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Abstract

The estimation of doses to humans in the main scenarios considered in SR-Can is carried out by multiplying the radionuclide releases to the biosphere by Landscape Dose Factors (LDF), which provide estimates of doses incurred by unit releases of activity of a specific radionuclide to the landscape. The landscape models considered in deriving the LDF's consist of a set of interconnected ecosystem models of different types, including aquatic and terrestrial ecosystems. Aquatic ecosystems comprise the sea, lakes and rivers. The terrestrial ecosystems include agricultural lands, forests and mires. In this report dose conversion factor for each individual ecosystem are reported.

Two release cases are considered in the report: a constant unit release rate during 10,000 years and a pulse release, i.e. a unit release during one year. For deriving the LDF values, at each considered time period an ecosystem model is assigned to each landscape object, according to the projected succession of ecosystems in the objects. The applied ecosystem models have been described elsewhere, but some modifications have been made which are described in this report. The main modifications applied to the models are to consider releases through bottom sediments and to consider upstream fluxes for the estimation of the fluxes of radionuclides between the different landscape objects.

To facilitate calculations of the radionuclide concentrations in the ingested food, aggregated transfer factors are derived for each ecosystem type. These relate the radionuclide concentrations in the edible carbon production in different ecosystem types to the radionuclide concentrations in the main environmental substrates of the ecosystems, i.e. the water in aquatic ecosystems and the soil in the terrestrial ecosystems. The report provides a description of the methods applied for the derivation of aggregated transfer factors for each ecosystem type and for irrigation. These factors are applicable for situations of chronic contamination.

From the simulations for the different release cases, activity concentrations in water and soil are obtained and then multiplied with the aggregated transfer factors to obtain concentrations in food products. For terrestrial ecosystems, the aggregated transfer factors in Becquerel per Kilogram of edible carbon in the food are used to calculate the activity intake and from this the effective dose rate per unit release to an adult individual. For aquatic ecosystems, only doses from the ingestion of water (for lakes) and food (for sea and lakes) are considered, as previous assessments have shown that in these types of ecosystems other exposure pathways give a very low contribution to the total doses.

A sensitivity analysis of the ecosystem models is presented in the report, identifying which parameters have the largest effect on the simulation endpoints of interest. The endpoints considered are the fraction of the release that is retained in the ecosystem, the activity concentrations in soil, water and sediments, and the total dose rates from external exposure, inhalation, and ingestion of water and food. These endpoints are evaluated at different times within the simulation and a sensitivity analysis using the Morris method is carried out.

For some of the scenarios considered in SR-Can, the LDF concept is not applicable. One of these scenarios comprises the contamination of ground caused by inadvertent drilling into the repository. Doses which would arise for a family using this contaminated ground for housing and food production are estimated. The other scenario which is assessed separately is the release of C-14 and Rn-222 from the repository in gaseous form, entering the biosphere via soil as a diffuse source. Pathways considered are doses from ingestion of C-14 and from inhalation of C-14 and Rn-222 outdoors as well as indoors. For these scenarios, specific dose calculations were carried out. The methods applied for these calculations and the results obtained are described in the report.

Sammanfattning

Beräkningen av dosen till människor i SR-Can:s huvudscenarierna utfördes genom att multiplicera radionuklidutsläppen till biosfären med Landskap Dos Factorer (LDF), vilka ger uppskattningar av doser som resulterar från ett enhets-utsläpp av en specifik radionuklid till landskapet. Landskapsmodellerna som betraktades vid härledningen av LDF-värdena består av grupper av ihopkopplade ekosystem modeller av olika typ, och inkluderar både akvatiska och land ekosystem. De akvatiska ekosystemen utgörs av hav, sjöar och floder. Landekosystemen utgörs av jordbruksland, skog, och våtmark. I denna rapport redovisas doskonverteringfaktorer för de individuella ekosystemen.

Två utsläppsvarianter studeras i rapporten. Bortsett från kontinuerliga enhets-utsläpp, dvs konstanta utsläpps av 1 Bq/år under en period av 10 000 år, inkluderas även ett fall med puls-utsläpp, dvs ett kontinuerligt utsläpp av 1 Bq/år under ett års tid. Under varje inkluderad tidsperiod bestäms en ekosystem-modell för varje landskapsobjekt vid beräkningen av LDF-värdena, baserat på den förmodade successionen av ekosystem i objektet. Ekosystem-modellerna som används beskrivs i tidigare publikationer, dock har vissa modifieringar gjorts vilket finns beskrivet i denna rapport. De huvudsakliga ändringar som gjorts är för att ta hänsysn till utsläpp genom bottensediment och för att ta hänsyn till flöden uppströms för att uppskatta flödet av radionuklider mellan de olika landskapsobjekten.

För att underlätta vid beräkningarna av radionuklidkoncentrationer i den intagna födan härleds s k *aggregated transfer factors* för varje ekosystem typ. Dessa relaterar radionuklidkoncentrationen i den ätbara mängden kolproduktion i olika ekosystem till radionuklidkoncentrationen i de huvudsakliga miljöbeståndsdelarna i de olika ekosystems typerna, såsom vatten för de akvatiska systemen, och jord för de terrestriella. Rapporten innehåller en fullständig beskrivning av metoderna som tillämpas för att härleda dessa faktorer för varje typ av ekosystem samt för bevattning. Faktorerna är tillämpbara vid situationer av kronisk kontaminering.

Från simuleringarna för de olika utsläppsscenarierna erhålles aktivitetskoncentrationer i vatten och jord, vilka sedan är multiplicerade med *aggregated transfer factors* för att ge koncentrationen i mat produkter. För terrestra ekosystem uttrycks *aggregated transfer factors* i Bequerel per kilogram ätbart kol i mat för att beräkna aktivitetsintaget och från detta den effektiva stråldosen per enhetsutsläpp till en vuxen människa. För akvatiska ekosystem betraktas enbart dosbidrag via intag av vatten (för sjöar) och mat (för sjöar och hav), då tidigare utvärderingar har visat att övriga exponeringsvägar i dessa ekosystem ger ett väldigt lågt bidrag till den totala dosen.

En känslighetsanalys av ekosystemmodellerna presenteras i rapporten, vilken identifierar de parametrar som har den största effekten på modellens beräknade resultat. De olika beräknade resultaten som betraktas är bråkdelen av utsläppet som bevaras i ekosystemet, aktivitetskoncentrationen i jord, vatten och i sediment, och den totala dosen från extern exponering, inhalation, samt intag av vatten och mat. Dessa beräkningsresultat utfördes för olika tidpunkter under simuleringens tidsintervall, och en känslighetsanalys utfördes med Morris metod.

För vissa av scenarierna inom SR-Can så är inte LDF-konceptet tillämpbart. Ett av dessa scenarier utgörs av kontaminering av marken orsakat av att man oavsiktligt borrat sig in i förvaret. Doser som skulle kunna drabba en familj som brukar denna kontaminerade jord för bosättningg samt matproduktion är uppskattade. Det andra scenariet som betraktas separat består av utsläpp av C-14 och Rn-222 från förvaret i gasform genom marklagret. Exponeringsvägar som beaktas är doser från intag av C-14 samt inhalation av C-14 och Rn-222 utomhus såväl som inomhus. De metoder som tillämpades för dessa beräkningar samt de erhållna resultaten beskrivs i rapporten.

Contents

1 Introduction

The estimation of doses to humans in the main scenarios considered in SR-Can were carried out by multiplying the radionuclide releases to the biosphere by Landscape Dose Factors (LDF). The LDF values were derived for both studied sites, Forsmark and Laxemar, by performing simulations with landscape models /Avila et al. 2006/. These landscape models consist of a set of interconnected ecosystem models of different types, including aquatic and terrestrial ecosystems. Aquatic ecosystems comprise the sea, lakes and rivers. The terrestrial ecosystems include agricultural lands, forests and mires.

The ecosystem models used in the landscape models are the same which were used in the assessments performed for SR-Can Interim /SKB 2004/ with the exception of the forest model /Avila 2006/, which was not available at that time and was especially developed for SR-Can. To make these models applicable in the landscape model, it was necessary to introduce some modifications, which are described in Chapter 2 of this report.

The basic methodology used in the SR-Can dose calculations is described in /Avila and Bergström 2006/. According to this methodology, the doses from food ingestion are calculated by multiplying the annual carbon intake by an individual with the radionuclide concentration in food, expressed in units of Bq/kgC. To facilitate calculations of the radionuclide concentrations in the ingested food, aggregated transfer factors were derived for each ecosystem type. These aggregated transfer factors relate the radionuclide concentrations in the food produced in different ecosystem types (based on edible carbon contents) to the radionuclide concentrations in the main environmental substrates of the ecosystems, i.e. the water in aquatic ecosystems and the soil in the terrestrial ecosystems. The method used for the derivation of the aggregated transfer factors and the values obtained are presented in Chapter 3 of the report.

In Chapter 4 of the report, results of dose calculations using each of the modified models are presented for two cases: one assuming a continuous unit release of a selection of radionuclides to the ecosystems and the other assuming a pulse release of the same radionuclides.

A sensitivity study of the modified models was carried out to identify the parameters that have the largest effect on the predictions with the models. The main findings of this study are presented in Chapter 5 of this report. Detailed results are given in Appendix I.

As mentioned above, dose calculations in SR-Can were carried out for the main scenarios using the LDF derived in /Avila et al. 2006/. However, for some scenarios the LDF concept is not applicable and therefore specific dose calculations are required. This applies to the drilling scenario, which considers the contamination of ground caused by inadvertent drilling into the repository. Doses which would arise for a family using this contaminated ground for housing and food production are estimated Chapter 6.

Another scenario where the LDF approach does not apply is the case of a pulse gas release containing C-14 and Rn-222. For this scenario, dose conversion factors were not derived, but instead dose calculations were carried out directly using a postulated value of the total release. The dose calculation methods and results obtained for this case are presented in Chapter 7.

2 Ecosystem models

As mentioned in Chapter 1, the Landscape Dose Factors /Avila et al. 2006/ used in the dose assessments in SR-Can were derived using landscape models. For this purpose, at each considered time period an ecosystem model was assigned to each landscape object, according to the projected succession of ecosystems in the objects. The ecosystem models applied are modifications of models described elsewhere /Bergström et al. 1999, SKB 2004, Avila 2006/. This section describes the modifications of the models and the values assigned to the model parameters.

2.1 Modifications of the ecosystem models

For lakes and sea objects the compartment models described in /Bergström et al. 1999/ were used. A modification was applied, as described in /SKB 2004/, to be able to consider releases through bottom sediments. In the lake model described in /Bergström et al. 1999/, a parameter is used for describing the residence time of the water in the lake. In the model that was used in SR-Can this parameter was calculated using the following expression:

$$\mathrm{Re}sTime = \frac{mean\_depth * Area\_lake}{area\_catch * runoff} \qquad (2.1)$$

where,

ResTime is the residence time of the water in the lake [y]

mean_depth is the mean depth of the lake [m],

Area_lake is the area of the lake [m^2],

area_catch is the catchment area of the lake [m^2],

runoff is the average runoff of the catchment [m/yr].

For running waters (rivers), a compartment model was not used. Instead, instantaneous and complete mixing of the released radionuclides with the running water was assumed. This means that the activity concentration of the radionuclides in the river water was calculated by dividing the flux of radionuclides by the water fluxes in the river. The water fluxes were calculated by multiplying the catchment area of the river with the average runoff in the catchment.

For agricultural lands and mires, the compartment models described in /Bergström et al. 1999/ were used. The model described in /Avila 2006/ was used for forests. In the original version of these three models, the subsurface water fluxes were assumed to equal the area of the ecosystem times the average runoff. Hence, the upstream water fluxes were not considered in the calculation of the radionuclide outflows with subsurface waters. This assumption is valid in a conservative assessments for isolated ecosystems. However, in the SR-Can assessments landscape models were used /Avila et al. 2006/, which require consideration of the upstream fluxes for estimation of the fluxes of radionuclides between the landscape objects. To account for these fluxes, the equations of the transfer rate coefficients, which are used in the calculation of the outflows of radionuclides from the ecosystems with subsurface waters /Bergström et al. 1999, Avila 2006/, were modified by multiplying with a correction coefficient equal to the ratio between the catchment area and the area of the biosphere object.

2.2 Parameter values

An overview of the parameters used and their values is provided in this section. The model parameters are classified in two broad categories: radionuclide-independent and radionuclide-dependent parameters.

2.2.1 Radionuclide-independent parameters

Most of the parameters used in the ecosystem models correspond to hydrological and ecological properties of the ecosystems and are radionuclide-independent. This category of parameters is described in more detail in /SKB 2006ab/, where also the origin of the data is provided.

Most of the parameters values were derived from the site investigation programmes. Tables with an overview of the parameter values used for Forsmark and Laxemar are provided in /Avila et al. 2006/. As the parameter values vary among the different objects, an interval of variation is provided for each parameter, which was used in the sensitivity studies presented in Chapter 5. These tables also include a generic interval of variation for most of the parameters, which has been taken from the reports in which the models have been described: lakes, sea, mires and agricultural lands in /Bergström et al. 1999/ and forests in /Avila 2006/.

2.2.2 Radionuclide-dependent parameters

Radionuclide-dependent parameters in the ecosystem models are the distribution coefficients (K_d) and the transfer factors from soil and water to biota. The K_d values in the lake, sea, mire and agricultural land models were taken from /Karlsson and Bergström 2002/, whereas the values for forest were taken from /Avila 2006/. In SR-Can, the transfer to biota was estimated using aggregated transfer factors, which were derived from the transfer factors in /Karlsson and Bergström 2002/ and /Avila 2006/ as described in Chapter 3.

3 Derivation of Aggregated Transfer Factors

To facilitate the calculation of doses from ingestion of food produced in different biosphere objects, aggregated transfer factors were derived for each ecosystem type. In the dose calculations for SR-Can /Avila et al. 2006, Avila and Bergström 2006/, it was assumed that the exposed individuals obtain the whole annual demand of carbon (a value of 110 kg C/yr /Avila and Bergström 2006/ was used) from the ecosystem considered. Hence, the total radionuclide intake with food can be expressed as:

$$Intake^j = IR_C * \sum_k f_k * C_k^j \qquad (3.1)$$

where,

IR_C is the annual intake of carbon by an individual [kgC/yr],

f_k is the fraction of the food product "*k*" in the annual intake of carbon [unitless],

$C_k{}^j$ is the *j-th* radionuclide concentration in the food product "k" [Bq/kgC].

The radionuclide concentration in each food product can be obtained by multiplying the radionuclide concentration in the main environmental media, i.e. water for aquatic ecosystems and soil for terrestrial ecosystems, with the corresponding concentration ratio. The following expression for the total radionuclide intake with food results:

$$Intake^j = IR_C * C_{media}^j * \sum_k f_k * CR_k^j \qquad (3.2)$$

where,

$C^j{}_{media}$ is the *j-th* radionuclide concentration in the water or soil [Bq/m^3 or Bq/kg DW],

$CR_k{}^j$ is the concentration ratio from water or soil to the food product "*k*" [Bq/kgC per Bq/m^3 or Bq/kgC per Bq/kg DW].

