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Probability distributions of dose conversion factors for radionuclides used in a long-term safety assessment

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PREFACE

The research presented in this report forms part of the PROSA (**PRO**babilistic Safety Assessment) project. The PROSA project aims to determine the radiological effects on humans and the characteristics relevant to safety of disposal concepts for radioactive waste in rock-salt formations. The PROSA project is carried out in the framework of the Dutch safety evaluation studies for geological disposal of radioactive waste (OPLA) continuing the safety assessment VEOS performed in phase 1. The selection of the scenarios for the release of the disposed waste is carried out in a more systematic manner and uncertainties are included.

The PROSA project is carried out by the Netherlands Energy Research Foundation (ECN), the National Institute of Public Health and Environmental Protection (RIVM) and the Geological Survey of the Netherlands (RGD). ECN models the repository and does the risk calculations. RIVM models the groundwater transport in the geosphere (Laboratory of Soil and Groundwater Research) and the transport of the radionuclides in the biosphere (Laboratory of Radiation Research). Geological expertise is given by RGD.

This report describes the modelling of the biosphere; the effects of the released radionuclides are described in nuclide-specific dose conversion factors.

Some parts of this report are included in the final report of PROSA. The biosphere model used is described in RIVM report no. 715204004.

VOORWOORD

Het in dit rapport beschreven onderzoek maakt deel uit van het project PROSA (PRobabilistisch Onderzoek aan de veiligheid van in Steenzout opgeborgen radioactief Afval). PROSA heeft als doel het bepalen van het gezondheidsrisico voor de mens ten gevolge van de opberging van radioactief afval in zoutformaties en het bepalen van een aantal relevante kenmerken, die voor een verdere selectie van mogelijke opbergconcepten gebruikt kunnen worden. PROSA, uitgevoerd in het kader van het Fase-1a onderzoeksprogramma van de commissie OPLA (OPberging te LAnd), is een vervolg op de in fase 1 uitgevoerde veiligheidsstudie VEOS, en kenmerkt zich door een meer systematische benadering van de selectie van de scenario's voor het vrijkomen van het afval en het meenemen van onzekerheden door middel van probabilistische rekentechnieken.
Het project PROSA is een gemeenschappelijk project van ECN, RIVM en RGD. Het ECN zorgt voor het project management, het uitvoeren van de risicoberekeningen en de modellering van de opbergfaciliteit. Het Laboratorium voor Bodem en Grondwateronderzoek van het RIVM verzorgt de modellering van de hydrologie in de geosfeer en het Laboratorium voor Stralingsonderzoek verzorgt de modellering van de biosfeer. De RGD levert expertise met betrekking tot de geologische aspecten.
Dit rapport beschrijft uitgebreid de modellering van de biosfeer. Centraal hierbij staat de berekening van de dosisconversiefactoren voor de radionucliden. Deze dosisconversiefactoren vormen in de uiteindelijke risicoberekeningen de vertaling van de radionuclide flux vanuit de geosfeer naar de radiologische belasting voor de mens.
De resultaten van het project PROSA en de gevolgde methodiek zijn beschreven in het PROSA-eindrapport. Sommige onderdelen van onderhavig rapport zijn in verkorte vorm opgenomen in dat eindrapport. Een beschrijving van het biosfeermodel, gebruikt voor deze berekeningen, is opgenomen in RIVM rapport 715204004.

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SUMMARY

For the PROSA (PRObabilistic Safety Assessment) project, probabilistic dose conversion factors for various radionuclides are determined for a biosphere where the radionuclides are released via groundwater discharge. Deterministic dose conversion factors are determined for a biosphere where the repository reaches the surface level. In the description of the biosphere the current level of technology is assumed. Because of the time scales involved in a safety assessment, the calculated dose conversion factors should be interpreted as an indication of possible radiation levels in the future, rather than as a prediction.

If the radionuclides are released via groundwater discharge several release points, like a river or a well, are possible. For a conservative approach, the release in a well is probably the best. However, there is a great uncertainty in the salt concentration of the groundwater and the area of the biosphere in which the groundwater is discharged. These factors have a large influence on the calculations for a well. Because they are of minor importance for release in a river, we chose for a release in a river.

The stochastic dose conversion factors for release in a river via groundwater discharge are calculated for a farmer who consumes only the (contaminated) produce of his own land. We assumed this to be a conservative option. For the calculation of the dose conversion factors the dynamic environmental transfer model, MiniBIOS, was used. The model incorporates a linked chain of terrestrial compartments, each comprising river water, sediments, soil boxes and biota and a simple ocean model. Activity is interchanged between these boxes through a variety of processes. The individual dose for various exposure pathways is calculated from the concentrations in the surface water and surface soil compartments. The dose due to ingestion includes the intake of drinking water, milk, cereals, leafy vegetables, root vegetables, meat, freshwater fish and seafood. Inhalation of resuspended soil and external exposure due to gamma emissions of contaminated soil are also included. The radiation dose depends on the time period of the model calculation, since the radionuclides accumulate in the soil with time, whereas the dose conversion factors are constant with time. The dose conversion factors are defined as the radiation dose to humans following a fixed time period of accumulation in the soil. Based on the occurrence of glaciation periods in the Netherlands a time period of 10,000 years was chosen.

In the calculations a number of processes (flow of river, irrigation, diffusion, bioturbation, sedimentation, erosion and sediment transfer to land) and properties (concentration factors, distribution coefficients and river dimensions) is taken stochastically into account.

For most radionuclides the ratio of the minimum to the maximum value of the calculated

distribution is 1000 to 100,000. The ratio of the 10 percentile to the 90 percentile, however, is usually less than 500. The most important exposure pathways (ingestion of contaminated water, fish and vegetables) and the most important sources of uncertainty (especially the flow of the river and the various distribution coefficients and concentration factors) in the calculated dose conversion factors are determined. An indication of the effect of other possible release points (a well, a lake, a deep soil layer or a sea) on the dose conversion factors is given.

If the repository reaches the surface level, the dose conversion factors are determined for a very conservative option which is not likely to happen. Almost the same approach as in the preceding project, VEOS, is used because no new insights were available. The biosphere consists of a salt desert in which vegetation is assumed to be absent. It is very unlikely that people will live continuously on the rather small repository field (about 0.5 km^2) since they will have to live on crops grown elsewhere and the circumstances outside this field are probably better. However, as the dose conversion factors are calculated for an adult who lives continuously on the repository field without protection against radiation or dust, a conservative option is chosen. Exposure pathways included in the dose conversion factors are the inhalation of radioactive particles and external radiation. Uncontaminated water and food will come from outside the repository field because of the saline conditions. A deterministic approach is chosen as the effect of less conservative assumptions can easily be calculated.

The calculated dose conversion factors give a good impression of future radiation levels. We recommend further investigations only if new and relevant information on the groundwater properties or future climatic types becomes available or if new insights for the biosphere if the repository reaches the surface level become available.

SAMENVATTING

Voor het project PROSA (PRobabilistisch Onderzoek aan de veiligheid van in Steenzout opgeborgen radioactief Afval) zijn tijdonafhankelijke dosisconversiefactoren berekend voor een biosfeer waarbij de nucliden vrijgezet worden in een rivier en voor een biosfeer waarbij het opbergveld onder droge omstandigheden aan het maaiveld komt.

Voor de beschrijving van de biosfeer is uitgegaan van de huidige toestand met betrekking tot het klimaat en de technologische kennis. Gezien de tijdschalen die bij een veiligheidsstudie naar de opslag van radioactief afval een rol spelen moeten de berekende dosisconversiefactoren daarom meer gezien worden als een illustratie van mogelijke effecten dan als een voorspelling.

In het geval dat de nucliden in de biosfeer vrijkomen door transport met het grondwater, zijn verschillende vrijzettingspunten mogelijk, zoals een rivier of een waterput. Voor een conservatieve benadering is de vrijzetting van de nucliden in een waterput waarschijnlijk de beste optie. Echter, er is weinig bekend over de zoutconcentratie van het grondwater, dat uit de diepe ondergrond komt, en het oppervlak van de biosfeer waar het grondwater vrijkomt. Deze factoren hebben een overheersende invloed op de berekeningen voor een waterput, maar zijn van ondergeschikt belang bij de berekeningen voor een rivier. Daarom is gekozen voor vrijzetting in een rivier. Stochastische dosisconversiefactoren zijn bepaald voor een volwassene die alleen voedsel uit de eigen omgeving consumeert.

Voor de berekening van de dosisconversiefactoren is het dynamische biosfeer model MiniBIOS gebruikt. MiniBIOS bevat een aantal terrestrische compartimenten, die ieder zijn onderverdeeld in water-, sediment-, en grondcompartimenten. Verschillende processen zorgen voor de uitwisseling van de nucliden tussen deze compartimenten. In de berekening van de stralingsbelasting van de mens is naast de ingestie van water, vis, groente, vlees en melk ook de inhalatie van opgewaaide stofdeeltjes en de blootstelling aan externe bestraling opgenomen.

De dosis is afhankelijk van het tijdstip na aanvang van de vrijzetting waarvoor de dosis wordt berekend omdat de nucliden in de bodem accumuleren. Uit analyses is gebleken dat de instelling van de evenwichtsituatie in de biosfeer erg lang duurt. De biosfeeranalyses zijn daarom beperkt tot 10.000 jaar omdat aangenomen mag worden dat de biosfeer niet gedurende een nog langere tijd constant zal zijn. Zo zal door een ijstijd de biosfeer geheel veranderen. In de berekeningen zijn een aantal processen (debiet van de rivier, irrigatie, diffusie, bioturbatie, sedimentatie, erosie, sediment overdracht op land) en grootheden (concentratiefactoren, distributiecoëfficiënten en dimensie van de rivier) stochastisch meegenomen. Voor de meeste nucliden bedraagt de verhouding tussen het minimum en maximum van de verdeling een factor 1000 tot 100.000. De verhouding tussen het 10 en 90 percentiel is daarentegen meestal minder dan 500. De belangrijkste belastingspaden zijn de ingestie van besmet drinkwater, vis en groenten. De belangrijkste bronnen van onzekerheid (met name het rivierdebiet en de verschillende distributiecoëfficiënten en concentratiefactoren) in de dosisconversiefactoren zijn bepaald. Een indicatie van de

mogelijke effecten van verschillende vrijzettingspunten wordt gegeven.

Indien het opbergveld onder droge condities aan het oppervlak komt zal de biosfeer bestaan uit een droge zoutwoestijn. De dosisconversiefactoren voor deze biosfeer zijn zeer conservatief omdat ze berekend worden voor mensen die continu op het opbergveld wonen. De levensomstandigheden buiten het opbergveld (0,5 km^2) zullen waarschijnlijk beter zijn en het is daarom vrij onwaarschijnlijk dat mensen continu op het beperkte gebied van het opbergveld zullen leven. In de berekende dosisconversiefactoren zijn de inhalatie van opgewaaide deeltjes en externe bestraling opgenomen. Het voedsel voor deze mensen komt van buiten het opbergveld als gevolg van de zoute omstandigheden. Voor deze dosisconversiefactoren zijn geen stochastische verdelingen bepaald omdat de effecten van minder conservatieve benaderingen eenvoudig bepaald kunnen worden.

