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Technical Note

2014:54

Further Modelling Comparison of Simple Reference Biosphere Models with the LDF Modelling Approach

Main Review Phase

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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 göra en mer djupgående jämförelse mellan referensbiosfärsmodeller och LDF modellering, för att förstå de signifikanta skillnaderna i dosfaktor mellan de två metoderna som framkommit i tidigare uppdrag (Walke, 2014).

Författarnas sammanfattnin

Denna Technical Note beskriver fortsatt modellering med enkla referensbiosfärsmodeller för granskning av metodologin med landskapsspecifika doskonverteringsfaktorer (LDF) som SKB använder i SR Site. Enkla biosfärmodeller för Forsmark med tempererade klimatförhållanden har tidigare utvecklats för SSM och beskrivs i Walke (2014), tillsammans med jämförelser mot SKB:s LDF modellering. Den aktuella studien har två syften:

- För det första, att utöka SSM:s enkla modeller av Forsmark så att varma och periglaciala klimattillstånd inkluderas.
- För det andra, att ytterligare undersöka skillnaderna mellan dosfaktorer för biosfären beräknade med SSM:s enkla modeller och de beräknade enligt LDF metoden som SKB använder i SR-Site.

Modelleringen av de varmare systemen i de enkla biosfärmodellerna bygger på beskrivningar i SR-Site av ett varmt klimat i Forsmark och innebär ökad avrinning, ökad bevattning och ökad tid utomhus. Dosfaktorer beräknade för varma klimatförhållanden visar sig vara genomgående högre än för dagens klimatförhållanden, främst på grund av ökad bevattning och tid utomhus.

I SR-Site finns ett fall som inkluderar ”global uppvärmning”. I SKB:s rapportering med beskrivningar av terrester, limnisk och marin biosfär i Forsmark redogörs för varmare förhållanden med ökad avrinning och för parametervärden som ger ökad produktivitet. Men dessa beaktas inte i dosmodelleringen utan där används istället ett fall med ”global uppvärmning” som beskrivs som att de interglaciala förhållandena pågår under längre tid än i referens glaciationscykeln utan att parameteriseringen av systemet ändras. Som väntat leder detta till att LDF värden för fallet ”global uppvärmning” bara skiljer sig för de långlivade radionuklider som inte har uppnått jämvikt i slutfasen av de interglaciala förhållandena i referens glaciationscykeln.

Denna Technical Note beskriver också hur periglaciala förhållanden inkluderas i den enkla biosfärs modelleringen av Forsmark. De periglaciala förhållandena bygger på beskrivningar av kallare förhållanden i SR-Site och innebär alternativa vattenflöden och vanor. Den enkla modellen för periglaciala förhållanden omfattar möjligheten till småskaligt jordbruk. I SR-Site rapporteringen presenteras parametervärden för jordbruksproduktion under permafrostförhållanden, men dessa värden används inte i dosberäkningsmodellerna.

Precis som LDF modelleringen visar den enkla biosfärsmodelleringen att dosfaktorer för periglaciala förhållanden typiskt är betydligt lägre än för dagens förhållanden. För de enkla biosfärsmodellerna beror detta främst på avsaknaden av bevattning med grundvatten, kortare tid utomhus och antagandet att endast en bråkdel av ett utsläpp kan gå till mark som gränsar till en öppen talik. Dosfaktorer för kortlivade radionuklider under periglaciala förhållanden är betydligt lägre än LDF värden under permafrostförhållanden. Detta beror på att det saknas spridningsvägar för vatten i båda modellerna, vilket innebär att resultaten är känsliga för den grova diskretisering som LDF modellerna har, vilket i sin tur har visat sig leda till mycket konservativa resultat för kortlivade radionuklider.

Ytterligare jämförelser mellan de enkla biosfärmodellerna och resultat från SR-Site understryker vikten av brunnsvattnen som spridningsväg i LDF modelleringen under interglaciala förhållanden. Förbrukning av vatten från en djup brunn visade sig bidra med mer än 50 % av dosen för 32 av de 39 studerade radionukliderna. Om den enkla modellen anpassas med liknande antaganden som i SKB:s LDF modeller (t.ex. att bevattning med grundvatten utesluts och att SKB:s modell för brunnsvattenkoncentrationer används) då ger den enkla biosfärsmodellen dosfaktorer som stämmer överens med LDF modelleringen under interglaciala förhållanden. Men det kan noteras att SKB:s modell för brunnsvattenkoncentrationer utelämnar bidrag från radionuklider som uttryckligen modelleras i biosfären, men inte explicit modelleras i geosfären (särskilt Po-210).

Med de enkla modellerna kan inte livsmiljöers succession och landskapsutveckling modelleras. Men de är mer komplexa i den vertikala diskretiseringen jämfört med LDF-modellerna. Den vertikala diskretiseringen i de enkla modellerna syftar till att tydligt reflektera tidsskalorna för spridning av radionuklider för en grundvattenkällterm.

Den grova diskretiseringen i LDF modellerna leder till mycket konservativa resultat för kortlivade radionuklider. Dessutom innebär den grova diskretiseringen att inte tillräcklig hänsyn tas till tidsskalor för radionuklid ackumulering och inväxt. Effekten av den grova diskretiseringen maskeras i LDF modelleringen av dominansen av spridningsvägen via brunnsvatten. Detta förenklade tillvägagångssätt stämmer dåligt med den omsorg SKB lägger på att studera och modellera landskapets evolution och de tillhörande tidsskalorna. Värdet av modelleringen av ett slutförvarssystem i Forsmark som utvecklas med tiden undermineras därför av det förenklade tillvägagångssättet för dosberäkningsmodelleringen.

Projektinformation

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Diarienummer avrop: SSM2014-1146
Aktivitetsnummer: 3030012-4089

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 purpose is to do a more in-depth comparison between reference biosphere models and the LDF modelling approach to understand the significant differences between the dose factors produced by the two methodologies.

Summary by the authors

This Technical Note describes further use of simple reference biosphere models for SSM's review of 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. Simple biosphere models for the Forsmark site under temperate climate conditions were previously developed for SSM's review and are described in Walke (2014), along with comparisons against SKB's LDF modelling approach. The current study had two objectives.

- Firstly, to extend SSM's simple models of the Forsmark site to include the capability to represent warm and periglacial climate states.
- Secondly, to further explore differences between the biosphere dose factors calculated with SSM's simple models and those calculated using the LDF approach used by SKB in its SR-Site assessment.

The representation of the warmer systems in the simple biosphere models draws on the SR-Site descriptions of a warm climate at Forsmark to justify increased runoff, increased irrigation and increased occupancies. Dose factors calculated for warm climate conditions are shown to be consistently higher than those for present-day climate conditions, principally due to increased irrigation and occupancies.

The SR-Site assessment includes a 'global warming' case. Descriptive reports on the terrestrial, limnic and marine biosphere at Forsmark describe warmer conditions with increased runoff and present parameter values for increased productivity. However, these are not taken into account in the dose assessment modelling, which instead simply represents a 'global warming' case as one where the interglacial conditions last longer than in the reference glacial cycle, without changing the parameterisation of the system. As might be expected, LDFs for the 'global warming' case only differ for those long-lived radionuclides that have not reached equilibrium by the end of the interglacial conditions in the reference glacial cycle.

This technical note also describes the inclusion of periglacial conditions in the simple biosphere modelling of the Forsmark site. The representation of periglacial conditions draws on the SR-Site descriptions of colder conditions to justify alternative water flows and habits. The simple model for periglacial conditions includes the potential for small-scale agriculture. The SR-Site reports present parameter values for agricultural production under permafrost conditions, however, these are then excluded from the dose assessment modelling.

Consistent with the LDF modelling, the simple biosphere modelling shows that dose factors for periglacial conditions are typically significantly lower than under present-day conditions. In the case of the simple biosphere models, this is principally due to the absence of irrigation with groundwater, lower occupancies and the assumption that only a fraction of a discharge might go to soils adjacent to an open talik. Dose factors for shorter-lived radionuclides under periglacial conditions are shown to be significantly lower than LDFs for permafrost conditions. This is due to the absence of well water pathways in both models, which means that the results are sensitive to the coarse discretisation adopted in LDF models, which is shown to be significantly conservative for shorter-lived radionuclides.

Further comparison of the simple biosphere models with the SR-Site results highlights the importance of the well water pathway to the LDFs for interglacial conditions. Consumption of water from a deep well is shown to contribute more than 50% of the dose for 32 out of the 39 radionuclides studied. If the simple model is adapted to resemble assumptions adopted in SKB's LDF models (e.g. if irrigation with groundwater is excluded and if the SKB's model for well water concentrations is used), then the simple biosphere model produces dose factors that are consistent with the SR-Site LDFs for interglacial conditions. However, it is noted that the SKB model for well water concentrations omits the contribution of radionuclides that are explicitly modelled in the biosphere, but are not explicitly modelled in the geosphere (notably Po-210).

The 'simple' models do not represent habitat succession and landscape evolution. However, they are more complex in their vertical discretisation, which is more refined in comparison to that adopted in the SR-Site LDF models. The vertical discretisation in the simple models aims to properly reflect the time scales for radionuclide migration for a groundwater source term.

The coarse discretisation adopted in the SR-Site LDF models is shown to be significantly conservative for shorter-lived radionuclides. In addition, the coarse discretisation means that the time scales for radionuclide accumulation and in-growth are not appropriately represented. The effect of the coarse discretisation is masked in the LDF modelling by the dominance of the well water pathway. This coarse approach is inconsistent with the care that is taken by SKB to study and model the landscape evolution and associated time scales. The value in the representation of the evolving system at Forsmark is therefore undermined by the coarse approach adopted in the dose assessment modelling.

Project information

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Contents

1. Introduction

This Technical Note describes further use of simple reference biosphere models for SSM's review of the Landscape Dose Factor (LDF) approach[1] adopted by SKB in the SR-Site safety assessment for the proposed final disposal of spent nuclear fuel at the Forsmark site. Simple biosphere models for the Forsmark site under present-day climate conditions were previously developed for SSM's review and are described in Walke (2014), along with comparisons against SKB's LDF modelling approach. The current study had two objectives.

- Firstly, to extend SSM's simple models of the Forsmark site to include the capability to represent warm and periglacial climate states.
- Secondly, to further explore differences between the biosphere dose factors calculated with SSM's simple models and those calculated using the LDF approach used by SKB in its SR-Site assessment.

The adaptation of the simple biosphere models to include additional climate states is described in Section 2. Further investigation of differences between the simple biosphere modelling and the SR-Site LDF modelling is described in Section 3. Conclusions are presented in Section 4. Finally, references are presented in Section 5.

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[1] The dose factors convert the calculated radionuclide releases to the biosphere into effective doses and have units of Sv Bq^{-1}.

2. Inclusion of Additional Climate States

The biosphere models described in Walke (2014) allow calculations for radionuclide releases to the biosphere under the existing climate conditions for the Forsmark site. The models allow releases to marine, lake, mire, forest, pasture and arable systems to be represented. The remit of this study was to develop simple biosphere models for additional climate states, but to use the information and modelling data used by SKB in its SR-Site assessments, where appropriate.

Descriptions of warm climate and periglacial conditions at the Forsmark area are provided in Section 2.1, based on the SR-Site documentation. Calculation cases are then defined in Section 2.2. Adaptations of the biosphere to represent the additional climate states are described in Section 2.3. Results for the additional climate states are then presented and compared against the SR-Site LDFs in Section 2.4.

2.1. Description of Additional Climate States

Warm climate conditions at Forsmark are described in Section 2.1.1 and periglacial conditions in Section 2.1.2.

2.1.1. Description of Warm Climate Conditions

The reference case for the SR-Site study was based on a reconstruction of the last glacial cycle, which is described in detail in SKB (2010a). However, SKB (2010a) notes that the next 100,000 year period is predicted to be characterised by exceptionally small amplitudes of insolation variation, which drives long-term climate cycles. The low variation in insolation suggests that the Earth will experience an extended interglacial period. Increasing greenhouse gas concentrations, coupled with the low variation in insolation, imply that the Earth may experience an extended period with a climate that is warmer than that at the present day.

SKB undertook global and regional climate modelling that took into account the low variation in insolation and projected increased levels of greenhouse gases (summarised in SKB, 2010a). Both the global and regional climate modelling projected warmer temperatures in Scandinavia. The regional climate modelling was used to support projections for the global warming case, which are summarised in Table 1. The table shows warmer temperatures, a 21% increase in annual precipitation and a 42% increase in surface runoff.

The primary impacts of a warmer climate are changes to the hydrology of the biosphere systems and changes to human habits. Although on an annual average basis, both precipitation and surface runoff increase, warmer climate conditions will result in increased evapotranspiration in the summer and a likely increase in the potential need for irrigation of crops.

Irrigation of crops is practiced in Sweden under present-day conditions, with 4.1% of the agricultural area irrigated in 1993 and an average rate[2] of 100 mm a^{-1} (Baldock et al., 2000). The amount of irrigation practised is highest in southern Sweden, with average rates of about 126 mm a^{-1} under the present-day climate in the southern area of the country bordering the Baltic Sea. Groundwater supplies about 30% of the irrigation water used in Sweden today and wide range of crops are irrigated, including cereals (Brundell et al., 2008).

Table 1: Simulated warm climate conditions and comparison against simulated present-day conditions (1961-2000).

Characteristic	Present-day	Warmed Conditions	Notes
Annual average temperature	4.7°C	8.3°C	Increase of 3.6°C compared to present-day. Comparative warming is stronger in winter than in summer.
Annual precipitation	666 mm	804 mm	Increase of 138 mm (21%) compared to present-day.
Annual surface runoff	175 mm	249 mm	Increase of 74 mm (42%) compared to present-day.

Note: Based on p232 of SKB (2010a) and on Tables 8-1 and 8-2 of Andersson (2010), although inconsistencies between the tables and references are noted[3].

2.1.2. Description of Periglacial Conditions

Periglacial conditions are defined based on the presence of permafrost. Permafrost is ground that remains frozen for more than two subsequent years. In the climatological modelling that supports the SR-Site assessment, the permafrost climate at the Forsmark site was associated with daily temperatures below 0°C for at least nine months of the year and below -10°C for at least six months of the year. Temperatures rarely exceed 20°C, although the ground surface melts in summer months.

Precipitation is lower than under present-day conditions, but evapotranspiration is also lower, so run-off can be about the same or slightly higher. However, given the frozen state for most of the year, the main part of the run-off and associated turnover occurs during a relatively short ‘active’ period each year.

There is no groundwater flow through permafrost, so there is no connectivity of the ground surface above permafrost with contaminated groundwater below. However, groundwater often remains unfrozen beneath lakes; these water pockets within areas of permafrost are called taliks (see Figure 1). Taliks are important because they represent locations of potential discharge for deeper contaminated groundwater to the surface. Taliks can represent locations for groundwater recharge, however, SKB

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[2] This average rate is consistent with that used for the arable system under present-day climate conditions in Walke (2014).

[3] 4.7°C plus 3.6°C does not equal 8.0°C, as indicated between Tables 8.1 and 8.2 of Andersson (2010). Annual surface runoff value of 337 mm on p232 of SKB (2010a) is not the same as the value of 249 mm presented in Table 8-1 of Andersson (2010).

modelling shows potential for some taliks at the Forsmark site to receive groundwater discharges.