The sum in Equation 3.2 represents the ratio between the radionuclide concentration in the diet and the radionuclide concentration in water or soil and is called in this report "Aggregated Transfer Factor (TF_{agg})". Hence, the TF_{agg} for a given ecosystem type is the sum, over all possible food components of the diet, of the CRs weighted with the fractional contribution of the various food products to the annual carbon intake.

3.1 Aggregated Transfer Factors for aquatic ecosystems

In the case of aquatic ecosystems (sea, lakes and rivers), fish was the only component of the diet considered in the calculation of the TF_{agg}. Hence, the TF_{agg} (Table 3-1) were obtained by dividing the bioaccumulation factors for fish reported in /Karlsson and Bergström 2002/ by the carbon content in fish. The carbon content in fish (Table 3-3) was estimated using the following equation, relating the protein, carbohydrates and fat content with the carbon content in food /Altman and Ditmer 1964, Dyson 1978, Rouwenhorst et al. 1991/:

$$CC_k = 0.53*Proteins_k + 0.44*Carbohydrates_k + 0.66*Lipids_k \qquad (3.3)$$

where,

CC_k is the carbon content in the food product "*k*" [kgC/kg FW],

$Proteins_k$ is the protein content in the food product "*k*" [kg /kg FW],

$Carbohydrates_k$ is the carbohhydrate content in the food product "*k*" [kg /kg FW],

$Lipids_k$ is the lipid content in the food product "*k*" [kg /kg FW].

The coefficients in Equation 3.3 are the carbon content (in kgC/kg) of proteins, carbohydrates and lipids, respectively. The values of the content of proteins, carbohydrates and lipid in fish, used in the calculations of the carbon content in fish were taken from the database of the Swedish Food Administration (Livsmedelverket) available online at www.slv.se.

3.2 Aggregated Transfer Factors for terrestrial ecosystems

Two different TF_{agg} were derived for terrestrial ecosystems: one for agricultural lands and one for forests and mires. The carbon content in terrestrial food products (Table 3-3) was also calculated by Equation 3.3, using values of proteins, carbohydrates and lipid content in the different foods taken from the database of the Swedish Food Administration (Livsmedelverket).

3.2.1 Aggregated Transfer Factors for agricultural lands

In the case of agricultural land, five types of food products were considered: roots, cereals, vegetables, cow milk and cow meat. In a first step, a transfer factor (TF) in units of Bq/kgC per Bq/kg DW was obtained for each of these types of agricultural food. For roots, cereals and vegetables the TFs were obtained by diving the concentration ratios reported in /Karlsson and Bergström 2002/ by the carbon content of each food type (Table 3-2). For milk and meat the TFs were calculated using Equations 3.4 and 3.5:

$$TF^{j}_{milk} = \left(CR^{j}_{pasture} * ConsPast + ConsSoil\right) * \frac{TC^{j}_{milk}}{Dens_{milk} * CC_{milk}} \qquad (3.4)$$

$$TF^{j}_{meat} = \left(CR^{j}_{pasture} * ConsPast + ConsSoil\right) * \frac{TC^{j}_{meat}}{CC_{meat}} \qquad (3.5)$$

where,

$CR^{j}_{pasture}$ is the "*j-th*" concentration ratio from soil to pasture [Bq/kg DW per Bq/kg DW],

ConsPast is the pasture consumption by cows [kg DW/d],

ConsSoil is the soil consumption by cows [kg DW/d],

TC^{j}_{milk} is the transfer coefficient to cow milk [d/l],

TC^{j}_{meat} is the transfer coefficient to cow meat [d/kg FW],

$Dens_{milk}$ is the milk density [kg/l],

CC_{milk} is the carbon content of milk [kgC/kg FW],

CC_{meat} is the carbon content of meat [kgC/kg FW]

The values of the *CR* and *TC* were taken from /Karlsson and Bergström 2002/. The values of *ConsPast* and *ConsSoil* given in /Bergström et al. 1999/ were used. A value of 1.03 kg/l was used for the milk density. The values of the carbon content of milk and meat are presented in Table 3-3.

Table 3-1. Derived values of the aggregated transfer factors (TF_{agg}) for the different ecosystem types: lakes and rivers, sea, agricultural lands, forests and mires.

Element	TF_{agg} Lakes and Rivers Bq/kgC per Bq/m³	TFa_{gg} Sea Bq/kgC per Bq/m³	TF_{agg} Agric Lands Bq/kgC per Bq/kg DW	TF_{agg} Forests and Mires Bq/kgC per Bq/kg DW
Cl	7.3E–03	7.3E–03	7.0E+01	3.6E+01
Ca	7.3E–01	1.5E+00	1.7E+00	2.4E+01
Ni	3.6E+02	1.5E+01	3.8E–01	1.8E+00
Se	3.6E–01	7.3E–03	3.8E+01	3.1E+00
Sr	1.5E+00	4.4E+00	1.7E+00	2.4E+01
Zr	2.2E+00	2.2E+00	1.6E–03	1.0E–02
Nb	7.3E–01	2.2E+00	7.6E–03	5.2E–02
Tc	1.5E+01	2.9E+01	8.7E+00	6.5E+00
Pd	4.4E–01	2.2E–01	2.5E–01	2.1E+00
Ag	1.5E+00	7.3E–01	1.3E+00	5.2E+00
Sn	2.2E+00	7.3E–01	6.4E–01	1.0E+00
I	7.3E–02	7.3E–02	7.2E–01	4.0E+00
Cs	1.5E–01	2.2E–01	3.7E–01	5.5E+01
Sm	7.3E–02	7.3E–02	1.5E–02	1.0E–01
Ho	7.3E–01	7.3E–02	1.5E–02	1.0E–02
Pb	3.6E–02	3.6E+00	2.1E–02	1.0E–02
Po	1.5E–01	1.5E+00	2.5E–02	5.2E–01
Ra	2.2E+01	7.3E+00	4.0E–02	7.4E+00
Th	1.5E+00	2.2E–01	5.9E–03	4.4E–03
Pa	7.3E+01	1.5E+00	4.9E–03	3.1E–02
U	2.2E–01	7.3E–01	1.6E–02	3.1E–02
Np	2.2E–01	2.2E–01	2.6E–02	1.9E–02
Pu	3.6E–01	7.3E–01	2.0E–04	1.0E–04
Am	2.2E–01	2.2E–01	4.6E–04	1.1E–04
Cm	2.2E+00	7.3E–01	4.7E–04	1.0E–02

Table 3-3. Derived values of the aggregated transfer factors (TF_{agg}) for irrigation.

Element	TF_{agg}, Irrigation Bq/kgC per Bq/m³
Cl–36	6.6E–02
Ca–41	5.6E–02
Ni–59	4.7E–02
Ni–63	3.8E–02
Se–79	2.2E–01
Sr–90	4.9E–02
Zr–93	2.8E–02
Nb–94	2.8E–02
Tc–99	1.3E–01
Pd–107	4.3E–02
Ag–108m	7.6E–02
Sn–126	5.5E–02
I–129	5.4E–02
Cs–135	5.0E–02

Element	TF_{agg}, Irrigation Bq/kgC per Bq/m³
Cs–137	3.3E–02
Sm–151	2.9E–02
Ho-166m	3.1E–02
Pb–210	2.8E–02
Po–210	2.8E–02
Ra–226	3.2E–02
Th–229	2.8E–02
Th–230	2.8E–02
Th–232	2.8E–02
Pa–231	2.8E–02
U–233	2.8E–02
U–234	2.8E–02
U–235	2.8E–02
U–236	2.8E–02
U–238	2.8E–02
Np–237	3.0E–02
Pu–239	2.8E–02
Pu–240	2.8E–02
Pu–242	2.8E–02
Am–241	2.8E–02
Am–243	2.8E–02
Cm–244	2.8E–02
Cm–245	2.8E–02
Cm–246	2.8E–02

The TF_{agg} for agricultural lands (Table 3-1) was then obtained by summing the TFs obtained for the five types of agricultural foods and dividing by 5. Hence, the TF_{agg} for agricultural lands is an average value of the TF's across different food types. This means that no preference is given to any particular agricultural use of the land. This is a reasonable assumption for long-term assessments, since it is not possible to know in advance which kind of food people will grow on a given land.

3.2.2 Aggregated Transfer Factors for forests and mires

For forests and mires, the diet components considered were roe deer and moose meat. Other forest foods like berries and mushrooms were not included in the derivation of the TF_{agg}. The TFs for roe deer and moose (in Bq/kg C/Bq/kg DW) were calculated with the following equations:

$$TF^{j}_{roedeer} = (f^{roedeer}_{mush} * CR^{j}_{mush} + f^{roedeer}_{und} * CR^{j}_{und} + f^{roedeer}_{leaves} * CR^{j}_{leaves} + f^{roedeer}_{wood} * CR^{j}_{wood}) * \frac{f^{j}_{gut} * F^{j}_{soft} * a^{j} * W^{b^{j}}_{roedeer}}{CC_{meat}} \quad (3.6)$$

$$TF^{j}_{roedeer} = (f^{moose}_{mush} * CR^{j}_{mush} + f^{moose}_{und} * CR^{j}_{und} + f^{moose}_{leaves} * CR^{j}_{leaves} + f^{moose}_{wood} * CR^{j}_{wood}) * \frac{f^{j}_{gut} * F^{j}_{soft} * a^{j} * W^{b^{j}}_{moose}}{CC_{meat}} \quad (3.7)$$

where,

$f_{mush}^{roedeer}, f_{und}^{roedeer}, f_{leaves}^{roedeer}, f_{wood}^{roedeer}$ are the fractions of mushrooms, understorey plants, tree leaves and tree wood, respectively, in the roe deer diet [dimensionless],

$f_{mush}^{moose}, f_{und}^{rmoose}, f_{leaves}^{rmoose}, f_{wood}^{moose}$ are the fractions of mushrooms, understorey plants, tree leaves and tree wood, respectively, in the roe deer diet [dimensionless],

CR^{j}_{mush}, CR^{j}_{und}, CR^{j}_{leaves}, CR^{j}_{wood} are *j-th* radionuclide concentration ratios from soil to mushrooms, understorey plants, tree leaves and tree wood respectively [Bq/kg DW per Bq/kg DW],

f_{gut}^{j} is the gut uptake fraction of the ***j-th*** radionuclide [unitless],

a^{j} is the multiplier in the allometric relationship for the ***j-th*** radionuclide [in appropriate units],

b^{j} is the exponent in the allometric relationship for the ***j-th*** radionuclide [unitless],

F_{soft}^{j} is the ***j-th*** radionuclide fraction in the animal soft tissues [unitless].

The values of the parameters in Equations 3.6 and 3.7 were taken from /Avila 2006/ with the exception of the fraction of radionuclides in soft-tissues, which were taken from /Coughtrey and Thorne 1993/. The TF_{agg} for forests and mires (Table 3-1) were obtained by adding the TFs for roe deer and moose and dividing by 2, i.e. it was assumed that roe deer and moose have an equal contribution to the diet of individuals exposed via ingestion of foods from forests and mires.

3.2.3 Aggregated Transfer Factors for irrigation

The aggregated transfer factor for irrigation is defined as the ratio between the radionuclide concentrations in vegetables and the irrigation water and is expressed in Bq/kgC per Bq/m^3. The TF_{agg} for irrigation (Table 3-2) were derived by running the irrigation model described in /Bergström and Barkefors 2004/ until equilibrium was reached. As input to the model, a unit concentration of the irrigation water was used. In this case, the TF_{agg} (in Bq/kgC per Bq/m^3) equals the concentration in vegetables (in Bq/kg FW) at equilibrium divided by the carbon content of vegetables (Table 3-3).

Table 3-3. Average values of the carbon content in different food types estimated with Equation 4.3 from the content of protein, carbohydrates and lipids in different food products taken from the database of the Swedish Food Administration (Livsmedelverket) available online at www.slv.se.

Food type	Carbon content kgC per kg FW
Cereals	0.395
Roots	0.058
Vegetables	0.049
Milk	0.064
Meat	0.136
Fish	0.138

4 Dose calculations

The models described in Chapter 2 were used for estimating doses resulting from radionuclide releases to the different ecosystem types (sea, lake, agricultural land, forest and mire). Two release cases were considered: i) continuous release – a constant unit release rate during 10,000 years and ii) pulse release – a unit release during one year. For the sea ecosystems, the releases were directed to the water in the top sediment, while for the lake two cases were considered: one with releases to the lake water and another with releases to the water in the top sediment. For agricultural lands, the releases were directed to the soluble part of the saturated zone. In the case of mires and forests the releases were directed to the peat and soil compartment, respectively.

From the simulations, activity concentrations in water and soil were obtained. These were then multiplied by the TF_{agg} (see Chapter 3) to obtain concentrations in food products (in Bq/kgC). Effective dose rates (in Sv/yr) per unit release rate (in Bq/yr) to an adult individual were calculated using the methods described in /Avila and Bergström 2006/. In this report, the term 'dose' refers to 'effective dose' which is the sum of the effective dose due to external exposure and the committed effective dose due to internal exposure. For terrestrial ecosystems, internal doses by inhalation and food ingestion and external doses were considered in the calculations. For aquatic ecosystems only doses from the ingestion of water (for lakes) and food (for sea and lakes) were considered, as previous assessments /SKB 1999, 2004/ have shown that in these types of ecosystems other exposure pathways give a very low contribution to the total doses. In the calculation of the food ingestion doses, a correction factor ($CorrD_{eco}$) was introduced in cases when the size of the food production in the ecosystem is not sufficient to support a single person with food:

$$CorrD_{eco} = \min(1, N_{eco})$$
$$N_{eco} = \frac{pty_{eco} * Area_{eco}}{IR_C} \quad (4.1)$$

where,

N_{eco} is the number of individual that can be supported by the ecosystem [unitless],

pty_{eco} is the productivity of the different ecosystem types [kgC/m^2/yr],

$Area_{eco}$ is the area of the ecosystem [m^2],

IR_C is the annual intake of carbon by an individual [kgC/yr].

The values of the productivity of the different ecosystems used for calculating the correction factors with Equation 4.1 are presented in Table 4-1. The areas of the ecosystems are given in /Avila et al. 2006/. A value of 110 kg C/yr /Avila and Bergström 2006/ was used for IR_C.

Table 4-1. Productivity of the different ecosystem types used for estimation of the number of individual that can be sustained by the ecosystem.

Ecosystem	Productivity kgC/m²/yr		
	Best estimate	Minimum	Maximum
Agricultural land	0.22	0.05	0.26
Forest	0.0038	0.0034	0.0040
Mire	5.5E–05		
Lakes and rivers	0.0024	0.0019	0.0028
Sea	0.0066	0.0033	0.0091

In the following sections the results of the dose calculations are presented for a selection of radionuclides, including those which, based on the previous assessments /SKB 1999, 2004/, are expected to give the highest dose contributions: Ni-59, Se-79, I-129 and Ra-226. Some further radionuclides (Cl-36, Tc-99, Cs-135, Pu-239 and Am-241) with contrasting properties and environmental behaviour were also considered. For the radionuclide-independent parameters the best estimate values given in /Avila et al. 2006/ for Laxemar were used.