De berekende dosisconversiefactoren geven een goede indruk van de mogelijke effecten in de toekomst als de nucliden in een rivier vrijkomen. Verder onderzoek wordt alleen aanbevolen als nieuwe en relevante informatie over het grondwater of klimaat beschikbaar komt of als er nieuwe inzichten voor de biosfeer, waarbij het opbergveld het maaiveld bereikt, beschikbaar komen.

1 INTRODUCTION

The PROSA (**PRO**babilistic Safety Assessment) project aims to determine the radiological effects on humans and the derivation of characteristics relevant to safety of disposal concepts for radioactive waste in rock-salt formations [PROSA93]. A scenario type of analysis followed by a probabilistic consequence analysis was chosen. In the probabilistic analysis, ranges of possible parameter values and their probabilities are used to determine the uncertainties in the radiological consequences. The method is also useful to do a sensitivity or uncertainty analysis and to determine the characteristics relevant to safety.
Two different models are used for calculating the radiological effects [PROSA93]:

- PANTER (Probabilistic Analysis of Nuclide Transport into the Environment of a Repository) for the probabilistic analysis of the subrosion scenarios [PROSA93];
- EMOS_ECN for the analysis of the water intrusion scenarios [PROSA93].

Both models are adapted versions of the code EMOS [St90], each containing three modules:

- REPOS, to model the near field of the repository;
- MASCOT, to model the groundwater transport in the geosphere;
- EXPOS, to calculate the exposure in the biosphere.

This report describes the input parameters for the EXPOS module. In EXPOS the dose is calculated by multiplying the flux of a radionuclide to the biosphere, calculated by MASCOT, by the appropriate dose conversion factor [PROSA93]. The parameters required in EXPOS are therefore nuclide-dependent dose conversion factors. Two types of biospheres can be distinguished in the various selected scenarios for the safety assessment [PROSA93]. In the first, where the radionuclides move gradually with the groundwater through the geosphere, the radionuclides enter the biosphere via discharge into a river. Exposure of humans to radionuclides occurs in this type of biosphere via the use of the river water. As probabilistic calculations are done, distributions of the dose conversion factors are determined. When entry is via the groundwater, the resulting individual dose rate (in Sv a^{-1}) is calculated in EXPOS by multiplying the flux of a radionuclide to the biosphere (in Bq a^{-1}) by the dose conversion factor for the radionuclide. The dose conversion factor in EXPOS for this type of biosphere is in (Sv a^{-1})(Bq a^{-1})$^{-1}$. The values of this dose conversion factor are determined using the environmental transfer model MiniBIOS [Ma91,Ui93]. In Chapter 2 a description of the biosphere used is given. A short description of MiniBIOS and the values or distributions of the input parameters of MiniBIOS used in the calculations of the dose conversion factors are given in Chapter 3. In Chapter 4 the calculated dose conversion factors are described. The most important sources of uncertainty in the calculated dose conversion factors are determined in Chapter 5. In Chapter 6 the influence of different release points on the dose conversion factors is indicated.

In the second type of biosphere, the radionuclides can reach the biosphere through a geological upward movement of the repository field (diapirism). The biosphere consists of a salt desert in which vegetation is assumed to be absent. Therefore, a second set of dose conversion factors is calculated for EXPOS. Because the concentration in the repository field is known as it reaches the surface, the dose conversion factors are given in $(\mathrm{Sv\ a^{-1}})(\mathrm{Bq\ m^{-3}})^{-1}$ instead of $(\mathrm{Sv\ a^{-1}})(\mathrm{Bq\ a^{-1}})^{-1}$. To determine this set of dose conversion factors a simple exposure model for external radiation and inhalation was developed. Chapter 7 describes the calculation of this set of dose conversion factors.

Finally, conclusions and recommendations are given in Chapter 8.

2 THE BIOSPHERE

In the calculation of radiation doses to humans for long-term safety assessments several difficulties arise. Human behaviour affects to a great extent the biosphere and the transport and accumulation of radionuclides in the environment, along with the various exposure pathways. On the time scales involved in a safety assessment of the disposal of radioactive waste, predictions on human behaviour are speculative. Hence, defining a biosphere to be used for these assessments is hardly possible. It is therefore generally accepted that biosphere calculations are to be interpreted as an indication of possible radiation levels in the future, rather than as a prediction [BIOMOVS92]. Since it is not possible to predict the development of humankind, the level of technology of human populations is assumed equal to the current level of technology [BIOMOVS92].

Possible release points of the radionuclides in the biosphere are a river, a well, a lake or a sea as the dose conversion factors are calculated for a generic site and in the geohydrological model a pressure gradient due to the withdrawal of groundwater in the biosphere is assumed [PROSA93]. We chose a terrestrial release position because the dose conversion factors for a release in a sea will be less in respect to the other release positions due to the strong dilution in a sea [Kö89]. It is difficult to select a proper terrestrial release position because the salt concentration of the groundwater and the area in which the groundwater is discharged, are not known. To ensure that the groundwater can be used for agricultural purposes and drinking water, the groundwater should be strongly diluted. Because of these uncertainties we chose to release the radionuclides in a river. A well assumes a local contamination and a low concentration of salt in the groundwater and we are not sure wether these conditions are satisfied. It is possible that the water of the well is too salty due to the discharge of saline groundwater and that the radionuclides are not only released in the well. We assumed that for release in a river the area of the biosphere in which the radionuclides are released and the salt concentration of the groundwater will have less effect. Possible effects of different release points are described in Chapter 6.

For the calculation of the dose conversion factors the same biosphere as in the preceding project VEOS [Kö89] is used. The biosphere consists of a river with adjacent agricultural land. Radionuclides enter the biosphere through the discharge of contaminated groundwater into the river. The river water is used both for drinking and irrigation. Radiation doses are calculated for a farmer who consumes only the produce of his own land. We assumed that the use of the land for agricultural purposes is with respect to other possible options, like the production of bricks or wood, one of the most conservative. Town-dwellers will receive, at most, a comparable dose if all food and drinking water is contaminated. Exposure pathways included are the ingestion of water, fish, vegetables, meat and milk, the inhalation of resuspended soil particles and external radiation (Figure 2.1). The consumption pattern is assumed to resemble the present-day average consumption pattern of an adult. To minimize the influence of human behaviour, we decided to take the consumption pattern deterministically into account. Features, Events and Processes (FEP) included in the calculations of the dose conversion factors are described in [PROSA93].

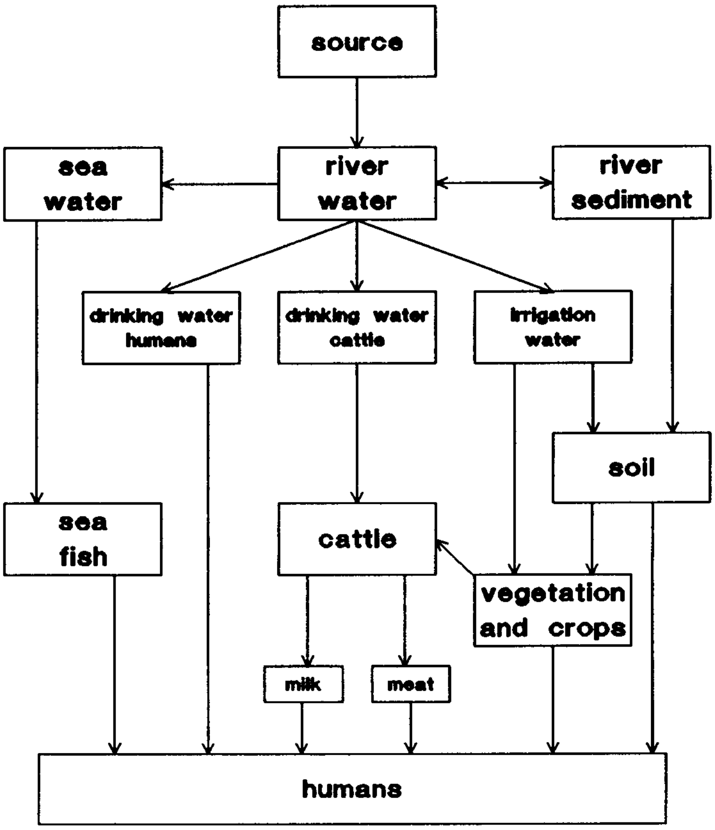

Figure 2.1 Overview of the exposure pathways included.

For the calculation of the dose conversion factors for EXPOS the dynamic environmental transfer model MiniBIOS [Ui93] is used. The radiation dose depends on the time period of the model calculation, since the radionuclides accumulate in the soil with time, whereas the required dose conversion factors for EXPOS are constant with time. This problem may for instance be resolved by assuming steady-state conditions. Equilibrium values of the radionuclides in the soil are then used to calculate the radiation dose. When radionuclides with long-lived daughter radionuclides, like U-238, are released, equilibrium is only reached after very long time scales. However, it is unlikely that the same area of land will be irrigated and used for agricultural purposes for millions of years. It has therefore been decided to define the dose conversion factors for EXPOS as the radiation dose to humans following a fixed time period of accumulation in the soil. Based on the occurrence of glaciation periods in the Netherlands, once in 100,000 years [PROSA93], a time period of constant conditions was chosen one order lower, i.e. 10,000 years.

3 MINIBIOS AND THE INPUT PARAMETERS

The dose conversion factors (Sv a^{-1})(Bq $a^{-1})^{-1}$ for release in a river are calculated with the model MiniBIOS (version MiniBIOS_1A4) [Ui93,Ma91]. In Section 3.1, a short description of MiniBIOS [Ui93] is given. The parameters used in the calculations of the dose conversion factors are given in Section 3.2.

3.1 Description of MiniBIOS

MiniBIOS is a biosphere transport model developed to calculate the dose to individuals due to the release of radionuclides from the disposal of radioactive waste. The model incorporates a linked chain of terrestrial compartments, each comprising river water, sediments, soil boxes and biota, and a simple ocean model. The river is subdivided into sequentially connected compartments and flows towards a sea compartment. Activity is interchanged between the boxes through a variety of processes. The code calculates the radionuclide concentrations in the various compartments as a function of time.

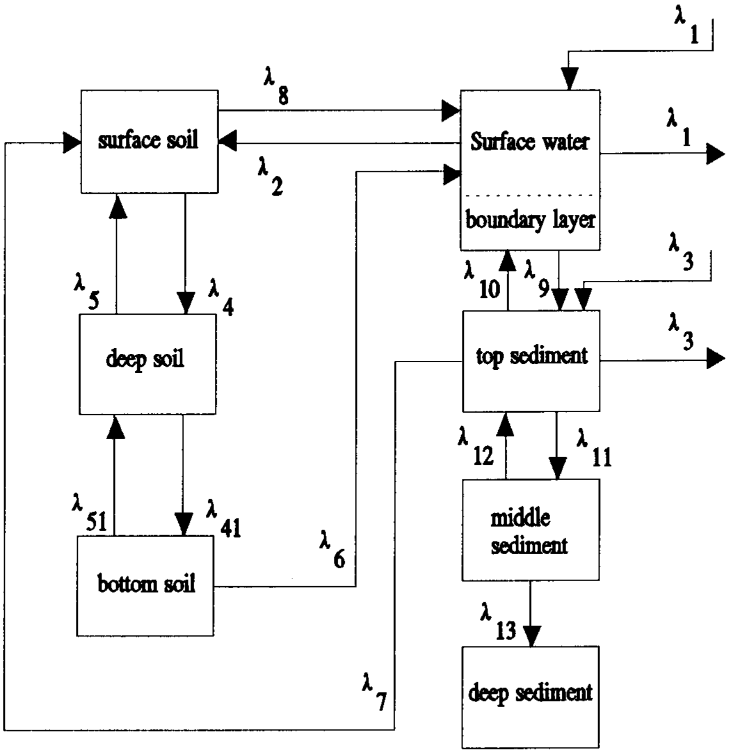

Figure 3.1 Structure of the terrestrial compartment in MiniBIOS.