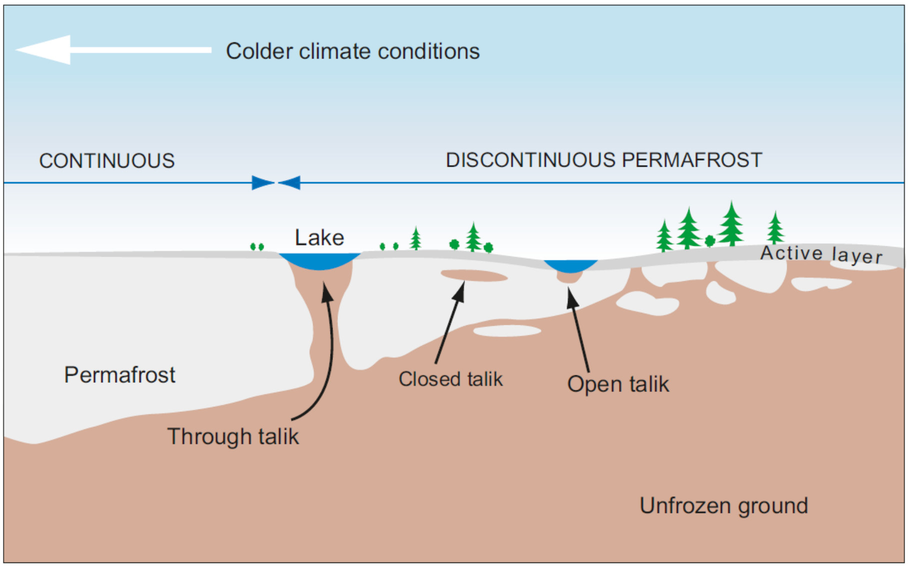

Figure 1: Fundamental features of the permafrost environment (Figure 3-7 from Lindborg, 2010).

Marine System Under Periglacial Conditions

The marine system under periglacial conditions will be subject to low temperatures and the presence of sea ice. The marine system will have lower productivity in comparison to the present-day. However, there is extensive fishing in present-day regions of periglacial climate (e.g. off the coast of Greenland), indicating that fishing will continue to be sustainable.

Limnic System Under Periglacial Conditions

Lakes under periglacial conditions would not have reed margins, but would instead be surrounded by mosses and vascular plants. Thermokarst lakes may form, where ground thaws above permafrost, but they have no connectivity to deep groundwater and so are not considered further. The magnitude of run-off under periglacial conditions is similar to the present-day, although circulation and nutrient status will be affected by the relatively short period without ice.

The concentration of particulate matter will probably be lower in periglacial conditions, even compared to the relatively clear-water lakes in the Forsmark area in the present-day. Periglacial lakes will have lower sedimentation rates in comparison to present-day lakes in the Forsmark area.

Primary productivity within periglacial lakes may be similar to the present-day. Crayfish are less likely to be present compared to present-day lakes due to the short growing season. Fish diversity, biomass and productivity will be reduced due to lower temperatures and potentially poor oxygen status during winter periods.

Terrestrial System under Periglacial Conditions

Periglacial landscapes are typified by tundra conditions, which are characterised by a treeless landscape. Shrubs may be present under more wet conditions, e.g. associated with the margins of taliks. Tundra systems exhibit lower biomass and primary productivity than the present day biosphere systems in the Forsmark area.

Although uncommon, it is feasible to produce some crops under tundra conditions during the short growing season (e.g. using 'polytunnels' and fertilizers)[4], as well as rear chickens. Grazing is not likely, so red meat may be obtained from herds of large migrating herbivores that utilize a wide area.

2.2. Calculation Cases for Additional Climate States

Based on the descriptions provided in Section 2.1, the additional calculation cases considered are listed in Table 2.

Table 2: Potential additional cases that merit future consideration.

Climate	Biosphere System	Case	Notes
Temperate	Local marine	Warm variant	Water flows likely to remain the same, but potential to modify habits (e.g. longer swimming occupancy).
	Lake	Warm variant	Potential to modify water flows and habits.
	Mire	Warm variant	Potential to modify water flows and habits.
	Forest	Warm variant	Potential to modify water flows and habits.
	Pasture	Warm variant	Potential to modify water flows and habits.
	Arable	Warm variant	Potential to modify water flows and habits, notably through increased irrigation.
Periglacial	Local marine	Reference	Some changes in comparison to models for the temperate system, e.g. in human occupancies.
	Lake	Reference	Representative of a lake associated with a talik receiving groundwater discharges.
	Mire	Reference	On the margins of a talik receiving groundwater discharges.
	Arable	Reference	Including small-scale agricultural production (some crops and chickens) on the margins of a talik receiving groundwater discharges.

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[4] See, for example, Section 11.4.2 http://www.alaskadispatch.com/article/20130609/farm-flourishes-alaska-tundra

Löfgren (2010)[5] notes examples of agricultural production in tundra areas and presents recommended production rates for cereals, root crops and vegetables under periglacial conditions. The productivity rates are repeated for periglacial systems in Table 5-2 of Avila et al. (2010). However, it is stated in Section 2.3 of Avila et al. (2010) that the calculations supporting the LDFs assume that no agricultural production is possible during periglacial conditions.

2.3. Adaptation of the Models to Represent Additional Climate States

Processes that move radionuclides around the biosphere system are the same under the present-day, warm and periglacial climate conditions, but differ in their magnitude. The models for radionuclide releases to biosphere systems under present-day climate conditions, described in Walke (2014), can therefore be adapted to represent warm and periglacial conditions by varying the parameter values used, which is described in Sections 2.3.1 and 2.3.2, respectively.

2.3.1. Adaptation to Represent Warm Climate Conditions

Calculations are needed for all six biosphere system types under warm climate conditions. The properties of the systems are taken to be the same as under present-day conditions, with the exception of:

- near-surface hydrology; and
- exposure group assumptions.

Changes to these components are described below.

Near-Surface Hydrology

The water flows between the different types of compartment under warm climate conditions are illustrated in Figure 2 and Figure 3. They are adapted from the water flows for the reference/present-day climate (see Figures 18 and 19 of Walke, 2014) by increasing many of the flows by about 20%. This increase is approximately equivalent to the increase in precipitation and consistent with the comment in Section 8.3.2 of Andersson (2010) that runoff is increased by about 20% in the global warming case considered in the SR-Site assessment. The mean residence time in the lake is reduced from 76 days to 60.8 days to be consistent with an increase in the turnover rate of about 20%.

Assumptions for the arable area are given in Table 3.

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[5] Discussion in Section 11.4.2 and parameter value recommendations for cereal, root crop and vegetable production rates under periglacial conditions in Section 13.3.5 of Löfgren (2010).

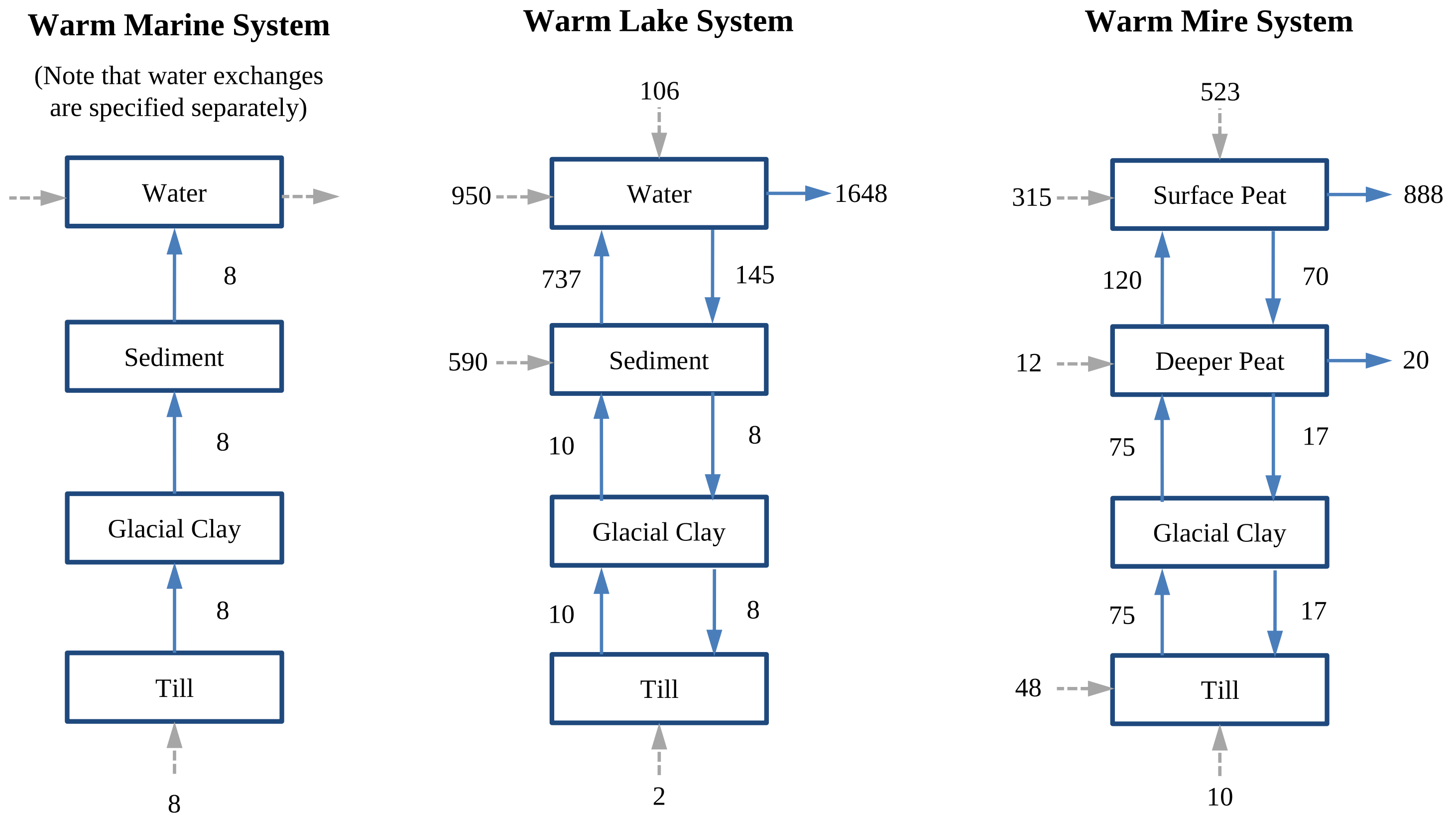

Figure 2: Water balances for marine, lake and mire systems under warm climate conditions, mm y^{-1}.

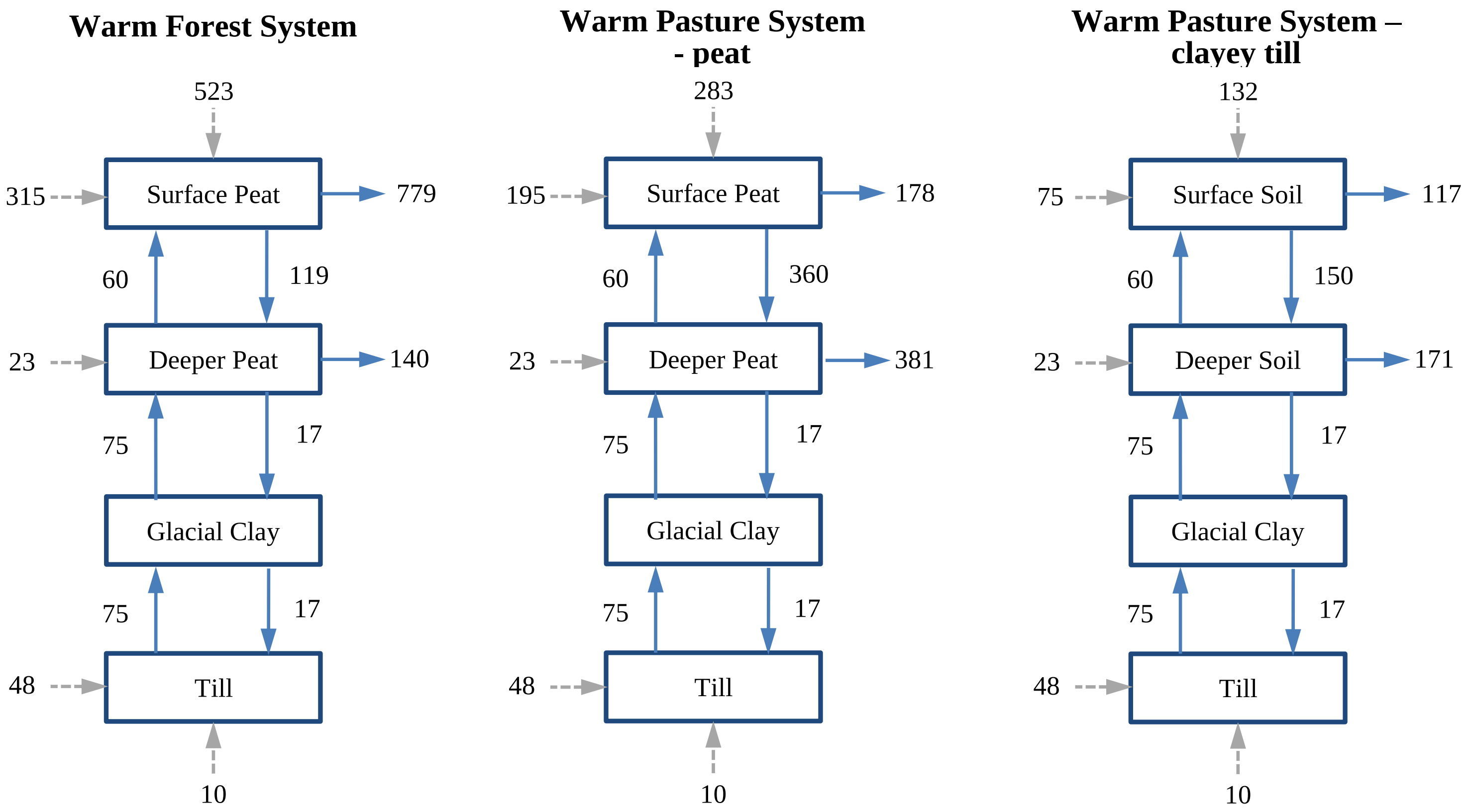

Figure 3: Water balances for forest and pasture systems under warm climate conditions, mm y^{-1}.

Table 3: Hydrological assumptions for the arable system under warm climate conditions, mm y^{-1}.

Parameter	Climate		Notes
	Present-day	Warm	
Groundwater discharge to the till	8	10	Increased, consistent with Figure 2 and Figure 3
Precipitation	580	700	Increased by about 20%
Irrigation	100	150	Increased to be a bit higher than average rates in Southern Sweden at the present-day
Actual evapotranspiration	380	500	Increased to reflect warmer temperatures
Infiltration/ recharge	300	350	Provides water balance

Exposure Group Assumptions

Exposure group assumptions that differ from those used for the reference/present-day climate are described in Table 8.

Table 4: Exposure group parameters for the marine system that change for the warm climate system in comparison to the reference/present-day system, hrs y^{-1}.

System	Item	Age Group			Notes
		Adult	Child	Infant	
Marine	Shoreline occupancy	336	168	84	1
	Swimming occupancy	42	21	0	2
Lake	Shoreline occupancy	336	168	84	3
	Swimming occupancy	42	21	0	4
Mire	Occupancy of mire	84	0	0	5
	Occupancy near burning of peat	6000	6000	6000	6
Forest	Occupancy	84	42	0	7
Pasture	Occupancy	1090	270	140	8
Arable	Occupancy outdoors	1640	410	210	9

Notes to Table 8:

1 Adult based on an average of 2 hours per day and increased from three to about six months of the year; child half of this rate; infants a quarter of this rate.

2 Adult based on an average 0.5 hour per day and increased from one to three months of the year; child half this rate; infant taken not to swim in the sea.

3 Adult based on an average of 2 hours per day and increased from three to six months of the year; child half of this rate; infants a quarter of this rate.

4 Adult based on an average 0.5 hour per day and increased from one to three months of the year; child half this rate; infant taken not to swim in the lake.

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

6 Occupancy near burning of peat is taken to be reduced in comparison to the reference/present-day climate.

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

8 Adult based on about four hours per day and increased from six to nine months of the year; child and infant values based on a quarter and an eighth of the adult values.

9 Adult based on about six hours per day and increased from six to nine months of the year; child and infant values based on a quarter and an eighth of the adult values.

