible and/or reasonable.

Some specific questions about the documentation of the SR-Site biosphere models have arisen during the course of this work. Most notably:

- Nordén et al. (2010) is not explicit about the secular equilibrium assumptions relating to short-lived radioactive daughters of modelled radionuclides. Reference is made to the assumptions included in calculations supporting exemption levels given in EU (1996), although assumptions about radionuclides that are explicitly modelled differ between the two assessments and branching ratios are not presented in EU (1996).

- Nordén et al. (2010) implies that the contribution of short-lived daughters is explicitly included in the dose coefficients used, however, many of the dose coefficients presented exclude the contribution of short-live daughters, so it is unclear if they were appropriately taken into account in the calculations or not.

Potential Further Work

The work presented in this report identifies several topics that warrant further consideration. These topics are summarised below.

- Further understanding of the SR-Site biosphere modelling could be developed by undertaking more detailed inter-comparisons to explore the more significant differences in calculated dose factors.
- Avila et al. (2010)[13] show that LDFs associated with the global warming variant can be higher than those for their reference interglacial period and that those for periglacial systems can be close (within an order of magnitude) to their reference dose factors. There is potential to explore both of these types of systems with variants to the simple reference biosphere models, which would help in understanding the way in which they have been represented in SR-Site.
- There is potential to improve understanding of key processes and uncertainties by undertaking sensitivity calculations; both alternative deterministic cases and probabilistic calculations could be used. For example, the implications of a focus on site-specific data within SR-Site could be explored with variant calculations based on generic data sets.
- The degree of pessimism introduced through using dose factors for systems that don't reach steady state/equilibrium conditions could be explored by undertaking calculations with the biosphere models in which the geosphere fluxes are used directly source terms.
- Comparison could be made by wider comparison of the calculated biosphere dose factors, e.g. with those used in support of other geological disposal programmes (e.g. Walke, 2013a; SNL, 2007) and/or in international studies (e.g. IAEA, 2003[14]).
- Potential exposures arising from discharges to forests could be further explored by including consideration of additional pathways not included in the present study. These include the potential use of wood as fuel and external irradiation from builds constructed with contaminated timber.

---

[13] Table 4-2 of Avila et al. (2010).

[14] It is noted that the maximum arable dose factors for Nb-94, Tc-99, I-129 and Np-237 compare well (within a factor of a few) with those of Example Reference Biosphere 2A (a simple biosphere model based on use of well water) in IAEA (2003), if account is taken of the flow rate in the till (15,400 m^3 y^{-1}) to provide an equivalent unit concentration in the well water.

- It is noted that the simple reference biosphere models do not address potential gaseous releases or potential impacts from C-14 or Rn-222 emanation.

11. References

Andersson E., 2010. The limnic ecosystems at Forsmark and Laxemar-Simpevarp, Svensk Kärnbränslehantering AB technical report TR-10-02.

Aquilonius K. (ed.), 2010. The marine ecosystems at Forsmark and Laxemar-Simpevarp, Svensk Kärnbränslehantering AB technical report TR-10-03.

Avila R., Ekström P-A., Åstrand P-G., 2010. Landscape dose conversion factors used in the safety assessment SR-Site, Svensk Kärnbränslehantering AB technical report TR-10-06.

Bergström U., Nordlinder S., 1990. Individual radiation doses from unit releases of long lived radionuclides, Svensk Kärnbränslehantering AB technical report TR-90-09.

Bergström U., Nordlinder S., Aggeryd I., 1999. Models for dose assessments: Modules for various biosphere types, Svensk Kärnbränslehantering AB technical report TR-99-14.

Bosson E., Sassner M., Sabel U., Gustafsson L.-G., 2010. Modelling of present and future hydrology and solute transport at Forsmark, Svensk Kärnbränslehantering AB report R-10-02.

Chamberlain A. C., 1970. Interception and retention of radioactive aerosols by vegetation, Atmospheric Environment, 4, 57-78.

Coughtrey P.J., Jackson D., Jones C.H., Kane P., Thorne M.C., 1984. Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems: A Critical Review of Data, Volume Four, A.A. Balkema, Rotterdam.

CSA, 2008. Guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operation of nuclear facilities, Canadian Standards Association guideline N288.1-08, Mississauga, Canada.

Eckerman K.F., Leggett R.W., 1996. DCFPAK: Dose coefficient data file package for Sandia National Laboratory. Report ORNL/TM-13347, Oak Ridge National Laboratory, U.S. Department of Energy.

Ekström P-A., 2010. Pandora – a simulation tool for safety assessments: Technical description and user’s guide, Svensk Kärnbränslehantering AB report R-11-01.

EU, 1996. Council Directive 96/92/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Luxembourg: European Commission.

Hedenström A., Sohlenius G., 2008. Description of the regolith at Forsmark, Site descriptive modelling SDM-Site Forsmark, Svensk Kärnbränslehantering AB report R-08-04.

IAEA, 1994. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments, International Atomic Energy Agency Technical Reports Series No. 364, Vienna, Austria

IAEA, 2003. “Reference Biospheres” for Solid Radioactive Waste Disposal. Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, International Atomic Energy Agency report IAEA-BIOMASS-6.

IAEA, 2004. Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment, International Atomic Energy Agency Technical Reports Series No. 422, Vienna, Austria.

IAEA, 2010. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, International Atomic Energy Agency Technical Reports Series No. 472, Vienna, Austria.

ICRP, 1975. Report on the Task Group on Reference Man. ICRP Publication 23.

ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Ann. ICRP 21 (1-3).

ICRP, 1996, Age-Dependent Doses to Members of the Public from Intakes of Radionuclides: Part 5 – Compilation of Ingestion and Inhalation Dose Coefficients. ICRP Publication 72, Ann. ICRP 26(1),

ICRP, 2008. Nuclear decay data for dosimetric calculations, ICRP Publication 107, Ann. ICRP 38 (3).

ICRP, 2013. Radiological protection in geological disposal of long-lived solid radioactive waste, ICRP Publication 122, Ann. ICRP 42 (3).

Jones C., 1987. Data for Alternative Biosphere States, and Soil Erosion, ANS Technical Note 595-27.

Jordbruks Verket, 2009a. Facts about Swedish Agriculture. Jordbruks Verket information booklet reference OVR2:GB.

Jordbruks Verket, 2009b. Livsmedelskonsumtionen 1960–2006, Statistik Från Jordbruks Verket Statistikrapport 2009:2.

Karlsson S., Bergström U., Meili M., 2001. Models for dose assessments: Models adapted to the SFR-area, Sweden, Svensk Kärnbränslehantering AB report TR-01-04.