The individual dose is calculated for various exposure pathways from the concentrations in the surface water, surface soil and marine water. The dose due to ingestion includes the intake of drinking water, milk, cereals, leafy vegetables, root vegetables, meat, freshwater fish and seafood. Inhalation pathways include the inhalation of resuspended soil or beach sediment and seaspray. External exposure is due to gamma emissions of contaminated soil.

Figure 3.1 shows the structure of a terrestrial compartment. Each transfer coefficient (λ) quantifies the processes which govern the exchange between the boxes. Table 3.1 gives the processes included in the transfer coefficients.

Table 3.1 Processes included in the transfer coefficients

λ_1	river flow
λ_2	irrigation with river water
λ_3	sediment flow
λ_4	infiltration of rain and irrigation water, bioturbation and diffusion
λ_{41}	infiltration of rain and irrigation water, diffusion
λ_5	diffusion and bioturbation
λ_{51}	diffusion and upwards groundwater flow
λ_6	groundwater flow towards the river
λ_7	sediment transport to land by flooding and dredging
λ_8	erosion
λ_9	sedimentation, bioturbation and diffusion
λ_{10}	diffusion and bioturbation
λ_{11}	diffusion and (only in a lake) burial by continued sedimentation
λ_{12}	upward transport in the sediment by diffusion
λ_{13}	burial by continued sedimentation (only in a lake)

3.2 Parameters used in the calculations of the dose conversion factors

The total number of parameters in the MiniBIOS model is 134. Taking all these parameters stochastically into account would require a large calculational effort. Furthermore, it was not worthwhile to put a large research effort into the determination of distributions of parameters, not important to the model results. Therefore it was decided in an early phase to identify those parameters, that are sensitive and/or important sources of uncertainty. Using a preliminary set of data and version of MiniBIOS (version MiniBIOS_1A2), a sensitivity analysis was carried out. From this analysis it was concluded that twenty-nine parameters have a significant influence on the dose conversion factors. For these parameters improved distributions were determined.

Most parameter values are derived from several sources found in the literature. Parameters describing river dimensions, river properties and the climate or parameters dependent on climate, for example, the irrigation rate and yields of vegetables, are as much as possible adapted to the present situation in the Netherlands. Because we used a generic description of the biosphere the parameter values were not screened for specific biosphere conditions (for example, soil types). If no value for a parameter was found in the literature or the parameter is assumed to be of no importance, the default value [Ma91] was taken. For some parameters we assumed a value or distribution having found no useful values in the literature. Parameters describing the biosphere dimensions, the transport pathways, and the various exposure pathways are subsequently given in Table 3.2, Table 3.3 and Table 3.4. Parameters of MiniBIOS which are only included in exposure pathways not taken into account in the dose conversion factors will not be described.

Table 3.2 Parameters describing the biosphere dimensions (alphabetical order)

parameter	description	value or distribution used
A	Area of contaminated land (m^2). We assumed that at each side of the river 250 m is available for agricultural purposes. The river length is 10 km. The area of contaminated land is therefore 5.0e+06 m^2.	5.0e+06
l_b	Depth of freshwater boundary layer (m). The depth of the freshwater boundary layer is 0.1 m [Ma91].	1.0e-01
l_c	Length of local marine coast (m). We assumed a length of 50 km.	5.0e+04
l_{ds}	Depth of deep soil (m). We assumed that the total depth of the surface soil and the deep soil is equal to the depth of the rooting zone of crops, i.e. 0.8 m [Sc92]. As a result, the deep soil layer is 0.5 m.	5.0e-01
l_{mb}	Depth of marine boundary layer (m). We assumed a depth of 5.0 m.	5.0e+00
l_{ms}	Depth of middle sediment layer (m). The depth of the middle sediment layer is 1.9 m [Ma91].	1.9e+00
l_{mms}	Depth of middle marine sediment layer (m). The depth of the marine middle sediment layer is 1.9 m [Ma91].	1.9e+00
l_{mw}	Depth of marine boxes (m). The depth of the local marine box (10 m) is equal to the average depth of the North Sea in the first 10 km from the coast [Wo81]. The depth of the second marine box is 20 m (assumption).	1.0e+01 (local sea), 2.0e+01 (sink)
l_r	Length of river section (m). We chose equal to the preceding project VEOS [Kö89] a length of 10 km.	1.0e+04

parameter	description	value or distribution used
l_{ss}	Depth of surface soil (m). The depth of the surface soil is equal to the depth of a furrow (0.3 m) [Ma91].	3.0e-01
l_{ts}	Depth of top sediment layer (m). The depth of the top sediment layer is 0.1 m [Ma91].	1.0e-01
l_{us}	Depth of marine top sediment layer (m). The depth of the marine top sediment layer is 0.1 m [Ma91].	1.0e-01
l_w	Depth of river (m). The assumed distribution includes most of the common rivers of the Netherlands. Of these, 75% are assumed to be small, 20% of a moderate size (IJssel) and 5% of a size comparable to that of the Rhine or Meuse. Small rivers: Witte Wijk, 2.50 m, Stadscompascuumkanaal, 2.20 m, Noord Willemskanaal 2.30 m [RW65]. Moderate rivers: IJssel, 4.30 m [RW92,DGW91]. Large rivers: Rhine, 6 m [RW92,DGW91]. We assumed the depth of the river to be strongly correlated to the volumetric flow (F) and the volume of the river compartment (V).	Histogram: 75%: 2.0 3.0 20%: 3.0 5.0 5% : 5.0 6.0 Correlation with: F : 0.9 V : 0.9
N_{ter}	Number of terrestrial compartments: Only one terrestrial compartment is needed as the width and depth of the river are chosen to be constant for its entire length.	1
N_{mar}	Number of marine compartments: There are two marine compartments included. The first marine box is a local sea. The second box acts only as a sink.	2
P_{rel}	Source position: As the radionuclides are released in a river, $P_{rel} = 1$ [Ma91].	1
V	Volume of a river compartment (m^3). The assumed distribution includes most of the common rivers of the Netherlands. Of these, 75% are assumed to be small, 20% of a moderate size (IJssel) and 5% of a size comparable to the Rhine or Meuse. Width of small rivers (m): Witte Wijk, 13 -16 m, Stadscompascuumkanaal, 13 -15 m, Noord Willemskanaal, 16 m [RW65]. Width of moderate rivers (m): IJssel 75 - 165 m. Width of large rivers: Upper Rhine and Waal 250 - 350 m, Pannerdensch kanaal, Lower Rhine, Lek 100 - 225 m [RW92] As a result it is assumed that 75% of the rivers has a width of 10-25 m, 20% 25-100 m and 5% 100-300 m. For the assumed depth of the rivers, see l_w. The length of a river compartment is 10 km, see l_r. We assumed the volume of the river to be strongly correlated to the volumetric flow (F) and depth of the river (l_w).	Histogram: 75% 2.0e+5 7.5e+5, 20% 7.5e+5 5.0e+6, 5% 5.0e+6 1.8e+7 Correlation with: l_w : 0.9 F : 0.9

parameter	description	value or distribution used
V_m	Volume of marine boxes (m^3). The volume of the local marine box is 5.0e+09 m^3 ($l_c \cdot l_w \cdot W$). The second marine box is chosen to be 10^6 times the volume of the local box, i.e. 5.0e+15 m^3, to ensure its function as a sink.	5.0e+09 (local sea), 5.0e+15 (sink)
W	Width of local marine box (m). The width of the local marine box is chosen to be 10 km.	1.0e+04

Table 3.3 Parameters included in biosphere transport pathways (alphabetical order)

parameter	description	value or distribution used
B	Bioturbation coefficient in soil ($m^2\ a^{-1}$). In MiniBIOS bioturbation is handled as a diffusion process [Ui93]. The bioturbation of earthworms is 0.5 - 10 kg soil $m^{-2}\ a^{-1}$ [Bi89]. The corresponding bioturbation coefficient is 10^{-4} - $2x10^{-3}$ $m^2\ a^{-1}$. Between these values a loguniform distribution is chosen.	Loguniform: 1.0e-4 2.0e-3
B_{ms}	Bioturbation coefficient in shallow seas ($m^2\ a^{-1}$). The default value is chosen [Ma91].	3.16e-05
B_{md}	Bioturbation coefficient in deep seas ($m^2\ a^{-1}$). The default value is chosen [Ma91].	3.16e-08
B_r	Bioturbation coefficient in freshwater sediment ($m^2\ a^{-1}$). $3.16x10^{-5}$ [Ma91]. A normal distribution with mean 3.16e-05 and variance 6.2e-11 (standard deviation 25% of mean) is chosen.	Normal: mean: 3.16e-05 variance: 6.2e-11
D	Diffusion coefficient in soil ($m^2\ a^{-1}$). 5.0e-3 [Ma91], 6.0e-2 [Ma90], 1.95e-2 2.9e-1 (water) [Ke86]. $D = \frac{D_{water}}{\tau}$ [0m88] The tortuosity (τ), which is not very different for different soils, is 2.6 [Om88]. The chosen distribution is loguniform between 7.5e-3 and 1.1e-1 $m^2\ a^{-1}$.	Loguniform: 7.5e-3 1.1e-1
D_m	Marine diffusion coefficient ($m^2\ a^{-1}$). The default value is chosen for both compartments [Ma91].	3.15e-02
D_r	Diffusion coefficient in freshwater ($m^2\ a^{-1}$). $3.15x10^{-2}$ $m^2\ a^{-1}$ [Ma91], 1.95e-2 - 2.9e-1 $m^2\ a^{-1}$ [Ke86]. A loguniform distribution between 1.95e-2 and 2.9e-1 is chosen.	Loguniform: 1.95e-2 2.9e-1