2.3.2. Adaptation to Represent Periglacial Conditions

Calculations for local marine, lake and mire systems are needed under periglacial conditions, along with variant calculations exploring the potential effect of small-scale agriculture. Unless described below, the parameter values are taken to be the same as under present-day conditions.

Areas and Release Fractions

For the marine, lake and mire systems, the same areas are used as were used for the present-day climate (see Section 7.1.1 of Walke, 2014).

It is conceivable that a periglacial open talik might receive the full groundwater discharge flux. However, a mire adjacent to a groundwater discharge open talik would only receive part of the discharging groundwater and, therefore potential only receive a fraction of the radionuclide releases. Consistent with SR-Site[6], a groundwater discharge fraction of 0.33 is adopted to represent the fraction of a contaminated release that might be directed to a mire adjacent to the open talik.

For small-scale arable production, sufficient, for example to provide about 50% of the vegetable needs of a small family and some poultry, an area of a small field or large allotment might be appropriate and include cultivation under polytunnels. However, it is improbable and overly conservative to assume that an area of about 0.2 ha (approximately 45 m by 45 m) would receive the full groundwater release. A fraction of 0.1 is used to describe the portion of a release to an open talik that might be routed to an adjacent 2000 m^2 of land that is being used for small-scale agriculture. This fraction is smaller than the fraction of 0.33 of upward advective groundwater flows that is used in SR-Site under permafrost conditions to reflect the proportion of upward flow routed to a mire[7], rather than to a lake associated with an

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[6] Table 13-7 of Löfgren (2010).

[7] Lake_fract_Mire in Table 5-2 of Avila et al. (2010).

open talik. The remainder of the radionuclide discharge flux is taken to occur to an adjacent lake and/or mire.

The arable, lake and mire biosphere systems are assessed independently, so the potential for groups to receive exposures from more than one of the systems is discussed in the assessment of the results (see Section 2.4.4).

Layer/Strata Thicknesses

The same discretisation and compartment thicknesses/depths are used for the periglacial marine, lake and marine systems, as for the present-day climate (see Section 7.1.2 of Walke, 2014).

Unlike the arable system represented within the model for present-day climate, the periglacial arable system has potential to receive direct groundwater discharge. Therefore, the compartment thicknesses used for the pasture system are used (Table 9 of Walke, 2014).

Media Properties

The same properties for the compartments are used as described for the present-day climate in Section 7.2 of Walke (2014), with the exception of suspended sediment concentrations in lake and marine water. The arable soil is represented as being the same as the peat pasture soil in the temperature system.

Suspended sediment concentrations under periglacial conditions are likely to be lower than those under present-day climate conditions. The documentation of the LDF models indicates that the parameter was not changed when representing periglacial system[8]. The suspended sediment concentration is modified for periglacial systems in this assessment, based on the minimum of the ranges reports in the SR-Site documentation, see Table 5.

Table 5: Suspended sediment concentration for periglacial systems, kg m^{-3}.

Media	**Value**		**Notes**
	Present-day*	**Periglacial**	
Local marine water	0.003	0.0015	Minimum value in Table 10-21 of Aquilonius (2010)
Lake water	0.0011	0.0003	Minimum value in Table 11-20 of Andersson (2010)

Note for Table 5: * Table 11 of Walke (2014).

Near-Surface Hydrology

Near surface hydrology will be an important influence on radionuclide migration in the periglacial system. In the model for present-day climate conditions, water flows

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[8] See, for example, Table 5-2 of Avila et al. (2010).

between the different media were explicitly represented[9]. The same approach is adopted here.

The water flows for the periglacial marine system are taken to be twice those under the present-day climate conditions. This is taken to be representative of increased groundwater flow and discharge to ‘sea taliks’[10]. This means that the flow rate vertically upwards through the till, glacial clay and sediment is taken to by 16 mm y^{-1}. As in the present-day system, a residence time of 27 days is used as the basis for defining the loss rate from the marine water compartment.

Water flows for the lake, mire and arable system are also adapted from those used for the present-day climate and are illustrated in Figure 4.

- For the periglacial lake system, the rate of groundwater discharge to the till is increased compared to the present-day lake to reflect potential for more focused discharge to the open talik. Horizontal flow into the sediment is reduced to reflect seasonal frozen conditions around the lake. Runoff under periglacial conditions is similar to that under present-day conditions[11], the mean residence time in the lake is therefore taken to be the same.
- For the periglacial mire system, reduced infiltration/percolation is represented, together with no horizontal in-flows below the surface peat.
- The flows for the periglacial arable system are adapted from the flow rates for the present-day pasture system based on peat sediments. As for the mire, it is represented with reduced infiltration/percolation, together with no horizontal in-flows below the surface peat.

Given that the biosphere systems are modelled independently of each other, irrigation under the polytunnels used to facilitate agriculture under periglacial conditions is taken to come from an uncontaminated source (e.g. stored precipitation). Consistent with SR-Site, groundwater wells are taken to be unnecessary and impracticable under periglacial conditions.

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[9] See Section 7.3 of Walke (2014).

[10] See discussion on p189 of Bosson et al. (2010).

[11] See discussion on p262 of Andersson (2010).

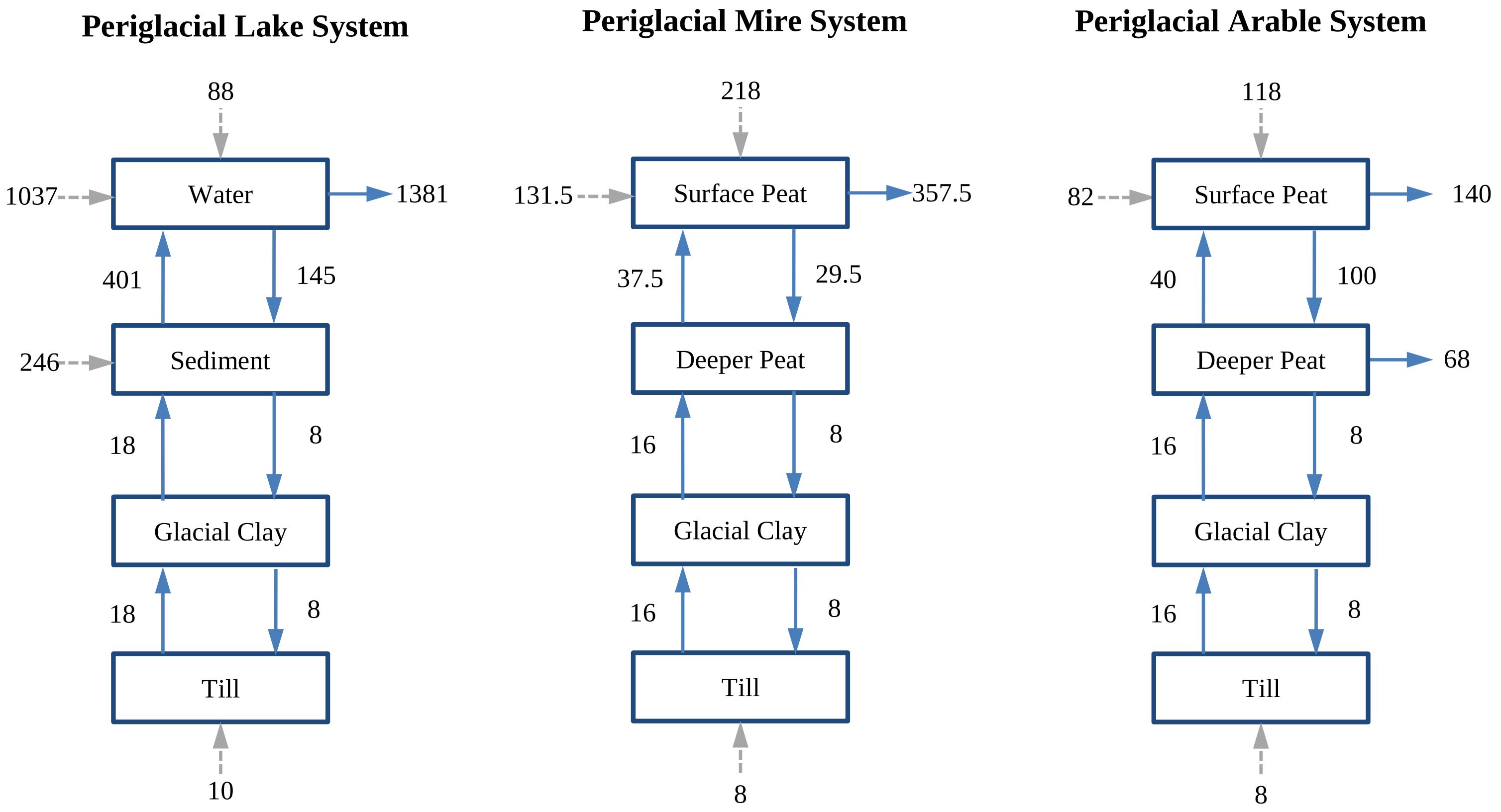

Figure 4: Water balances for the periglacial lake, mire and arable systems, mm y^{-1}.

Sedimentation and Resuspension

Sedimentation and resuspension rates are expected to be reduced under periglacial conditions. The rates used in the LDF models were calculated based on the Quaternary development model (RLDM) that is described in Brydsten and Strömgren (2010). Therefore, no values are explicitly presented in the SR-Site documentation for non-evolving periglacial conditions.

For the simple biosphere models, sedimentation and resuspension rates are calculated by scaling the values used for the present-day systems by the relative suspended sediment concentrations shown in Table 5. The resulting values are presented in Table 6; the same value is used for sedimentation and resuspension to reflect non-evolving systems.

Table 6: Sedimentation and resuspension rates for periglacial systems, kg m^{-2} y^{-1}.

Media	Value		Notes
	Present-day*	Periglacial	
Local marine water	0.2	0.1	Scaled based on the suspended sediment concentrations given in Table 5.
Lake water	1	0.27	

Note for Table 6: * Section 7.4.2 of Walke (2014).

Erosion

Soil erosion is taken to occur on the land used for small-scale agricultural production. The erosion rate is taken to be half of that used for the present-day arable system[12], so a rate of 0.5 mm y^{-1} is adopted. As for the present-day system, the erosive loss is taken to be compensated by an input of uncontaminated material so that there is no net loss from the system.

Bioturbation

The bioturbation rates for the marine, lake and arable systems are taken to be half of the equivalent rates under present-day conditions to reflect the colder climate, see Table 7.

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[12] See Section 7.4.3 of Walke (2014).

Table 7: Bioturbation rates between surface soil/sediment layers for periglacial systems, kg m^{-2} y^{-1}.

System	Bioturbation rate		Notes
	Present-day	Periglacial	
Marine	1	0.5	1
Lake	0.25	0.125	1
Mire	0	0	2
Arable	2	0.5	3

Notes for Table 7:

1 The bioturbation rate under periglacial conditions is taken to be half of that under present-day climate conditions presented in Table 16 of Walke (2014).

2 Consistent with Table 16 of Walke (2014), no bioturbation is taken to occur between the mire sediment compartments.

3 The arable periglacial system soils are based on the peaty pasture soils represented under present-day climate conditions, therefore the bioturbation rate is taken to be half of that described for present-day pasture systems in Table 16 of Walke (2014).

Exposure Group Assumptions

Exposure group assumptions for the periglacial marine, lake, mire and arable systems are presented in Table 8 to Table 11. The values are adapted from the representation of present-day climate conditions, which are given in Tables 18, 19, 20 and 24 of Walke (2014).

Parameters associated with the use of peat as fuel are taken to be the same as under present-day climate conditions.

Table 8: Exposure group parameters for the periglacial marine system.

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

Notes to Table 8:

1. Occupancy rate taken to be the same as under present-day climate conditions, given the relatively short duration and the relatively large extent of shoreline involved (2 km).
2. No swimming is taken to occur during periglacial conditions.
3. Dust concentration, sea spray concentration and inhalation rate while on the shoreline are taken to be the same as under present-day climate conditions.
4. Although productivity of the marine system may be lower under periglacial conditions, the area modelled is 2 km by 1 km, which will be sufficient to supply the requirements of a small family group. Therefore the ingestion rates for periglacial conditions remain the same as those for present-day climate conditions.

Table 9: Exposure group parameters for the periglacial lake system.

Item	Units	Age Group			Notes
		Adult	Child	Infant	
Shoreline occupancy	hrs y^{-1}	84	42	21	1
Swimming occupancy	hrs y^{-1}	0	0	0	2
Incidental ingestion of water	m^3 hr^{-1}	0	0	0	2
Drinking water	L y^{-1}	600	350	260	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	4
Ingestion rates					
Wild fowl	kg fw y^{-1}	2	1.5	1	5
Fish	kg fw y^{-1}	6	3	2	5
Crustaceans	kg fw y^{-1}	0	0	0	6
Inadvertent ingestion of sediment	mg dw hr^{-1}	5	10	50	7

Notes to Table 9:

1 Shoreline occupancy taken to be 50% of that under present-day climate conditions given the cold conditions and relatively small size of the lake.

2 No swimming is taken to occur during periglacial conditions.

3 Drinking water assumed to be taken from the lake under periglacial conditions, in the absence of a groundwater well.

4 Dust concentration and inhalation rate while on the shoreline are taken to be the same as under present-day climate conditions.

5 A productivity rate for fish of 3.2E-5 kgC m^{-2} y^{-1}, combined with an area of about 50,000 m^2 for the lake (see Section 7.1.1 of Walke, 2014) would be sufficient to produce about 11 kg fw fish meat per year, based on a carbon content of fish of 0.138 from Table 3-3 of Avila (2006).

6 No crustaceans under periglacial conditions.

7 Same hourly rate of inadvertent ingestion asunder present-day climate conditions.

Table 10: Exposure group parameters for the periglacial 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	2
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	2
Ingestion rate of wild fowl	kg fw y^{-1}	1	0.5	0	3
Inadvertent ingestion rate of sediment	mg dw hr^{-1}	5	0	0	2

Notes to Table 10:

1 Low value used in present-day climate system considered appropriate for use under periglacial conditions as well.

2 Occupancy near burning of peat, dust concentration, inhalation rate and rate of inadvertent ingestion of sediment taken to be the same as in present-day mire systems.

3 Ingestion rate reduced compared to present-day climate systems to reflect lower productivity of the periglacial system.

Table 11: Exposure group data for the arable system.

Item	Units	Age Group			Notes
		Adult	Child	Infant	
Occupancy outdoors	hrs y^{-1}	545	135	70	1
Occupancy bathing	hrs y^{-1}	n/a	n/a	n/a	2
Dust concentration	kg dw m^{-3}	5E-6	1E-7	1E-7	3
Inhalation rate	m^3 hr^{-1}	1.375	1.12	0.22	3
Ingestion rates					
Drinking water	L y^{-1}	n/a	n/a	n/a	2
Vegetables	kg fw y^{-1}	15	7.5	3.75	4
Root vegetables	kg fw y^{-1}	17.5	15	5	4
Cereals	kg fw y^{-1}	n/a	n/a	n/a	4
Pork	kg fw y^{-1}	n/a	n/a	n/a	4
Poultry meat	kg fw y^{-1}	8.75	5.25	1.75	4
Eggs	kg fw y^{-1}	2.5	2	1.5	4
Inadvertent ingestion of sediment	kg dw y^{-1}	0.0021	0.0045	0.011	5

Notes to Table 11:

1 Occupancy taken to be half that under present-day climate conditions.

2 There is no use of well water under periglacial conditions, so bathing and drinking exposure pathways are not relevant.

3 Dust concentration and inhalation rates are taken to be the same as under present-day climate conditions.

4 Ingestion rates for food arising from the potentially contaminated area are taken to be a quarter of those under present-day climate conditions, reflecting the lower productivity of the periglacial system; no cereals or pork are taken to be consumed.

5 The rate of inadvertent ingestion of sediment is also taken to be a quarter of that under present-day climate conditions.