4.1 Doses for continuous releases

The dose rate values, averaged over 50 years, at the end of the simulation period for the case of a continuous radionuclide release of 1 Bq/yr are presented in Table 4-2. For all radionuclides, the same time dynamics is observed with a continuous monotonic increase until an equilibrium value of the doses is reached. The time to achieve equilibrium varied between the ecosystems and between the radionuclides depending on their distribution coefficients. The doses were much lower for the Sea than for other ecosystems, which can be explained by a higher dilution of the released radionuclides in Sea objects. The maximum values of the dose rates for different ecosystem types depend on the radionuclide. The doses for the lake were up to a factor of 10 lower for releases to the water in the top sediment as compared to releases to the lake water (values presented in Table 4-2).

4.2 Doses for pulse releases

Table 4-3 presents the maximum values of the moving average, taken over 50 years, of the dose rates obtained for the case of a pulse radionuclide release of 1 Bq during one year. In this case, the maximum values were obtained either for the forest ecosystem or for the lake (assuming releases to the lake water). These maximum values were lower than the equilibrium values obtained for the case with continuous releases. For all ecosystems, with the exception of agricultural lands, a maximum value of the dose rate was observed during the first year, which was then followed by a fast decrease. For agricultural lands a similar time dynamics of the dose rates was observed for the most mobile radionuclides (Cl-36, Tc-99 and Se-79). For other radionuclides the maximum was observed at later times. This is due to the fact that the release to agricultural lands was directed to the saturated zone and some time is required for the radionuclides to reach the top layer of the soil, where they can be taken up by the agricultural plants.

Table 4-2. Estimates of the averaged (over 50 years) dose rates (Sv/yr) at the end of the simulation period (10,000 years) for the case with a continuous unit release rate (1 Bq/yr) of the studied radionuclides. Values for each ecosystem type are given. The values for lakes are given for the case with releases to water.

Radionuclide	Sea	Lake	Agricultural land	Forest	Mire
Cl-36	1.2E–21	7.7E–15	1.2E–14	1.1E–13	6.5E–15
Ni-59	1.6E–20	9.7E–16	3.0E–16	5.3E–14	3.1E–15
Se-79	9.7E–18	9.1E–13	5.7E–14	4.8E–12	2.8E–13
Tc-99	2.9E–20	2.2E–15	9.0E–15	7.5E–15	2.7E–16
I-129	3.7E–18	3.6E–12	1.1E–12	3.1E–12	1.8E–13
Cs-135	3.5E–19	3.1E–12	5.6E–15	2.7E–11	5.9E–13
Ra-226	1.1E–17	2.2E–12	6.0E–14	1.1E–09	7.5E–11
Pu-239	6.2E–18	7.9E–13	9.4E–16	3.8E–13	2.2E–14
Am-241	1.3E–17	9.7E–13	2.1E–16	4.9E–13	6.3E–13

Table 4-3. Estimates of the maximum values during the simulation period (10,000 years) of the moving average (taken over 50 years) of the dose rates (Sv/yr) for the case of a pulse release of 1 Bq/yr during one year of the studied radionuclides. Values for each ecosystem type are given. The values for lakes are given for the case with releases to water.

Radionuclide	Sea	Lake	Agricultural land	Forest	Mire
Cl-36	1.5E–23	1.5E–16	1.8E–16	2.3E–15	1.3E–16
Ni-59	8.9E–23	1.9E–17	1.5E–19	1.8E–16	6.1E–17
Se-79	5.4E–20	1.8E–14	1.6E–16	7.7E–15	5.5E–15
Tc-99	5.5E–22	4.3E–17	4.7E–17	1.5E–16	5.4E–18
I-129	3.1E–20	7.1E–14	4.8E–16	6.1E–14	3.5E–15
Cs-135	2.0E–21	6.1E–14	3.4E–18	1.1E–13	1.2E–14
Ra-226	6.4E–20	4.3E–14	2.6E–17	2.3E–12	1.5E–12
Pu-239	3.5E–20	1.5E–14	6.2E–19	6.9E–16	4.4E–16
Am-241	8.8E–20	1.9E–14	1.3E–19	7.8E–16	1.9E–15

5 Sensitivity study

A sensitivity analysis of the ecosystem models was carried out to identify which parameters have the largest effect on the simulation endpoints of interest. The endpoints considered were the fraction of the release that is retained in the ecosystem, the activity concentrations in soil, water and sediments, and the total dose rates from external exposure, inhalation, and ingestion of water and food. These endpoints were evaluated at different times after the start of the simulations.

The sensitivity analysis was carried out for a reduced set of radionuclides, including those which, based on the previous assessments /SKB 1999, 2004/, are expected to give the highest dose contributions: Ni-59, Se-79, I-129 and Ra-226. Some further radionuclides (Cl-36, Tc-99, Cs-135, Pu-239 and Am-241) with contrasting properties and environmental behaviour were also considered.

For the radionuclide-independent parameters, the intervals of variation given in /Avila et al. 2006/ for Laxemar were used in the sensitivity analysis. The radionuclide-dependent parameters considered in the study were the aggregated transfer factors TF_{agg} (see Chapter 3) and the distribution coefficients K_d. For the K_d values the intervals of variation given in /Karlsson and Bergström 2002/ were used. For the TF_{agg}, an interval of variation was derived for the studied radionuclides by running the models described in Chapter 3 probabilistically. The obtained intervals of variation, presented in Table 5-1, were used in the sensitivity study.

Table 5-1. Interval of variation of the (TF_{agg}) used in the sensitivity study for the different ecosystem types: lakes and rivers, sea, agricultural lands, forests and mires. For each radionuclide the minimum and maximum values are given corresponding to the 5 and 95 percentiles, respectively, of the simulated probability distributions.

Radionuclide	TF_{agg} Lakes and Rivers Bq/kgC per Bq/m^3	TFa_{gg} Sea Bq/kgC per Bq/m^3	TF_{agg} Agric Lands Bq/kgC per Bq/kg DW	TF_{agg} Forests and Mires Bq/kgC per Bq/kg DW
Cl-36	7.26E–02	7.26E–04	5.06E+01	6.04E+00
	7.26E–01	7.26E–02	2.09E+02	1.70E+02
Ni-59	7.26E–02	2.18E–01	8.42E–02	6.94E–01
	7.26E+00	3.63E+00	1.84E+00	3.38E+01
Se-79	3.63E+00	1.45E+01	5.14E+00	3.44E–01
	3.63E+01	5.81E+01	5.12E+01	7.13E+00
Tc-99	1.45E–02	7.26E–03	9.10E–01	2.37E+00
	5.81E–01	7.26E–01	3.08E+02	7.24E+01
I-129	7.26E–02	7.26E–02	1.54E–01	5.10E–01
	3.63E+00	7.26E–01	6.03E+00	9.46E+00
Cs-135	3.63E+00	7.26E–01	7.72E–02	5.18E+00
	1.45E+02	3.63E+00	2.26E+00	5.26E+02
Ra-226	7.26E–02	7.26E–02	6.52E–03	1.44E+00
	1.45E+00	7.26E–01	3.77E–01	1.61E+01
Pu-239	2.90E–02	3.63E–02	3.71E–05	3.94E–06
	2.18E+00	3.63E–01	1.25E–03	2.36E–03
Am-241	7.26E–02	7.26E–02	9.06E–05	4.25E–06
	2.18E+00	1.45E+00	3.43E–03	3.02E–02

The simulations were carried out for a constant unit input rate of radionuclides to the ecosystems. For the sea ecosystems, detailed results are presented for an accumulation time of 10,000 years, which is close to the duration of the Sea Period during the biosphere development /Avila et al. 2006/. For other ecosystems, the results are presented for an accumulation time of 3,000 years, which is close to the assumed average lifetime of these ecosystems in the landscape models /Avila et al. 2006/.

5.1 Sensitivity analysis method

The sensitivity analysis was carried out using the Morris method /Morris 1991/ implemented in the software package Eikos /Ekström and Broed 2006/. This method allows to screen out parameters that have negligible effects and to rank the parameters by their effect on the endpoints of interest. It is also possible to identify which parameters have non-linear effects or are involved in interactions with other parameters.

The Morris method uses two sensitivity measures: the mean (μ) and the standard deviation (σ) of the elementary effects of the parameters. The elementary effects are obtained from simulations using "one factor a time" sampling for evaluating the impact of changing one parameter at a time. Both sensitivity measures have to be taken into account when interpreting the results. To facilitate this, the estimated mean and standard deviation can be displayed in the (σ, μ) plane (see examples in Figures 5-1 to 5-8).

The mean (μ) measures the effect that each single parameter has on the endpoint of interest and indicates the sign of the effect. The standard deviation (σ) is a measure of non-linearity in the effects of the parameters and/or of parameter interactions. A parameter with a high absolute value of the mean and a low standard deviation will have a strong effect on the endpoint independently of the value of other parameters. The effect could either positive (if $\mu > 0$) or negative. On the other hand, a parameter with a low absolute value of the mean and a high standard deviation will have a low direct effect on the endpoint, but significant indirect effects through interactions with other parameters.

The green lines represented in the (σ, μ) planes constitute a wedge described by the standard error of the mean elementary effect. A parameter having coordinates below the wedge formed by these two lines is a strong indication that the mean elementary effect of the parameter is non-zero. A location of the parameter coordinates above the wedge indicates that interaction effects with other parameters or non-linear effects are dominant.

For ranking the parameters, it is convenient to use a sensitivity index (SI) that combines the mean and the standard deviation. The SI used in this study was the square root of the sum of the squared mean and standard deviation, normalised by the sum over all parameters and expressed in percent units.

5.2 Sensitivity analysis of the aquatic ecosystem models

For the aquatic ecosystem models, i.e. the lake and the sea, the endpoints considered in the sensitivity study were the fraction of the releases retained in the ecosystems, the activity concentration in water and sediments and the dose rate. The results obtained for each of the ecosystem models are presented below.

5.2.1 Sensitivity analysis of the sea model

The values of the sensitivity indices obtained for the sea model are presented in Tables I.1–I.4 of Appendix I. The main findings of the sensitivity analysis of the sea model are discussed below for each considered endpoint.

Sensitivity of the retained fractions in Sea Objects

The parameters with the largest effect on the fraction of the releases retained in Sea Objects (Table I.1 in Appendix I) are the fraction of accumulation bottoms (acc_bottom), with a positive effect, and the velocity of the upward water fluxes in the sea bottom (v_bottom), which has a negative effect. If the distribution coefficient (K_d_peat) increases, there is a decrease in the effect of the parameter v_bottom and an increase in the effect of the parameter acc_bottom (Figure 5-1). For radionuclides with high K_d values (for example Pu-239) the fraction of accumulation bottoms becomes dominant and the effect of other parameters is mainly through interactions. In general, there are strong interactions between the parameters and non-linearity in their effects. The effects of the distribution coefficient for the suspended sediments (K_d_sea) on the retained fraction are negligible, whereas the distribution coefficients in the bottom sediments (K_d_peat) have positive effects that decrease with the increase of K_d_peat. For Am-241, the effect of K_d_peat is practically negligible because of its high value in combination with the relatively short half-life of this radionuclide. The effect of the retention time was negligible for all radionuclides.

Sensitivity of the radionuclide concentrations in sea water

The parameters with the largest effect on the radionuclide concentrations in sea water (Table I.2 in Appendix I) are the fraction of accumulation bottoms (acc_bottom), with a negative effect, and the velocity of the upward water fluxes in the sea bottom (v_bottom), which has a positive effect. As for the retained fraction, for radionuclides with high K_d values (for example Pu-239) the fraction of accumulation bottoms becomes dominant and the effect of other parameters is mainly through interactions. Strong interactions are observed between the parameters and non-linearity in their effects on the water concentrations. As for the retained fraction, the effect of the retention time was negligible for all radionuclides.

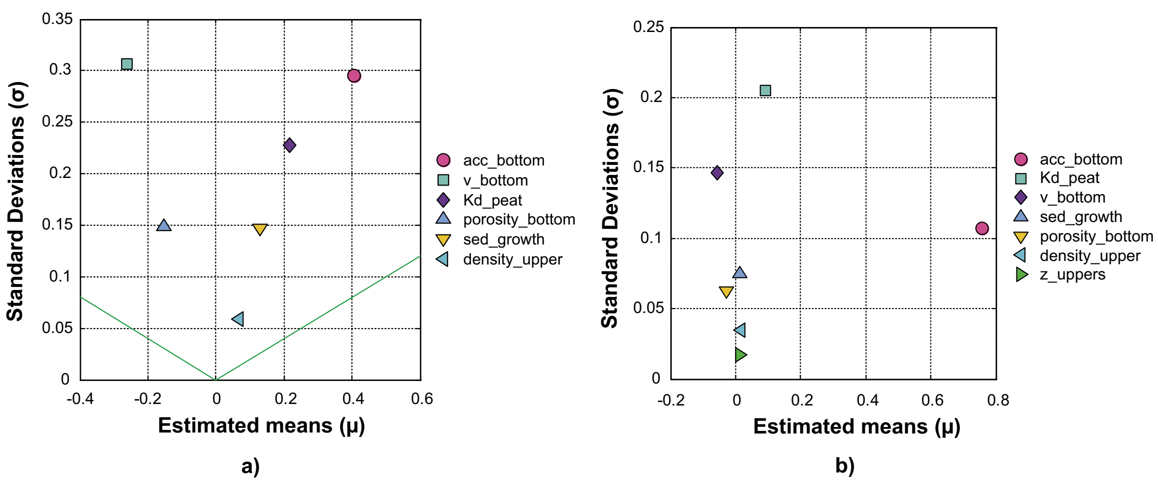

Figure 5-1. *Mean and standard deviation of the elementary effects of the model parameters on the release fraction of Cl-36 (a) and Pu-239 (b) at 10,000 years after the start of a continuous release to the water in the top sediment of a sea ecosystem. Only the parameters with a sensitivity index higher than 1 are shown.*

Sensitivity of the radionuclide concentrations in sea sediments

The parameters with the largest effect on the radionuclide concentrations in sea sediments (Table I.3 in Appendix I) are the area of the object, with a negative effect, and the fraction of accumulation bottoms, which has a positive effect. These two parameter become more dominant the largest the K_d (see Figure 5-2). The effect of K_d_peat is positive and reduces as the K_d values increase, becoming practicably negligible for Pu-239.

Sensitivity of the dose rates from the use of sea objects

The parameter v_bottom has a positive effect on the dose rates, while the parameter acc_bottom has a negative effect (Figure 5-3). The same type of dependency with K_d_peat as for the retained fraction is observed. The effects of K_d_peat on the dose rates are negative and weaker than the effects on the retained fraction. The aggregated transfer factors for the sea (TF_{agg} Sea) have a positive effect on the dose rates, of approximately the same magnitude as the effects of the acc_bottom. Other parameters have a weak direct effect on the dose rates, which decreases as the distribution coefficients increase. For example, for Ra-226 (see Figure 5-3b) the estimated mean of all parameters except acc_bottom and TF_{agg} Sea is close to zero.

5.2.2 Sensitivity analysis of the lake model

For the lake model, two cases where considered in the sensitivity study. In one case, the releases were directed to the lake water. The values of the sensitivity indices obtained for this case are presented in Tables I.5 –I.8 of Appendix I. In the other case, the releases were directed to the water in the top sediment compartment. The values of the sensitivity indices obtained for this case are presented in Tables I.9 –I.12 of Appendix I. The main findings of the sensitivity analysis for each of the endpoints considered are discussed below.