parameter	description	value or distribution used
D_s	Diffusion coefficient in sediment ($m^2\ a^{-1}$). 5.0e-3 [Ma91], 6.0e-2 [Ma90], 1.95e-2 2.9e-1 (water) [Ke86]. $D_s = \frac{D_{water}}{\tau}$ [0m88] The tortuosity (τ), which is not very different for different soils, is 2.6 [Om88]. The chosen distribution is loguniform between 7.5e-3 and 1.1e-1 $m^2\ a^{-1}$.	Loguniform: 7.5e-03 1.1e-01
E_{ss}	Erosion rate ($m\ a^{-1}$). In the Netherlands, erosion is only of importance in the southeast [Kw92]. We assumed that there is no net heightening of the soil by the transfer of sediment to land, therefore, the distribution for the erosion rate is equal to the distribution of the heightening of the soil (S). The erosion rate is strongly correlated to the heightening of the soil (S).	Uniform: 0.0 1.0e-03 Correlation with: S : 0.99
F	Volumetric flow ($m^3\ a^{-1}$). The assumed distribution includes most of the common rivers of the Netherlands. Of these, 75% are assumed to be small, 20% of a moderate size (IJssel) and 5% of a size comparable to that of the Rhine or Meuse. Small rivers: Drentsche Aa 9.21e+7 [WGO75]. Geul 3.2e+7-9.5e+7 [Le91]. Moderate rivers: IJssel (Olst) 1.00e+10 [DGW91] Large rivers: Rhine (Lobith) 6.33e+10 [DGW91] We assumed the volumetric flow to be strongly correlated to the depth of the river (l_w) and the volume of the river compartment (V).	Histogram: 75% 1.0e+7 1.0e+8 20% 1.0e+8 1.0e+10 5% 1.0e+10 1.0e+11 Correlation with: l_w : 0.9 V : 0.9
f_{desorb}	Fraction desorbed in estuary (-). No desorption is assumed.	0.0
I_i	Irrigation rate ($m\ a^{-1}$). The sum of the infiltrated rain and irrigation rate has to be minimally equal to the evaporation rate of the crops used (pasture 540 mm a^{-1}, winter corn 380 mm a^{-1}, summer barley 300 mm a^{-1}, potatoes 200-370 mm a^{-1}, beet 450 mm a^{-1} [Kr71]). As the infiltrated rainfall is 300-400 mm a^{-1}, see r, only pasture should be irrigated. In the study of the area of Gorleben (Germany) [Ja85] the irrigation rates used are: leafy vegetables 120 mm a^{-1}, potatoes 80 mm a^{-1} and cereals 50 mm a^{-1}. In [Ko90] the irrigation rate is equal to 1 mm d^{-1} in the growing season (150 mm a^{-1}). As the contaminated area will not be used for the same crop for 10,000 years, it is chosen to take a uniform distribution between 50 and 150 mm a^{-1}. We assumed the irrigation rate to be strongly negatively correlated to the infiltrated rainfall (r).	Uniform: 5.0e-2 1.5e-01 Correlation with: r : -0.99

parameter	description	value or distribution used
K_d	Soil distribution coefficient (Bq t^{-1})(Bq m^{-3})$^{-1}$. The values for the distribution coefficients are taken from several references. Between the maximum and minimum value a loguniform distribution is chosen. The uncertainty in the distribution coefficients is high because of a strong natural variability and experimental uncertainty in the determination [Ha85].	Appendix A
K_{dd}	Deep marine distribution coefficient (Bq t^{-1})(Bq m^{-3})$^{-1}$. In [IAEA82] no difference is made between the shallow and deep marine distribution coefficient. Therefore, the values for the deep marine distribution coefficient are equal to the values for the shallow marine distribution coefficient.	Appendix B
K_{dm}	Shallow marine distribution coefficient (Bq t^{-1})(Bq m^{-3})$^{-1}$. The shallow marine distribution coefficient is determined from [IAEA82]. For Molybdenum (Mo) no value is available, as in [Ma90] the same value is taken as for Technetium (Tc).	Appendix B
K_{sr}	Distribution coefficient in freshwater (Bq t^{-1})(Bq m^{-3})$^{-1}$. The values for the distribution coefficients are taken from several references. Between the maximum and minimum value a loguniform distribution is chosen. The uncertainty in the distribution coefficients is high because of a strong natural variability and experimental uncertainty in the determination [Ha85].	Appendix A
r	Infiltrated rainfall (m a^{-1}). In the Netherlands the infiltrated rainfall is 0.3 - 0.4 m a^{-1} [COR].	Uniform: 0.3 0.4
S	Heightening of soil by river sediment (m a^{-1}). Extreme values for the Netherlands are 0.4 to 1.4 cm a^{-1} [Le91]. It is assumed that such values will not occur continuously during a period of 10,000 years, the time period of release. Therefore, a uniform distribution between 0 and 10^{-3} m a^{-1} is chosen.	Uniform: 0.0 1.0e-03 Correlation with: E_{ss} : 0.99
S_m	Sedimentation rate in marine boxes (t m^{-3} a^{-1}). The sedimentation rate for the coast of the Netherlands is $2x10^{-5}$ t m^{-3} a^{-1} [WeEc84]. This value is chosen for both compartments.	2.0e-05
v_g	Groundwater velocity (m a^{-1}). For the groundwater velocity several estimates are given: $3x10^{-4}$ [Ma91]. Clay 10^{-5} - 0.2 [Sl92]. We chose the highest value.	0.2
$V_{m,out}$	Flow from local sea to second marine compartment (m^3 a^{-1}). The net-residual current velocity along the coast of the Netherlands in northern direction is 0.05 m s^{-1} [Pa86,WeEc84]. With the dimensions of the local sea, the flow is $1.58x10^{11}$ m^3 a^{-1}.	1.58e+11
$V_{m,in}$	Flow from second marine compartment to local sea (m^3 a^{-1}). This flow is equal to the flow from the local sea towards the second marine compartment, $V_{m,out}$.	1.58e+11

parameter	description	value or distribution used
v_{sed}	Sediment velocity (m a^{-1}). 200 m a^{-1} [Ma91]. In [Ma90] values for Belgium rivers are given: Neet 820 m a^{-1}, Rupel 977 m a^{-1}, Scheldt 1550 m a^{-1}. A uniform distribution is chosen between 200 and 1500 m a^{-1}.	Uniform: 2.0e+02 1.5e+3
α_{m}	Marine suspended sediment load (t m^{-3}). The suspended sediment load in the western Wadden Sea is $4\mathrm{x}10^{-5}$ t m^{-3}, in the North Sea 10^{-5} t m^{-3} [DGW91].	4.0e-05 (local sea), 1.0e-05 (sink)
α_{r}	Suspended sediment load in freshwater (t m^{-3}). The suspended sediment load in Rhine and Meuse is 10^{-5}-$5\mathrm{x}10^{-5}$ t m^{-3} [DGW91]. In smaller rivers like the Rupel and Nete (Belgium) the suspended sediment load is $2\mathrm{x}10^{-5}$-$5\mathrm{x}10^{-5}$ t m^{-3} [Ma90]. A uniform distribution is chosen between 10^{-5} and $5\mathrm{x}10^{-5}$ t m^{-3}.	Uniform: 1.0e-5 5.0e-5
θ	Angle of groundwater flow (degrees). 10^{-5}-10^{-3} [Sl92]. The highest value is chosen.	1.0e-03
κ	Schaeffer sedimentation (m^{-1}). The Schaeffer sedimentation is determined for a point source [NRPB79]. It depends on the freshwater distribution coefficient, K_{sr}. K_{sr} 0 - 10^3 $\kappa = 0.0$ K_{sr} 10^3 - 10^4 $\kappa = 2.0\mathrm{x}10^{-6}$ K_{sr} $> 10^4$ $\kappa = 10^{-5}$ From the minimum and maximum value of the distribution of K_{sr}, the boundaries of the range of κ are determined. Between these boundaries a loguniform distribution is chosen. The Schaeffer sedimentation is strongly correlated to the freshwater distribution coefficient.	Depends on K_{sr}. Correlation with: K_{sr}: 0.99
λ	Decay constant (s^{-1}). The decay constants of the radionuclides are well-known. They are determined from the half-life of the radionuclides [ICRP83].	Appendix B
ρ	Dry bulk soil density (t m^{-3}). The range between different soils is 1.0 - 1.6 t m^{-3} [Lo87].	Uniform: 1.0 1.6
ρ_{m}	Mineral density of marine sediments (t m^{-3}). The default value is chosen [Ma91].	2.6e+00
ρ_{s}	Mineral density of river sediments (t m^{-3}). 2.60 t m^{-3} [Ma91], 2.55 - 2.65 [Sl92]. A uniform distribution between 2.55 and 2.65 is chosen.	Uniform: 2.55 2.65
φ_{fs}	Porosity of freshwater sediments (-). 0.40 - 0.60 [Sl92], 0.75 [Ma91]. A uniform distribution between 0.5 and 0.8 is chosen.	Uniform: 0.5 0.8
φ_{m}	Porosity of marine sediments (-). The default value is chosen [Ma91].	7.5e-01
φ_{s}	Soil porosity (-). 0.25-0.35 (fine sand), 0.30-0.40 (clay) [Sl92], 0.35-0.45 [La79]. A uniform distribution is chosen between 0.25 and 0.45.	Uniform: 0.25 0.45

Table 3.4 Parameters included in the various exposure pathways included in the calculations of the dose conversion factors (alphabetical order)

parameter	description	value or distribution used
A_{drink}	Fraction of animal drinking water affected (-). We assumed that all drinking water is contaminated.	1.0e+00
a_{dust}	Dust level (t m^{-3}). The same value as in VEOS [Kö89] is chosen: $1.4x10^{-11}$. For the present situation in the Netherlands the value used is low [Me87].	1.4e-11
D_{ing}	Dose factor for ingestion (Sv Bq^{-1}). The dose factors for ingestion for an adult are taken from [No85]. They are in accordance with ICRP-30 [ICRP82]. If more than one value is available for a nuclide, the highest value is chosen.	Appendix B
D_{inh}	Dose factor for inhalation (Sv Bq^{-1}). The dose factors for inhalation for an adult are taken from [No85]. They are in accordance with ICRP-30 [ICRP82]. If more than one value is available for a nuclide, the highest value is chosen.	Appendix B
$E_p(i)$	Sum of probabilities for γ- or X-ray disintegration in energy bands (-). The sum of the probabilities for γ- or X-ray disintegration in each energy band included is determined from [ICRP83]. It is a well-known parameter and therefore taken deterministically into account in the calculations of the dose conversion factors. The energy bands (MeV) included are: 0.010 0.015 0.020 0.030 0.050 0.100 0.200 0.500 1.000 1.500 2.000 4.000 The determined probability for a specific energy is proportionally divided over the nearest bands [Ui93]. If the energy of the γ or X-ray disintegration is lower than 0.010 MeV or higher than 4.00 MeV, the probability is totally assigned to the boundary of 0.010 MeV, 4.00 MeV respectively. The contribution of short-lived daughters is included.	Appendix C
F_{be}	Fraction of the daily intake retained in meat (Bq kg^{-1})(Bq $d^{-1})^{-1}$. The values are taken from several references. Between the maximum and minimum value a loguniform distribution is chosen.	Appendix D
F_{li}	Fraction of the daily intake retained in liver (Bq kg^{-1})(Bq $d^{-1})^{-1}$. The values are taken from several references, and chosen to be equal to the factors for meat, F_{be}. Between the maximum and minimum value a loguniform distribution is chosen.	Appendix D
F_{mi}	Fraction of daily intake retained in milk (Bq kg^{-1})(Bq $d^{-1})^{-1}$. The values are taken from several references. Between the maximum and minimum value a loguniform distribution is chosen.	Appendix D
f_{gv}	Fraction remaining after processing green vegetables (-). We assumed that all radionuclides remain during processing.	1.0e+00
f_{ce}	Fraction remaining after processing cereals (-). We assumed that all radionuclides remain during processing.	1.0e+00
H_{ce}	Harvesting rate cereals (a^{-1}). The default value is chosen, 1.0 [Ma91]	1.0e+00
H_{gv}	Harvesting rate green vegetables (a^{-1}). The default value is chosen, 1.0 [Ma91].	1.0e+00