2.4. Results for Additional Climate Conditions

Dose factors calculated with the simple biosphere models for the present-day climate are discussed in Section 2.4.1. Dose factors for warm and periglacial climates presented in Section 2.4.2 and Section 2.4.3. The highest dose factors are then compared against the equivalent LDFs from the SR-Site assessment in Section 2.4.4.

2.4.1. Dose Factors for the Present-day Climate

Dose factors for the present-day climate conditions were presented in Section 9 of Walke (2014). In December 2013, SKB issued an erratum to Nordén et al. (2010) stating that the best estimate equilibrium sorption coefficients originally given for Ra in inorganic and organic sediments did not reflect those actually used in the modelling. The incorrect values originally included in Nordén et al. (2010) were used in the Walke (2014) study and were presented in Tables 28 and 29 of that report. Corrected values have been used in this study (see Table 12) – a reduction by almost a factor of three in the sorption coefficient in the till is notable as the most significant change.

Table 12: Best estimate sorption coefficients for Ra on inorganic till and organic sediments, $m^3\ kg^{-1}$ dry weight

Media	Original TR-10-07	Updated TR-10-07	Notes
Inorganic till	7.3E+0	2.5E+0	1
Organic sediments	2.3E+0	2.5E+0	2

Notes for Table 12.

1 Original value from Table 3-1 of Nordén et al. (2010) version dated January 2013, updated value from the same table in Nordén et al. (2010) version dated December 2013.

2 Original value from Table 3-2 of Nordén et al. (2010) version dated January 2013, updated value from the same table in Nordén et al. (2010) version dated December 2013.

The change to the sorption coefficient affects the dose factors calculated for radioisotopes of radium, as well as those for which explicitly modelled radium isotopes in-grow. For convenience, the full set of adult dose factors is given in Table 13, along with the ratio to the original values reported in Walke (2014).

Table 13 shows that the updated sorption coefficients result in a significant difference (an increase by up to about a factor of 200) to the dose factors for Ra-226 and Ra-228 in dose factors for pasture, forest, mire, lake and marine systems. Transport through the till, glacial clay and post-glacial deposits is required for these systems. The reduced degree of sorption in the till means that retention in the till is reduced, which means that more radium gets to the surface soils and sediments before decaying, resulting in higher dose factors.

Table 13 shows less of an impact on the dose factors for Ra-226 and Ra-228 for the arable system (within a factor of three). This reflects the irrigation transport from the till to the arable soil, which means that there is less retention and less of an opportunity for radioactive decay to affect the original results.

Table 13: Adult biosphere dose conversion factors for the six different biosphere systems under present-day climate conditions.

Radio-nuclide	Dose Conversion Factor under Present-day Climate Conditions (Sv/Bq)						Ratio to Original Results					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Ac-227	4.7E-13	3.0E-29	2.1E-30	1.3E-31	2.2E-30	2.8E-34	1	1	1	1	1	1
Ag-108m	2.7E-13	6.6E-18	3.6E-18	4.5E-21	1.1E-20	1.1E-22	1	1	1	1	1	1
Am-241	7.8E-13	3.0E-17	1.8E-17	4.0E-18	3.5E-15	1.0E-18	1	1	1	1	1	1
Am-243	3.0E-11	3.1E-15	2.4E-16	2.4E-16	5.6E-15	1.6E-17	1	1	1	1	1	1
Ca-41	1.3E-13	4.3E-15	7.1E-18	6.5E-17	3.2E-15	1.2E-18	1	1	1	1	1	1
Cd-113m	5.2E-14	8.1E-28	4.7E-28	7.0E-31	8.0E-30	2.9E-33	1	1	1	1	1	1
Cl-36	8.6E-13	1.7E-13	4.7E-15	1.5E-15	1.7E-14	1.7E-18	1	1	1	1	1	1
Cm-244	1.0E-13	1.7E-18	1.4E-19	1.2E-19	4.7E-19	1.1E-21	1	1	1	1	1	1
Cm-245	1.9E-11	5.9E-16	3.6E-16	7.8E-17	6.8E-14	2.0E-17	1	1	1	1	1	1
Cm-246	3.8E-12	7.9E-16	6.7E-17	1.8E-16	4.0E-14	1.2E-16	1	1	1	1	1	1
Cs-135	8.5E-13	3.4E-14	2.1E-13	7.3E-17	6.2E-17	6.2E-21	1	1	1	1	1	1
Cs-137	3.9E-16	9.2E-36	6.2E-35	2.9E-40	6.7E-39	2.8E-42	1	1	1	1	1	1
Ho-166m	2.2E-14	9.1E-22	8.0E-23	1.8E-24	3.4E-25	6.3E-28	1	1	1	1	1	1
I-129	6.6E-11	2.0E-11	1.4E-13	7.3E-15	2.8E-12	1.8E-15	1	1	1	1	1	1
Mo-93	3.9E-12	1.3E-14	3.2E-16	2.3E-16	3.1E-17	9.6E-21	1	1	1	1	1	1

Radio-nuclide	Dose Conversion Factor under Present-day Climate Conditions (Sv/Bq)						Ratio to Original Results					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Nb-93m	2.2E-17	9.2E-37	2.8E-37	5.1E-41	2.7E-39	5.5E-42	1	1	1	1	1	1
Nb-94	7.0E-13	1.8E-14	3.1E-15	3.0E-16	5.7E-17	1.4E-19	1	1	1	1	1	1
Ni-59	3.9E-14	6.3E-15	2.6E-16	3.5E-17	9.6E-17	5.9E-19	1	1	1	1	1	1
Ni-63	1.5E-15	3.7E-24	3.1E-25	7.6E-28	1.8E-28	8.7E-32	1	1	1	1	1	1
Np-237	4.9E-11	1.5E-13	9.1E-14	2.0E-14	1.7E-11	5.0E-15	1	1	1	1	1	1
Pa-231	5.2E-10	1.6E-13	6.8E-15	5.7E-15	1.7E-13	1.5E-16	1	1	1	1	1	1
Pb-210	5.0E-12	5.5E-33	1.2E-32	7.1E-37	5.6E-35	1.1E-38	1	1	1	1	1	1
Pd-107	1.9E-14	8.4E-17	1.7E-17	1.1E-19	2.3E-15	1.5E-18	1	1	1	1	1	1
Po-210	8.9E-14	4.2E-38	1.3E-37	1.8E-41	7.5E-40	1.4E-43	1	1	1	1	1	1
Pu-239	6.9E-11	9.3E-15	7.1E-16	7.1E-16	1.7E-14	4.9E-17	1	1	1	1	1	1
Pu-240	3.5E-11	6.1E-16	4.9E-17	4.3E-17	1.7E-16	4.1E-19	1	1	1	1	1	1
Pu-242	1.0E-10	6.2E-14	5.3E-15	1.4E-14	3.2E-12	9.8E-15	1	1	1	1	1	1
Ra-226	3.5E-10	1.2E-17	1.5E-17	4.7E-20	4.1E-20	3.4E-23	0.99	158	163	168	194	188
Ra-228	4.3E-14	4.5E-35	2.3E-33	2.0E-38	3.9E-38	5.4E-41	2.85	195	196	182	194	195
Se-79	2.5E-11	1.8E-11	3.7E-12	7.9E-13	4.4E-12	5.1E-15	1	1	1	1	1	1
Sm-151	3.8E-17	1.9E-32	9.9E-34	2.7E-36	6.0E-35	1.1E-37	1	1	1	1	1	1
Sn-126	2.6E-12	1.7E-13	1.4E-14	9.7E-16	4.7E-13	3.3E-14	1	1	1	1	1	1

Radio-nuclide	Dose Conversion Factor under Present-day Climate Conditions (Sv/Bq)						Ratio to Original Results					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Sr-90	6.3E-14	3.7E-25	1.0E-26	1.7E-28	1.1E-27	5.3E-33	1	1	1	1	1	1
Tc-99	4.0E-13	3.3E-15	2.5E-16	1.5E-16	9.1E-15	1.7E-16	1	1	1	1	1	1
Th-228	1.8E-16	5.8E-47	2.2E-47	5.0E-51	7.8E-51	1.5E-53	1	1	1	1	1	1
Th-229	3.4E-12	8.4E-22	1.1E-21	2.2E-23	5.0E-25	1.8E-28	1	1	1	1	1	1
Th-230	1.5E-08	4.2E-14	5.6E-14	4.2E-16	7.8E-17	1.1E-19	0.99	2.45	2.27	1.61	3.72	1.99
Th-232	3.2E-09	1.2E-13	9.3E-12	4.8E-15	9.6E-17	1.1E-19	2.71	1.00	1.01	1.00	1.07	0.99
U-233	3.5E-11	3.9E-13	2.5E-13	9.3E-14	7.5E-14	3.5E-16	1	1	1	1	1	1
U-234	5.0E-09	2.3E-11	3.5E-11	2.0E-12	1.1E-11	1.0E-13	0.99	1.78	1.67	1.20	1.91	1.13
U-235	4.8E-10	3.0E-12	1.5E-13	5.4E-13	1.1E-10	1.3E-13	1	1	1	1	1	1
U-236	2.4E-11	2.9E-13	3.1E-14	7.8E-14	9.5E-14	2.4E-16	1	1	1	1	1	1
U-238	6.1E-10	1.8E-11	2.7E-11	3.5E-12	4.3E-11	3.8E-13	0.99	1.74	1.66	1.19	1.87	1.12
Zr-93	4.6E-13	4.1E-16	1.9E-16	9.6E-17	9.5E-15	1.1E-16	1	1	1	1	1	1

Note for Table 13: Radionuclides potentially affected by the change in radium sorption coefficients are highlighted in grey cells.

The effect of the change in radium sorption is less marked for radionuclides for which radium isotopes in-grow.

2.4.2. Dose Factors for a Warmer Climate

The dose factors that are calculated for the warm climate conditions are shown in Table 14 and compared against those for the present-day climate. The dose factors for the arable system (with irrigation) continue to dominate those from other biosphere systems. The dose factors for the arable system under warm climate conditions are higher than those under present-day conditions. The increase for the arable system is principally due to the 50% increase in the irrigation rate modelled.

For the pasture, forest, mire and lake systems, the calculated dose factors increase by about a factor of two for radionuclides for which occupancy is an important contributor (e.g. Ac-227, Ag-108m), reflecting the increased occupancy assumed under warm climate conditions. For radionuclides for which ingestion pathways are important (e.g. Am-241, Ca-41), the dose factors are similar or slightly lower than under present-day climate conditions, reflecting the fact that consumption rates are unchanged and water flows are increased by about 20%.

Dose factors for the marine system are increased by up to about a factor of two, reflecting increased occupancy assumed under warm climate conditions.

In the SR-Site assessment, LDFs for a ‘global warming’ scenario are compared against ‘interglacial’ LDFs based on the reference glacial cycle in Table 4-2 of Avila et al. (2010). In the reference glacial cycle, the interglacial conditions persist for 18,400 years from the start of the calculations. In the global warming case, the interglacial conditions extend for 68,600 years. The parameterisation of the interglacial conditions remains the same in both cases. Comparison of the LDFs calculated for the reference glacial cycle and global warming case shows little difference in most cases, with the values either remaining the same or increasing. This is because the dose factors have reached close to equilibrium with the unit discharges within 18,400 years, so that the extended period of interglacial conditions makes no difference. The main difference in LDFs occurs for those long-lived radionuclides that don’t approach equilibrium within the interglacial time frame considered in the reference glacial cycle. These include Zr-93, Nb-94, Cs-135, Th-230, U-234 and U-238.

Within the SR-Site assessment, global warming is discussed in some depth in the climate report (SKB, 2010a) and in the reports describing the terrestrial, limnic and marine conditions at Forsmark (Löfgren, 2010; Andersson, 2010; Aquilonius, 2010). The description of warmer conditions includes temperatures that are significantly warmer, along with significant changes in runoff and in agricultural productivity. The potential implications of such changes are not explored in the radiological assessment modelling in either the reference assessment calculations nor in variant or uncertainty calculations.

Table 14: Adult biosphere dose conversion factors for the six different biosphere systems under warm climate conditions.

Radio-nuclide	Dose Conversion Factor under Warm Climate Conditions (Sv/Bq)						Ratio to Result for Present-day Climate					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Ac-227	6.9E-13	7.0E-29	5.9E-30	2.4E-31	3.3E-30	3.3E-34	1.46	2.39	2.84	1.76	1.51	1.19
Ag-108m	4.5E-13	1.5E-17	6.8E-18	1.6E-20	2.6E-20	1.4E-22	1.69	2.28	1.88	3.58	2.39	1.29
Am-241	1.2E-12	2.7E-17	1.5E-17	3.0E-18	2.8E-15	1.8E-18	1.50	0.92	0.80	0.75	0.80	1.80
Am-243	4.2E-11	4.2E-15	2.9E-16	2.2E-16	6.7E-15	2.2E-17	1.39	1.34	1.21	0.93	1.20	1.32
Ca-41	1.6E-13	3.2E-15	5.6E-18	5.5E-17	2.8E-15	1.4E-18	1.26	0.73	0.78	0.84	0.86	1.17
Cd-113m	7.7E-14	1.6E-27	9.2E-28	1.7E-30	1.4E-29	2.9E-33	1.47	1.99	1.96	2.37	1.71	1.00
Cl-36	1.0E-12	1.2E-13	3.6E-15	1.3E-15	1.3E-14	3.4E-18	1.22	0.72	0.77	0.83	0.80	1.97
Cm-244	1.4E-13	2.5E-18	1.8E-19	1.1E-19	6.2E-19	1.6E-21	1.42	1.47	1.31	0.96	1.31	1.41
Cm-245	2.9E-11	5.4E-16	2.9E-16	5.8E-17	5.5E-14	3.6E-17	1.51	0.92	0.80	0.75	0.80	1.80
Cm-246	5.6E-12	8.6E-16	6.4E-17	1.3E-16	4.4E-14	1.6E-16	1.46	1.09	0.96	0.71	1.09	1.32
Cs-135	1.2E-12	4.3E-14	2.4E-13	9.8E-17	6.3E-17	6.4E-21	1.38	1.27	1.15	1.34	1.01	1.04
Cs-137	5.7E-16	1.6E-35	1.0E-34	7.6E-40	9.7E-39	5.1E-42	1.47	1.71	1.64	2.60	1.45	1.80
Ho-166m	4.1E-14	2.4E-21	2.6E-22	6.8E-24	9.3E-25	1.2E-27	1.88	2.58	3.21	3.75	2.74	1.93
I-129	8.3E-11	1.5E-11	1.1E-13	6.5E-15	2.2E-12	2.1E-15	1.25	0.76	0.79	0.88	0.80	1.22
Mo-93	5.1E-12	1.3E-14	3.3E-16	2.8E-16	3.4E-17	1.3E-20	1.32	1.02	1.03	1.22	1.09	1.39