Kemanian A.R., Stöckle C.O., Huggins D.R., Viega L.M., 2007. A simple method to estimate harvest index in grain crops, Field Crops Research 103 (2007) 208–216.

Larsson-McCann S., Karlsson A., Nord M., Sjögren J., Johansson L., Ivarsson M., Kindell S., 2002. Meteorological, hydrological and oceanographical information and data for the site investigation program in the communities of Östhammar and Tierp in the northern part of Uppland, Svensk Kärnbränslehantering AB technical report TR-02-02.

Leggett R.W., 2004. A biokinetic model for carbon dioxide and bicarbonate, Radiation Protection Dosimetry 108 (3) pp. 203-213.

Limer L.M.C., Thorne M.C., 2010. The biosphere transport, distribution and radiological impact of Se-79 released in groundwater from a geological disposal facility, Quintessa Limited report to NDA RWMD, QRS-1378W-4, Version 1.1, Henley-on-Thames, UK.

Lindborg T. (ed.), 2010. Landscape Forsmark – data, methodology and results for SR-Site, Svensk Kärnbränslehantering AB report TR-10-05.

Liu J., Löfgren M., Neretnieks I., 2006. Data and uncertainty assessment: Matrix diffusivity and porosity in situ, Svensk Kärnbränslehantering AB report for SR-Can, R-06-111.

Löfgren A. (ed.), 2010. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp, Svensk Kärnbränslehantering AB report TR-10-01.

Ludvigson J.-E., 2002. Brunnsinventering i Forsmark, Svensk Kärnbränslehantering AB report R-02-17.

Nordén S., Avila R., de la Cruz I., Stenberg K., Grolander S., 2010. Element-specific and constant parameters used for dose calculations in SR-Site, Svensk Kärnbränslehantering AB report TR-10-07.

Quintessa 2005. Modelling Advection, Dispersion and Diffusion, AMBER Guidance Note, Quintessa Limited.

Quintessa, 2012. AMBER 5.6: Reference Guide, Quintessa Limited report QE-AMBER-1, Version 5.6.

Sheppard S.C., Long J., Sanipelli B., Sohlenius G., 2009. Solid/liquid partition coefficients (Kd) for selected soils and sediments at Forsmark and Laxemar-Simpevarp, Svensk Kärnbränslehantering AB report R-09-27.

Smith K.R., Jones A.L., 2003. Generalised Habit Data for Radiological Assessments, National Radiological Protection Board report NRP-W41, UK.

SKB, 2010. Climate and climate-related issues for the safety assessment SR-Site, Svensk Kärnbränslehantering AB report TR-10-49.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project, Svensk Kärnbränslehantering AB report TR-11-01.

SNL, 2007. Biosphere Model Report, prepared by Sandia National Laboratories for the U.S. Department of Energy in support of the Yucca Mountain Project, MDL-MGR-MD-000001 REV 02, Las Vegas, U.S.A.

SSM, 2008. The Swedish Radiation Safety Authority’s regulations concerning safety in connection with the disposal of nuclear material and nuclear waste, Swedish Radiation Safety Authority Regulatory Code SSMFS 2008:21.

Thibault D.H., Sheppard M.I., Smith P.A., 1990. A critical compilation and review of default soil solid/liquid partition coefficients, Kd, for use in environmental assessments, Atomic Energy of Canada Limited, AECL‑10125.

Thorne M.C., 2008. LLWR Lifetime Project: The Biosphere Database for Use from the Present Day through to Scenario Termination, Mike Thorne and Associates Limited report to Nexia Solutions Limited MTA/P0022/2007-3, Issue 3, UK.

Walke R.C., Humphreys P., King F., Little R., Metcalfe R., Penfold J., Towler G., Walsh R., Wilson J., 2011. Postclosure Safety Assessment: Data, Nuclear Waste Management Organization report NWMO DGR-TR-2011-32, Toronto, Canada.

Walke R.C., Thorne M.C., Watson C.E., Limer L.M.C., 2012a. The PRISM Foodchain Modelling Software: Version 3.3 Technical Report, Quintessa Limited report to the UK Food Standards Agency QRS-3004G-1, Version 1.0, April 2012, UK.

Walke R.C., Thorne M.C., Limer L.M.C., 2012b. The PRISM Foodchain Modelling Software: Version 3.3 Data Report, Quintessa Limited report to the UK Food Standards Agency QRS-3004G-2, Version 1.0, April 2012, UK.

Walke R.C., Thorne M.C., Limer L.M.C., 2013a. RWMD Biosphere Assessment Model: Terrestrial Component, AMEC and Quintessa report to NDA RWMD, Quintessa reference QRS-1628A-2, Issue 2, March 2013, UK.

Walke R.C., Thorne M.C., Smith J.T., 2013b. RWMD Biosphere Assessment Model: Marine Component, AMEC and Quintessa report to NDA RWMD, Quintessa reference QRS-1628A-1, Issue 2, March 2013, UK.

Wasiolek M., Agüero A., Albrecht A., Bergström U., Grogan H., Smith G.M., Thorne M.C., Willans M. and Yoshida H., 2005. Modelling the Inhalation Exposure Pathway, report of Theme 2, Task 2, of the Bioprota collaborative project.

APPENDIX 1

Additional Results

A full set of biosphere dose conversion factors for all three age groups and for each of the six biosphere systems is given in Tables A1-1 to A1-6.

The adult results are broken down by exposure pathway in Figures A1-1 to A1-6.