parameter	description	value or distribution used
H_{rv}	Harvesting rate root vegetables (a^{-1}). The default value is chosen, 1.0 [Ma91]	1.0e+00
I_b	Consumption of meat (kg a^{-1}). We assumed that humans only consume meat from cattle. The total consumption per year is assumed to be 40 kg (± 100 g d^{-1}).	4.0e+01
I_{ce}	Consumption of cereals (kg a^{-1}). The present situation in the Netherlands is chosen: 58 kg a^{-1} [Ve90].	5.8e+01
I_{ff}	Consumption of freshwater fish (kg a^{-1}). The consumption of fish in the Netherlands is 6.0 kg a^{-1} [Ve90]. We assumed that one-third is freshwater fish.	2.0e+00
I_{gv}	Consumption of green vegetables (kg a^{-1}). The present situation in the Netherlands is chosen: 96.0 kg a^{-1} [Ve90].	9.6e+01
I_{inh}	Inhalation rate of air (m^3 a^{-1}). For light work, ICRP-30 [ICRP82] assumes an inhalation rate of 1.2 m^3 h^{-1}.	1.0e+04
I_{li}	Consumption of liver (kg a^{-1}). It is assumed that liver is only eaten occasional. The total consumption per year is assumed to be 1 kg.	1.0e+00
I_{mf}	Consumption of marine fish (kg a^{-1}). The consumption of fish in the Netherlands is 6.0 kg a^{-1} [Ve90]. We assumed that two-thirds are marine fish.	4.0e+00
I_{mi}	Consumption of milk (kg a^{-1}). The present situation in the Netherlands is chosen: 125-138 kg a^{-1} [Jo90], 166 kg a^{-1} [Ve90]. The highest value is chosen.	1.66e+02
I_{pa}	Consumption of dry pasture by cattle (kg d^{-1}). 12 kg d^{-1} [Ma91], 14 kg d^{-1} [Ma90]. The highest value is chosen.	1.4e+01
I_{rv}	Consumption of root vegetables (kg a^{-1}). The present situation for the consumption of potatoes in the Netherlands is chosen: 75-100 kg a^{-1} [Jo90].	8.0e+01
I_w	Consumption of freshwater (m^3 a^{-1}). Humans are assumed to drink 2.0 l d^{-1}.	7.5e-01
I_{wa}	Water drunk by animals (m^3 d^{-1}). The total need of water of cattle is 0.03-0.15 m^3 d^{-1} [Pe84]. The mean value, i.e. 0.09 m^3 d^{-1} is chosen. The water content in pasture is 83% (Z = 5.7) and as the consumption of dry pasture (I_{pa}) is 14 kg d^{-1}, the total intake of water via pasture is 0.066 m^3 d^{-1}. The intake of water should therefore be 0.024 m^3 d^{-1}.	2.4e-02

parameter	description	value or distribution used
K_{ce}	Concentration factor of cereals (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$ The values are taken from several references. If the values are based on the dry weight of cereals the conversion factor is 1.1 [Ba84]. Between the maximum and minimum value a loguniform distribution is chosen. Remark: The concentration factors and the soil distribution coefficients are correlated. This is not included in the calculations because the concentration factors and distribution coefficients are determined from independent data sets.	Appendix D
K_{ff}	Concentration factor of freshwater fish (Bq t^{-1})(Bq m^{-3})$^{-1}$. The values are taken from several references. A loguniform distribution is chosen between the maximum and minimum value.	Appendix D
K_{gv}	Concentration factor of green vegetables (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight soil)$^{-1}$. The values are taken from several references. If the values are based on the dry weight of green vegetables the conversion factor is 8.30 [IAEA93]. Between the maximum and minimum value a loguniform distribution is chosen. Remark: The concentration factors and the soil distribution coefficients are correlated. This is not included in the calculations because the concentration factors and distribution coefficients are determined from independent data sets.	Appendix D
K_{mf}	Concentration factor marine fish (Bq t^{-1})(Bq m^{-3})$^{-1}$. The concentration factors of marine fish are determined from [Kö89].	Appendix B
K_{pa}	Concentration factor of pasture (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$ The values are taken from several references. If the values are based on the dry weight of pasture the conversion factor is 5.70 [Ba84]. Between the maximum and minimum value a loguniform distribution is chosen. Remark: The concentration factors and the soil distribution coefficients are correlated. This is not included in the calculations because the concentration factors and distribution coefficients are determined from independent data sets.	Appendix D
K_{rv}	Concentration factor of root vegetables (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$ The values are taken from several references. If the values are based on the dry weight of root vegetables the conversion factor is 4.50 [Ba84]. Between the maximum and minimum value a loguniform distribution is chosen. Remark: The concentration factors and the soil distribution coefficients are correlated. This is not included in the calculations because the concentration factors and distribution coefficients are determined from independent data sets.	Appendix D

parameter	description	value or distribution used
N_{cattle}	Density of cattle (km^{-2}). The present situation in the Netherlands is chosen: 200 [Pe84].	2.0e+02
S_a	Soil uptake by cattle as fraction of dry pasture uptake (-). 0.04 [Ma90,Ma91].	4.0e-02
S_{ce}	Soil contamination on cereals as fraction of wet weight (-). 9.0x10^{-5} [Ma91]. Corn 1.4x10^{-3} (dry weight), cereal 4.8x10^{-3} (dry weight) [Pi89]. We assumed a dry weight fraction of 83% [CBS91] for cereals → corn 1.0x10^{-3}, cereal 4.2x10^{-3}. We chose the mean value: 2.6x10^{-3}.	2.6e-03
S_{gv}	Soil contamination on green vegetables as fraction of wet weight (-). cabbage 1.1x10^{-3} (dry weight), lettuce 2.6x10^{-4} (dry weight) [ML84]. We assumed a dry weight fraction of 25% for green vegetables → cabbage 2.8x10^{-4}, lettuce 6.5x10^{-4}. 2.0x10^{-4} [Ma91]. We chose as value 4.0x10^{-4}.	4.0e-04
T_{exin}	Transfer from external to internal in root vegetables (a^{-1}). The values used are determined from references [Ma90,Kö89].	Appendix B
t_{soil}	Conversion factor for external radiation for radionuclides homogeneously distributed in a 30 cm deep soil layer for discrete energy bands (Sv s^{-1})(Bq m^{-3})$^{-1}$. The energies (MeV) of the various bands are: 0.010 0.015 0.020 0.030 0.050 0.100 0.200 0.500 1.000 1.500 2.000 4.000 The values used are determined from [Ba92].	Appendix C
W_{ce}	Weathering rate cereals (a^{-1}). 18.1 [Ma90], 17.98 [Ba84,Ko90] for all radionuclides except for I, 31.55	17.98, except for I: 31.55
W_{gv}	Weathering rate green vegetables (a^{-1}). 18.1 [Ma90], 17.98 [Ba84,Ko90] for all radionuclides except for I, 31.55	17.98, except for I: 31.55
W_{pa}	Weathering rate pasture (a^{-1}). 18.1 [Ma90], 17.98 [Ba84] for all radionuclides except for I, 31.55	17.98, except for I: 31.55
W_{rv}	Weathering rate root (a^{-1}). 18.1 [Ma90], 17.98 [Ba84,Ko90] for all radionuclides except for I, 31.55	17.98, except for I: 31.55
Y_{ce}	Yield of cereals (wet weight) (kg m^{-2}). The present situation in the Netherlands is chosen: 0.7 [CBS91].	7.0e-01
Y_{gv}	Yield of green vegetables (wet weight) (kg m^{-2}). The present situation in the Netherlands is chosen: 3.8 [LEI86].	3.8e+00
Y_{pa}	Yield of pasture (dry weight) (kg m^{-2}). The present situation in the Netherlands is chosen: 1.1 [CBS91].	1.1e+00
Y_{rv}	Yield of root vegetables (wet weight) (kg m^{-2}). The present situation in the Netherlands for potatoes is chosen [CBS91].	4.0e+00
Z	Weight of wet pasture equivalent to 1 kg dry pasture (-) 5.7 [Jo81], 5.0 [Ma91]. The highest value is chosen.	5.7e+00
μ_{ce}	Interception constant of cereals (m^2 kg^{-1}). 0.0846 [Ba84], 0.13 [Si82]. We chose the highest value.	1.3e-01

parameter	description	value or distribution used
μ_{gv}	Interception constant of green vegetables (m^2 kg^{-1}). 0.0846 [Ba84], 0.36 [Si82]. We chose the highest value.	3.6e-01
μ_{pa}	Interception constant of pasture (m^2 kg^{-1}). 2.88 [Ba84], 2.90 [Si82].	2.9e+00
μ_{rv}	Interception constant of root vegetables (m^2 kg^{-1}). 0.0846 [Ba84], 0.14 [Si82]. We chose the highest value.	1.4e-01

4 DOSE CONVERSION FACTORS

Distributions of the dose conversion factors (Sv a^{-1})(Bq a^{-1})$^{-1}$ are calculated for all radionuclides which may be released into the biosphere [PROSA93] with the model MiniBIOS_1A4 [Ui93]. Each distribution is a result of 400 individual runs which is sufficient to determine the distributions of the dose conversion factors (Figure 4.1). The distributions and values of the parameters used are described in Chapter 3. The stochastic parameter values are sampled from the distributions using Latin Hypercube Sampling [Ja91].

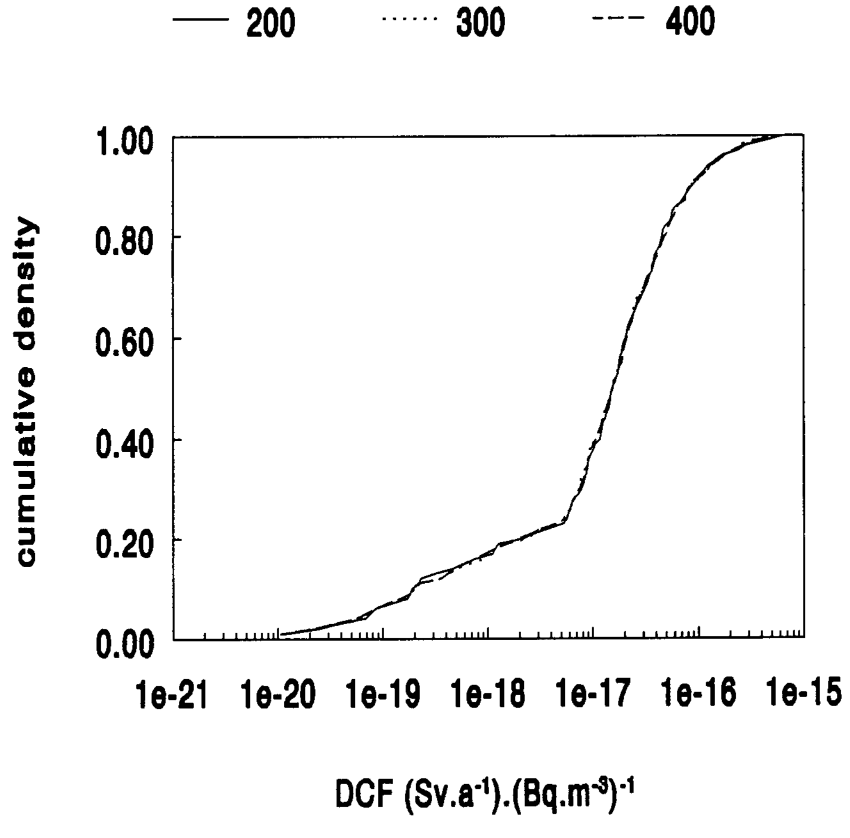

Figure 4.1 The effect of the number of runs (200, 300 and 400) on the cumulative density distribution of the dose conversion factor (DCF) of Tc-99.