Radio-nuclide	Dose Conversion Factor under Warm Climate Conditions (Sv/Bq)						Ratio to Result for Present-day Climate					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Nb-93m	3.2E-17	1.9E-36	6.1E-37	1.6E-40	4.3E-39	5.8E-42	1.45	2.04	2.14	3.11	1.60	1.06
Nb-94	1.3E-12	3.6E-14	7.4E-15	8.6E-16	1.3E-16	2.7E-19	1.85	2.01	2.41	2.87	2.31	1.99
Ni-59	4.9E-14	5.5E-15	2.2E-16	3.3E-17	1.0E-16	6.1E-19	1.27	0.87	0.85	0.95	1.04	1.03
Ni-63	2.2E-15	7.1E-24	5.5E-25	1.6E-27	2.9E-28	9.0E-32	1.46	1.90	1.80	2.13	1.59	1.03
Np-237	6.3E-11	1.3E-13	7.2E-14	1.5E-14	1.4E-11	9.0E-15	1.28	0.92	0.80	0.75	0.80	1.80
Pa-231	7.2E-10	2.0E-13	9.1E-15	5.9E-15	1.8E-13	1.8E-16	1.38	1.28	1.34	1.03	1.03	1.22
Pb-210	7.4E-12	1.1E-32	2.3E-32	1.7E-36	8.5E-35	1.1E-38	1.47	1.91	1.89	2.33	1.51	1.00
Pd-107	2.4E-14	6.2E-17	1.3E-17	1.2E-19	1.9E-15	1.6E-18	1.25	0.73	0.78	1.03	0.83	1.06
Po-210	1.3E-13	8.0E-38	2.4E-37	4.1E-41	1.2E-39	1.4E-43	1.47	1.92	1.91	2.34	1.55	1.00
Pu-239	9.4E-11	1.2E-14	8.5E-16	6.6E-16	2.0E-14	6.5E-17	1.35	1.34	1.21	0.93	1.19	1.32
Pu-240	5.0E-11	9.1E-16	6.4E-17	4.1E-17	2.3E-16	5.8E-19	1.42	1.47	1.31	0.96	1.31	1.41
Pu-242	1.3E-10	6.8E-14	5.1E-15	1.0E-14	3.5E-12	1.3E-14	1.29	1.09	0.96	0.71	1.09	1.32
Ra-226	5.2E-10	1.9E-17	2.2E-17	8.1E-20	5.0E-20	3.5E-23	1.46	1.55	1.50	1.73	1.23	1.01
Ra-228	6.3E-14	1.0E-34	4.4E-33	6.8E-38	7.1E-38	7.6E-41	1.46	2.27	1.92	3.35	1.81	1.40
Se-79	2.9E-11	1.4E-11	2.9E-12	6.6E-13	3.5E-12	5.2E-15	1.18	0.75	0.78	0.83	0.80	1.01
Sm-151	5.5E-17	3.7E-32	2.2E-33	6.8E-36	9.4E-35	1.2E-37	1.45	1.92	2.16	2.49	1.56	1.02
Sn-126	3.3E-12	1.6E-13	1.3E-14	1.7E-15	4.6E-13	3.3E-14	1.26	0.94	0.89	1.79	0.98	1.00

Radio-nuclide	Dose Conversion Factor under Warm Climate Conditions (Sv/Bq)						Ratio to Result for Present-day Climate					
	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine	Arable (peat)	Pasture (peat)	Forest	Mire	Lake	Marine
Sr-90	9.1E-14	5.9E-25	1.6E-26	3.2E-28	1.4E-27	9.2E-33	1.45	1.61	1.62	1.95	1.31	1.76
Tc-99	4.9E-13	2.4E-15	1.9E-16	1.2E-16	7.3E-15	1.7E-16	1.23	0.73	0.78	0.83	0.80	1.00
Th-228	2.6E-16	2.0E-46	6.7E-47	2.1E-50	2.2E-50	2.3E-53	1.45	3.38	3.05	4.14	2.81	1.50
Th-229	5.3E-12	2.3E-21	2.3E-21	4.1E-23	9.7E-25	2.3E-28	1.55	2.68	2.00	1.87	1.93	1.24
Th-230	2.1E-08	6.5E-14	8.3E-14	6.8E-16	1.1E-16	1.1E-19	1.44	1.54	1.48	1.64	1.42	1.01
Th-232	4.3E-09	2.2E-13	1.3E-11	9.2E-15	1.5E-16	1.5E-19	1.36	1.88	1.40	1.92	1.61	1.35
U-233	4.7E-11	4.5E-13	2.4E-13	8.5E-14	8.9E-14	4.5E-16	1.35	1.15	0.93	0.92	1.19	1.28
U-234	6.3E-09	2.1E-11	3.0E-11	1.8E-12	1.2E-11	1.0E-13	1.25	0.91	0.86	0.94	1.03	1.01
U-235	5.7E-10	2.9E-12	1.5E-13	4.1E-13	1.0E-10	1.6E-13	1.18	0.96	0.98	0.76	0.95	1.22
U-236	3.1E-11	2.6E-13	2.7E-14	6.6E-14	9.7E-14	4.3E-16	1.28	0.89	0.84	0.85	1.02	1.83
U-238	6.5E-10	1.3E-11	1.9E-11	2.8E-12	4.4E-11	3.9E-13	1.08	0.75	0.71	0.80	1.01	1.01
Zr-93	5.8E-13	4.3E-16	1.7E-16	1.0E-16	9.0E-15	1.2E-16	1.25	1.05	0.91	1.04	0.95	1.04

2.4.3. Dose Factors for a Periglacial Climate

The dose factors calculated for the periglacial conditions are shown in Table 15 and compared against those for the present-day climate. The dose factors for the arable system (representing small-scale cultivation, but without irrigation with groundwater) dominate those of the mire, lake and marine systems. However, with the exception of Se-79, the dose factor for the periglacial arable system is significantly lower than that under other climate conditions. For Se-79, the arable dose factor under periglacial conditions is similar to that under present-day conditions. The lower dose factors in comparison to the present-day reflect the absence of irrigation with contaminated groundwater, fractional (10%) discharge to the small arable area adjacent to an open talik, lower productivity and lower occupancy.

Dose factors for the periglacial mire system are consistently and significantly lower than those for the present-day climate. This reflects the fractional (33%) discharge to the mire, as well as lower productivity and occupancy.

For the lake system, dose factors are broadly similar to those for the lake under present-day climate conditions. This is because:

- the exposure group is taken to drink the lake water, because under periglacial conditions, there is no other source of drinking water considered (this is also consistent with assumptions within the SR-Site modelling); this compensates for lower rate of ingestion of lake produce; and
- there is increased groundwater discharge through the sediments, reflecting focusing of flow through the talik, this means that radionuclides can reach the surface sediments more quickly, increasing dose factors for radionuclides for which direct exposure to the sediments is important (e.g. via external irradiation on shoreline and inhalation of resuspended dust).

Dose factors for the marine system are higher under periglacial conditions in comparison to those for present-day conditions. This reflects higher groundwater discharge through the sediments whilst the mean residence time for the marine water and consumption rates remain the same as under present-day conditions.

In the SR-Site assessment, LDFs for a ‘permafrost’ conditions during the reference glacial cycle are compared against those for ‘interglacial’ conditions in Table 4-2 of Avila et al. (2010). LDFs for all radionuclides (excluding C-14, which is not included in the simple biosphere modelling) are lower than those under interglacial conditions. The average ratio of the permafrost LDFs to the interglacial LDFs is 0.12. This ratio compares favourably with the average ratio between the periglacial and present-day dose factors shown in Table 15 for the arable system, which is 0.08, even though different modelling assumptions have been adopted. The arable system results in the highest dose factors and are therefore the closest equivalent to the LDF for the simple biosphere modelling.

Table 15: Adult biosphere dose conversion factors for the four biosphere systems relevant to periglacial climate conditions.

Radio-nuclide	Dose Conversion Factor under Periglacial Climate Conditions (Sv/Bq)				Ratio to Result for Present-day Climate			
	Arable (peat)	Mire	Lake	Marine	Arable (peat)	Mire	Lake	Marine
Ac-227	2.8E-29	1.4E-35	1.1E-30	1.1E-33	<0.01	<0.01	0.49	4.04
Ag-108m	1.4E-18	2.9E-23	1.8E-20	3.9E-22	<0.01	0.01	1.69	3.69
Am-241	3.1E-15	4.1E-19	3.1E-16	1.7E-18	<0.01	0.10	0.09	1.64
Am-243	1.8E-13	6.1E-19	2.6E-15	7.3E-17	0.01	<0.01	0.47	4.49
Ca-41	2.8E-15	4.3E-18	1.0E-15	1.4E-18	0.02	0.07	0.31	1.14
Cd-113m	7.3E-29	5.9E-35	1.1E-31	1.2E-32	<0.01	<0.01	0.01	4.30
Cl-36	2.4E-13	1.2E-16	6.9E-15	1.0E-18	0.28	0.08	0.41	0.60
Cm-244	4.0E-17	1.6E-21	3.4E-19	6.4E-21	<0.01	0.01	0.71	5.65
Cm-245	6.1E-14	8.1E-18	6.0E-15	3.3E-17	<0.01	0.10	0.09	1.64
Cm-246	2.1E-13	2.6E-18	1.0E-14	2.5E-16	0.05	0.01	0.25	2.01
Cs-135	4.7E-16	2.2E-19	5.1E-17	2.2E-20	<0.01	<0.01	0.82	3.56
Cs-137	1.1E-37	5.2E-43	4.0E-39	9.0E-42	<0.01	<0.01	0.60	3.18
Ho-166m	5.1E-23	5.2E-27	1.3E-24	6.8E-27	<0.01	<0.01	3.72	10.80
I-129	5.4E-12	9.2E-16	8.0E-13	2.0E-15	0.08	0.13	0.29	1.16
Mo-93	1.5E-14	8.2E-19	4.1E-17	5.0E-20	<0.01	<0.01	1.32	5.24
Nb-93m	6.2E-38	2.8E-44	1.2E-39	1.9E-41	<0.01	<0.01	0.44	3.42

Radio-nuclide	Dose Conversion Factor under Periglacial Climate Conditions (Sv/Bq)				Ratio to Result for Present-day Climate			
	Arable (peat)	Mire	Lake	Marine	Arable (peat)	Mire	Lake	Marine
Nb-94	2.9E-15	4.0E-18	2.1E-16	1.3E-18	<0.01	0.01	3.73	9.74
Ni-59	3.1E-15	7.6E-19	7.3E-17	1.4E-18	0.08	0.02	0.76	2.29
Ni-63	2.1E-26	9.7E-32	3.0E-28	5.4E-31	<0.01	<0.01	1.61	6.12
Np-237	1.5E-11	2.0E-15	1.5E-12	8.2E-15	0.32	0.10	0.09	1.64
Pa-231	2.7E-12	1.5E-17	8.5E-14	7.4E-16	0.01	<0.01	0.50	4.94
Pb-210	3.7E-35	9.3E-41	3.9E-36	3.5E-38	<0.01	<0.01	0.07	3.25
Pd-107	8.2E-16	3.1E-20	4.7E-16	1.6E-18	0.04	0.27	0.20	1.03
Po-210	1.8E-40	2.2E-45	4.1E-41	2.9E-43	<0.01	<0.01	0.05	2.02
Pu-239	5.5E-13	1.8E-18	7.9E-15	2.2E-16	0.01	<0.01	0.46	4.47
Pu-240	1.5E-14	5.6E-19	1.2E-16	2.3E-18	<0.01	0.01	0.71	5.65
Pu-242	1.6E-11	2.1E-16	8.1E-13	2.0E-14	0.16	0.01	0.25	2.01
Ra-226	2.8E-19	2.2E-23	7.1E-21	2.3E-22	<0.01	<0.01	0.17	6.65
Ra-228	2.1E-36	1.2E-41	1.7E-37	2.3E-40	<0.01	<0.01	4.29	4.18
Se-79	2.6E-11	6.3E-14	6.9E-13	5.2E-15	1.05	0.08	0.16	1.01
Sm-151	1.2E-33	1.3E-39	1.7E-35	4.9E-37	<0.01	<0.01	0.28	4.25
Sn-126	7.0E-13	2.4E-16	2.7E-13	5.8E-14	0.27	0.25	0.56	1.77
Sr-90	1.5E-26	5.1E-32	1.4E-27	4.6E-32	<0.01	<0.01	1.32	8.74
Tc-99	8.6E-14	1.2E-17	4.8E-15	1.7E-16	0.22	0.08	0.52	1.00

Radio-nuclide	Dose Conversion Factor under Periglacial Climate Conditions (Sv/Bq)				Ratio to Result for Present-day Climate			
	Arable (peat)	Mire	Lake	Marine	Arable (peat)	Mire	Lake	Marine
Th-228	8.6E-49	3.8E-55	2.4E-50	2.1E-52	<0.01	<0.01	3.10	13.83
Th-229	1.0E-22	7.1E-28	2.2E-24	6.3E-27	<0.01	<0.01	4.39	34.64
Th-230	6.6E-16	1.4E-19	3.1E-17	1.4E-18	<0.01	<0.01	0.39	13.02
Th-232	1.3E-14	4.9E-18	2.1E-15	3.0E-18	<0.01	<0.01	22.47	26.67
U-233	5.2E-12	7.5E-16	7.0E-14	1.9E-15	0.15	0.01	0.94	5.34
U-234	1.9E-11	3.8E-14	1.2E-12	2.3E-13	<0.01	0.02	0.10	2.24
U-235	3.0E-10	1.3E-14	3.0E-11	2.9E-13	0.63	0.02	0.28	2.24
U-236	5.4E-12	1.9E-15	1.1E-13	8.6E-16	0.22	0.02	1.15	3.66
U-238	4.4E-11	1.4E-13	3.8E-12	6.7E-13	0.07	0.04	0.09	1.75
Zr-93	1.9E-14	2.0E-17	5.6E-15	1.4E-16	0.04	0.21	0.59	1.21

Note for Table 15: Pasture and forest systems are not considered relevant to the periglacial climate conditions.

2.4.4. Potential Exposure from Multiple Biosphere Systems

The dose factors presented in the tables above reflect potential exposure to each independent biosphere system. It is conceivable that a group that is potentially exposed to one system (e.g. the arable system) is also exposed to another (e.g. by also spending time on the lake). In principle, some of the dose factors could be combined, however, they would also need to be adapted to reflect the fraction of a unit release that might be directed to each system. In practice, the dose factors for the arable systems dominate throughout, such that combining dose factors is a degree of complexity that is not required.

2.4.5. Comparison Against LDFs

The inclusion of dose factors for global warming and periglacial conditions enables a full comparison of the results from the simple biosphere modelling against the LDF values presented in Table 4-2 of Avila et al. (2010). For the simple biosphere modelling, the dose factors relate to the highest values calculated between the different biosphere systems under the equivalent climate conditions. In each case, the highest dose factors are associated with arable land use.

- For the present-day and warmer climate conditions, the arable cases are based on use of shallow groundwater for irrigation of peaty soils, there is no groundwater discharge direct to the soils.
- For the periglacial conditions, the arable results are based on groundwater release to peaty soils adjacent to an open talik.

The comparison is presented in Table 16 and illustrated for the present-day climate in Figure 5.

The comparison shows that the simple biosphere models calculates dose factors that are significantly higher than the LDFs (more than three orders of magnitude higher in some cases) for some radionuclides, notably Ra-226, Th-230, Th-232 and the uranium isotopes. Investigation of the dose factors for Ra-226 and Th-232 show that irrigation of crops with groundwater is key in these cases, which is a pathway that is not represented in SKB's LDF values. It is also notable, that the contribution of radioactive progeny to Ra-226 and Th-232 dominates their associated dose factors, Po-210 in the case of Ra-226 and Ra-228 in the case of Th-232.

SKB investigate the potential importance of irrigation with groundwater as part of uncertainty calculations in Avila et al. (2010)[13]. In their analysis, half of the irrigation water needed for crops is taken from groundwater and it is shown that the effect on the LDF is typically within a factor of a few. The use of a model for water from a deep well in SR-Site means that there is no in-growth of explicitly modelled progeny in the irrigation water used in the SKB calculations. It is interesting that the source of irrigation water (i.e. from either shallow or deep groundwater wells) should have such a notable impact on the dose factors that include irrigation.

A very large discrepancy in calculated dose factors under the periglacial conditions is evident in Table 16 for some radionuclides. The discrepancy is greatest for shorter-lived radionuclides like Cs-137 (half-life 30.1 years) and Po-210 (half-life

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[13] p60 of Avila et al. (2010).

0.4 years). A key feature of the periglacial system is that there is no contribution of well water to calculated doses, meaning that exposure to soil contaminated by groundwater discharge then becomes more important. The LDF model is coarsely discretised for a groundwater discharge pathway and is subject to significant numerical dispersion in comparison to the simple model. The degree of numerical dispersion in the LDF models means that radionuclides reach the surface soils/sediments more quickly than in the simple model. The quicker transport in the LDF models results in less time for radioactive decay. Shorter-lived radionuclides are affected more. The result is that the LDF model calculates much higher concentrations in surface soils/sediments for these shorter-lived radionuclides under periglacial conditions and therefore results in much higher dose factors. This issue is explored further in Section 3.