Sensitivity of the retained fractions in Lakes

In the case of releases to the lake water, the catchment area (area_catchment) and the time to sorption equilibrium (Tk) have a negative effect on the retained fraction of releases. Note, however, that Tk was varied within a very wide range of values (from 10^{-5} to 10^{-1} years). Judging from the high standard deviations, these parameters have non-linear effects and/or strong interactions with other parameters. The area of the lake (lake_area), its mean depth (mean depth) and the distribution coefficient for the suspended sediments (K_d_lake) have a

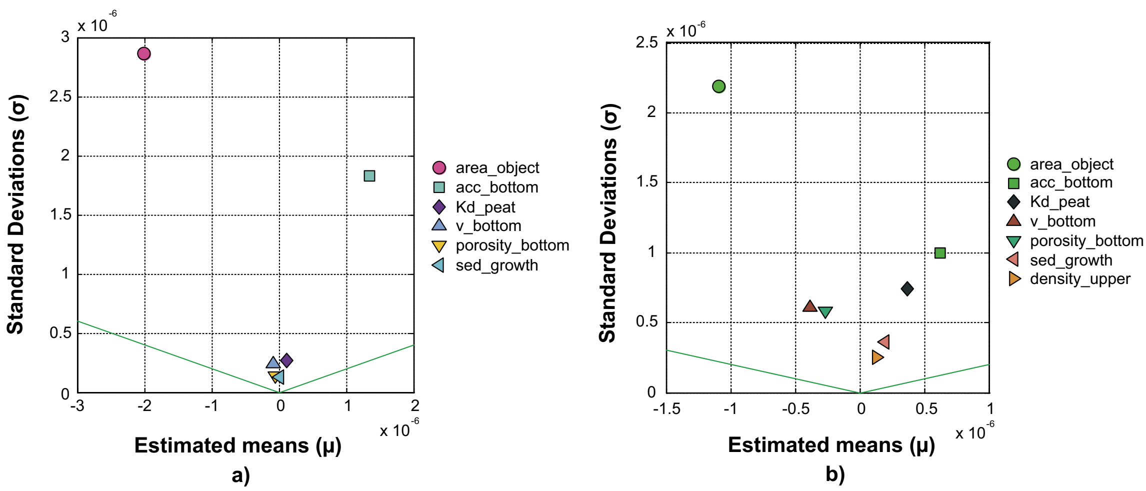

Figure 5-2. Mean and standard deviation of the elementary effects of the model parameters on the concentrations in sediments of Cl-36 (a) and Pu-239 (b) at 10,000 years after the start of a continuous release to the water in the top sediment of a sea ecosystem. Only the parameters with a sensitivity index higher than 1 are shown.

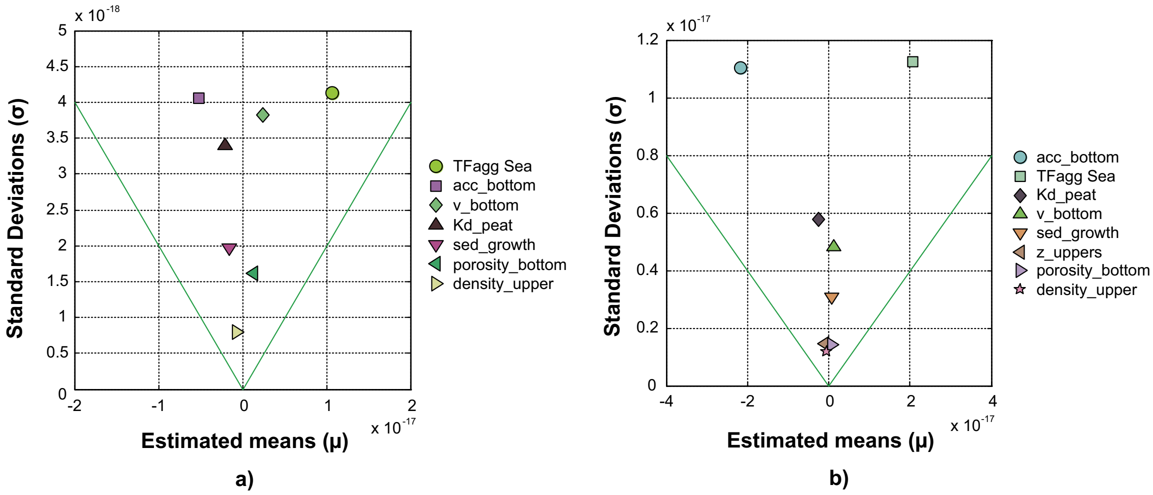

Figure 5-3. *Mean and standard deviation of the elementary effects of the model parameters on the dose rates from I-129 (a) and Ra-226 (b) at 10,000 years after the start of a continuous release to the water in the top sediment of a sea ecosystem. Only the parameters with a sensitivity index higher than 1 are shown.*

positive effect, especially for radionuclides with high K_d values. Other parameters identified as important (Table I.5 in Appendix I) affect the retained fractions mainly through interactions with other parameters.

In the case of releases to the water in the top sediment layer, the sediment growth rate (sed_growth), v-bottom and K_d-peat are the most sensitive parameters. The fraction of accumulation bottoms has some effect, but much lower than the effect observed for the sea model. This is due to the fact that the assumed interval of variation of this parameter in the lake model was much lower than the assumed interval of variation in the sea model.

Sensitivity of the radionuclide concentrations in lake water

In the case of releases to the lake water, the catchment area (area_catchment) has a dominating effect on the radionuclide concentrations in lake water, which is in particular pronounced for radionuclides with low K_d_lake values, like Cl-36 (see Figure 5-4). The distribution coefficient in the bottom sediments (K_d_peat) seems to have a very small effect on the water concentrations. Other parameters that have some effect on the water concentrations are the runoff and the area of the objects (for radionuclide with high K_d values).

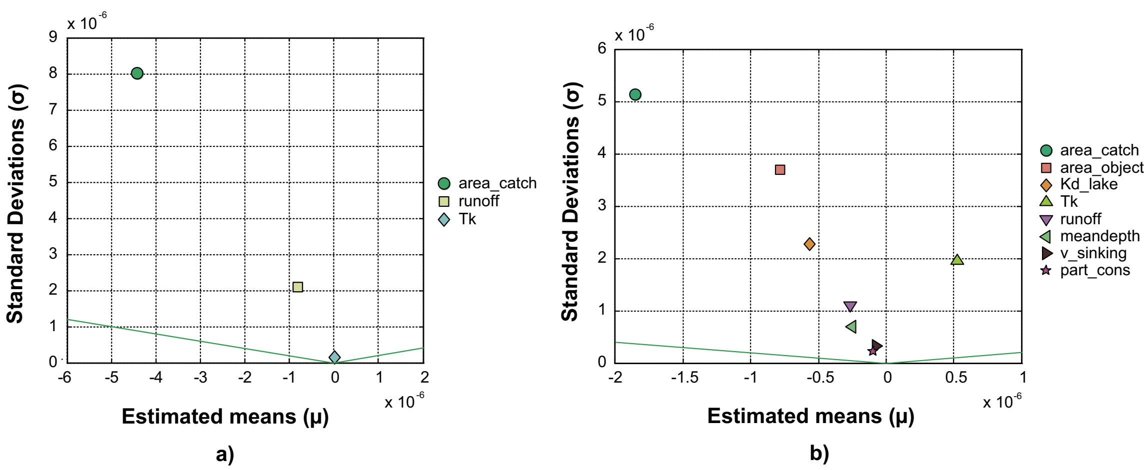

Figure 5-4. *Mean and standard deviation of the elementary effects of the model parameters on the activity concentrations of Cl-36 (a) and Pu-239 (b) at 3,000 years after the start of a continuous release to the lake water. Only the parameters with a sensitivity index higher than 1 are shown.*

In the case of releases to the water in the top sediment layer, the catchment area, v-bottom, sed_growth, area_lake, K_d_peat and K_d_lake are the most sensitive parameters. For Ra-226, K_d_peat shows an exceptionally large effect, which is due to the exceptionally large variation of the K_d_peat values assumed for this radionuclide, as compare with other studied radionuclides.

Sensitivity of the radionuclide concentrations in lake sediments

In the case of releases to the lake water, the sensitivity of the activity concentrations in lake sediments to the model parameters is rather complex. As it can be seen from Figure 5-5, showing two extreme cases, the effects of the parameters is quite different between radionuclides with low K_d values, like Tc-99, and radionuclides with high K_d values, like Pu-239. For low K_d values, K_d_peat has strong positive effect and negligible effects of K_d_lake are observed. For high K_d values, the effect of K_d is in general lower. Moreover, K_d_lake has a larger effect than K_d_peat. For radionuclides with low K_d values, the parameters v_bottom and Tk have an important negative effect, whereas for radionuclides with high K_d values large negative effects are observed for the parameters area_lake, area_catchment and Tk.

In the case of releases to the water in top sediment, area_lake, sed_growth and v_bottom are the most sensitive parameters. As for the water concentrations, the fraction of accumulation bottoms has a lower effect than in the sea model. K_d_peat has a moderate effect for all radionuclides, especially for those with low K_d values, whereas K_d_lake has negligible effects on this endpoint.

Sensitivity of the dose rates from the use of lakes

In the case of releases to the lake water, the parameter area_catchment has a dominant negative effect on the dose rates (Figure 5-6), which is more accentuated for the most mobile radionuclides. For radionuclides with high K_d values, lake_area and K_d_lake have also a moderate negative effect on the dose predictions. The parameter with the highest positive effect on the dose rates is the aggregated transfer factor (TF_{agg} Lake), which is more pronounced for mobile radionuclides. Other parameters identified as important (Table I.8 in Appendix I), including the distribution coefficients, affect the dose rates mainly through interactions with other parameters.

In the case of releases to the water in top sediment, the catchment area, v_bottom, area_lake, TF_{agg} Lake and K_d_peat are the most sensitive parameters. Other parameters have weak effects, mainly through interactions with the most sensitive parameters. For Ra-226 the exceptionally high effect of K_d_peat that was observed for the water concentrations is also observed for the dose rates.

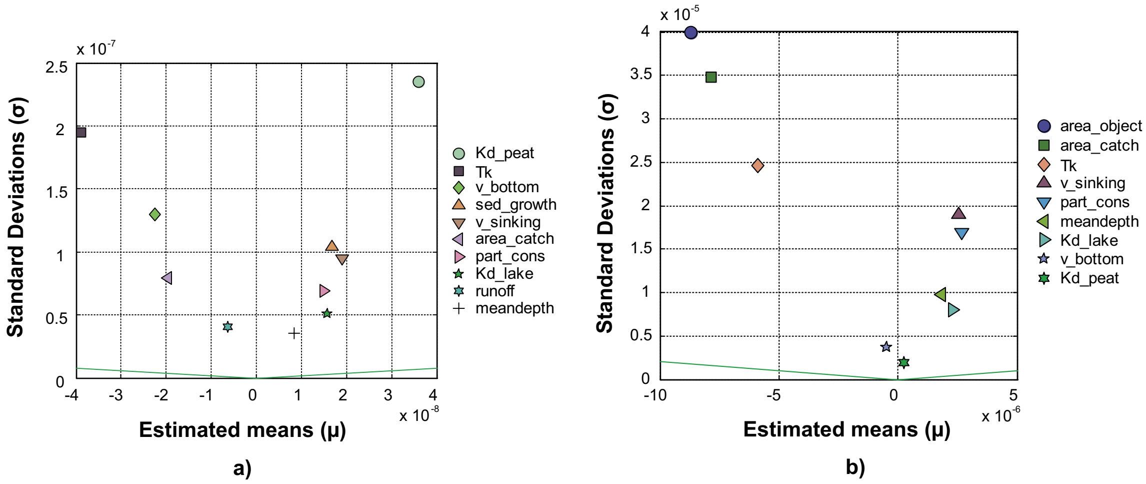

Figure 5-5. *Mean and standard deviation of the elementary effects of the model parameters on the activity concentration in lake sediments of Tc-99 (a) and Pu-239 (b) at 3,000 years after the start of a continuous release to the lake water. Only the parameters with a sensitivity index higher than 1 are shown.*

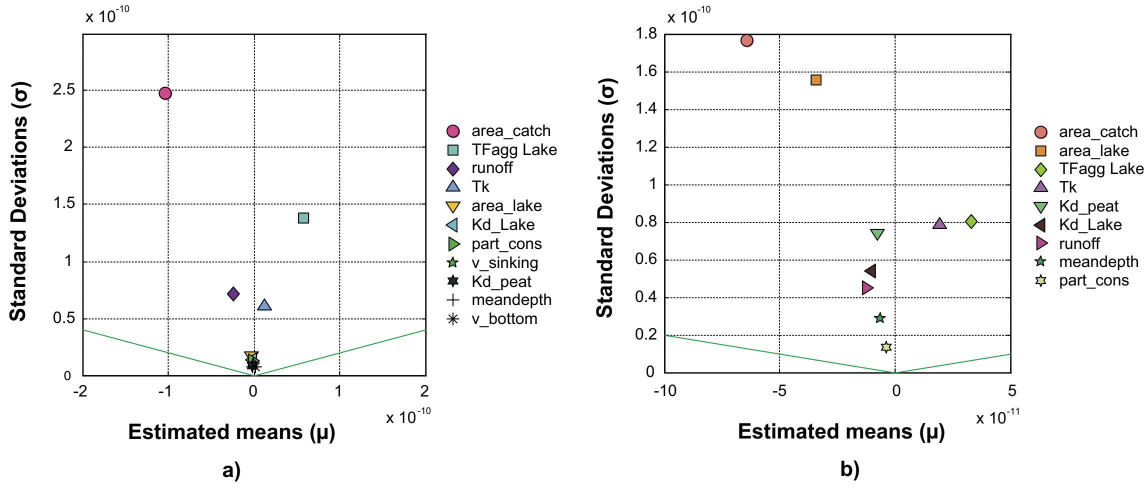

Figure 5-6. *Mean and standard deviation of the elementary effects of the model parameters on the dose rates from I-129 (a) and Ra-226 (b) at 3,000 years after the start of a continuous release to the lake water.*

5.3 Sensitivity analysis of the terrestrial ecosystem models

For the terrestrial ecosystem models, i.e. the agricultural land, the mire and the forest, the endpoints considered in the sensitivity study were the fraction of the releases retained in the ecosystems, the activity concentration in the top soil (for the agricultural land model), in the peat (for the mire model) and in the soil (for the forest model) as well as the dose rate. The results obtained for each of the ecosystem models are presented below.

5.3.1 Sensitivity analysis of the agricultural land model

The values of the sensitivity indices obtained for the agricultural land model are presented in Tables I.13 –I.15 of Appendix I. The main findings of the sensitivity analysis of the agricultural land model are discussed below for each of the endpoints considered.

Sensitivity of the retained fractions in agricultural lands

The fraction of radionuclides retained in agricultural lands is affected mostly by three parameters: K_d_soil, the area of the agricultural land and the catchment area. In the SR-Can calculations it was assumed that the catchment area equals the area of the agricultural land. This reduces substantially the negative effect of the catchment area on the retained fraction.