Calculations were made for a continuous release of 1 Bq a^{-1} for 10,000 years. On this time scale the growth of daughter nuclides may be of importance. The decay chains taken into account are listed in Table 4.1 [Kö89], while for all other nuclides the dose of the nuclide itself is calculated.

Table 4.1 Decay chains used in the dose calculations

Cm-244	Cm-245	Cm-246	Cm-247	Cm-248	Am-242m
↓	↓	↓	↓	↓	↓
Pu-240	Pu-241	Pu-242	Am-243	Pu-244	Pu-238
↓	↓	↓	↓	↓	↓
U-236	Am-241	U-238	Pu-239	Pu-240	U-234
↓	↓	↓	↓	↓	↓
Th-232	Np-237	Th-234	U-235	U-236	Th-230
↓	↓	↓	↓	↓	↓
Ra-228	U-233	U-234	Pa-231	Th-232	Ra-226
↓	↓	↓	↓	↓	↓
Th-228	Th-229	Th-230	Ac-227	Ra-228	Pb-210
↓	↓	↓		↓	↓
Ra-224	Ra-225	Ra-226		Th-228	Po-210
	↓	↓		↓	
	Ac-225	Pb-210		Ra-224	
		↓			
U-232		Po-210			
↓					
Th-228					
↓					
Ra-224					

In Table 4.2, the calculated distributions are given in the format used for EXPOS [PROSA93]. Figure 4.2 gives some examples of calculated distributions. Type and range of the distributions are not equal for each nuclide because of differences in the distributions of the nuclide-specific parameters. For most nuclides the ratio of the minimum to the maximum value is 1000 to 100,000. The ratio of the 10 percentile to the 90 percentile, however, is usually less than 500.

Table 4.2 Percentile values of the calculated distributions

	percentile values of the dose conversion factors (Sv a^{-1})(Bq a^{-1})$^{-1}$						
nuclide	0	10	25	50	75	90	100
C-14	3.082e-19	2.785e-18	3.795e-17	1.921e-16	1.023e-15	2.396e-15	2.044e-14
Co-60	1.360e-18	3.313e-17	1.314e-16	3.014e-16	5.453e-16	8.602e-16	1.652e-15
Ni-59	1.900e-20	1.755e-19	6.288e-19	1.196e-18	2.091e-18	3.291e-18	8.204e-18
Ni-63	4.079e-20	3.177e-19	1.263e-18	2.800e-18	5.044e-18	8.498e-18	2.040e-17
Se-79	6.745e-19	1.953e-17	3.649e-16	1.521e-15	5.152e-15	1.154e-14	7.498e-14
Rb-87	6.180e-20	1.717e-18	4.212e-17	1.390e-16	2.626e-16	5.512e-16	2.223e-15
Sr-90	4.036e-19	9.821e-18	3.582e-16	8.744e-16	1.982e-15	4.273e-15	2.135e-14
Zr-93	4.684e-20	1.399e-18	3.895e-18	8.869e-18	2.189e-17	6.197e-17	7.151e-16

	percentile values of the dose conversion factors (Sv a^{-1})(Bq a^{-1})$^{-1}$						
nuclide	0	10	25	50	75	90	100
Mo-93	4.165e-21	7.853e-20	3.384e-18	7.092e-18	1.611e-17	3.121e-17	4.505e-16
Nb-94	2.520e-18	5.906e-17	1.646e-15	3.951e-15	7.761e-15	1.503e-14	5.843e-14
Tc-99	7.571e-21	1.913e-19	5.530e-18	1.561e-17	3.864e-17	8.524e-17	6.288e-16
Pd-107	6.647e-20	1.195e-18	2.692e-18	6.121e-18	1.439e-17	2.452e-17	6.082e-17
Sn-126	7.930e-16	6.351e-15	1.197e-14	2.067e-14	3.079e-14	4.229e-14	1.001e-13
AI-129	6.845e-19	9.613e-18	5.249e-16	9.224e-16	1.679e-15	3.002e-15	6.314e-15
I-129	6.845e-19	9.613e-18	5.249e-16	9.224e-16	1.679e-15	3.002e-15	6.314e-15
Cs-135	9.750e-20	8.930e-18	1.357e-16	7.839e-16	3.700e-15	1.286e-14	2.528e-13
Cs-137	5.421e-19	2.128e-17	3.626e-16	1.642e-15	4.810e-15	1.023e-14	5.797e-14
Sm-147	9.285e-18	4.223e-17	1.869e-16	4.660e-16	8.107e-16	1.399e-15	3.585e-15
Sm-151	7.445e-21	2.716e-20	1.885e-19	6.750e-19	1.316e-18	2.351e-18	6.397e-18
Eu-154	1.595e-17	1.121e-16	2.405e-16	5.094e-16	6.930e-16	8.769e-16	1.318e-15
Cm-248	1.332e-16	1.278e-15	7.453e-15	2.478e-14	4.287e-14	8.229e-14	2.207e-13
Pu-244	1.360e-16	2.723e-15	7.857e-15	2.396e-14	4.264e-14	7.156e-14	3.001e-13
Cm-244	3.876e-18	4.012e-17	6.104e-16	2.949e-15	5.058e-15	1.019e-14	2.707e-14
Pu-240	1.957e-17	1.458e-16	9.377e-16	2.170e-15	4.877e-15	1.432e-14	1.199e-13
U-236	5.038e-19	9.055e-18	2.844e-16	9.387e-16	1.592e-15	2.955e-15	7.144e-15
Th-232	4.868e-16	1.856e-14	4.444e-14	7.422e-14	1.214e-13	1.736e-13	7.880e-13
Ra-228	8.615e-18	6.236e-17	2.091e-15	6.056e-15	1.057e-14	2.031e-14	8.166e-14
Th-228	1.951e-18	2.175e-17	3.471e-16	1.326e-15	3.170e-15	5.428e-15	2.541e-14
Ra-224	1.017e-18	1.382e-17	2.116e-16	8.748e-16	1.581e-15	2.663e-15	6.846e-15
U-232	2.963e-18	4.683e-17	1.581e-15	4.524e-15	7.518e-15	1.421e-14	3.108e-14
Cm-245	7.293e-17	7.388e-16	3.271e-15	8.584e-15	1.367e-14	2.449e-14	6.469e-14
Pu-241	1.089e-19	6.370e-18	2.008e-17	4.137e-17	6.738e-17	1.133e-16	3.909e-16
Am-241	5.046e-18	1.201e-16	1.053e-15	4.846e-15	9.855e-15	1.857e-14	5.748e-14
Np-237	1.042e-17	1.358e-16	6.490e-15	1.463e-14	2.391e-14	4.456e-14	1.400e-13
U-233	7.624e-19	1.239e-17	4.386e-16	1.152e-15	2.417e-15	4.107e-15	2.738e-14
Th-229	2.298e-16	6.680e-15	2.233e-14	3.867e-14	6.330e-14	1.016e-13	3.381e-13
Ra-225	1.689e-18	1.236e-17	3.644e-16	1.320e-15	2.443e-15	4.355e-15	1.360e-14
Ac-225	7.693e-20	1.427e-18	3.762e-17	1.437e-16	2.964e-16	5.249e-16	1.238e-15
Cm-246	3.639e-17	2.799e-16	2.338e-15	6.642e-15	1.101e-14	2.204e-14	5.624e-14
Pu-242	5.184e-18	2.367e-16	9.564e-16	1.984e-15	5.121e-15	1.110e-14	1.430e-13
Am-242m	7.742e-18	1.339e-16	1.259e-15	4.698e-15	8.889e-15	1.851e-14	5.075e-14
U-238	7.482e-19	8.620e-18	2.123e-16	8.907e-16	1.518e-15	2.795e-15	8.264e-15
Pu-238	2.394e-18	4.669e-17	5.601e-16	1.305e-15	2.733e-15	5.215e-15	2.674e-14

	percentile values of the dose conversion factors $(\mathrm{Sv\ a^{-1}})(\mathrm{Bq\ a^{-1}})^{-1}$						
nuclide	0	10	25	50	75	90	100
U-234	5.937e-19	9.975e-18	3.934e-16	1.018e-15	1.872e-15	3.326e-15	1.388e-14
Th-234	5.610e-21	1.229e-19	3.979e-18	1.711e-17	4.482e-17	1.091e-16	7.260e-16
Th-230	4.585e-16	5.996e-15	1.219e-14	2.596e-14	5.569e-14	1.046e-13	7.371e-13
Ra-226	1.556e-17	2.120e-16	6.524e-15	1.913e-14	3.882e-14	7.941e-14	2.573e-13
Pb-210	4.852e-17	6.944e-16	5.554e-15	1.660e-14	2.914e-14	5.094e-14	1.588e-13
Po-210	1.741e-17	6.241e-17	1.135e-15	4.850e-15	1.181e-14	2.084e-14	7.848e-14
Cm-247	1.209e-16	1.281e-15	6.051e-15	1.088e-14	1.778e-14	2.703e-14	8.585e-14
Am-243	8.166e-18	3.707e-16	2.410e-15	7.562e-15	1.279e-14	2.309e-14	5.860e-14
Pu-239	2.792e-18	2.278e-16	1.018e-15	2.256e-15	4.852e-15	1.292e-14	1.725e-13
U-235	7.495e-19	1.123e-17	5.226e-16	1.148e-15	2.328e-15	4.690e-15	3.838e-14
Pa-231	1.820e-15	2.373e-14	5.395e-14	1.084e-13	2.193e-13	3.267e-13	1.092e-12
Ac-227	4.981e-17	6.347e-16	7.052e-15	2.403e-14	4.681e-14	8.839e-14	2.293e-13