Table 16: Comparison of LDFs against the highest adult dose factors calculated under equivalent climate conditions with the simple biosphere models

Radio-nuclide	Interglacial/Present-day Climate			Global Warming/Warm Climate			Permafrost/Periglacial Climate		
	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site
Ac-227	8.0E-12	4.7E-13	5.9E-02	8.0E-12	6.9E-13	8.7E-02	8.9E-16	2.8E-29	3.2E-14
Ag-108m	7.1E-13	2.7E-13	3.7E-01	7.1E-13	4.5E-13	6.3E-01	8.8E-15	1.4E-18	1.6E-04
Am-241	1.5E-12	7.8E-13	5.2E-01	1.5E-12	1.2E-12	7.8E-01	1.1E-14	3.1E-15	2.8E-01
Am-243	1.5E-12	3.0E-11	2.0E+01	1.6E-12	4.2E-11	2.6E+01	2.0E-13	1.8E-13	9.2E-01
Ca-41	9.9E-14	1.3E-13	1.3E+00	9.9E-14	1.6E-13	1.6E+00	9.3E-15	2.8E-15	3.0E-01
Cl-36	5.8E-13	8.6E-13	1.5E+00	5.8E-13	1.0E-12	1.8E+00	4.4E-13	2.4E-13	5.6E-01
Cm-244	8.7E-13	1.0E-13	1.2E-01	8.7E-13	1.4E-13	1.7E-01	8.1E-19	4.0E-17	5.0E+01
Cm-245	1.6E-12	1.9E-11	1.2E+01	1.6E-12	2.9E-11	1.8E+01	2.2E-14	6.1E-14	2.8E+00
Cm-246	1.6E-12	3.8E-12	2.4E+00	1.6E-12	5.6E-12	3.5E+00	1.6E-14	2.1E-13	1.3E+01
Cs-135	4.0E-14	8.5E-13	2.1E+01	2.9E-13	1.2E-12	4.0E+00	3.0E-13	4.7E-16	1.6E-03
Cs-137	1.2E-13	3.9E-16	3.2E-03	1.2E-13	5.7E-16	4.7E-03	9.5E-18	1.1E-37	1.1E-20
Ho-166m	5.9E-14	2.2E-14	3.7E-01	5.9E-14	4.1E-14	7.0E-01	8.4E-16	5.1E-23	6.1E-08
I-129	6.5E-10	6.6E-11	1.0E-01	6.5E-10	8.3E-11	1.3E-01	2.6E-11	5.4E-12	2.1E-01
Nb-94	4.0E-12	7.0E-13	1.7E-01	1.2E-11	1.3E-12	1.1E-01	1.1E-13	2.9E-15	2.6E-02
Ni-59	7.4E-14	3.9E-14	5.2E-01	2.0E-13	4.9E-14	2.5E-01	1.3E-15	3.1E-15	2.4E+00

Radio-nuclide	Interglacial/Present-day Climate			Global Warming/Warm Climate			Permafrost/Periglacial Climate		
	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site
Ni-63	1.2E-15	1.5E-15	1.3E+00	1.2E-15	2.2E-15	1.9E+00	6.3E-18	2.1E-26	3.4E-09
Np-237	4.8E-11	4.9E-11	1.0E+00	4.8E-11	6.3E-11	1.3E+00	2.2E-11	1.5E-11	7.0E-01
Pa-231	8.1E-12	5.2E-10	6.4E+01	1.3E-11	7.2E-10	5.5E+01	1.7E-13	2.7E-12	1.6E+01
Pb-210	5.1E-12	5.0E-12	9.8E-01	5.1E-12	7.4E-12	1.4E+00	2.6E-17	3.7E-35	1.4E-18
Pd-107	6.7E-15	1.9E-14	2.9E+00	9.4E-15	2.4E-14	2.6E+00	2.7E-15	8.2E-16	3.0E-01
Po-210	8.9E-12	8.9E-14	1.0E-02	8.9E-12	1.3E-13	1.5E-02	3.1E-20	1.8E-40	5.7E-21
Pu-239	1.9E-12	6.9E-11	3.7E+01	2.0E-12	9.4E-11	4.7E+01	2.0E-13	5.5E-13	2.8E+00
Pu-240	1.9E-12	3.5E-11	1.8E+01	1.9E-12	5.0E-11	2.6E+01	1.3E-13	1.5E-14	1.1E-01
Pu-242	1.9E-12	1.0E-10	5.3E+01	2.2E-12	1.3E-10	5.9E+01	2.3E-13	1.6E-11	7.0E+01
Ra-226	3.8E-12	3.5E-10	9.3E+01	3.8E-12	5.2E-10	1.4E+02	9.8E-13	2.8E-19	2.9E-07
Se-79	1.2E-09	2.5E-11	2.1E-02	1.2E-09	2.9E-11	2.4E-02	5.8E-11	2.6E-11	4.5E-01
Sm-151	7.2E-16	3.8E-17	5.3E-02	7.2E-16	5.5E-17	7.7E-02	1.0E-20	1.2E-33	1.2E-13
Sn-126	2.5E-11	2.6E-12	1.0E-01	1.1E-10	3.3E-12	3.0E-02	6.1E-13	7.0E-13	1.2E+00
Sr-90	2.2E-13	6.3E-14	2.8E-01	2.2E-13	9.1E-14	4.1E-01	7.2E-17	1.5E-26	2.1E-10
Tc-99	9.0E-13	4.0E-13	4.4E-01	9.0E-13	4.9E-13	5.4E-01	2.8E-13	8.6E-14	3.1E-01
Th-229	3.6E-12	3.4E-12	9.5E-01	3.7E-12	5.3E-12	1.4E+00	7.0E-14	1.0E-22	1.4E-09
Th-230	1.3E-11	1.5E-08	1.1E+03	6.4E-11	2.1E-08	3.3E+02	1.5E-11	6.6E-16	4.4E-05

Radio-nuclide	Interglacial/Present-day Climate			Global Warming/Warm Climate			Permafrost/Periglacial Climate		
	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site	SR-Site Sv/Bq	Simple Sv/Bq	Ratio Simple:SR-Site
Th-232	1.7E-12	3.2E-09	1.9E+03	2.6E-12	4.3E-09	1.7E+03	4.5E-13	1.3E-14	2.9E-02
U-233	2.5E-12	3.5E-11	1.4E+01	1.9E-11	4.7E-11	2.5E+00	2.5E-12	5.2E-12	2.1E+00
U-234	3.6E-12	5.0E-09	1.4E+03	7.1E-11	6.3E-09	8.9E+01	1.1E-11	1.9E-11	1.7E+00
U-235	2.8E-12	4.8E-10	1.7E+02	2.0E-11	5.7E-10	2.8E+01	1.3E-13	3.0E-10	2.3E+03
U-236	1.9E-12	2.4E-11	1.3E+01	1.1E-11	3.1E-11	2.8E+00	2.9E-14	5.4E-12	1.8E+02
U-238	1.9E-12	6.1E-10	3.2E+02	1.6E-11	6.5E-10	4.1E+01	8.1E-13	4.4E-11	5.4E+01
Zr-93	2.8E-14	4.6E-13	1.7E+01	1.1E-13	5.8E-13	5.3E+00	6.5E-16	1.9E-14	2.9E+01

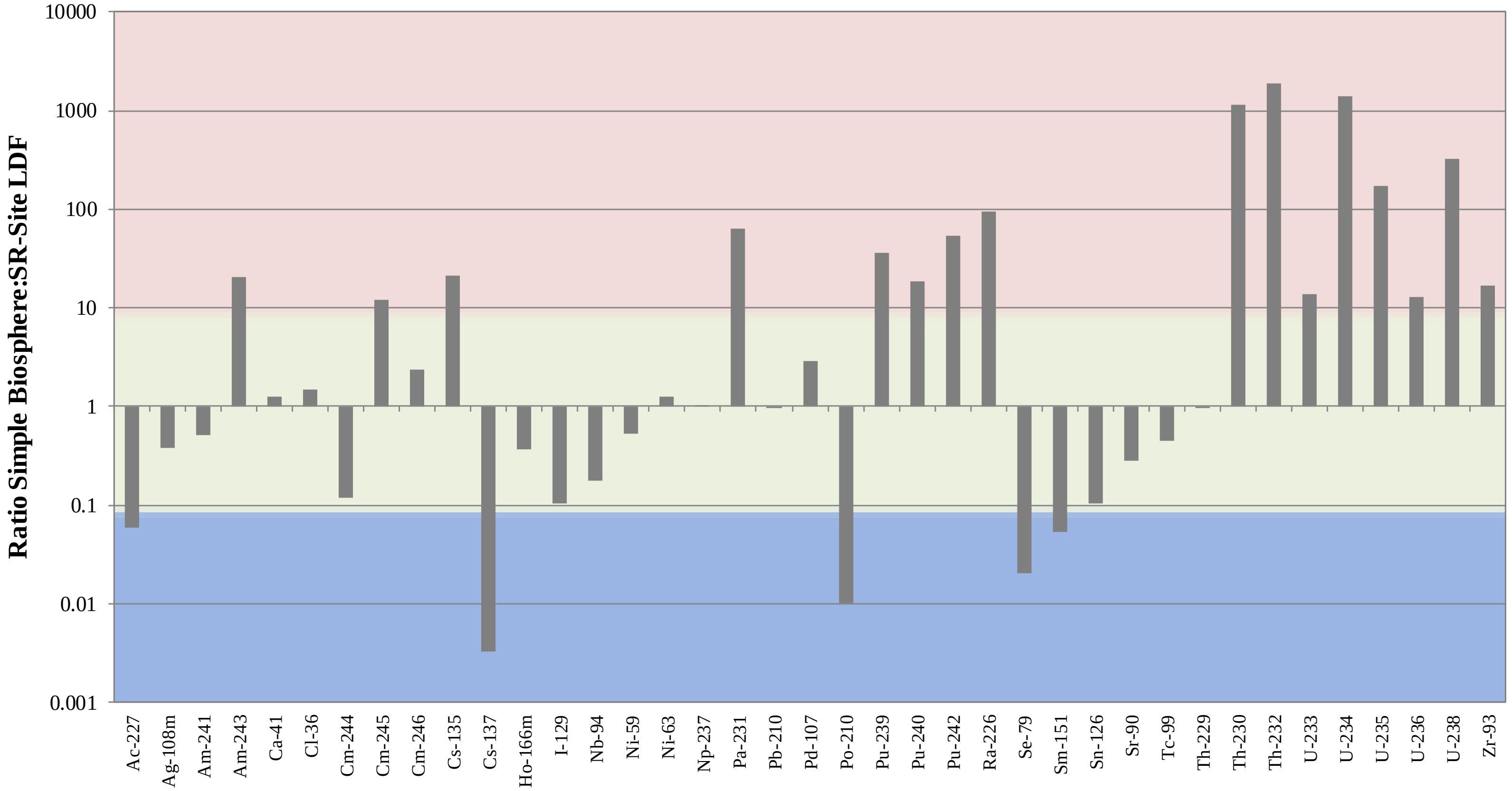

Figure 5: Maximum simple biosphere model dose factors for present-day climate conditions compared with the SR-Site interglacial LDFs.

3. Further Comparison against SR-Site

Walke (2014) included a variant calculation in which the modelling assumptions adopted in the simple biosphere models sought to reflect the assumptions adopted in SKB's LDF models. The LDFs are typically dominated by exposure to landscape object 121-03 during terrestrial interglacial conditions (Table 4-1 of Avila et al., 2010). A variant calculation with the simple biosphere models was set up to calculate dose factors arising from groundwater discharge only (i.e. without use of well water for irrigation) and combining exposures from the arable and pasture systems. The comparison of the resulting dose factors with the LDF values is reproduced in Figure 6.

Two aspects are reviewed further below, the representation of a well (Section 3.1) and the representation of the regolith (Section 3.2).

3.1. Representation of the Well

Figure 6 shows that the simple biosphere model calculates significantly lower dose factors for some radionuclides, notably Cs-137 and Po-210. These are notable as having relatively short half-lives for assessments relating to post-closure safety. Ingestion of contaminated well water is an important exposure pathway for these radionuclides, so the calculation of the well water concentration merits review in each case.

- In SKB's LDF model, individuals obtain half of their drinking water from surface water and the remaining half from a groundwater well. The well water concentration is calculated simply as the unit flux to the biosphere divided by a flow rate of 8426 m^3 y^{-1}, which is taken to be representative of flow rates for percussion drilled wells[14].
- In the simple model calculations set up to resemble SKB's LDFs models in Walke (2014), individuals also obtain half of their drinking water from a groundwater well. However, the well water radionuclide concentration is calculated as the average concentration in groundwater within the till.

The till in the simple model for the pasture systems is represented with four compartments[15], which means that the well water concentration is affected by retention in the regolith and radioactive decay, unlike the model used in SKB's LDF models. If the well water concentration is calculated in the same way as in SKB's LDF models, then there is a marked improvement in the degree of agreement between the two models (compare Figure 7 with Figure 6 and see Table 17). The modification demonstrates the importance of the drinking pathway to the LDFs calculated by SKB. In the simple model used to generate the results shown in Figure 7, the well pathway accounts for more than 50% of the dose for 32 out of 39 radionuclides. It is notable that this pathway requires no explicit biosphere modelling, as it is simply calculated by diluting the unit flux by the well capacity.

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[14] The model for the well water concentration is given on p136 of Avila et al. (2010) and the flow rate/well capacity is discussed on p361 of Löfgren (2010).

[15] See Table 68 of Walke (2014). The same discretisation is used for the arable system when irrigation is not included and the soil is contaminated via groundwater discharge.

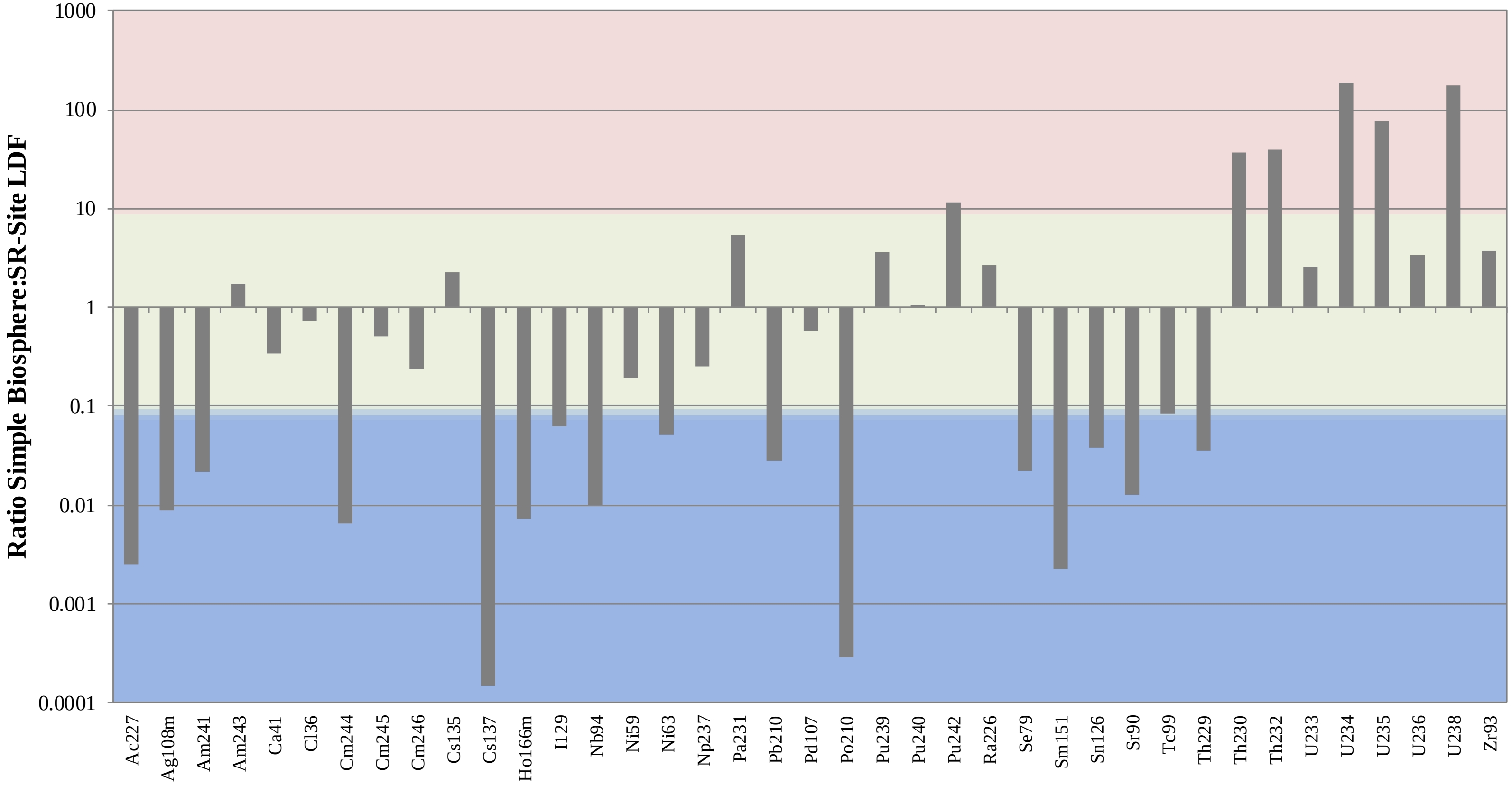

Figure 6: Maximum dose factors for groundwater release to combined arable and pasture system compared with SR-Site interglacial LDFs (Figure 28 from Walke, 2014).