Table A1 - 1: Calculated dose conversion factors for the arable system with peaty soil.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Ac227	4.7E-13	4.0E-13	4.5E-13	70	70	70
Ag108m	2.7E-13	2.2E-13	2.4E-13	1,000	1,000	1,000
Am241	7.8E-13	4.0E-13	3.6E-13	1,000	1,000	1,000
Am243	3.0E-11	1.5E-11	1.3E-11	30,000	30,000	30,000
Ca41	1.3E-13	1.8E-13	9.4E-14	2,000	2,000	2,000
Cd113m	5.2E-14	3.7E-14	3.4E-14	50	50	50
Cl36	8.6E-13	1.0E-12	1.5E-12	30	30	30
Cm244	1.0E-13	5.2E-14	4.4E-14	14,000	14,000	14,000
Cm245	1.9E-11	9.7E-12	8.6E-12	20,000	20,000	20,000
Cm246	3.8E-12	1.8E-12	1.6E-12	30,000	30,000	30,000
Cs135	8.5E-13	4.0E-13	2.3E-13	800,000	800,000	800,000
Cs137	3.9E-16	1.6E-16	8.8E-17	100	100	100
Ho166m	2.2E-14	1.2E-14	1.4E-14	4,000	4,000	4,000
I129	6.6E-11	6.5E-11	3.9E-11	400	400	400
Mo93	3.9E-12	3.0E-12	2.0E-12	5,000	5,000	5,000
Nb93m	2.2E-17	2.5E-17	4.4E-17	50	50	50
Nb94	7.0E-13	3.7E-13	4.6E-13	40,000	40,000	40,000
Ni59	3.9E-14	3.9E-14	5.6E-14	18,000	18,000	18,000
Ni63	1.5E-15	1.6E-15	2.3E-15	300	300	300
Np237	4.9E-11	2.3E-11	2.4E-11	1,000	1,000	1,000
Pa231	5.2E-10	3.8E-10	3.9E-10	40,000	40,000	40,000
Pb210	5.0E-12	6.2E-12	9.9E-12	70	70	70
Pd107	1.9E-14	2.3E-14	3.9E-14	8,000	8,000	8,000
Po210	8.9E-14	1.1E-13	1.8E-13	1	1	1
Pu239	6.9E-11	3.5E-11	2.9E-11	20,000	20,000	20,000
Pu240	3.5E-11	1.8E-11	1.5E-11	14,000	14,000	14,000
Pu242	1.0E-10	5.2E-11	4.2E-11	40,000	40,000	40,000
Ra226	3.6E-10	4.4E-10	7.1E-10	5,000	5,000	5,000
Ra228	1.5E-14	4.5E-14	3.3E-14	10	10	10
Se79	2.5E-11	7.9E-11	6.1E-11	1,000	1,000	1,000
Sm151	3.8E-17	3.9E-17	6.6E-17	200	200	200
Sn126	2.6E-12	3.0E-12	4.3E-12	16,000	16,000	16,000
Sr90	6.3E-14	6.8E-14	5.0E-14	90	90	90
Tc99	4.0E-13	4.3E-13	7.9E-13	10	10	10
Th228	1.8E-16	2.8E-16	3.8E-16	6	6	6
Th229	3.4E-12	3.0E-12	3.2E-12	20,000	20,000	20,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	1.5E-08	1.9E-08	3.0E-08	200,000	200,000	200,000
Th232	1.2E-09	3.3E-09	2.5E-09	800,000	800,000	800,000
U233	3.5E-11	2.7E-11	2.6E-11	80,000	80,000	80,000
U234	5.1E-09	6.3E-09	1.0E-08	200,000	200,000	200,000
U235	4.8E-10	3.5E-10	3.5E-10	120,000	120,000	120,000
U236	2.4E-11	1.8E-11	1.7E-11	90,000	90,000	90,000
U238	6.1E-10	7.5E-10	1.2E-09	300,000	300,000	300,000
Zr93	4.6E-13	1.3E-13	1.1E-13	20,000	20,000	20,000

Table A1 - 2: Calculated dose conversion factors for the pasture system with peat soil.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	**Child**	**Infant**	**Adult**	**Child**	**Infant**
Ac227	3.0E-29	1.7E-29	1.5E-29	300	300	300
Ag108m	6.6E-18	2.1E-18	1.5E-18	4,000	4,000	4,000
Am241	3.0E-17	1.6E-17	1.2E-17	8,000	10,000	50,000
Am243	3.1E-15	1.1E-15	1.0E-15	100,000	100,000	100,000
Ca41	4.3E-15	9.1E-15	9.9E-15	9,000	9,000	9,000
Cd113m	8.1E-28	9.0E-28	2.0E-27	200	200	200
Cl36	1.7E-13	3.0E-13	1.1E-12	100	100	100
Cm244	1.7E-18	7.6E-19	1.0E-18	100,000	200,000	300,000
Cm245	5.9E-16	3.2E-16	2.4E-16	30,000	40,000	70,000
Cm246	7.9E-16	2.8E-16	2.6E-16	180,000	200,000	200,000
Cs135	3.4E-14	2.3E-14	3.0E-14	900,000	900,000	900,000
Cs137	9.2E-36	5.4E-36	6.2E-36	400	400	400
Ho166m	9.1E-22	2.3E-22	1.5E-22	14,000	14,000	14,000
I129	2.0E-11	3.1E-11	4.1E-11	2,000	2,000	2,000
Mo93	1.3E-14	9.6E-15	8.4E-15	16,000	16,000	16,000
Nb93m	9.2E-37	1.6E-36	6.4E-36	200	200	200
Nb94	1.8E-14	4.5E-15	3.0E-15	120,000	120,000	120,000
Ni59	6.3E-15	9.7E-15	3.4E-14	70,000	70,000	70,000
Ni63	3.7E-24	6.1E-24	2.1E-23	1,000	1,000	1,000
Np237	1.5E-13	7.9E-14	6.0E-14	7,000	10,000	50,000
Pa231	1.6E-13	1.1E-13	1.2E-13	140,000	140,000	140,000
Pb210	5.5E-33	8.4E-33	1.1E-32	300	300	300
Pd107	8.4E-17	1.6E-16	6.2E-16	30,000	30,000	30,000
Po210	4.2E-38	6.0E-38	8.7E-38	6	6	6
Pu239	9.3E-15	3.1E-15	3.0E-15	90,000	90,000	90,000
Pu240	6.1E-16	2.8E-16	3.8E-16	100,000	200,000	300,000
Pu242	6.2E-14	2.2E-14	2.1E-14	180,000	180,000	180,000
Ra226	7.6E-20	1.2E-19	1.5E-19	18,000	18,000	18,000
Ra228	2.3E-37	7.3E-37	8.4E-37	90	90	90
Se79	1.8E-11	6.7E-11	1.1E-10	6,000	6,000	6,000
Sm151	1.9E-32	2.8E-32	2.9E-32	1,000	1,000	1,000
Sn126	1.7E-13	2.5E-13	6.1E-13	70,000	70,000	70,000
Sr90	3.7E-25	6.7E-25	1.0E-24	300	300	300
Tc99	3.3E-15	5.8E-15	2.4E-14	50	50	50
Th228	5.8E-47	2.7E-47	2.6E-47	30	30	30
Th229	8.4E-22	6.4E-22	5.4E-22	90,000	90,000	90,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	1.7E-14	2.6E-14	3.5E-14	600,000	600,000	600,000
Th232	1.2E-13	3.7E-13	4.2E-13	900,000	900,000	900,000
U233	3.9E-13	3.6E-13	5.0E-13	300,000	300,000	300,000
U234	1.3E-11	1.9E-11	2.6E-11	400,000	400,000	400,000
U235	3.0E-12	2.2E-12	2.7E-12	400,000	400,000	400,000
U236	2.9E-13	3.5E-13	7.3E-13	400,000	400,000	400,000
U238	1.0E-11	1.5E-11	2.1E-11	600,000	600,000	600,000
Zr93	4.1E-16	3.8E-16	1.4E-15	120,000	120,000	120,000