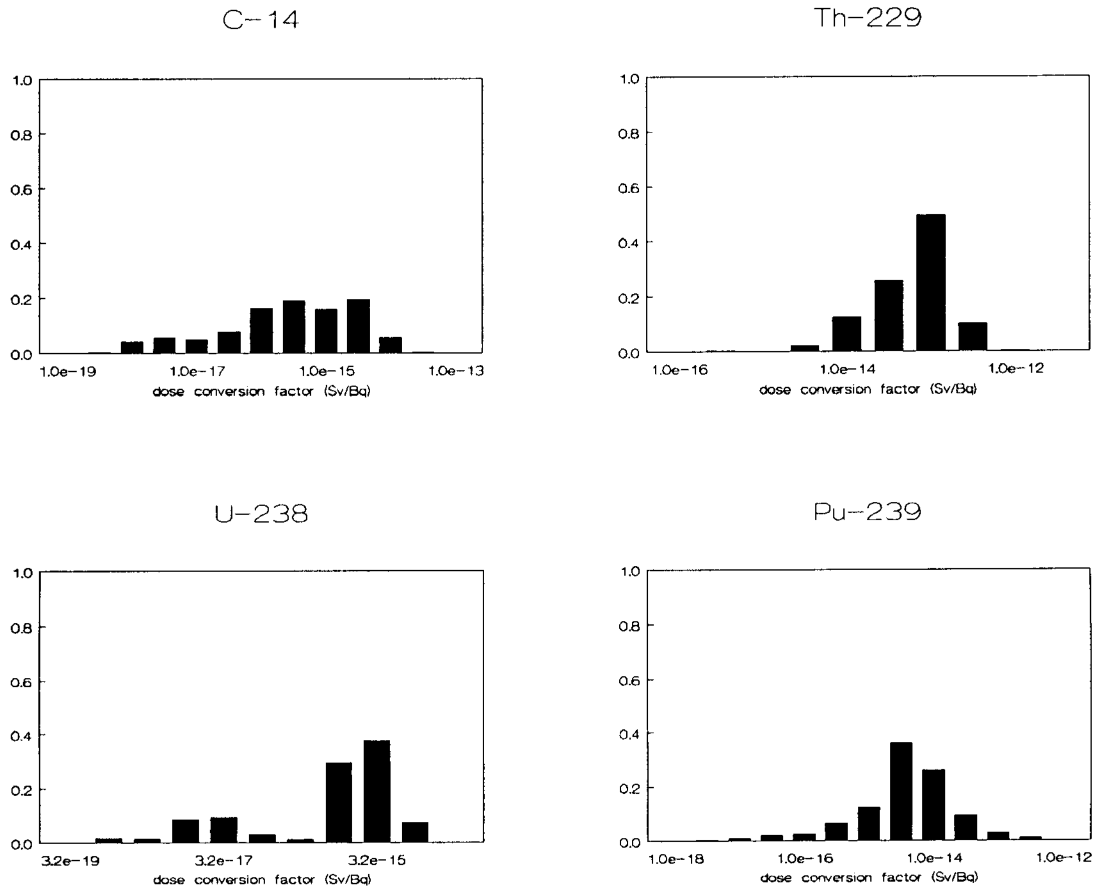

Figure 4.2 Some examples of calculated distributions of dose conversion factors.

The relative contribution of the exposure pathways (water, fish, crops, meat, inhalation and external radiation) to the mean value of the dose conversion factor is determined for all radionuclides (Table 4.3). The exposure pathway 'fish' includes the contribution of freshwater fish and sea fish, the pathway 'crops' the contribution of green vegetables, cereals and root vegetables and the pathway 'meat, milk' the ingestion of meat, liver and milk.

Table 4.3 Relative contribution (%) of the exposure pathways on the mean of the dose conversion factor

nuclide	water	fish	crops	meat, milk	inhalation	external radiation
C-14	0.9	71.0	25.9	2.2	< 0.1	-
Co-60	21.1	13.2	7.0	1.6	< 0.1	57.0
Ni-59	25.9	26.3	31.5	15.2	< 0.1	0.8
Ni-63	29.5	30.0	26.7	13.6	< 0.1	-
Se-79	0.7	3.0	45.7	50.5	< 0.1	-
Rb-87	8.0	44.9	19.0	28.1	< 0.1	-
Sr-90	29.9	10.0	49.0	11.1	< 0.1	-
Zr-93	3.7	0.6	85.7	1.9	0.2	7.4
Mo-93	30.4	0.8	56.7	7.4	< 0.1	4.6
Nb-94	0.3	3.0	0.4	0.2	< 0.1	96.2
Tc-99	14.3	2.3	70.5	12.5	< 0.1	-
Pd-107	3.1	1.0	58.5	37.3	< 0.1	-
Sn-126	0.1	6.0	5.5	1.6	< 0.1	86.8
I-129	75.1	6.1	8.7	10.0	< 0.1	< 0.1
Cs-135	0.3	1.2	74.8	23.5	< 0.1	-
Cs-137	3.4	15.7	55.6	21.4	< 0.1	3.8
Sm-147	48.0	4.3	38.1	7.0	2.7	-
Sm-151	58.7	5.2	32.2	3.5	0.1	0.2
Eu-154	1.6	0.4	1.4	0.1	< 0.1	96.6
Cm-248	56.7	14.5	26.9	0.2	1.6	< 0.1
Pu-244	2.4	1.3	19.4	< 0.1	0.7	76.0
Cm-244	63.8	16.3	19.6	< 0.1	< 0.1	< 0.1
Pu-240	12.3	6.4	78.2	0.2	2.8	< 0.1
U-236	73.2	1.2	19.3	5.8	0.4	< 0.1

nuclide	water	fish	crops	meat, milk	inhalation	external radiation
Th-232	4.6	3.7	34.2	6.0	1.0	50.4
Ra-228	54.4	27.2	12.3	3.9	< 0.1	2.1
Th-228	47.0	32.4	16.3	1.6	< 0.1	2.6
Ra-224	58.9	24.6	12.4	4.0	< 0.1	< 0.1
U-232	70.8	1.3	17.0	3.8	0.1	6.8
Cm-245	49.2	12.6	25.6	0.5	1.9	10.2
Pu-241	33.7	16.7	39.9	2.3	3.8	3.6
Am-241	60.1	15.4	23.0	0.4	0.5	0.5
Np-237	70.8	1.6	25.5	0.4	0.1	1.6
U-233	49.4	0.9	32.0	11.8	1.0	4.8
Th-229	14.2	10.4	48.8	13.8	1.7	10.9
Ra-225	57.6	25.9	12.5	3.9	< 0.1	< 0.1
Ac-225	63.2	1.9	29.3	5.6	< 0.1	< 0.1
Cm-246	57.7	14.7	25.9	0.2	1.5	< 0.1
Pu-242	13.4	6.4	76.3	0.2	3.6	< 0.1
Am-242	58.1	14.8	25.8	0.4	0.5	0.5
U-238	70.7	1.4	19.1	5.1	0.3	3.5
Pu-238	34.3	17.9	46.2	0.1	1.3	< 0.1
U-234	67.9	1.1	23.0	5.9	0.4	1.7
Th-234	41.2	39.4	19.2	< 0.1	< 0.1	< 0.1
Th-230	1.9	1.5	67.0	6.8	0.3	22.4
Ra-226	14.9	7.4	53.3	6.3	< 0.1	18.1
Pb-210	49.3	20.1	27.8	2.8	< 0.1	< 0.1
Po-210	43.1	39.9	15.1	1.8	< 0.1	< 0.1
Cm-247	35.7	9.7	17.8	0.2	1.2	35.4
Am-243	46.0	11.8	22.0	0.6	1.1	18.5
Pu-239	12.6	5.6	78.2	0.2	3.4	< 0.1
U-235	42.3	0.8	32.0	7.8	0.7	16.3
Pa-231	7.7	0.7	68.1	18.4	1.5	3.6
Ac-227	61.1	1.8	29.9	6.2	0.3	0.7

The ingestion of water, fish and crops are the most important exposure pathways for most radionuclides. The ingestion of animal produce is only of importance for some radionuclides, like Se-79 and Pd-107. The inhalation of resuspended particles is unimportant. This is in agreement with the results of the preceding project VEOS [Kö89]. For a few radionuclides, like Nb-94 and Th-232, external radiation is the most important exposure pathway.

In the determination of the dose conversion factors a calculation time period of 10,000 years is assumed. Equilibrium in the surface soil will be reached within the time period under consideration, i.e. 10,000 years, for both mobile and immobile parent nuclides with short-lived daughters (Figure 4.3). Mobile elements like Tc-99 rapidly reach equilibrium concentrations due to the relatively quick transport to the deeper soil layers by infiltration of rain and irrigation water. For immobile elements like Th-229 it takes a long time to reach equilibrium in the upper soil layer because the transport to the deeper soil layers is governed by slow processes like bioturbation and diffusion. In water, equilibrium is reached rapidly for all elements because of the high removal rate of the river.

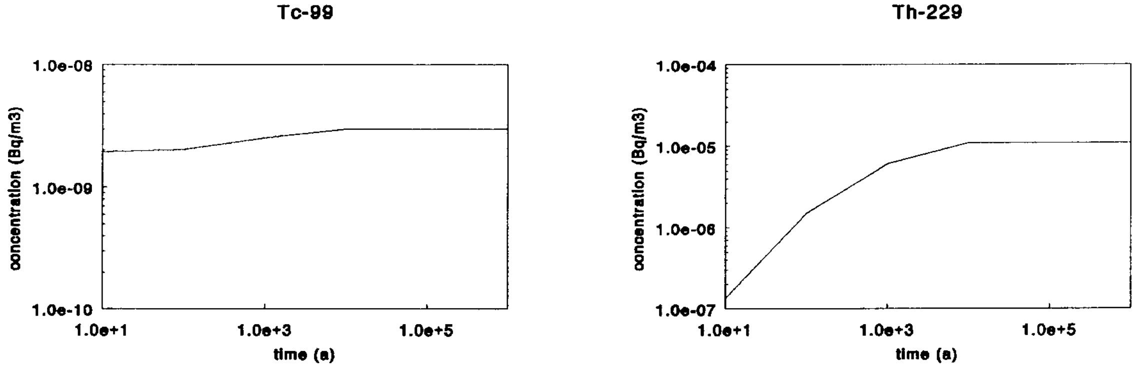

Figure 4.3 Time-dependent concentrations in the surface soil for mobile (Tc-99, left) and immobile (Th-229, right) radionuclides.

The contribution of the ingrowth of daughter nuclides to the dose is small if the decay chain includes long-lived daughters. For U-238, daughter nuclides have almost no influence on the dose after a time period of 10,000 years (Figure 4.4). Even after 1,000,000 years, when equilibrium is nearly reached, the decay products have little effect. Th-229 is in equilibrium with its short-lived daughters, like Ra-225 and Ac-225, within a year. The decay products have a greater influence, compared with U-238, on the dose at all times.