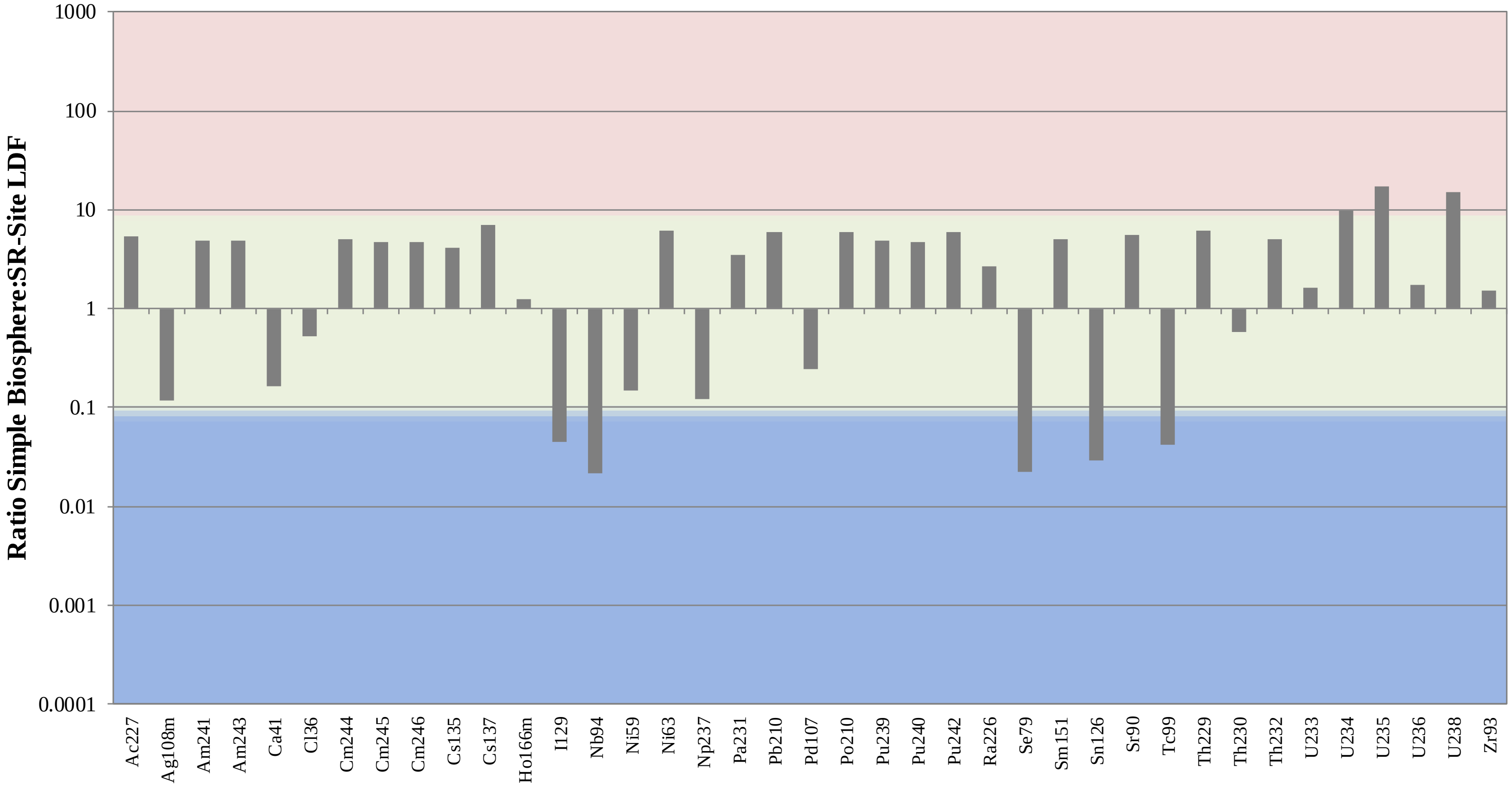

Figure 7: Maximum dose factors for groundwater release to combined arable and pasture system with a deep well compared with SR-Site interglacial LDFs.

Table 17: 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}	Simple model for groundwater release combining arable and pasture systems			
		Using shallow groundwater for drinking water		Using the SR-Site well model for drinking water	
		Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF	Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF
Ac-227	8.0E-12	2.0E-14	2.4E-03	4.3E-11	5.4E+00
Ag-108m	7.1E-13	6.2E-15	8.8E-03	8.3E-14	1.2E-01
Am-241	1.5E-12	3.2E-14	2.2E-02	7.2E-12	4.8E+00
Am-243	1.5E-12	2.6E-12	1.7E+00	7.3E-12	4.9E+00
Ca-41	9.9E-14	3.4E-14	3.4E-01	1.6E-14	1.6E-01
Cl-36	5.8E-13	4.2E-13	7.2E-01	3.0E-13	5.2E-01
Cm-244	8.7E-13	5.7E-15	6.5E-03	4.3E-12	5.0E+00
Cm-245	1.6E-12	8.1E-13	5.1E-01	7.5E-12	4.7E+00
Cm-246	1.6E-12	3.7E-13	2.3E-01	7.6E-12	4.7E+00
Cs-135	4.0E-14	9.0E-14	2.3E+00	1.7E-13	4.2E+00
Cs-137	1.2E-13	1.8E-17	1.5E-04	8.5E-13	7.1E+00
Ho-166m	5.9E-14	4.3E-16	7.3E-03	7.4E-14	1.3E+00
I-129	6.5E-10	4.0E-11	6.2E-02	2.9E-11	4.4E-02
Nb-94	4.0E-12	4.0E-14	1.0E-02	8.5E-14	2.1E-02
Ni-59	7.4E-14	1.4E-14	1.9E-01	1.1E-14	1.5E-01

Radio-nuclide	SR-Site Interglacial LDF Sv Bq^{-1}	Simple model for groundwater release combining arable and pasture systems			
		Using shallow groundwater for drinking water		Using the SR-Site well model for drinking water	
		Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF	Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF
Ni-63	1.2E-15	6.0E-17	5.0E-02	7.4E-15	6.2E+00
Np-237	4.8E-11	1.2E-11	2.5E-01	5.8E-12	1.2E-01
Pa-231	8.1E-12	4.4E-11	5.4E+00	2.8E-11	3.5E+00
Pb-210	5.1E-12	1.4E-13	2.8E-02	3.1E-11	6.0E+00
Pd-107	6.7E-15	3.9E-15	5.8E-01	1.7E-15	2.5E-01
Po-210	8.9E-12	2.5E-15	2.8E-04	5.3E-11	5.9E+00
Pu-239	1.9E-12	6.8E-12	3.6E+00	9.3E-12	4.9E+00
Pu-240	1.9E-12	2.0E-12	1.0E+00	8.9E-12	4.7E+00
Pu-242	1.9E-12	2.2E-11	1.2E+01	1.1E-11	5.9E+00
Ra-226	3.8E-12	1.0E-11	2.7E+00	1.0E-11	2.7E+00
Se-79	1.2E-09	2.7E-11	2.2E-02	2.6E-11	2.2E-02
Sm-151	7.2E-16	1.6E-18	2.3E-03	3.6E-15	5.0E+00
Sn-126	2.5E-11	9.5E-13	3.8E-02	7.2E-13	2.9E-02
Sr-90	2.2E-13	2.8E-15	1.3E-02	1.2E-12	5.6E+00
Tc-99	9.0E-13	7.5E-14	8.3E-02	3.7E-14	4.1E-02
Th-229	3.6E-12	1.3E-13	3.5E-02	2.2E-11	6.1E+00

Radio-nuclide	SR-Site Interglacial LDF Sv Bq^{-1}	Simple model for groundwater release combining arable and pasture systems			
		Using shallow groundwater for drinking water		Using the SR-Site well model for drinking water	
		Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF	Dose Factor Sv Bq^{-1}	Ratio to SR-Site LDF
Th-230	1.3E-11	4.9E-10	3.7E+01	7.6E-12	5.8E-01
Th-232	1.7E-12	6.7E-11	3.9E+01	8.5E-12	5.0E+00
U-233	2.5E-12	6.6E-12	2.6E+00	4.1E-12	1.6E+00
U-234	3.6E-12	6.9E-10	1.9E+02	3.5E-11	9.8E+00
U-235	2.8E-12	2.2E-10	7.8E+01	4.8E-11	1.7E+01
U-236	1.9E-12	6.3E-12	3.3E+00	3.3E-12	1.8E+00
U-238	1.9E-12	3.3E-10	1.7E+02	2.9E-11	1.5E+01
Zr-93	2.8E-14	1.1E-13	3.8E+00	4.2E-14	1.5E+00

Note for Table 17: 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.

If the source flux from the geosphere is used directly as the basis for calculating well water concentrations, then care is needed in the treatment of radionuclides that are not explicitly modelled in the geosphere but are explicitly represented in the biosphere (see Table 18). The contribution of the radioactive progeny to the well water concentration should be included in the calculation, otherwise the dose factors derived directly from the well water concentrations will be underestimated. This is particularly important for Po-210 and Ra-228, for which the ingestion dose coefficients exceed those of their parent radionuclides. Po-210 and Ra-228 are also subject to less sorption than their parent radionuclides, which will result in increased concentrations in groundwater relative to their parent radionuclides.

Table 18: Differences in the explicit representation of radionuclides.

Explicitly Represented in SR-Site Geosphere	Explicitly Modelling in SR-Site Biosphere	Explicitly Modelled in Simple Biospheres
Pb-210	Pb-210 → Po-210	Pb-210 → Po-210
Th-232	Th-232	Th-232 → Ra-228 → Th-228

The additional contribution of Po-210, Ra-228 and Th-228 to well water concentrations has not been included in either the SKB or simple model calculations illustrated in Figure 7. They are omitted from the variant simple biosphere modelling partly because their inclusion requires the sorption coefficient (K_d) for Po in the geosphere, which is not available in the SR-Site reports. K_d values for Ra and Th in the geosphere are included in SKB (2010b), which enables the potential implications of excluding shorter-lived radionuclides to be evaluated. The sorption coefficient for Ra in the geosphere shows that, if present in equilibrium with Th-232, then the concentration of Ra-228 in the well water would be 220 times higher than that of its parent. This, coupled with an ingestion dose factor that is three times higher for Ra-228 than for Th-232, means that the drinking water dose factor for Th-232 would be underestimated by a factor of 660. The calculations that support Figure 7 show drinking water to account for more than 96% of the dose factor for Th-232.

3.2. Representation of the Regolith

An important difference in the way in which the simple and SKB LDF models represent the biosphere is in the degree of discretisation adopted for the regolith. The SKB LDF models use only three compartments, compared to eight compartments in the simple models. The use of three compartments will result in significant numerical dispersion in the representation of groundwater transport of radionuclides through the till, glacial clays, post-glacial sediments and soils.

The discretisation of the lower regolith was investigated in the SR-Site assessment[16]. The lower regolith was sub-divided into “several compartments” and the effect on LDFs investigated. That analysis states that the effect on the LDFs was insignificant, principally due to the increasing importance of the well pathway if a finer discretisation is used. The well pathway is independent of the radionuclide

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[16] p68 of Avila et al. (2010).

transport model and its importance effectively masks the effect of a finer discretisation on radionuclide migration and accumulation, such that the implication of a finer discretisation is not fully investigated. It is notable that there is no discussion of the effect of a finer discretisation on the timescale of radionuclide accumulation nor the potential effect of a finer discretisation of the middle and upper regolith.

In a system that is subject to significant and reasonably predictable environmental change and succession, and for which a great deal of effort has been expended by SKB in evaluating and modelling the timescales of environmental change, it is inconsistent for the radionuclide transport model to not take equal care in ensuring that the time scales of migration and accumulation are appropriately represented.

The implications of a coarse discretisation have been investigated with the simple biosphere models by developing a variant that is discretised less. Four compartments are used, instead of the original eight, with one each representing the till, glacial clay, deep and surface sediments[17]. The effect of the coarse discretisation on the ability to reproduce the SR-Site LDFs is illustrated in Figure 8; the basis of the calculation is the same as that illustrated in Figure 7, except for the coarser discretisation[18].

The effect of the coarse discretisation on the simple biosphere dose factors is not marked (compare Figure 8 with Figure 7). However, this is a system within which the well water pathway dominates for many radionuclides and the well pathway is completely unaffected by the compartment model used to represent the biosphere. It is, however, notable that agreement with the SKB LDF for Nb-94 is improved with a coarser discretisation. External irradiation from the surface soils/sediments is important for Nb-94, so there is less dominance of the well water pathway in its case.

The effect of a coarse discretisation is better explored through a comparison of the peak radionuclide concentration in the surface soil/sediment and their associated time scales. This is done with the results for the simple biosphere modelling in Table 19.

Table 19 shows that a coarse discretisation makes a very significant difference to the calculated radionuclide concentrations in the surface sediments. The effect is particularly marked for short-lived radionuclides (notably Cs-137 and Po-210), with differences greater than ten orders of magnitude.

Neither the SKB LDF model for permafrost conditions nor the simple biosphere model for periglacial conditions include the use of deep well water, so the radionuclide transport results are not masked by the well water pathway. The coarse discretisation adopted in the SKB LDF models explains the significant difference in the dose factors calculated under periglacial conditions (see Table 16).

Table 19 shows the coarse discretisation adopted in the SKB LDFs to be conservative, indeed extremely conservative for shorter-lived radionuclides. However, the table also shows that the coarse discretisation has a marked effect on

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[17] The discretisation of the simple biosphere models is shown explicitly in Table 68 of Walke (2014).

[18] i.e. the calculation is based on groundwater release to a combined arable and pasture area and the well water concentration is calculated as in the SR-Site model.

the time scales required to approach equilibrium. As identified above, the treatment of the time scales for radionuclide migration in the biosphere is inconsistent with the care taken by SKB to understand and represent the time scales for biosphere evolution.