Sensitivity of the radionuclide concentrations in the top soil of agricultural lands

The catchment areas, the area of the objects and the run-off have important effects on the concentration in the top soil by affecting the fraction retained in the object. The distance to the saturated zone (z_deeps) and the parameters related to the vertical water fluxes, particularly the fluxes from the saturated zone to the deep soil (Fsads), also have important effects, which are larger for the most mobile radionuclides. K_d_soil has important positive effects for all radionuclides, especially for the most mobile ones.

Sensitivity of the dose rates from the use of agricultural lands

For radionuclides that give rise to exposure mainly through food ingestion (Cl-36, Ni-59, Se-79, I-129, Cs-135 and Ra-226), the aggregated transfer factor (TFagg Agric Land) has the largest positive effect on the dose rates. For radionuclides with low concentration ratios (Pu-239 and Am-241), exposures by inhalation dominate and, therefore, the parameter with the highest positive effect is the dust concentration. Other parameters that have a positive but lesser effect are the upward water fluxes in soil (Fsads and Fdsts). The parameters catchment area (area_cathment), area of agricultural land (area_agriland), depth of the deep soil (z_deeps), runoff and percolation have a negative effect. The effect of the distribution coefficient (K_d_soil) is complex. For some radionuclides (Cl-36, Tc-99, Se-79 and Ra-226) the effect is positive, whereas for others the effect is negative. This is illustrated in Figure 5-7 for I-129 and Ra-226. The strength of the effect of K_d_soil also varies between radionuclides. There is no clear relationship between the sign of the effect and the K_d_soil values, which suggests that there are strong interactions with other parameters such as the transfer factors.

5.3.2 Sensitivity analysis of the forest model

The values of the sensitivity indices obtained for the forest model are presented in Tables I.16–I.18 of Appendix I. The main findings of the sensitivity analysis of the forest model are discussed below for each of the endpoints considered.

Sensitivity of the retained fractions in forests

The parameters with the largest effect on the fraction of the releases retained in forests are the area of the forest object, the catchment area and K_d_forest. For radionuclides with high transfer factor to plants (like Cl-36) the productivity of wood and the concentration ratio from soil to wood also affect the retained fraction, reflecting the fact that an important part of the radionuclide inventory in the system is retained in the vegetation compartments.

Sensitivity of the radionuclide concentrations in forest soils

The catchment area, the runoff and K_d_forest have an important effect on the radionuclide concentrations in forest soils for all radionuclides. For the most mobile radionuclides (Cl-36, Tc-99 and I-129), these three parameters have dominating effects on the soil concentrations. For other radionuclides the area of the forest object also has an important effect.

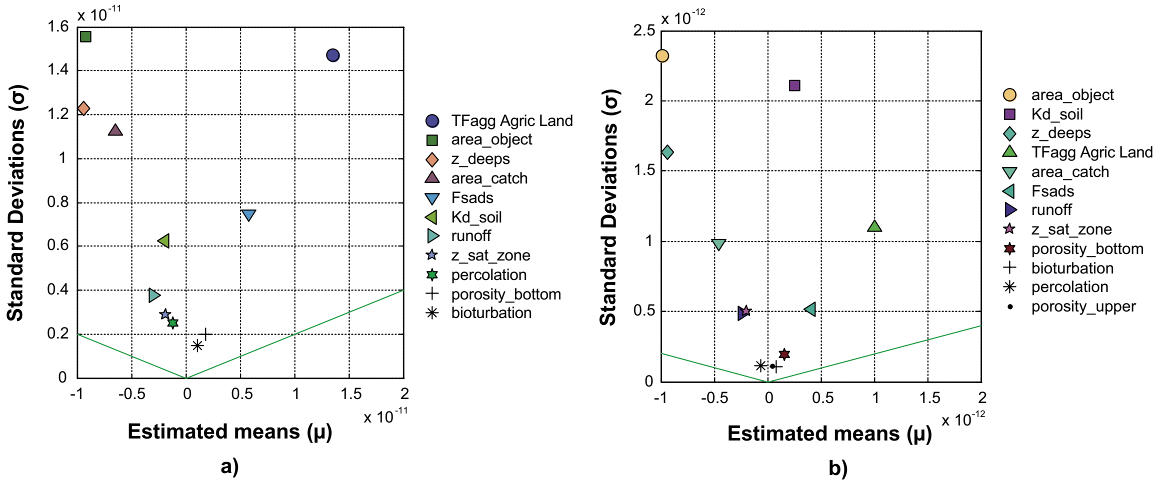

Figure 5-7. Mean and standard deviation of the elementary effects of the model parameters on the dose rates from I-129 (a) and Ra-226 (b) at 3,000 years after the start of a continuous release to the saturated zone of the agricultural land.

Sensitivity of the dose rates from the use of forests

The aggregated transfer factor for forests (TFagg forest), the distribution coefficient (K_d_forest) and the dust concentration (for Pu-239) are the only parameters with a positive effect on dose rates in a forest ecosystem (Table I.19 and Figure 5-8). The effects of these parameters are of approximately equal size and there seem to be interactions between them. The catchment area and the area of the forest have strong negative effects on the dose rates, whereas other relatively important parameters seem to influence mainly through interactions.

5.3.3 Sensitivity analysis of the mire model

The values of the sensitivity indices obtained for the mire model are presented in Tables I.19 –I.21 of Appendix I. The main findings of the sensitivity analysis of the mire model are discussed below for each of the endpoints considered.

Sensitivity of the retained fractions in mires

The parameters with the largest effect on the retained fraction in mires are the catchment area, the object area, the thickness of the peat (z_uppers) and the distribution coefficient in the peat (K_d_peat). The density of the peat (density_upper) has also some influence on this endpoint.

Sensitivity of the radionuclide concentrations in the peat

The radionuclide concentrations in the peat are strongly dominated by the catchment area and K_d_peat. Other important parameters are the runoff, z_uppers and the object area, although the last two are unimportant for the mobile radionuclides.

Sensitivity of the dose rates from the use of mires

The parameters that are important for the concentrations in peat are also important for the dose rate and influence this endpoint in the same way. The aggregated transfer factor (TFagg Mire) is also an important parameter.

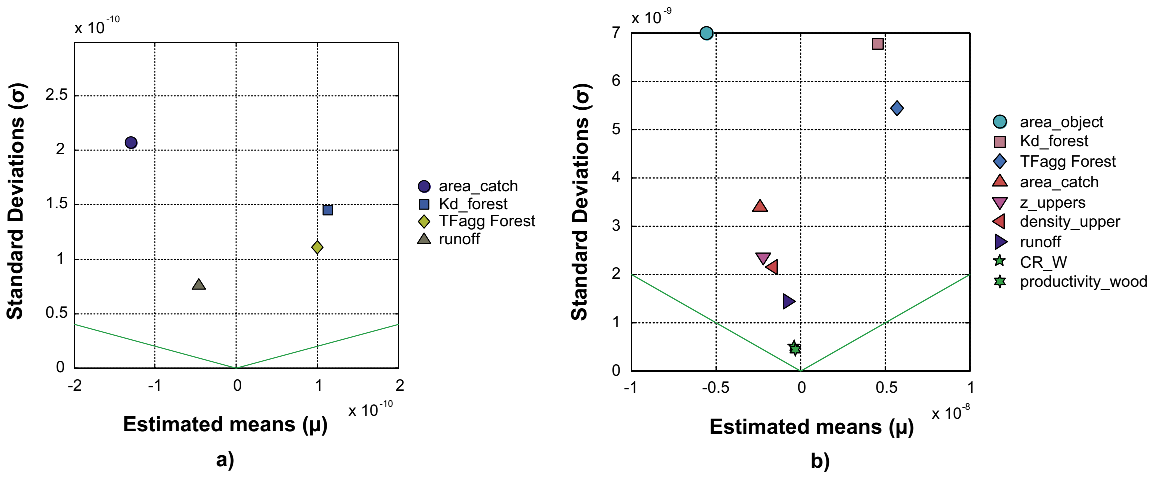

Figure 5-8. *Mean and standard deviation of the elementary effects of the model parameters on the dose rates from I-129 (a) and Ra-226 (b) at 3,000 years after the start of a continuous release to the forest soil.*

6 Derivation of Dose Conversion Factors for the drilling scenario

In one of the scenarios considered in SR-Can, it is assumed that, as result of drilling activities, the soil of a small circular area with a diameter of 6 metres is contaminated with particles containing spent fuel. The thickness of the contaminated soil layer is assumed to be 10 centimetres. Further, it is assumed that the contaminated area is abandoned after the drilling without remediation measures. It is further assumed that one month later a family moves to the site and operates a farm based on domestic production. In this situation, individuals from the family would be exposed to contaminated food via ingestion, to contaminated dust via inhalation and by external irradiation to radionuclides present in the soil.

6.1 Method for the derivation of the Dose Conversion Factors

The following assumptions were made for estimating the doses to an adult member of the family during the first year starting from the moment when the family starts using the contaminated area for farming:

- The whole radionuclide inventory in the contaminated area is instantaneously available for transfer to the agricultural production and to air with contaminated dust. This assumption leads to a conservative value of the annual exposure during the first year, since most likely only a fraction of the inventory would be available from the beginning.
- There are no losses of radionuclides from the contaminated area other than by radioactive decay.
- The calculations assume maximum food production in the contaminated land, as defined by its area and the productivity of agricultural lands in the region. If this food production is not sufficient to cover the nutritional needs of a person, then the intake is diluted by consumption of uncontaminated food.

To calculate the annual dose during the first year from a radionuclide, the total activity of the radionuclide introduced in the area is multiplied by a Dose Conversion Factor (DCF):

$$Dose^{j} = A^{j} * DCF^{j} \quad (6.1)$$

where,

$Dose^{j}$ is the annual effective dose to an individual from the *j-th* radionuclide during the first year [Sv/yr],

A^{j} is the initial activity of the *j-th* radionuclide in the contaminated area [Bq],

DCF^{j} is the Dose Conversion Factor for the *j-th* radionuclide [Sv/yr per Bq].

The DCF is defined as the annual effective dose during the first year for unit initial activity of the radionuclide in the contaminated area. The annual effective dose equals the sum of the committed annual doses from food ingestion, inhalation and external exposure calculated with the equations given in /Avila and Bergström 2006/. The inputs to these equations are the radionuclide concentrations in soil, air and in the diet, which are calculated with the following equations, with the radionuclide initial activity (A^j) set to 1 Bq:

$$C_{soil}^{j} = \frac{1}{\pi * r^2 * h * \rho} * \frac{\exp(-\lambda^j * T1) * (1 - \exp(-\lambda^j * T2)}{\lambda^j * T2} \quad (6.2)$$

where,

$C_{soil}{}^{j}$ is the average concentration in soil of the *j-th* radionuclide during the exposure period [Bq/kg DW],

r is the radius of the contaminated area [m],

h is the thickness of the contaminated soil layer [m],

ρ is soil bulk density [kg DW/m^3],

λ^j is the decay constant of the *j-th* radionuclide [1/yr],

T1 is the time period before the exposure starts [years],

T2 is the exposure time period [years].

$$C_{air}^{j} = C_{soil}^{j} * C_{dust} \quad (6.3)$$

where,

$C_{air}{}^{j}$ is the average concentration in air of the *j-th* radionuclide during the exposure period [Bq/m^3],

C_{dust} is the dust concentration in air [kg/m^3].

$$C_{diet}^{j} = C_{soil}^{j} * TF_{agg\ Agric\ Land}^{j} \quad (6.4)$$

where,

$C_{diet}{}^{j}$ is the concentration in the diet of the *j-th* radionuclide [Bq/kgC],

$TF_{agg\ Agric\ Land}{}^{j}$ is the *j-th* radionuclide aggregated transfer for agricultural lands [Bq/kgC per Bq/kg DW].

$TF_{agg\ Agric\ Land}$ is the aggregated factor that relates the radionuclide concentration in soil and in the food produced in agricultural lands (see Chapter 3).

By substituting Equations 6.2, 6.3 and 6.4 in the corresponding equations for the food ingestion, inhalation and external doses given in /Avila and Bergtröm 2006/, and summing over these three doses, the following equation is obtained for the *DCF*:

$$DCF^j = \frac{1}{\pi * r^2 * h * \rho} * \frac{\exp(-\lambda^j * T1) * (1 - \exp(-\lambda^j * T2)}{\lambda^j * T2} * (\rho * H * DCC_{ext}^{j} + C_{dust} * InhR * H * DCC_{inh}^{j} + \min(1, \frac{\pi * r^2 * pty}{IR_C}) * TF_{agg\ Agric\ Land}^{j} * IR_C * DCC_{ing}^{j}) \quad (6.5)$$

where,

H is the time that the exposed individual expends in the contaminated area [h/yr],

InhR is the inhalation rate by an individual [m^3/h],

IR_C is the annual intake of carbon by an individual [kgC/yr],

pty is the productivity in the contaminated area [kgC/m^2/yr],

$DCC_{ext}{}^{j}$ is the dose coefficient of the *j-th* radionuclide for external exposure [Sv/h per Bq/m^3],

$DCC_{inh}{}^{j}$ is the dose coefficient of the *j-th* radionuclide for inhalation [Sv/Bq],

$DCC_{ing}{}^{j}$ is the dose coefficient of the *j-th* radionuclide for ingestion [Sv/Bq].

The last term in Equation 6.5, corresponding to the ingestion dose, includes a correction factor to account for the dilution of the diet with uncontaminated food that takes place in cases when the food production in the contaminated area is less than the annual carbon intake by an individual. The food production is expressed as the area multiplied by the productivity of agricultural lands in the region (see Chapter 4).

6.2 Parameter values

The radionuclide-independent parameter values used in the derivation of LDF values are presented in Table 6-1. As far as possible, the parameter values used in the calculation of Landscape Dose Factors (LDF) in /Avila et al. 2006/ were used. The same radionuclide-dependent parameters used for the dose calculations in Chapter 4 and in /Avila et al. 2006/ were used when available. For radionuclides that were not considered in the above-mentioned dose calculations, the parameter values were taken from /IAEA 2005/, where a similar exposure scenario (exposure of a worker from contaminated material dumped on a landfill) is used in the derivation of clearance levels.

The TF_{agg} Agric Land presented in Table 3-1 were used in the calculations. For most radionuclides, the Dose Conversion Coefficients (DCCs) were taken from /Avila and Bergström 2006/. For radionuclides that are not included in /Avila and Bergström 2006/, DCCs given in /IAEA 2005/ were used.

6.3 Dose Conversion Factors for the drilling scenario

The values of the Dose Conversion Factors for the drilling scenario, derived with the method described above are presented in Table 6-2. Estimates of the percentage contribution of different exposure pathways (external exposure, inhalation and food ingestion) to the total dose are presented in Table 6-3.

Table 6-1. Values of the radionuclide-independent parameters used in the calculations of the DCFs for the drilling scenario.