Table A1 - 3: Calculated dose conversion factors for the forest system.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Ac227	2.1E-30	1.8E-30	5.7E-31	300	300	300
Ag108m	3.6E-18	3.4E-18	3.7E-18	4,000	4,000	4,000
Am241	1.8E-17	9.1E-18	7.8E-18	8,000	40,000	60,000
Am243	2.4E-16	1.2E-16	5.9E-17	100,000	100,000	100,000
Ca41	7.1E-18	1.1E-17	5.6E-18	9,000	9,000	9,000
Cd113m	4.7E-28	2.6E-28	2.2E-28	200	200	200
Cl36	4.7E-15	4.7E-15	7.0E-15	100	100	100
Cm244	1.4E-19	7.7E-20	4.1E-20	180,000	200,000	300,000
Cm245	3.6E-16	1.8E-16	1.5E-16	30,000	60,000	70,000
Cm246	6.6E-17	3.7E-17	2.0E-17	200,000	200,000	400,000
Cs135	2.1E-13	8.0E-14	4.6E-14	900,000	900,000	900,000
Cs137	6.2E-35	2.1E-35	1.1E-35	400	400	400
Ho166m	8.0E-23	4.0E-23	3.0E-25	14,000	14,000	14,000
I129	1.4E-13	1.6E-13	9.8E-14	2,000	2,000	2,000
Mo93	3.2E-16	1.9E-16	1.4E-16	16,000	16,000	16,000
Nb93m	2.8E-37	3.3E-37	3.8E-37	200	200	200
Nb94	3.1E-15	1.5E-15	1.6E-17	140,000	140,000	140,000
Ni59	2.6E-16	2.0E-16	2.6E-16	70,000	70,000	70,000
Ni63	3.1E-25	2.5E-25	3.3E-25	1,000	1,000	1,000
Np237	9.1E-14	4.5E-14	3.9E-14	7,000	40,000	60,000
Pa231	6.8E-15	4.7E-15	2.0E-15	140,000	140,000	140,000
Pb210	1.2E-32	1.9E-32	3.3E-32	300	300	300
Pd107	1.7E-17	1.7E-17	2.6E-17	40,000	40,000	40,000
Po210	1.3E-37	2.0E-37	3.5E-37	6	6	6
Pu239	7.1E-16	3.7E-16	1.8E-16	90,000	90,000	90,000
Pu240	4.9E-17	2.8E-17	1.5E-17	180,000	200,000	300,000
Pu242	5.2E-15	2.9E-15	1.6E-15	200,000	200,000	400,000
Ra226	9.0E-20	1.3E-19	1.8E-19	18,000	18,000	18,000
Ra228	1.2E-35	2.9E-35	1.8E-35	90	90	90
Se79	3.7E-12	1.3E-11	1.4E-11	6,000	6,000	6,000
Sm151	9.9E-34	1.1E-33	1.0E-33	1,000	1,000	1,000
Sn126	1.4E-14	1.5E-14	2.1E-14	70,000	70,000	70,000
Sr90	1.0E-26	9.7E-27	5.8E-27	300	300	300
Tc99	2.5E-16	3.4E-16	6.4E-16	60	60	60
Th228	2.2E-47	3.6E-47	4.2E-47	30	30	30
Th229	1.1E-21	1.5E-21	1.5E-21	90,000	90,000	90,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	2.5E-14	3.5E-14	4.9E-14	700,000	700,000	700,000
Th232	9.3E-12	2.3E-11	1.4E-11	900,000	900,000	900,000
U233	2.5E-13	3.2E-13	3.1E-13	300,000	300,000	300,000
U234	2.1E-11	3.0E-11	4.1E-11	400,000	400,000	400,000
U235	1.5E-13	1.0E-13	4.9E-14	400,000	400,000	400,000
U236	3.1E-14	2.5E-14	1.7E-14	400,000	600,000	600,000
U238	1.6E-11	2.3E-11	3.2E-11	600,000	600,000	600,000
Zr93	1.9E-16	7.7E-17	5.5E-17	120,000	120,000	120,000

Table A1 - 4: Calculated dose conversion factors for the mire system.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Ac227	1.3E-31	1.3E-31	6.1E-32	300	300	300
Ag108m	4.5E-21	1.2E-22	1.7E-22	5,000	5,000	5,000
Am241	4.0E-18	3.2E-18	1.5E-18	160,000	200,000	200,000
Am243	2.4E-16	1.9E-16	6.2E-17	140,000	140,000	140,000
Ca41	6.5E-17	1.2E-16	7.1E-17	20,000	20,000	20,000
Cd113m	7.0E-31	6.6E-31	6.8E-31	200	200	200
Cl36	1.5E-15	2.4E-15	4.2E-15	400	400	400
Cm244	1.2E-19	1.1E-19	7.4E-20	600,000	600,000	700,000
Cm245	7.8E-17	6.3E-17	2.9E-17	180,000	200,000	200,000
Cm246	1.8E-16	1.5E-16	5.0E-17	300,000	400,000	400,000
Cs135	7.3E-17	4.6E-17	3.3E-17	900,000	900,000	900,000
Cs137	2.9E-40	1.2E-40	7.4E-41	500	500	500
Ho166m	1.8E-24	3.3E-27	1.5E-27	16,000	16,000	16,000
I129	7.3E-15	8.9E-15	5.5E-15	6,000	6,000	6,000
Mo93	2.3E-16	2.2E-16	2.1E-16	20,000	20,000	20,000
Nb93m	5.1E-41	4.3E-41	5.8E-41	200	200	200
Nb94	3.0E-16	4.8E-19	4.6E-19	160,000	160,000	160,000
Ni59	3.5E-17	4.5E-17	7.5E-17	140,000	140,000	140,000
Ni63	7.6E-28	1.0E-27	1.7E-27	1,000	1,000	1,000
Np237	2.0E-14	1.6E-14	7.3E-15	160,000	200,000	200,000
Pa231	5.7E-15	5.5E-15	2.5E-15	180,000	180,000	180,000
Pb210	7.1E-37	1.2E-36	2.0E-36	300	300	300
Pd107	1.1E-19	1.2E-19	1.7E-19	90,000	90,000	90,000
Po210	1.8E-41	2.8E-41	5.1E-41	6	6	6
Pu239	7.1E-16	5.6E-16	1.9E-16	120,000	120,000	140,000
Pu240	4.3E-17	4.0E-17	2.7E-17	600,000	600,000	700,000
Pu242	1.4E-14	1.2E-14	4.0E-15	300,000	300,000	400,000
Ra226	2.8E-22	4.6E-22	7.9E-22	18,000	18,000	18,000
Ra228	1.1E-40	1.3E-40	9.8E-41	90	90	90
Se79	7.9E-13	2.9E-12	3.1E-12	14,000	14,000	14,000
Sm151	2.7E-36	1.8E-36	1.0E-36	1,000	1,000	1,000
Sn126	9.7E-16	5.1E-17	4.4E-17	140,000	140,000	140,000
Sr90	1.7E-28	2.5E-28	1.9E-28	300	300	300
Tc99	1.5E-16	2.3E-16	4.4E-16	100	100	100
Th228	5.0E-51	2.8E-51	2.1E-51	30	30	30
Th229	2.2E-23	2.1E-23	9.7E-24	100,000	100,000	100,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	2.6E-16	4.2E-16	7.2E-16	700,000	700,000	700,000
Th232	4.8E-15	5.2E-15	3.3E-15	900,000	900,000	900,000
U233	9.3E-14	9.2E-14	5.1E-14	500,000	500,000	400,000
U234	1.6E-12	2.6E-12	4.4E-12	600,000	600,000	600,000
U235	5.4E-13	5.2E-13	2.8E-13	700,000	700,000	700,000
U236	7.8E-14	8.4E-14	7.7E-14	700,000	700,000	700,000
U238	3.0E-12	4.8E-12	8.0E-12	800,000	800,000	800,000
Zr93	9.6E-17	2.8E-17	1.9E-17	300,000	300,000	300,000