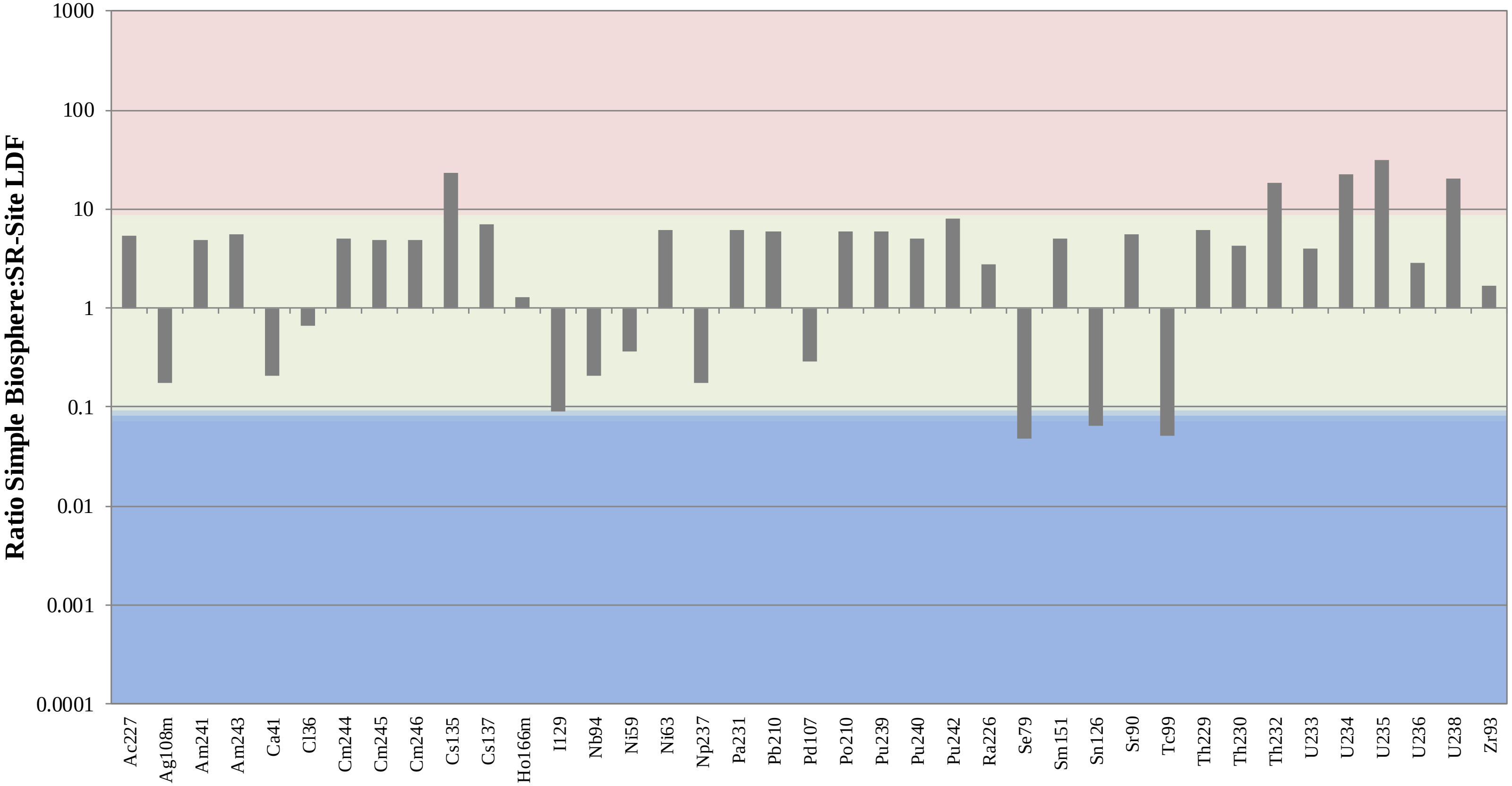

Figure 8: Maximum dose factors for groundwater release to combined arable and pasture system with a deep well and coarse discretisation compared with SR-Site interglacial LDFs.

Table 19: Maximum calculated concentrations in the surface soil for a combined arable and pasture system under a present-day climate receiving only groundwater discharges (no irrigation) with fine and coarse discretisation.

Radio-nuclide	Full Model		Coarse Discretisation		Ratio of max. conc. Coarse:Full Disc.
	Conc. (Bq kg^{-1})	Time to 90% (y)	Conc. (Bq kg^{-1})	Time to 90% (y)	
Ac-227	2.5E-22	300	9.9E-13	100	4.0E+09
Ag-108m	1.6E-10	4,000	3.7E-07	2,000	2.4E+03
Am-241	1.9E-15	5,000	1.9E-09	2,000	1.0E+06
Am-243	2.4E-09	60,000	7.5E-07	30,000	3.2E+02
Ca-41	2.6E-07	9,000	5.1E-07	7,000	1.9E+00
Cl-36	6.8E-08	100	9.4E-08	100	1.4E+00
Cm-244	4.8E-28	200	9.4E-15	100	2.0E+13
Cm-245	4.6E-11	80,000	2.9E-07	40,000	6.3E+03
Cm-246	2.6E-12	50,000	8.9E-08	20,000	3.4E+04
Cs-135	1.2E-06	900,000	2.5E-05	800,000	2.2E+01
Cs-137	4.4E-29	400	5.1E-15	200	1.1E+14
Ho-166m	2.0E-14	14,000	1.1E-08	7,000	5.4E+05
I-129	4.5E-06	2,000	1.1E-05	2,000	2.3E+00
Nb-94	4.2E-07	120,000	1.3E-05	60,000	3.1E+01
Ni-59	1.1E-05	70,000	3.2E-05	50,000	3.0E+00
Ni-63	2.7E-15	1,000	1.6E-09	700	6.1E+05
Np-237	5.5E-06	6,000	1.2E-05	5,000	2.2E+00
Pa-231	8.4E-07	140,000	6.9E-06	80,000	8.2E+00
Pb-210	1.3E-27	300	2.9E-14	100	2.2E+13
Pd-107	9.5E-07	30,000	1.9E-06	30,000	2.1E+00
Po-210	1.3E-32	6	8.5E-18	3	6.4E+14
Pu-239	5.6E-07	90,000	3.3E-06	50,000	5.9E+00
Pu-240	3.3E-08	40,000	9.8E-07	20,000	3.0E+01
Pu-242	4.1E-06	180,000	9.7E-06	140,000	2.4E+00
Ra-226	2.6E-12	18,000	4.8E-08	9,000	1.8E+04
Se-79	3.5E-06	6,000	7.5E-06	5,000	2.2E+00
Sm-151	1.0E-21	1,000	6.5E-12	700	6.5E+09
Sn-126	2.5E-05	70,000	6.5E-05	50,000	2.6E+00
Sr-90	2.3E-18	300	1.4E-11	200	6.3E+06
Tc-99	1.7E-08	50	3.0E-08	40	1.7E+00
Th-229	1.3E-14	90,000	2.4E-08	40,000	1.8E+06
Th-230	1.3E-09	700,000	2.0E-06	300,000	1.5E+03
Th-232	4.2E-07	900,000	3.3E-05	900,000	7.8E+01
U-233	1.3E-05	300,000	4.2E-05	200,000	3.3E+00

Radio-nuclide	Full Model		Coarse Discretisation		Ratio of max. conc. Coarse:Full Disc.
	Conc. (Bq kg^{-1})	Time to 90% (y)	Conc. (Bq kg^{-1})	Time to 90% (y)	
U-234	1.7E-05	300,000	4.9E-05	200,000	2.9E+00
U-235	3.1E-05	400,000	7.1E-05	300,000	2.3E+00
U-236	3.0E-05	400,000	7.1E-05	300,000	2.3E+00
U-238	3.1E-05	400,000	7.1E-05	300,000	2.3E+00
Zr-93	2.7E-05	120,000	6.4E-05	100,000	2.3E+00

4. Conclusions

This technical note presents further review of the biosphere modelling undertaken in support of SKB's SR-Site assessment through the further consideration and investigation using independently developed simple biosphere models for the Forsmark system. The work contributes to the regulatory review of the SR-Site assessment undertaken by SKB.

Specific objectives of the work reported here were (i) to extend the simple biosphere models previously developed and documented in Walke (2014) to include climate states in addition to present-day conditions, and (ii) to further investigate differences between the results of the simple biosphere models and the LDF values used in the SR-Site assessment. Conclusions relating to each of these objectives are presented in Sections 4.1 and 4.2, respectively. Overall conclusions are summarised in Section 4.3.

4.1. Representation of Climate States

This technical note describes the extension of simple biosphere models for the Forsmark system to represent warmer conditions. The representation of the warmer systems draws on the SR-Site descriptions of a warm climate at Forsmark to justify increased runoff, increased irrigation and increased occupancies. Dose factors calculated for warm climate conditions are shown to be consistently higher than those for present-day climate conditions, principally due to increased irrigation and occupancies.

The SR-Site assessment includes a 'global warming' case. Descriptive reports on the terrestrial, limnic and marine biosphere at Forsmark describe warmer conditions with increased runoff and present parameter values for increased productivity. However, these are not taken into account in the dose assessment modelling, which instead simply represents a 'global warming' case as one where the interglacial conditions last longer than in the reference glacial cycle, without changing the parameterisation of the system. As might be expected, LDFs for the 'global warming' case only differ for those long-lived radionuclides that have not reached equilibrium by the end of the interglacial conditions in the reference glacial cycle.

This technical note also describes the inclusion of periglacial conditions in the simple biosphere modelling of the Forsmark site. The representation of periglacial conditions draws on the SR-Site descriptions of colder conditions to justify alternative water flows and habits. The simple model for periglacial conditions includes the potential for small-scale agriculture. The SR-Site reports present parameter values for agricultural production under permafrost conditions, however, these are then excluded from the dose assessment modelling.

Consistent with the LDF modelling, the simple biosphere modelling shows that dose factors for periglacial conditions are typically significantly lower than under present-day conditions. In the case of the simple biosphere models, this is principally due to the absence of irrigation with groundwater, lower occupancies and the assumption that only a fraction of a discharge might go to soils adjacent to an open talik. Dose factors for shorter-lived radionuclides under periglacial conditions are shown to be significantly lower than LDFs for permafrost conditions. This is due to the absence of well water pathways in both models, which means that the results are sensitive to the coarse discretisation adopted in LDF models, which is shown to be significantly conservative for shorter-lived radionuclides.

4.2. Investigation of Modelling Approaches

Further comparison of the simple biosphere models with the SR-Site results highlights the importance of the well water pathway to the LDFs for interglacial conditions. Consumption of water from a deep well is shown to contribute more than 50% of the dose for 32 out of the 39 radionuclides studied. If the simple model is adapted to resemble assumptions adopted in SKB’s LDF models (e.g. if irrigation with groundwater is excluded and if the SKB’s model for well water concentrations is used), then the simple biosphere model produces dose factors that are consistent with the SR-Site LDFs for interglacial conditions. However, it is noted that the SKB model for well water concentrations omits the contribution of radionuclides that are explicitly modelled in the biosphere, but are not explicitly modelled in the geosphere (notably Po-210).

The ‘simple’ models do not represent habitat succession and landscape evolution. However, they are more complex in their vertical discretisation, which is more refined in comparison to that adopted in the SR-Site LDF models. The vertical discretisation in the simple models aims to properly reflect the time scales for radionuclide migration for a groundwater source term.

The coarse discretisation adopted in the SR-Site LDF models is shown to be significantly conservative for shorter-lived radionuclides. In addition, the coarse discretisation means that the time scales for radionuclide accumulation and in-growth are not appropriately represented. The effect of the coarse discretisation is masked in the LDF modelling by the dominance of the well water pathway. This coarse approach is inconsistent with the care that is taken by SKB to study and model the landscape evolution and associated time scales. The value in the representation of the evolving system at Forsmark is therefore undermined by the coarse approach adopted in the dose assessment modelling.

4.3. Overall Conclusions

The independent development of simple biosphere models of the Forsmark system has been a useful way to explore the LDF models used by SKB. The exercise has revealed several weaknesses in the dose assessment modelling undertaken in support of the SR-Site assessment. Some of the weaknesses are highlighted below.

- The dose assessment modelling is difficult to interpret, principally because its documentation is distributed across five reports. Understanding is not helped by inconsistencies between those reports, especially regarding how warmer and colder climate states are represented. Mistakes in the documentation, such as the discrepancy between the reported sorption coefficients for radium and those that were actually used, do not help to build confidence in the quality of the work that was undertaken.
- The documentation of the LDF models is not explicit about the treatment of short-lived daughters of the radionuclides represented in the modelling. The reports state that short-lived daughters are taken into account, but refer to assumptions in an EC directive that are inappropriate for long-term dose assessment modelling. Having stated that the contribution of short-lived

daughters is included in dose coefficients for the radionuclides that are represented in the LDF modelling, the contributions are actually excluded from the dose coefficients presented and used in SR-Site. This affects the dose coefficients for Ac-227, Am-243, Cs-137, Np-237, Pb-210, Ra-226, Sr-90, Th-229 and U-238.

- The contributions of radioactive progeny that are explicitly modelled in the biosphere but not in the geosphere are not accounted for in calculating well water concentrations. In the case of Po-210, its lower degree of sorption on geosphere rocks and its higher dose factor mean that the dose factor for Pb-210 is underestimated in the LDF models. The contribution of Ra-228 and Th-228 to the dose factor for Th-232 is similarly overlooked by SKB.
- The LDF models adopt a coarse discretisation of the regolith, which is inappropriate for representing the groundwater discharge pathway. Whilst the approach is particularly conservative for shorter-lived radionuclides, it also means that the time scales for radionuclide migration and accumulation are not properly represented. The improper treatment of the timescales for radionuclide migration in the regolith is inconsistent with the care that has been taken by SKB to understand and represent the time scales of landscape evolution and succession.
- Detailed hydrological modelling is used to underpin the representation of near-surface hydrology in the dose assessment modelling. However, the extrapolation of the hydrological modelling results are inappropriate, with some water flows being ignored and net water flows being used elsewhere so that advective exchanges are not properly represented.
- A carbon based model is used to underpin the resource usage represented in the dose assessment model. This helps to give some confidence that assumptions are reasonable, but it also means that the habits that are represented, notably consumption rates, are not transparent.

There are, however, some features of the LDF models that help to build confidence in the SR-Site assessment.

- The assessment conservatively uses the highest dose factors modelled across all objects and all time.
- The dose assessment model includes consumption of groundwater from a deep well, which is a dominant pathway in many cases and helps to compensate for some of the weaknesses in the dose assessment modelling.

In addition, if similar modelling assumptions are adopted, then it is possible for the simple biosphere models to calculate dose factors that are in reasonable agreement with the LDFs used in the SR-Site assessment.

Having explored the LDF modelling at some length, it is evident that there are some important issues that are not fully addressed in the SR-Site assessment.

- The dose assessment modelling does not fully represent or explore the potential implications of warmer climate conditions at Forsmark. Such conditions are projected to occur in the current interglacial and cannot be discounted from occurring in future interglacial periods.
- Potential dose implications for small-scale agriculture under permafrost conditions are not explored. However, this is of limited radiological

importance, given the low radiological consequences of releases under periglacial conditions compared to releases under temperate climate conditions.

- The potential for irrigation is not fully explored. Use of shallow groundwater for small-scale irrigation is shown to have the potential to significantly increase dose factors for some radionuclides. There is some evidence of the use of shallow groundwater for small-scale irrigation in the Forsmark under present-day conditions, let alone under warmer climate conditions that are projected to occur.

It should be noted that the higher dose factors that are calculated with the simple biosphere modelling are associated with releases to smaller areas and smaller potential exposure groups than are typically considered in the LDF modelling. Regulatory guidance (SSM, 2008) states that, in the case where the exposed group only consists of a few individuals, the criterion for individual risk can be considered as being complied with if the highest calculated individual risk does not exceed 10^{-5} per year rather than a criterion of 10^{-6} per year for exposure of larger groups.

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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.

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