Parameter	Units	Value	Comment
Radius of the contaminated area (r)	m	3	Assumed
Thickness of the contaminated soil layer (h)	m	0.1	Assumed
Soil bulk density (ρ)	kg dw/m^3	1,180	/Avila et al. 2006/
Time period before the exposure starts (T1)	years	0.083	One month assumed as in /IAEA 2005/
Time period of the exposure (T2)	years	1	As annual doses are calculated during the first year
Dust concentration in air (C_{dust})	kg dw/m^3	5.0E–07	/IAEA 2005/
Time that the exposed individual spends in the contaminated area (H)	h	2,920	Assuming 8 hours each day during the whole year.
Inhalation rate by an individual (InhR)	m^3/h	1	/Avila and Bergström 2006/
Annual intake of carbon by an individual (IR_C)	kgC/yr	110	/Avila and Bergström 2006/
Productivity in the contaminated area (pty)	kgC/m^2/yr	0.22	See Table 3-2

Table 6-2. Values of the Dose Conversion Factors (DCFs), expressed in Sv/yr per Bq, for the Drilling Scenario. The short-lived radionuclides included in the calculations are indicated where applicable.

Radionuclide	DCF
H-3	2.92E–12
C-14	2.75E–15
Cl-36	8.11E–11
Ca-41	4.06E–13
Fe-55	6.13E–15
Co-60	2.88E–10
Ni-59	3.00E–14
Ni-63	7.12E–14
Se-79	1.38E–10
Sr-90 –Y-90	5.90E–11
Zr-93	1.31E–14
Nb-93m	1.31E–15
Nb-94	1.86E–10
Mo-93	5.53E–12
Tc-99	6.87E–12
Ru-106 –Rh-106	1.43E–11
Pd-107	1.15E–14
Ag-108m – Ag-108	1.79E–10
Cd-113m	2.58E–10
Sn-121m – Sn-121	4.85E–13
Sn-126 – Sb-126m	2.97E–10
I-129	9.76E–11
Cs-134	1.52E–10
Cs-135	9.15E–13
Cs-137 – Ba-137m	7.21E–11
Ra-226	1.87E–11
Pm-146	1.01E–10
Pm-147	7.19E–15
Sm-151	3.61E–15
Eu-152	1.30E–10
Eu-154	1.38E–10
Eu-155	2.95E–12
Ho-166m	1.96E–10
Th-229	1.14E–10
Th-230	4.53E–11
Th-232	4.98E–11
Pa-231	6.91E–11
Pa-233	1.25E–12
U-233	5.23E–12
U-234	5.09E–12
U-235	1.81E–11
U-236	4.74E–12
U-237	1.40E–14
U-238 – Th-234 – Pa-234m	4.39E–12
Np-237	2.67E–11
Np-239	2.06E–17

Radionuclide	DCF
Pu-238	4.80E–11
Pu-239	5.26E–11
Pu-240	5.26E–11
Pu-241	9.80E–13
Pu-242	4.82E–11
Am-241	4.28E–11
Am-242m	4.03E–11
Am-242	5.35E–29
Am-243	4.46E–11
Cm-242	1.06E–12
Cm-243	2.65E–11
Cm-244	2.45E–11
Cm-245	4.95E–11
Cm-246	4.30E–11

Table 6-3. Percentage contributions of different pathways (Ext – External exposure, Inh – Inhalation and Ing – Ingestion) to the DCF values derived for the Drilling Scenario. The short–lived radionuclides included in the calculations are indicated where applicable.

Radionuclide	% Ext	% Inh	% Ing
H-3	0.0	0.0	100.0
C-14	7.9	92.1	0.0
Cl-36	0.1	0.0	99.9
Ca-41	0.0	0.0	100.0
Fe-55	0.0	2.3	97.7
Co-60	99.8	0.0	0.2
Ni-59	0.0	0.6	99.4
Ni-63	0.0	0.8	99.2
Se-79	0.0	0.0	100.0
Sr-90 – Y-90	0.0	0.1	99.9
Zr-93	0.0	83.7	16.3
Nb-93m	0.0	16.6	83.4
Nb-94	100.0	0.0	0.0
Mo-93	0.1	0.0	99.8
Tc-99	0.0	0.1	99.9
Ru-106 – Rh-106	93.9	0.1	6.1
Pd-107	0.0	2.2	97.8
Ag-108m – Ag-108	97.9	0.0	2.1
Cd-113m	13.1	0.0	86.9
Sn-121m – Sn-121	1.0	0.4	98.6
Sn-126 – Sb-126m	98.7	0.0	1.3
I-129	0.2	0.0	99.8
Cs-134	95.3	0.0	4.7
Cs-135	0.1	0.4	99.5
Cs-137 – Ba-137m	91.9	0.0	8.1
Ra-226	3.1	22.2	74.7
Pm-146	100.0	0.0	0.0
Pm-147	3.8	26.2	70.0

Radionuclide	% Ext	% Inh	% Ing
Sm-151	0.0	48.3	51.7
Eu-152	100.0	0.0	0.0
Eu-154	100.0	0.0	0.0
Eu-155	99.7	0.1	0.2
Ho-166m	100.0	0.0	0.0
Th-229	5.1	91.8	3.1
Th-230	0.0	96.6	3.4
Th-232	0.0	96.6	3.4
Pa-231	5.1	88.7	6.2
Pa-233	100.0	0.0	0.0
U-233	0.5	80.3	19.2
U-234	0.1	80.9	19.0
U-235	74.3	20.6	5.1
U-236	0.1	80.4	19.5
U-237	99.9	0.0	0.1
U-238 – Th-234 – Pa-234m	0.0	79.8	20.2
Np-237	5.0	81.9	13.1
Np-239	99.8	0.0	0.1
Pu-238	0.0	99.9	0.1
Pu-239	0.0	99.9	0.1
Pu-240	0.0	99.9	0.1
Pu-241	0.0	99.9	0.1
Pu-242	0.0	99.9	0.1
Am-241	1.7	98.0	0.3
Am-242m	0.1	99.7	0.3
Am-242	98.6	1.4	0.0
Am-243	5.6	94.2	0.3
Cm-242	0.0	99.6	0.3
Cm-243	49.1	50.6	0.3
Cm-244	0.0	99.7	0.3
Cm-245	12.3	87.5	0.2
Cm-246	0.0	99.7	0.3

7 Dose calculations for the gas release scenario

In one of the scenarios considered in SR-Can, it is assumed that C-14 and Rn-222 are released from the repository in gaseous form and enter the biosphere via soil as a diffuse source. C-14 may be released as methane (CH_4) or carbon dioxide (CO_2). If it is released as methane from the repository, it is assumed that it is oxidised by soil organisms to carbon dioxide. Radon is a noble gas and will not undergo chemical transformation. For C-14, exposure may occur via inhalation or ingestion, for Rn-222 only inhalation of Rn-222 and its radioactive daughter products needs to be taken into account.

7.1 Doses from ingestion of C-14

The ingestion dose is estimated by means of a modified specific activity model. The key assumption is that C-14 is released during a relative short time, which may be in the range of some days to several ten days. If the release occurs during the vegetation period, C-14 is metabolised by photosynthesis and enters the human food chain via this pathway. A release during the vegetation period is more likely, since then the soil is not frozen, which facilitates the exchange of gases from deep soil to the lower atmosphere. The following boundary conditions are assumed:

- A single release of 10^{10} Bq C-14 is assumed.
- CO_2 is metabolised with photosynthesis leading to an increase of the natural $^{14}C/^{12}C$-ratio.
- Over the area that releases CO_2, the CO_2 is homogeneously mixed in the mixing layer with the height *h*. As a default, it is assumed that this mixing layer is 20 m. The CO_2 within this 20 m-layer is used on a sunny summer day for photosynthesis. A well developed canopy is able to assimilate 2–3 g CO_2 /m² soil /Geisler 1980/, the CO_2-content in air is 0.04% (mass) which corresponds to nearly 0.5 g CO_2/m³ air (~ 0.13 g C/m³). Thus, the plant canopy uses about 100% of the CO_2 which is present in a layer with the height of 20 m. In reality, there is a gradient of CO_2 in the air, since, due to photosynthesis, the canopy is an effective CO_2-sink that causes a permanent flux of CO_2 from upper atmosphere layers to the ground. However, this effect is not taken into account in this estimation.
- There is an air exchange within this layer due to wind. The exchange rate of the air is the ratio of the wind speed v and the radius (r) of the area (λ_{ex} =v/r).
  - The mean annual wind speed at a height of 10 m is in the order of 3–5 m/s, depending on the site characteristics. The wind speed increases with height following an exponential wind profile. Applying a Gaussian plume model for a neutral stability class of the atmosphere, a wind speed of 2 m/s on the ground corresponds to a wind speed of about 3.5 m/s at a height of 10 m /IAEA 2001/.
  - The radius r corresponds to the radius of the area that releases CO_2. In this estimation a default area of 10,000 m² is assumed, the radius is then about 56 m.

Under these assumptions the excess $^{14}C/^{12}C$-ratio can be calculated according to:

$$R_{^{14}C/^{12}C} = \frac{R}{h \cdot \lambda_{ex} \cdot C_{^{12}C} * \Delta T} \quad (7.1)$$

where,

$R_{14C/12C}$ is the $^{14}C/^{12}C$-Ratio in air [Bq/g]

R is the area normalised release of ^{14}C from soil [Bq m^{-2}]

h is the height of the mixing layer [m]

C_{12C} is the ^{12}C content of air [g m^{-3}]

λ_{ex} is the exchange rate of the air [s^{-1}]

ΔT is the averaging period [s]

With these parameters and for an averaging period of one year, an excess $^{14}C/^{12}C$-ratio of 0.25 $Bq^{14}C/g^{12}C$ is obtained. According to /UNSCEAR 1988/, a natural $^{14}C/^{12}C$-ratio of 0.227 $Bq^{14}C/g^{12}C$ corresponds to an effective annual dose of 12 μSv a^{-1}. However, this relationship is only valid if the $^{14}C/^{12}C$-ratio occurs over an infinite area and all the food consumed is produced under those conditions. In this estimation, only a relatively small area of 10,000 m² is affected. So, a factor is introduced that accounts for this effect. A rough estimation of this factor is:

- The minimum area for the validity of the relationship given by /UNSCEAR 1988/ is 1 km² (1.0E+6 m²).
- The reduction factor to account for the limited area of the release of C-14 is the ratio of the area of 1 km² and the area over which the release occurs. Under the circumstances of this assessment, this leads to a reduction factor of 10.

Taking this factor into account, and using the relationship given in /UNSCEAR 1988/, the release would cause an additional exposure of 1.3 μSv during the first year (Table 7-1). However, wind speed and mixing height vary with the weather conditions. Varying wind speed and mixing height in the ranges of 1–10 m/s and 10–50 m, respectively, the resulting effective dose during the first year varies in the range of 0.11–5.4 μSv/yr. A release in winter time would cause lower ingestion doses because photosynthesis is lower in winter periods.

Table 7-1. Parameter values used in the estimations of the ingestion dose due to a pulse gas release of C-14 and estimated values of the doses.

Parameters	Values
Total release (Bq)	1.00E+10
Area (m²)	1.00E+04
Radius of the area (m)	56.4
Area normalised release (Bq/m²)	1.0E+06
Carbon content of air (g/m³)	0.176
Seconds per year (s/a)	31,536,000
Conversion factor: μSv per Bq C-14 per g C-12	52.9
Factor for local production	0.1
Exposure during the first year (annual effective dose, μSv/yr)	
For the case with Wind speed: 2 m/s, Mixing height: 20 m	1.3
For the case with Wind speed: 1–10 m/s and Mixing height 10–50 m	0.11–5.4

7.2 Doses from inhalation of C-14 and Rn-222 outdoors

The concentration of C-14 and Rn-222 in air is calculated according to:

$$C_{C-14/Rn222} = \frac{R}{h \cdot \lambda_{ex}} \tag{7.2}$$

The same boundary conditions as above are assumed. An inhalation rate of 8,100 m^3/a is assumed /ICRP 1995/. For C-14, an inhalation dose factor of 6.2 E–12 Sv/Bq /ICRP 1996/ is used. For a wind speed in the range of 1–10 m/s and a mixing height of 10–50 m, this causes an inhalation dose from C-14 of about 0.00018–0.009 µSv/yr (Table 7-2).

For Rn-222, a release rate of 25 GBq is assumed. The dose is calculated using a dose conversion factor of 47 µSv/yr per Bq/m^3. This dose factor assumes an equilibrium factor of 0.6 /UNSCEAR 2000/, which is typical for outdoor conditions where the unattached fraction of the Rn-222 daughters is high. For a wind speed in the range of 1–10 m/s and a mixing height of 10–50 m, this causes an inhalation dose varying in the range of 0.4–20 µSv/yr.

7.3 Doses from inhalation of C-14 and Rn-222 indoors

The activity concentration of C-14 and Rn-222 indoors is calculated from the release (Bq/m^2), the ground area of the house A (m^2), the volume of the house V (m^3) and the ventilation rate ν_{ex} (h^{-1}):

$$C_{C-14/Rn222} = \frac{E \cdot A}{V \cdot \nu_{ex}} \tag{7.3}$$

The same release inside and outside the house is assumed, which is a very cautious assumption since walls and floors inhibit the diffusion of C-14 and Rn-222 from soil to indoor air. For the ventilation rate a value of 2 h^{-1} is assumed, which should be typical for an average over winter and summer. In winter, the ventilation rate is less due to the low temperatures, whereas it is higher in summer. However, also in winter a minimum value for the ventilation is not much less than 1 h^{-1} to maintain a reasonable air quality indoors. An occupancy factor of 0.5 is assumed, this means, people stay 50% of their time in their house. The same dosimetric parameters are assumed as above, however, for the dose conversion factor of Rn-222, a value of 32 µSv/yr per Bq/m^3 is assumed due to the lower equilibrium factor of 0.4, which is a typical indoor value /UNSCEAR 2000/.

Table 7-2. Parameter values used in the estimations of outdoor inhalation doses due to a pulse gas release of C-14 and Rn-222 and estimated value of the doses.

Parameters	Value C-14	 Rn-222
Total release (Bq)	1.0E+10	2.5E+10
Area (m^2)	1.0E+04	1.0E+04
Radius of the area (m)	56.4	56.4
Release (Bq/m^2)	1.0E+06	2.5E+06
Dose Conversion Factor	6.2E–12 Sv/Bq	47 µSv/a per Bq/m^3
Underlying equilibrium factor	not applicable	0.6
Exposure during the first year (annual effective dose, µSv/yr)		
For the case with Wind speed: 2 m/s, Mixing height : 20 m	0.0022	5.3
For the case with Wind speed: 1–10 m/s, Mixing height: 10–50 m	0.00018–0.009	0.4–20

The resulting indoor exposures during the first year for a house with a volume of 1,000 m³ and a ventilation rate of 2 h^{-1} are 0.14 µSv/yr and 230 µSv/yr for C-14 and Rn-222 respectively (Table 7-3). For house volumes of 500–1,500 m³ and ventilation rates of 1–5 h^{-1}, the inhalation dose varies for C-14 from 0.038 to 0.57 µSv/yr and for Rn-222 from 60 to 900 µSv/yr.

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Table 7-3. Parameter values used in the estimations of indoor inhalation doses due to a pulse gas release of C-14 and Rn-222 and estimated value of the doses.