Table A1 - 5: Calculated dose conversion factors for the lake system.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Ac227	2.1E-30	1.9E-30	1.9E-30	300	300	300
Ag108m	1.1E-20	6.3E-21	5.1E-21	5,000	5,000	5,000
Am241	3.5E-15	1.9E-15	1.7E-15	100,000	120,000	120,000
Am243	5.4E-15	3.5E-15	2.7E-15	700,000	700,000	800,000
Ca41	3.2E-15	4.6E-15	2.3E-15	120,000	120,000	120,000
Cd113m	7.7E-30	5.4E-30	4.2E-30	200	200	200
Cl36	1.7E-14	1.8E-14	3.3E-14	2,000	2,000	2,000
Cm244	4.6E-19	2.9E-19	2.0E-19	500,000	700,000	700,000
Cm245	6.8E-14	3.7E-14	3.4E-14	120,000	120,000	120,000
Cm246	3.9E-14	2.3E-14	1.5E-14	800,000	800,000	800,000
Cs135	6.1E-17	2.6E-17	2.3E-17	900,000	900,000	900,000
Cs137	6.6E-39	2.6E-39	2.0E-39	400	400	400
Ho166m	3.3E-25	1.7E-25	1.1E-25	16,000	16,000	16,000
I129	2.8E-12	2.5E-12	1.5E-12	40,000	40,000	40,000
Mo93	3.0E-17	2.4E-17	1.9E-17	20,000	20,000	20,000
Nb93m	2.6E-39	3.2E-39	5.3E-39	200	200	200
Nb94	5.5E-17	2.8E-17	1.9E-17	180,000	180,000	180,000
Ni59	9.3E-17	9.1E-17	1.3E-16	300,000	300,000	300,000
Ni63	1.8E-28	1.9E-28	2.6E-28	1,000	1,000	1,000
Np237	1.7E-11	9.3E-12	8.6E-12	100,000	120,000	120,000
Pa231	1.7E-13	1.5E-13	1.5E-13	200,000	200,000	200,000
Pb210	5.5E-35	6.6E-35	9.3E-35	300	300	300
Pd107	2.3E-15	2.7E-15	5.0E-15	600,000	600,000	600,000
Po210	7.3E-40	8.8E-40	1.2E-39	6	6	6
Pu239	1.7E-14	1.1E-14	8.3E-15	700,000	800,000	800,000
Pu240	1.7E-16	1.0E-16	7.1E-17	500,000	700,000	700,000
Pu242	3.1E-12	1.8E-12	1.2E-12	800,000	800,000	800,000
Ra226	2.1E-22	2.5E-22	3.6E-22	18,000	18,000	18,000
Ra228	2.0E-40	5.0E-40	4.4E-40	90	90	90
Se79	4.4E-12	1.1E-11	1.3E-11	120,000	120,000	120,000
Sm151	5.8E-35	6.6E-35	9.1E-35	1,000	1,000	1,000
Sn126	4.7E-13	4.9E-13	9.7E-13	300,000	300,000	300,000
Sr90	1.1E-27	1.3E-27	7.2E-28	300	300	300
Tc99	9.1E-15	9.6E-15	2.1E-14	1,000	1,000	1,000
Th228	7.2E-51	9.3E-51	1.1E-50	30	30	30
Th229	4.6E-25	4.6E-25	4.4E-25	90,000	90,000	90,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	2.1E-17	2.5E-17	3.5E-17	700,000	700,000	700,000
Th232	8.9E-17	1.8E-16	1.6E-16	900,000	900,000	900,000
U233	7.3E-14	7.1E-14	6.6E-14	700,000	700,000	700,000
U234	5.9E-12	7.1E-12	1.0E-11	800,000	800,000	800,000
U235	1.0E-10	9.3E-11	9.4E-11	900,000	900,000	900,000
U236	9.3E-14	7.8E-14	6.1E-14	900,000	900,000	900,000
U238	2.3E-11	2.8E-11	3.9E-11	900,000	900,000	900,000
Zr93	9.3E-15	3.6E-15	3.6E-15	800,000	800,000	800,000

Table A1 - 6: Calculated dose conversion factors for the marine system with accumulation sediments.

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Ac227	2.8E-34	2.7E-34	2.4E-34	300	300	300
Ag108m	1.1E-22	9.8E-23	8.4E-23	5,000	5,000	5,000
Am241	1.0E-18	5.2E-19	4.5E-19	50,000	60,000	60,000
Am243	1.6E-17	1.0E-17	6.7E-18	200,000	400,000	600,000
Ca41	1.2E-18	1.8E-18	2.3E-18	80,000	80,000	80,000
Cd113m	2.8E-33	2.2E-33	1.4E-33	200	200	200
Cl36	1.7E-18	1.9E-18	1.2E-17	3,000	3,000	3,000
Cm244	1.1E-21	6.9E-22	5.6E-22	500,000	600,000	800,000
Cm245	2.0E-17	1.0E-17	8.8E-18	70,000	70,000	80,000
Cm246	1.2E-16	7.5E-17	4.7E-17	700,000	700,000	700,000
Cs135	6.2E-21	2.8E-21	2.8E-21	900,000	900,000	900,000
Cs137	2.8E-42	1.4E-42	9.4E-43	400	400	400
Ho166m	6.3E-28	3.4E-28	2.3E-28	16,000	16,000	16,000
I129	1.8E-15	2.0E-15	1.8E-15	18,000	18,000	18,000
Mo93	9.6E-21	1.1E-20	2.7E-20	30,000	30,000	30,000
Nb93m	5.5E-42	7.5E-42	1.2E-41	200	200	200
Nb94	1.4E-19	7.0E-20	4.6E-20	200,000	200,000	200,000
Ni59	5.9E-19	6.4E-19	8.5E-19	200,000	200,000	200,000
Ni63	8.7E-32	1.0E-31	1.3E-31	1,000	1,000	1,000
Np237	5.0E-15	2.6E-15	2.2E-15	50,000	60,000	60,000
Pa231	1.5E-16	1.4E-16	1.2E-16	200,000	200,000	200,000
Pb210	1.1E-38	1.4E-38	1.8E-38	300	300	300
Pd107	1.5E-18	2.2E-18	3.8E-18	300,000	300,000	300,000
Po210	1.4E-43	1.8E-43	2.5E-43	6	6	6
Pu239	4.9E-17	3.0E-17	2.0E-17	200,000	500,000	600,000
Pu240	4.1E-19	2.5E-19	2.0E-19	500,000	600,000	800,000
Pu242	9.7E-15	5.9E-15	3.7E-15	700,000	700,000	700,000
Ra226	1.8E-25	2.4E-25	3.0E-25	20,000	20,000	20,000
Ra228	2.8E-43	5.1E-43	5.7E-43	90	90	90
Se79	5.1E-15	1.3E-14	1.5E-14	50,000	50,000	50,000
Sm151	1.1E-37	1.4E-37	1.7E-37	1,000	1,000	1,000
Sn126	3.3E-14	4.1E-14	4.2E-14	300,000	300,000	300,000
Sr90	5.1E-33	7.0E-33	1.8E-32	400	400	400
Tc99	1.7E-16	2.4E-16	3.0E-16	1,000	1,000	1,000
Th228	1.5E-53	1.9E-53	2.0E-53	30	30	30
Th229	1.8E-28	2.0E-28	1.7E-28	90,000	90,000	90,000

Radio-nuclide	Maximum Dose Factor			Time to 90% Maximum Dose Factor		
	Adult	Child	Infant	Adult	Child	Infant
Th230	5.6E-20	7.4E-20	9.0E-20	800,000	800,000	800,000
Th232	1.1E-19	1.8E-19	1.9E-19	900,000	900,000	900,000
U233	3.5E-16	3.7E-16	3.3E-16	700,000	700,000	700,000
U234	8.9E-14	1.2E-13	1.4E-13	800,000	800,000	800,000
U235	1.3E-13	1.2E-13	1.1E-13	900,000	900,000	900,000
U236	2.4E-16	1.7E-16	2.7E-16	900,000	900,000	900,000
U238	3.4E-13	4.6E-13	5.5E-13	900,000	900,000	900,000
Zr93	1.1E-16	4.7E-17	3.7E-17	700,000	700,000	700,000