Parameters	**Value** **C-14**	 **Rn-222**
Total release (Bq)	1.0E+10	2.5E+10
Area (m²)	1.0E+04	1.0E+04
Ground area of the house (m²)	100	100
Release (Bq/m²)	1.0E+06	2.5E+06
DoseFactor	6.2E–12 Sv/Bq	32 µSv/yr per Bq/m³
Underlying equilibrium factor	not applicable	0.4
Occupancy factor	0.5	0.5
Exposure during the first year (annual effective dose, µSv/yr)		
For the case with House volume: 1,000 m³, Ventilation rate: 2 h–1	0.14	230
For the case with House volume: 500–1,500 m³, Ventilation rate: 1–5 h–1	0.038–0.57	60–900

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Appendix I

Results of the sensitivity study

This appendix presents detailed results of the sensitivity analysis of the ecosystem models described in Chapter 5.

Table I.1. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the sea model on the fraction of the total radionuclide release over 10,000 years that is retained in a sea object.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
acc_bottom	28.2	57.8	61.9	26.7	33.6	51.3	53.2	52.5	64.8
v_bottom	23.6	9.9	7.2	24.5	19.9	11.6	10.1	11.4	0.5
sed_growth	11.1	7.2	8.3	11.6	11.8	8.9	9.0	7.7	18.9
Porosity_bottom	12.3	6.7	4.6	12.4	10.7	7.0	4.0	5.0	0.7
Z_uppers	1.5	4.7	6.0	1.6	1.8	3.8	6.4	4.3	13.5
density_upper	5.2	2.8	2.6	5.1	4.9	3.4	3.0	2.9	0.3
Tk	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
v_sinking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
area_ coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
part_cons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
retentiontime	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
meandepth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	18.1	11.0	9.4	18.0	17.2	13.9	14.2	16.2	1.2
Kd_coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFagg Sea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.2. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the sea model on the radionuclide concentration in sea water at year 10,000 after the start of a continuous constant release to the water in the top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
acc_bottom	28.6	61.1	66.7	27.1	34.2	54.0	54.8	56.3	63.6
v_bottom	22.7	9.7	7.3	23.6	19.2	11.1	10.0	11.4	0.5
sed_growth	11.2	5.7	5.3	11.4	12.1	8.3	7.1	5.4	18.4
Porosity_bottom	12.0	6.8	4.9	12.3	10.5	7.0	4.0	5.0	0.7
density_upper	5.1	2.8	2.7	5.0	4.8	3.4	3.0	2.8	0.3
z_uppers	0.2	0.6	1.1	0.2	0.2	0.4	4.9	0.8	13.2
Retention time	1.2	1.2	1.3	1.3	1.2	1.2	1.1	1.2	1.2
mean depth	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5
area_ coast	0.7	0.5	0.4	0.8	0.6	0.6	0.4	0.4	0.4
Tk	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
v_sinking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	17.7	10.9	9.6	17.7	16.9	13.4	14.3	16.2	1.2
Kd_coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFagg Sea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.3. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the sea model on the radionuclide concentration in sea sediments at year 10,000 after the start of a continuous constant release to the water in the top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_ coast	37.2	49.7	53.3	34.3	35.3	44.7	46.4	52.0	56.6
acc_bottom	17.5	29.9	32.9	14.1	20.1	27.6	27.6	32.0	29.0
v_bottom	11.2	4.1	3.5	10.9	10.4	6.4	4.4	3.8	0.1
sed_growth	6.0	2.3	2.6	8.2	6.8	4.0	3.7	3.0	8.8
Porosity_bottom	9.8	4.6	2.0	12.2	7.1	3.2	3.4	2.0	0.2
density_upper	4.4	1.1	0.5	4.4	3.8	2.5	2.1	0.9	0.1
z_uppers	1.0	2.0	2.1	1.8	1.3	1.7	2.5	1.9	5.0
Tk	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
v_sinking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
part_cons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Retention time	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mean depth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	12.8	6.2	3.2	14.0	15.2	9.9	9.8	4.4	0.3
Kd_coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFagg Sea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.4. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the sea model on the total doses from each radionuclide at year 10,000 from the start of a continuous and constant release t < o the water in the top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
acc_bottom	15.2	35.8	46.4	13.5	20.2	35.0	35.8	37.6	39.1
v_bottom	13.9	5.8	3.8	10.7	14.0	8.0	7.4	7.5	0.2
sed_growth	6.6	3.2	3.0	5.9	7.7	6.4	4.8	3.9	13.1
Porosity_bottom	6.3	2.9	2.7	6.7	6.4	4.9	2.4	3.0	0.4
density_upper	3.3	1.6	1.8	2.9	3.2	2.3	1.8	2.1	0.2
z_uppers	0.1	0.4	0.9	0.1	0.1	0.2	2.7	0.6	8.0
retentiontime	0.8	1.0	0.9	0.7	0.6	0.8	0.8	0.7	0.5
area_coast	0.4	0.3	0.3	0.6	0.2	0.4	0.2	0.2	0.3
meandepth	0.2	0.2	0.5	0.2	0.3	0.3	0.3	0.3	0.4
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
v_sinking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
part_cons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	10.0	6.8	4.6	9.5	12.2	9.2	9.2	8.4	0.8
Kd_coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TFagg Sea	43.2	42.1	35.2	48.9	35.1	32.5	34.6	35.6	37.1

Table I.5. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the fraction of the total radionuclide release to the lake water over 3,000 years that is retained in a lake.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
Tk	29.9	16.5	20.1	29.0	33.6	13.4	16.5	13.6	19.0
area_catchment	20.5	19.3	20.5	8.8	22.9	18.2	18.4	14.8	21.0
area_ lake	10.4	16.6	15.5	6.1	6.9	14.7	17.0	18.2	14.5
meandepth	8.8	9.7	11.4	5.0	4.5	12.8	11.3	13.6	13.0
part_cons	14.2	5.8	7.3	7.6	6.0	5.5	5.8	5.4	6.2
v_sinking	1.9	7.2	8.3	7.1	6.8	7.1	6.8	6.1	7.7
v_bottom	5.7	2.4	2.1	9.0	4.1	2.1	1.4	1.7	0.1
Runoff	2.3	3.2	3.5	2.5	1.5	3.3	3.1	2.8	3.5
sed_growth	0.6	3.4	0.6	6.2	2.0	3.1	4.0	2.3	0.3
acc_bottom	0.2	0.5	0.5	0.1	0.6	0.5	0.5	0.3	0.5
Z_uppers	0.0	1.0	0.4	0.0	0.0	0.6	0.6	0.8	0.0
Porosity_sed	0.1	0.2	0.2	0.6	0.2	0.2	0.1	0.2	0.0
Density_upper	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	0.6	2.2	1.2	12.8	6.2	2.7	4.5	2.8	0.1
Kd_lake	4.8	12.0	8.3	5.3	4.7	15.8	9.8	17.5	14.0
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.6. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the radionuclide concentration in lake water at year 3,000 after the start of a continuous constant release to the lake water.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	78.2	33.6	38.3	53.4	54.9	33.9	32.6	33.3	35.9
area_ lake	0.0	21.5	14.4	2.3	2.9	21.0	21.5	23.1	15.2
Tk	1.4	13.1	15.8	12.9	15.4	10.8	10.8	12.4	13.7
Runoff	19.2	6.8	8.2	12.7	13.5	8.3	6.7	6.8	6.9
meandepth	0.0	6.9	6.6	2.1	1.8	6.8	5.7	4.5	7.1
part_cons	0.6	3.3	5.0	3.3	2.6	2.3	3.5	1.5	4.4
v_sinking	0.1	1.6	1.7	2.5	2.2	1.6	1.6	2.1	2.4
v_bottom	0.3	2.6	2.4	3.5	1.6	0.7	0.6	0.4	0.0
sed_growth	0.0	4.9	0.1	1.6	0.4	2.3	0.3	0.6	0.0
z_uppers	0.0	0.8	0.7	0.0	0.0	0.3	0.3	0.2	0.0
Porosity_sed	0.0	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.0
acc_bottom	0.0	0.2	0.2	0.0	0.2	0.3	0.0	0.0	0.0
Density_upper	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	0.0	0.4	0.9	3.5	2.2	0.5	8.6	0.5	0.0
Kd_lake	0.2	4.1	5.3	2.0	2.2	11.1	7.5	14.3	14.4
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.7. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the radionuclide concentration in lake sediments at year 3,000 after the start of a continuous constant release to the lake water.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
Tk	41.6	6.1	25.9	18.6	34.2	12.6	12.2	15.4	26.0
area_catchment	13.7	29.6	23.4	7.6	12.0	25.6	25.4	21.7	15.0
area_ lake	0.1	27.0	17.0	0.5	0.3	24.2	27.0	24.9	12.8
v_sinking	2.6	2.1	9.5	9.0	21.4	12.4	12.1	11.6	8.3
part_cons	20.1	10.6	9.2	6.6	5.1	5.5	12.4	10.4	8.1
meandepth	0.7	2.6	6.3	3.4	2.3	2.4	3.5	6.0	10.7
v_bottom	8.6	0.4	1.1	12.3	11.3	0.6	0.3	2.3	0.1
sed_growth	2.0	0.6	0.3	9.8	2.0	0.8	0.7	0.3	0.2
Runoff	1.6	0.7	2.1	3.8	1.6	0.6	0.9	0.2	2.2
acc_bottom	0.6	0.3	0.3	0.1	0.7	0.1	0.5	0.5	0.3
Porosity_sed	0.3	0.6	0.1	1.0	0.1	0.8	0.0	0.3	0.0
lake_z_uppers	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0
Density_upper	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	1.9	0.3	0.9	22.2	5.6	0.3	0.6	1.2	0.0
Kd_lake	6.2	19.1	3.8	5.0	3.2	14.0	0.0	5.1	16.3
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.8. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the total doses from each radionuclide at year 3,000 from the start of a continuous and constant release to the lake water.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	55.4	24.1	31.4	39.7	42.2	32.0	25.2	33.4	35.0
area_ lake	0.0	24.8	10.5	2.0	2.8	10.4	21.4	25.1	16.3
Runoff	13.4	4.8	9.3	9.2	11.9	9.1	6.2	5.1	7.2
Tk	1.4	7.9	12.9	8.2	9.8	14.3	10.9	5.2	5.2
meandepth	0.0	3.8	7.5	0.6	1.2	5.6	3.9	1.6	6.1
part_cons	0.7	2.3	2.7	2.8	2.1	1.6	1.9	1.8	4.2
v_sinking	0.1	0.8	1.3	3.3	1.6	1.9	0.4	0.9	0.6
v_bottom	0.3	1.7	0.9	4.2	1.1	0.5	0.3	0.3	0.0
sed_growth	0.0	2.4	0.0	0.9	0.3	0.3	0.3	0.8	0.0
z_uppers	0.0	0.4	0.8	0.0	0.0	0.0	0.4	0.2	0.0
acc_bottom	0.0	0.0	0.1	0.0	0.1	0.4	0.0	0.0	0.0
porosity_sed	0.0	0.1	0.2	0.3	0.1	0.1	0.1	0.0	0.0
density_upper	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	0.0	0.5	0.6	1.8	1.4	0.2	9.9	0.4	0.0
Kd_lake	0.2	4.6	4.5	1.1	2.1	7.1	7.3	15.2	12.1
TFagg Lake	28.6	21.8	17.1	25.8	23.5	16.5	11.7	9.9	13.2

Table I.9. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the fraction of the total radionuclide release to the water in the top sediment over 3,000 years that is retained in a lake.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
sed_growth	27.7	28.5	27.0	23.9	28.8	27.2	22.5	17.1	16.7
v_bottom	35.0	16.1	13.6	34.4	25.7	18.8	19.2	12.6	4.4
area_lake	0.6	7.9	5.9	1.2	1.2	5.7	6.5	10.3	16.3
acc_bottom	3.0	4.0	5.2	2.7	3.2	3.8	4.8	4.2	13.8
z_uppers	0.7	6.2	6.2	0.7	0.9	4.4	5.7	4.8	8.6
v_sinking	1.2	3.5	3.7	2.1	1.6	2.9	3.6	5.2	11.2
area_catchment	0.4	4.8	4.7	2.0	2.3	3.9	3.7	5.7	5.3
Tk	0.7	4.1	3.9	3.6	3.4	2.5	4.1	4.9	5.8
meandepth	0.4	4.8	1.8	0.5	0.5	5.0	2.3	3.8	3.2
Porosity_sed	2.0	1.3	1.2	2.0	1.7	1.4	1.2	1.1	0.3
part_cons	0.1	1.2	0.7	1.3	0.4	1.4	1.2	1.3	1.2
Density_upper	1.1	0.7	0.6	1.1	0.9	0.7	0.6	0.5	0.1
Runoff	0.1	0.8	0.5	0.5	0.1	0.9	1.1	1.0	1.3
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	26.9	13.3	23.3	23.1	29.0	16.4	21.3	20.6	6.6
Kd_lake	0.1	2.8	1.6	0.8	0.2	4.9	2.0	6.6	4.9
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.10. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the radionuclide concentration in lake water at year 3,000 after the start of a continuous constant release to the water in the top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	39.9	25.6	19.3	39.1	31.1	19.3	10.1	26.1	25.6
V_bottom	25.0	7.9	19.6	19.4	22.2	18.5	4.8	3.4	1.6
sed_growth	8.0	19.3	6.7	8.1	11.2	16.2	4.2	19.8	3.6
area_lake	0.0	17.2	10.1	1.6	0.7	11.2	4.5	16.0	5.6
Tk	1.0	7.9	8.9	5.8	7.1	2.7	4.5	6.1	1.9
acc_bottom	1.5	2.5	4.5	0.5	1.5	2.3	6.0	7.0	19.3
Runoff	8.6	3.0	2.9	6.9	7.4	2.1	1.4	2.5	0.9
V_sinking	0.3	0.7	2.5	2.4	1.4	0.6	2.3	1.8	11.2
Z_uppers	0.0	2.1	5.8	0.0	0.0	5.8	2.3	2.0	1.0
meandepth	0.1	4.8	1.5	0.5	0.2	0.5	2.4	3.0	4.3
Porosity_sed	1.1	0.8	1.4	0.9	0.9	1.6	0.5	1.4	0.2
part_cons	0.2	0.4	0.4	2.1	0.7	0.5	0.2	0.6	0.9
Density_upper	0.5	0.4	1.0	0.4	0.4	0.6	0.7	0.1	0.1
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	13.6	5.9	9.8	11.1	14.7	2.9	54.3	9.1	1.8
Kd_lake	0.1	1.5	5.5	1.1	0.4	15.1	2.0	1.3	22.0
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.11. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the radionuclide concentration in lake sediments at year 3,000 after the start of a continuous constant release to the water in top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_lake	34.9	62.6	67.5	36.5	44.6	58.5	68.8	62.8	78.0
sed_growth	14.3	12.3	11.6	16.7	14.9	13.9	6.0	9.0	6.0
v_bottom	21.7	4.8	3.7	23.5	12.3	6.2	1.6	3.8	0.0
acc_bottom	3.1	4.1	4.5	3.4	3.2	3.8	4.5	4.4	4.6
z_uppers	0.5	5.2	5.3	0.3	0.5	3.3	4.0	1.5	3.9
area_catchment	0.8	1.4	1.7	0.9	1.2	1.2	1.7	1.5	1.9
Porosity_sed	1.5	0.4	0.1	2.0	1.2	0.6	0.1	0.8	0.0
v_sinking	0.2	0.9	1.0	0.2	0.5	0.9	1.0	1.0	1.1
Tk	0.3	1.0	1.0	0.2	0.7	0.8	1.0	0.6	1.1
Density_upper	0.8	0.5	0.3	0.9	0.6	0.4	0.2	0.4	0.0
Runoff	0.1	0.4	0.4	0.1	0.2	0.3	0.4	0.4	0.4
meandepth	0.0	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2
part_cons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	21.6	6.3	2.6	15.4	20.0	9.9	10.6	13.5	2.8
Kd_lake	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0
TFagg Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.12. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the lake model on the total doses from each radionuclide at year 3,000 from the start of a continuous and constant release to the water in top sediment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	30.2	16.7	15.2	29.7	24.7	12.7	4.7	30.5	34.8
v_bottom	22.0	6.6	8.7	13.0	23.9	24.2	2.9	2.2	0.8
area_lake	0.0	21.2	7.2	2.0	0.8	9.3	4.5	19.6	6.9
sed_growth	6.2	12.9	4.7	5.2	5.0	5.0	2.5	24.0	4.8
acc_bottom	1.4	0.4	6.8	0.4	1.4	4.9	3.8	4.0	26.8
Tk	0.8	5.3	9.2	6.7	4.0	6.2	4.9	3.0	2.1
Runoff	6.9	1.6	3.3	4.0	6.8	4.0	1.4	1.5	0.9
v_sinking	0.2	0.5	1.9	3.6	1.1	1.2	0.5	0.9	5.4
meandepth	0.0	3.4	2.0	0.3	0.2	0.8	2.6	1.2	4.6
z_uppers	0.0	1.7	7.8	0.0	0.0	0.4	2.2	1.5	0.7
Porosity_sed	0.9	1.2	1.6	0.8	0.8	0.8	0.4	1.6	0.1
part_cons	0.3	0.7	0.3	2.3	0.4	0.5	0.1	0.5	1.0
Density_upper	0.4	0.2	1.1	0.4	0.4	0.2	0.7	0.1	0.0
pty_lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	10.4	2.1	12.6	6.4	13.4	4.9	60.2	5.3	1.2
TFagg Lake	20.2	23.3	11.4	24.5	16.7	23.8	6.8	2.9	2.7
Kd_lake	0.1	2.2	6.1	0.8	0.4	1.2	1.6	1.1	7.3