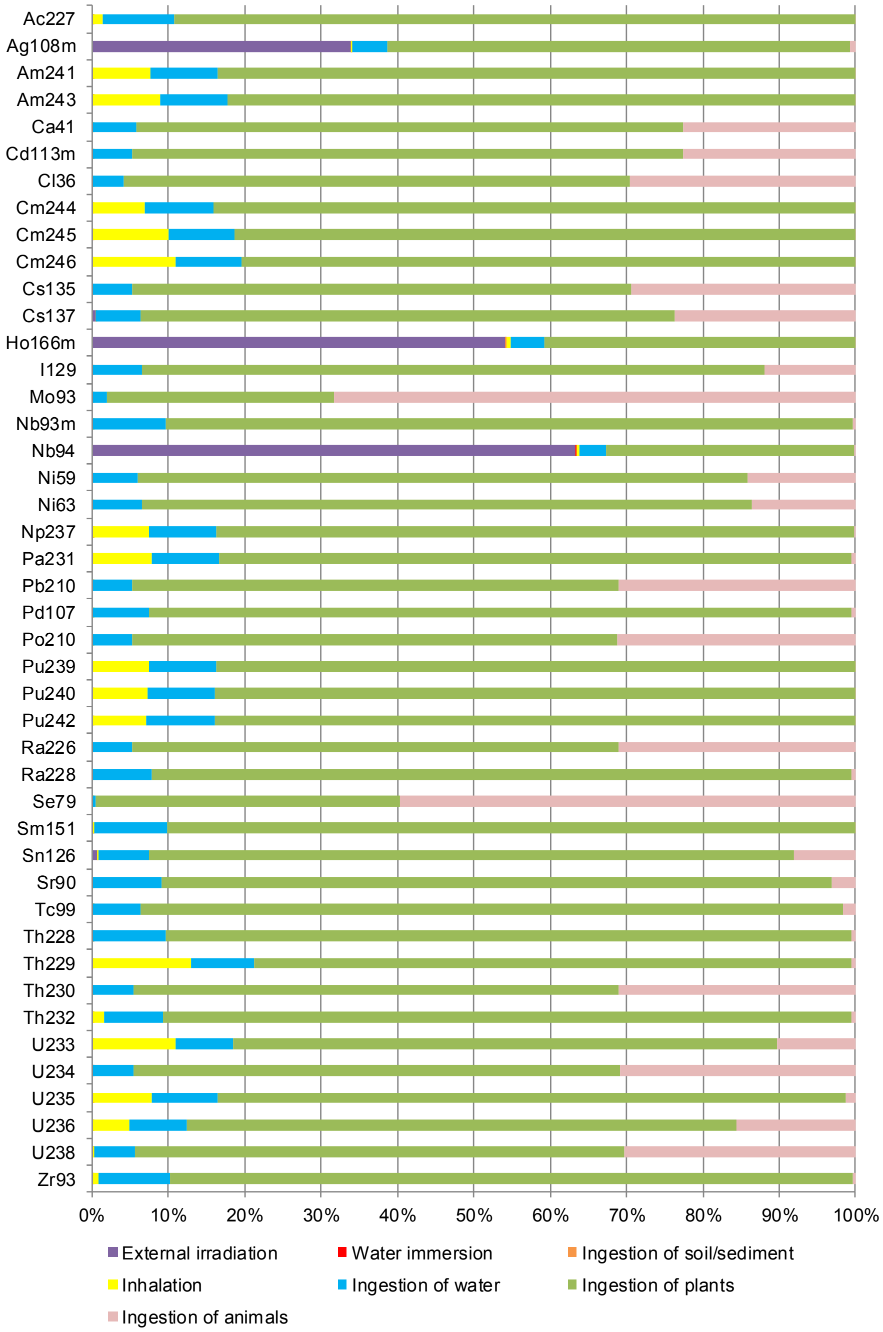


Figure A1-1: Contribution of different exposure pathways to the maximum dose factor for adults in the arable system for each radionuclide.

Figure A1-2: Contribution of different exposure pathways to the maximum dose factor for adults in the pasture system for each radionuclide.

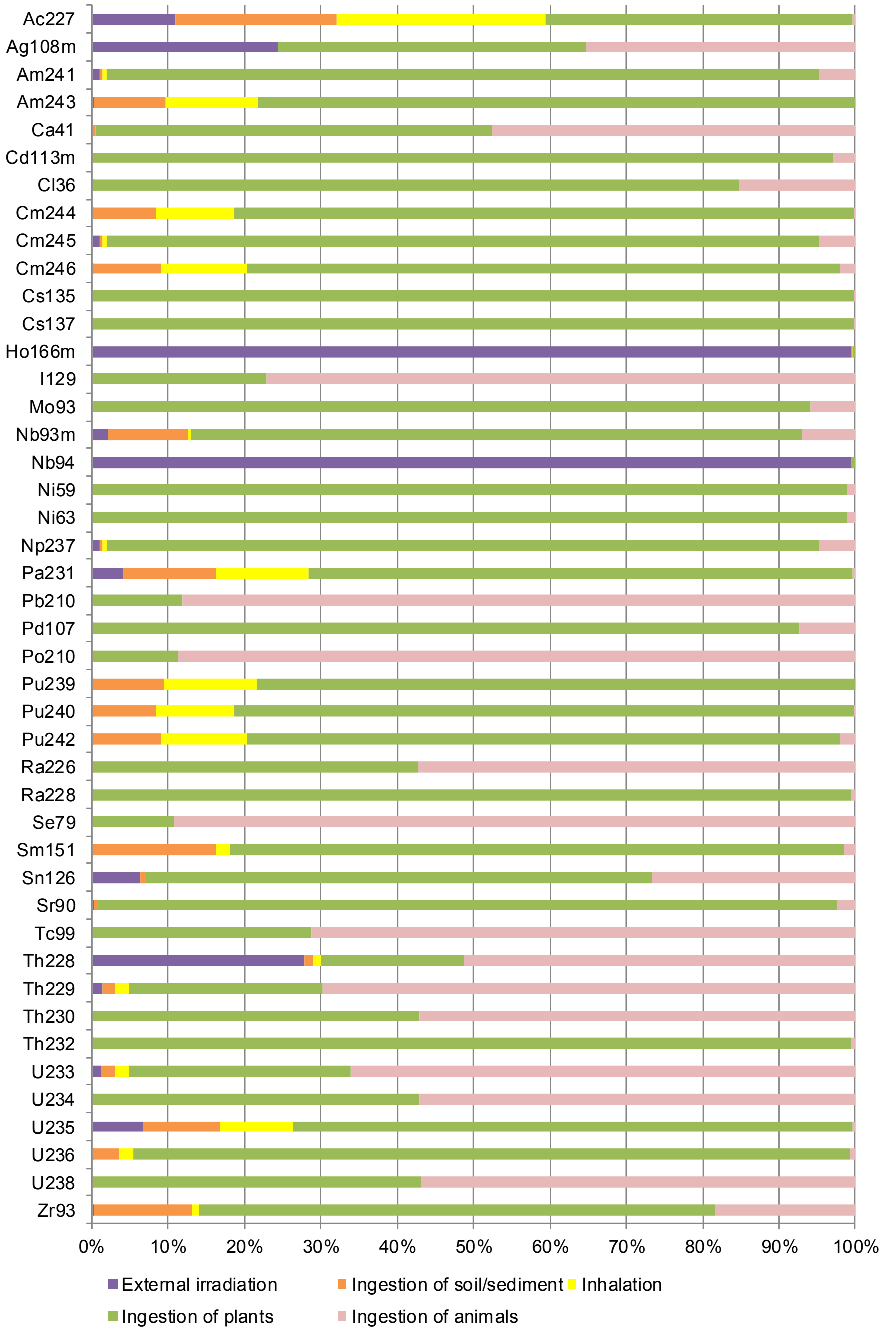


Figure A1-3: Contribution of different exposure pathways to the maximum dose factor for adults in the forest system for each radionuclide.

Figure A1-4: Contribution of different exposure pathways to the maximum dose factor for adults in the mire system for each radionuclide.

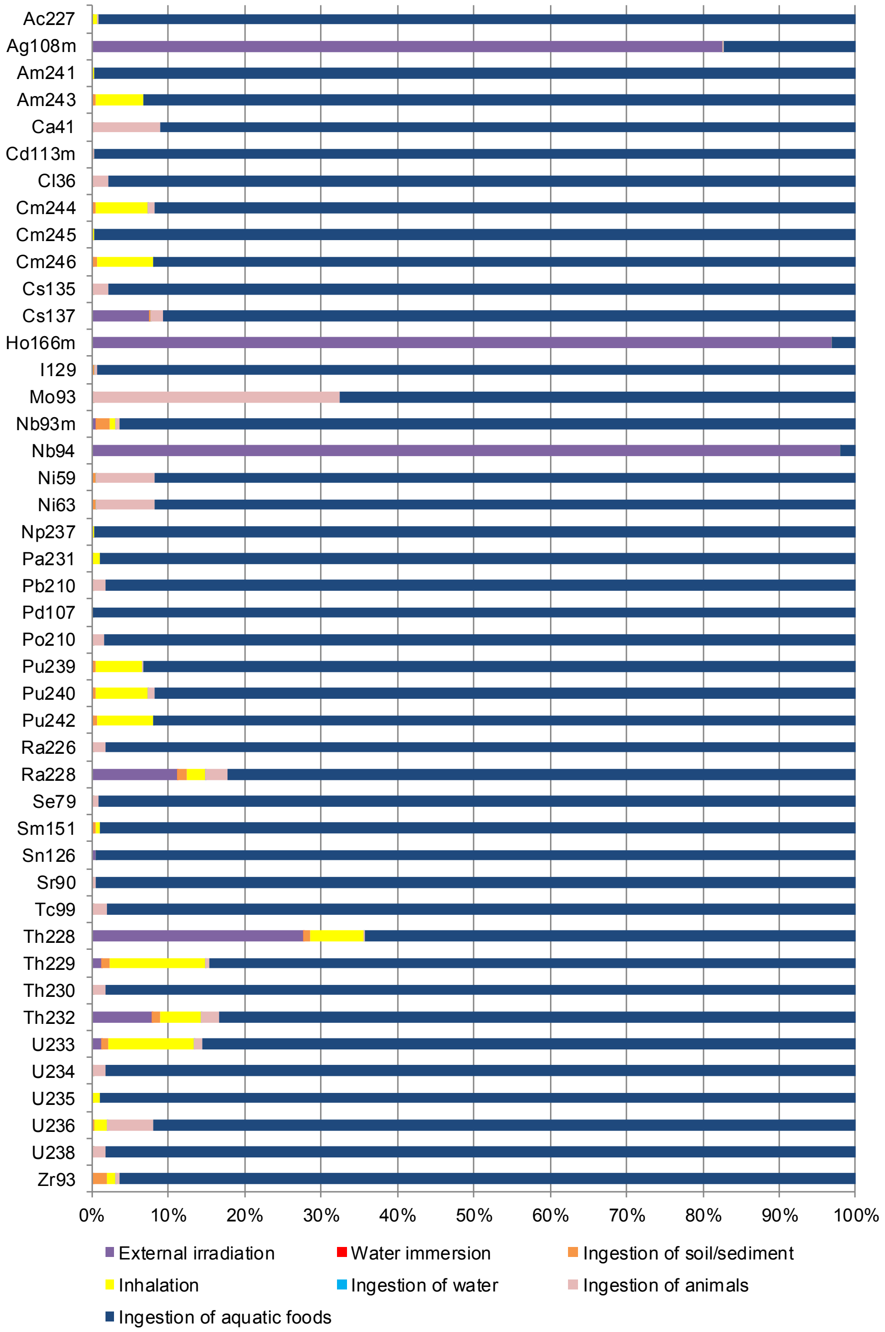


Figure A1-5: Contribution of different exposure pathways to the maximum dose factor for adults in the lake system for each radionuclide.

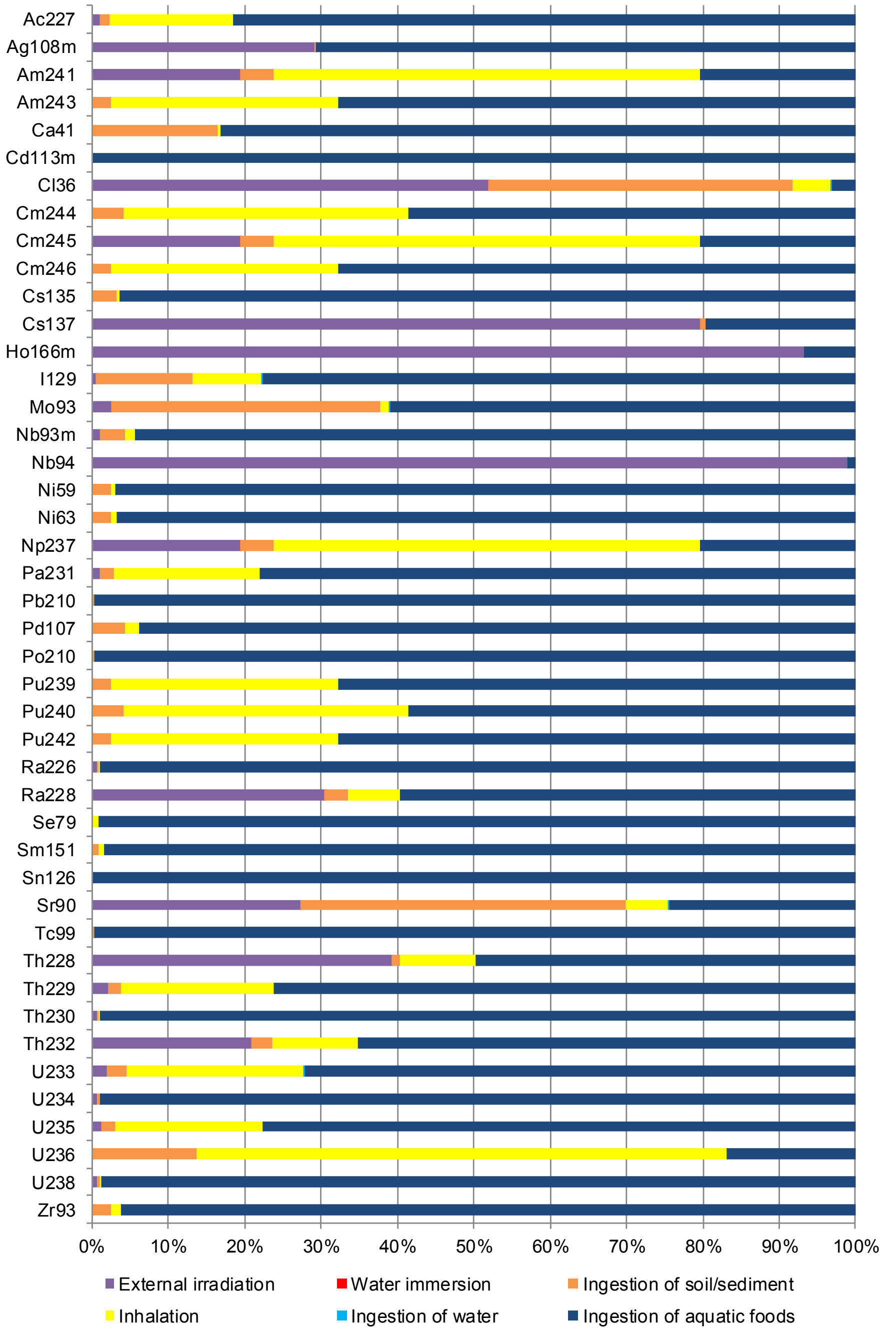


Figure A1-6: Contribution of different exposure pathways to the maximum dose factor for adults in the marine system for each radionuclide.

2014:34

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 315 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se