Table I.13. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the agricultural land model on the fraction of the total radionuclide release over 3,000 years, to the water in the saturated zone, that is retained in an agricultural land object.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
Area_ agriland	20.8	22.3	22.6	21.5	29.8	21.8	26.2	22.6	21.8
Area_catchment	28.7	17.6	27.5	24.2	24.6	15.7	23.1	17.9	16.1
Runoff	7.2	6.3	8.7	10.1	8.1	6.0	7.4	6.8	5.8
z_saturated_zone	3.5	6.3	4.7	3.7	7.5	6.2	6.9	6.6	5.6
z_deeps	12.1	1.7	5.2	9.7	1.4	1.9	1.0	0.9	0.3
Fsads	6.0	1.1	3.6	5.7	1.6	1.3	1.0	1.2	0.5
Porosity_saturated_zone	1.1	2.0	1.7	1.4	2.4	2.0	2.1	2.2	1.8
Percolation	2.9	0.3	1.4	4.4	0.3	0.2	0.3	0.2	0.0
Porosity_bottom	1.7	0.3	0.9	1.8	0.2	0.2	0.2	0.2	0.1
Density	0.4	0.8	0.4	0.4	0.4	0.3	0.4	0.3	0.3
z_uppers	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Porosity_upper	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Fdsts	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Bioturbation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Loss_soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_agriland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_soil	15.5	41.7	23.1	16.9	23.7	44.4	31.3	41.2	47.3
TFagg Agric Land	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.14. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the agricultural land model on the radionuclide concentrations in the top soil at year 3,000 from the start of a continuous and constant release to the water in the saturated zone.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
Area_catchment	34.0	10.3	25.0	26.9	14.2	9.6	13.7	6.7	7.8
z_deeps	1.8	26.6	8.6	0.4	23.1	22.0	19.4	20.5	22.8
area_ agriland	1.4	20.5	11.5	0.6	21.1	24.5	20.5	22.8	16.6
Fsads	12.5	10.7	11.1	14.1	10.2	9.8	8.1	9.3	7.5
Runoff	14.9	4.0	10.4	18.1	7.4	4.6	5.8	3.9	3.0
percolation	7.4	1.8	5.5	10.5	2.4	1.4	1.5	1.6	1.8
z_saturated_zone	0.1	3.3	1.6	0.1	4.5	3.2	4.0	5.2	3.1
Porosity_bottom	0.2	3.3	2.6	0.2	3.1	3.1	2.5	3.7	3.4
Fdsts	7.2	0.7	2.3	7.2	0.5	0.8	0.5	0.8	0.8
bioturbation	1.0	1.3	2.5	1.0	1.7	1.7	1.8	1.4	2.6
Porosity_saturated_zone	0.0	2.3	0.7	0.1	1.5	1.8	1.1	1.8	1.3
Porosity_upper	0.8	1.6	0.2	0.7	1.0	1.0	1.2	1.3	1.2
z_uppers	0.0	1.7	0.2	0.0	1.2	1.2	1.0	1.3	1.3
Density	0.1	0.8	0.4	0.1	0.6	0.7	0.5	0.9	0.8
loss_soil	0.0	0.2	0.1	0.0	0.2	0.1	0.1	0.2	0.1
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_agriland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_soil	18.6	11.0	17.3	20.2	7.3	14.5	18.2	18.6	25.8
TFagg Agric Land	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.15. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the agricultural land model on the total doses from each radionuclide at year 3,000 from the start of a continuous and constant release to the water in the saturated zone.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_agriland	1.0	14.7	12.3	0.3	17.8	26.0	21.4	17.4	12.5
area_catchment	28.2	11.1	17.8	22.2	12.8	7.5	9.2	4.8	8.1
Z_deeps	0.6	14.7	7.5	0.4	15.2	20.1	16.0	17.8	21.2
Fsads	10.8	7.7	9.4	10.7	9.3	8.9	5.6	7.2	6.1
Runoff	11.7	3.8	9.3	16.9	4.7	3.3	4.6	3.2	2.5
percolation	6.6	1.7	4.1	9.2	2.7	0.8	1.1	0.5	1.5
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.1	7.3
Z_saturated_zone	0.1	3.0	1.5	0.1	3.4	2.3	4.5	4.5	2.7
Porosity_bottom	0.2	2.7	2.9	0.1	2.7	2.5	2.2	4.1	2.4
Fdsts	5.2	0.6	2.4	6.7	0.5	0.5	0.4	0.8	0.7
bioturbation	0.7	1.2	2.8	1.0	1.8	1.3	1.1	1.2	2.7
Porosity_saturated_zone	0.0	2.4	0.8	0.1	1.0	1.1	1.0	1.9	1.2
Porosity_upper	0.7	1.1	0.2	0.5	0.7	0.8	1.0	0.9	1.0
Z_uppers	0.0	1.4	0.2	0.0	0.7	1.2	0.8	1.1	1.0
Density	0.0	0.8	0.5	0.1	0.6	0.5	0.4	0.8	0.5
loss_soil	0.0	0.2	0.1	0.0	0.1	0.1	0.1	0.2	0.1
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_agriland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_soil	16.4	10.3	12.9	14.9	6.4	13.8	18.0	16.0	22.4
TFagg Agric Land	17.7	22.4	15.4	17.0	19.7	9.2	12.6	2.8	5.8

Table I.16. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the forest model on the fraction of the total radionuclide release over 3,000 years, to the soil compartment, that is retained in a forest.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_ forest	16.7	23.5	22.0	20.2	18.5	18.7	22.9	16.6	21.8
area_catchment	19.2	19.6	17.3	28.0	29.7	12.3	16.3	10.4	16.7
z_uppers	4.5	11.6	6.0	9.6	11.5	5.9	9.2	8.9	8.2
Runoff	7.6	6.8	5.9	8.3	7.6	4.9	5.7	4.6	6.4
Density_upper	4.0	0.8	3.7	8.0	8.4	3.7	6.0	4.9	8.2
Productivity_wood	12.9	0.1	4.7	0.8	0.4	4.7	1.4	0.0	0.0
Productivity_leaf	1.6	0.0	3.6	0.4	0.5	1.2	0.4	0.0	0.0
loss_litter	1.1	0.1	2.0	0.3	0.1	1.2	0.4	0.0	0.0
Productivity_understory	1.1	0.1	0.4	0.2	0.0	0.7	0.1	0.0	0.0
loss_understory	0.2	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0
waterContent	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_forest	20.3	30.6	24.6	22.8	22.6	39.9	35.5	54.6	38.0
TFagg forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CR_W	7.8	0.1	5.3	0.4	0.3	4.6	1.6	0.0	0.0
CR_L	1.5	0.0	3.8	0.5	0.3	1.1	0.3	0.0	0.0
CR_U	1.7	0.1	0.4	0.4	0.0	0.9	0.1	0.0	0.0

Table I.17. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the forest model on the radionuclide concentrations in soil at year 3,000 from the start of a continuous and constant release to the soil compartment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_ forest	0.6	27.2	26.3	0.0	0.7	32.4	30.4	37.7	47.4
area_catchment	38.0	18.1	13.0	45.0	43.2	5.5	12.2	6.3	2.4
z_uppers	0.1	10.8	7.2	0.0	1.8	15.2	11.9	20.0	29.1
Runoff	16.1	7.4	5.7	15.3	14.7	2.9	5.0	2.7	0.8
density_upper	0.3	0.8	3.9	0.2	1.2	6.1	8.1	11.8	14.8
Productivity_wood	1.3	0.1	4.6	0.0	0.0	5.9	1.8	0.0	0.0
Productivity_leaf	0.1	0.1	2.9	0.0	0.0	1.7	0.4	0.0	0.0
forest_loss_litter	0.0	0.1	1.6	0.0	0.0	1.6	0.3	0.0	0.0
Productivity_understory	0.0	0.2	0.3	0.0	0.0	1.2	0.2	0.0	0.0
waterContent	0.2	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0
loss_understory	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_forest	42.7	28.4	20.6	39.2	38.2	15.7	26.6	21.5	5.4
TFagg forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CR_W	0.5	0.2	9.3	0.0	0.0	8.5	2.4	0.0	0.0
CR_L	0.0	0.0	4.1	0.0	0.0	1.3	0.4	0.0	0.0
CR_U	0.1	0.1	0.4	0.0	0.0	1.8	0.2	0.0	0.1

Table I.18. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the forest model on the total doses from each radionuclide at year 3,000 from the start of a continuous and constant release to the soil compartment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_ forest	0.2	21.4	21.9	0.0	0.6	24.7	23.4	27.7	34.5
area_catchment	29.1	13.1	11.2	34.8	35.7	5.3	10.8	5.2	1.4
z_uppers	0.0	7.5	6.2	0.0	0.9	10.7	8.4	15.2	17.9
Runoff	12.5	5.8	6.5	13.4	13.1	2.4	4.2	2.4	0.5
density_upper	0.3	0.8	2.5	0.1	0.8	5.5	7.1	8.6	10.3
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.6	3.5
Productivity_wood	1.2	0.1	3.3	0.0	0.0	3.8	1.3	0.0	0.0
Productivity_leaf	0.1	0.0	2.2	0.0	0.0	1.5	0.3	0.0	0.0
loss_litter	0.0	0.1	1.4	0.0	0.0	1.1	0.2	0.0	0.0
Productivity_understory	0.0	0.2	0.3	0.0	0.0	0.9	0.1	0.0	0.0
loss_understory	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0
waterContent	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
DensitySoilBulk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
pty_forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_forest	30.3	25.6	15.7	23.4	26.9	13.2	21.4	17.1	4.0
Tfagg forest	25.9	21.2	20.4	28.1	21.9	21.0	20.7	8.2	27.6
CR_W	0.1	0.1	4.3	0.0	0.0	7.7	1.6	0.0	0.0
CR_L	0.0	0.0	3.7	0.0	0.0	1.1	0.3	0.0	0.0
CR_U	0.1	0.1	0.5	0.0	0.0	1.0	0.1	0.0	0.0

Table I.19. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the mire model on the fraction of the total radionuclide release over 3,000 years, to the water compartment, that is retained in a mire.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	37.8	34.8	32.4	28.8	31.7	36.0	34.2	31.8	20.3
z_uppers	18.2	19.6	15.9	24.4	19.1	20.5	16.1	17.2	12.6
area_ mire	13.0	11.2	12.9	7.3	10.7	8.8	14.1	13.5	25.1
density_upper	10.4	10.0	12.4	11.1	9.7	13.9	11.4	11.8	11.0
Runoff	3.1	4.5	5.6	4.0	3.3	5.8	5.3	5.6	4.0
DensitySoilBulk	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
porosity_upper	0.2	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.0
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_mire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	17.3	19.8	20.7	23.9	25.5	15.0	18.9	20.2	26.9
TFagg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.20. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the mire model on the radionuclide concentrations in the peat at year 3,000 from the start of a continuous and constant release to the water compartment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	52.0	45.1	34.8	48.0	52.2	46.5	26.2	30.9	10.1
Runoff	10.7	11.5	6.4	15.3	11.3	14.4	5.1	6.4	1.6
z_uppers	0.0	16.6	12.9	0.0	0.0	3.6	15.4	21.4	9.6
area_ mire	0.0	1.7	10.9	0.0	0.0	0.1	15.7	9.0	30.5
density_upper	0.0	7.3	11.8	0.0	0.0	4.1	14.2	10.9	6.6
DensitySoilBulk	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
porosity_upper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_mire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	37.3	17.7	23.2	36.7	36.5	31.4	23.4	21.4	41.6
TFagg Mire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table I.21. Sensitivity indices, expressed in %, obtained with the Morris method as a combined measure of the effect of the parameters of the mire model on the total doses from each radionuclide at year 3,000 from the start of a continuous and constant release to the water compartment.

Parameter	Cl-36	Ni-59	Se-79	Tc-99	I-129	Cs-135	Ra-226	Pu-239	Am-241
area_catchment	38.4	36.9	24.7	47.7	42.4	40.0	21.5	31.0	4.0
Runoff	8.3	9.6	5.8	12.1	9.1	11.5	3.1	3.0	0.6
z_uppers	0.0	11.7	9.6	0.0	0.0	2.6	10.2	18.6	6.2
area_mire	0.0	1.1	5.5	0.0	0.0	0.1	15.5	9.2	22.6
density_upper	0.0	6.0	13.5	0.0	0.0	2.9	10.8	3.7	2.9
DustConc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1	1.2
DensitySoilBulk	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
porosity_upper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pty_mire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kd_peat	21.9	12.3	19.0	29.2	23.2	23.8	15.8	18.2	32.1
TFagg Mire	31.4	22.4	21.8	11.0	25.3	19.0	23.1	6.2	30.4