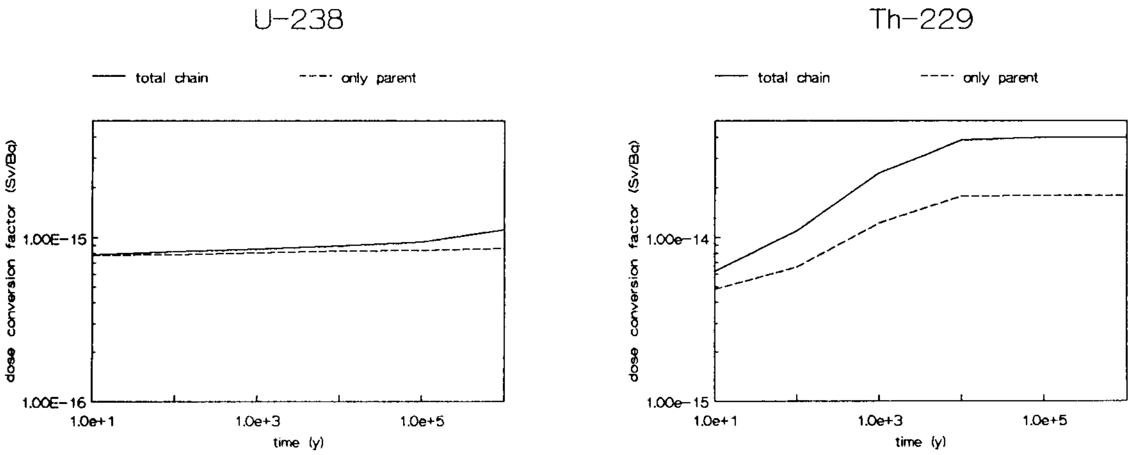

Figure 4.4 Contribution of the ingrowth of daughter nuclides with time of U-238 (left) and Th-229 (right).

5 SENSITIVITY AND UNCERTAINTY ANALYSES

5.1 Introduction

The model MiniBIOS [Ui93] is used to determine distributions of dose conversion factors (Sv a^{-1})(Bq a^{-1})$^{-1}$ for radionuclides released into the biosphere via groundwater discharge. A sensitivity analysis of the model MiniBIOS (version MiniBIOS_1A2) was done, using a preliminary set of data. Out of this analysis it was concluded that twenty-nine parameters have a significant influence on the dose conversion factors. After it was decided to take these parameters into account stochastically, MiniBIOS was adapted, finally resulting in version MiniBIOS_1A4. Therefore, after calculating the distributions of the dose conversion factors a second uncertainty analysis was done to determine the most important sources of uncertainty in the dose conversion factors, along with the most sensitive parameters.

It should be stressed that in the calculations with MiniBIOS at least four different sources of uncertainty can be identified: uncertainty in the conditions of the biosphere, uncertainty in the model description, uncertainty in the release point and uncertainty in the model parameters.

The calculations for the safety assessment extend to a period of over millions of years. The biosphere adopted for these calculations is, however, based on current practices and present-day state of technology. Due to lack of knowledge the uncertainty caused by the evolution of the biosphere and humankind is not taken into account, although this is probably the largest source of uncertainty. The biosphere calculations should therefore be interpreted as an indication of possible radiation levels rather than as a prediction.

To be able to calculate the transport of radionuclides, processes in the biosphere are translated into equations. In this translation of reality into a mathematical model simplifications and mistakes are made, both due to incomplete knowledge. The associated uncertainty in the model description is not taken into account in the distribution of the dose conversion factors. In the model validation study BIOMOVS [BIOMOVS90] the uncertainty in the model descriptions was investigated. Important discrepancies between the investigated models were observed.

It is assumed that the radionuclides are released in a river. However, other release points, like a well, the deep soil or the sea, are imaginable. Different release points result in different dose conversion factors. The uncertainty in the dose conversion factors due to the choice of the release point is not considered in the distribution of the dose conversion factors. Chapter 6 gives an indication of its possible contribution to the uncertainty.

Finally, the parameters in the model have an uncertainty due to either lack of knowledge or natural variability. This is the only uncertainty taken into account in the calculations of the dose conversion factors. The uncertainty due to natural variability in parameter values is considered by choosing the highest and lowest values found in the literature, as the bounds of the distribution used in the calculations. In this way some of the uncertainties in the characteristics of the biosphere, like the soil characteristics, are considered. As a consequence, some parameters exhibit large uncertainties.

In this chapter, the results of the uncertainty analysis for the model MiniBIOS (version MiniBIOS_1A4) are described. The software package UNCSAM [Ja90,Ja91] is used to conduct the uncertainty analyses on MiniBIOS. Information about UNCSAM is given in Section 5.2. The method used to determine the most important parameters is described in Section 5.3. The results of the analyses are given in Section 5.4. In Section 5.5 the results are discussed.

5.2 The UNCSAM software package

UNCSAM uses Monte Carlo sampling methods, discussed in Section 5.2.1, to generate randomly model parameter values from, by the user chosen, distributions. The sampled values are subsequently used to run the model, resulting in model outputs. The analysis of the outputs consists of computing and showing basic statistical information and performing regression and correlation analysis. Herewith, the sensitivity and uncertainty contribution of the various parameters to the model output can be determined.

The method used is an uncertainty analysis, in which both a sensitivity measure and an uncertainty measure are used to determine the importance of the various parameters. The measures of sensitivity and uncertainty used are described in Section 5.2.2.

5.2.1 *Sampling method*

The Latin Hypercube Sampling (LHS) sampling method is used. It is an effective sampling method and consists of the following steps:
First, the range of each parameter is divided in N disjunct equi-probable intervals. N is the number of samples to be generated and should be at least 2-5 times the number of parameters under consideration. Second, one random sample from each of these disjunct intervals is taken according to the prevailing distribution of this interval. Third, the values obtained in the previous step are combined in a random fashion. The sampled values of the first parameter are randomly paired with the sampled values of the second parameter. These pairs are subsequently randomly combined with the samples of the third parameter etc. If correlations between parameters are considered the parameters are combined in a correlated fashion instead of using random pairing.

The distributions which can be used in UNCSAM for the various parameters are: (log)normal, (log)uniform, (log)triangular, exponential, logistic, Weilbull, Beta, Gamma or histogram distributions.

5.2.2 *Uncertainty analysis*

UNCSAM calculates, among rank regression and Kolmogorov-Smirnov statistics, linear regression relations which result from regressing the model output y (dependent variable) on the input parameters $x_1,\ldots,x_i$ (independent variables) using a least-squares criterion:

$$y(k) = \beta_0 + \beta_1 x_1(k) + \ldots. + \beta_i x_i(k) + e(k) \qquad k = 1,\ldots, N$$

The quantities $\beta_0,\beta_1,\ldots,\beta_i$ denote the ordinary regression coefficients determined from the values of $y(k)$ and $x_1(k),\ldots,x_i(k)$ in the various model simulation runs ($k = 1,\ldots, N$). The quantity $e(k)$ denotes the regression residual i.e. that part of the model output $y(k)$ left unexplained by the linear regression model output. The percentage of the variance of y, which is explained by the regression model is given by the 'adjusted' coefficient-of-determination R^2_{adj} (%). This is a measure for the goodness of the fit. For a useful analysis of the model, R^2_{adj} should be larger than 70% [Ja91]. If R^2_{adj} is lower than 70%, an other regression method, for example rank regression, should be used.

If the fit of the regression model is satisfactory, several uncertainty and sensitivity measures are available in UNCSAM [Ja91]. The Standardized Regression Coefficient (SRC) and the Normalized Regression Coefficient (NRC) are chosen as measures for the uncertainty or sensitivity.
The Standardized Regression Coefficient (SRC),

$$SRC_i = \beta_i \frac{S_{x_i}}{S_y}$$

gives the fraction of the uncertainty, i.e. range, in model output, y, which is contributed by the model input (x_i), while the other sources remain constant. It measures the change, Δy, of y in terms of its standard deviation, S_y, if x_i changes in terms of its standard deviation, S_x:

$$\frac{\Delta y}{S_y} = SRC_i \frac{\Delta x_i}{S_{x_i}}$$

The Normalized Regression Coefficient (NRC),

$$NRC_i = \beta_i \frac{\bar{x}_i}{\bar{y}}$$

gives an impression of the sensitivity, i.e. the influence of variations in model input (x_i) on model output y, while the other sources remain constant:

$$\frac{\Delta y}{\bar{y}} = NRC_i \frac{\Delta x_i}{\bar{x}_i}$$

Both measures are independent of the units or scale due to normalization. For the uncertainty analyses no correlations between the various parameters should be taken into account [Ja91].

The significance of the values of the uncertainty or sensitivity measures is given with student-t statistics. If |t-stat.| < 2, the result for the parameter under consideration is due to coincidences and therefore statistically not significant [Ja90,Sn89]. In the results of the analyses these results are not listed.

To clarify the difference between the NRC and the SRC, the contribution of two parameters (x_1 and x_2) (with equal NRC and different distribution sizes) to the uncertainty of the model output (y) is given in Figure 5.1.

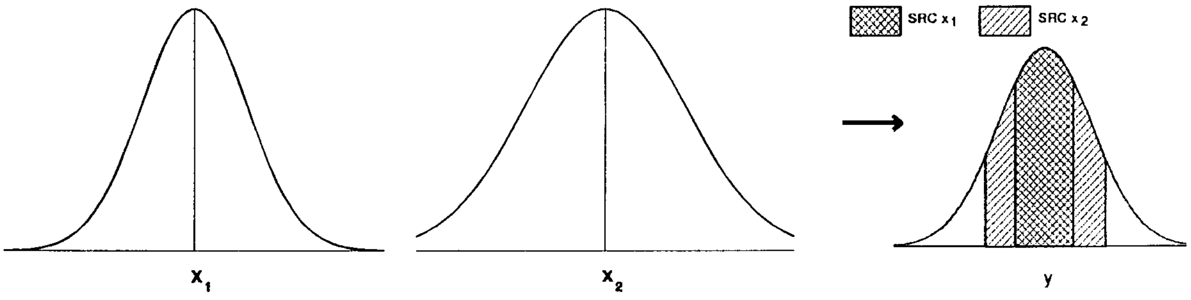

Figure 5.1 The contribution of two parameters (x_1 and x_2) (with equal NRC and different distribution widths) to the uncertainty of the model output (y).

An input parameter with low uncertainty (x_1) will contribute less to the uncertainty of the model output (y) than an input parameter with equal sensitivity and high uncertainty (x_2). In the latter it is more worthwhile to reduce the uncertainty of this parameter in order to reduce the uncertainty in the model output.

The uncertainty in the model output will depend on both the sensitivity and the distribution size of the input parameters. Also, parameters with a low sensitivity but a high uncertainty can contribute significantly to the uncertainty in the model output. The uncertainty is either due to incomplete knowledge or to natural variability. In the first case further investigations can reduce the uncertainty while in the latter case reduction of the uncertainty is not possible.

5.3 Method and parameter values

The calculations of the dose conversion factors with MiniBIOS [Ui93] are divided into two parts. First, the inventory of the radionuclides in the boxes of the river and marine compartments is calculated. Second, from the inventory in the surface-water box and surface-soil box, the dose conversion factor, including several contamination pathways, is determined. As a result, the uncertainty analysis is also divided into two steps. First, the most important parameters for the radionuclide inventory in the surface-water box and surface-soil box are determined. Second, the most important parameters within the various contamination pathways are determined.

In the uncertainty analyses the parameter values used are identical to the parameter values used in the calculations of the dose conversion factors with some exceptions:

- As a result of a first uncertainty analysis with an earlier version of MiniBIOS (version MiniBIOS_1A2), some parameters are taken deterministically into account in the calculations of the dose conversion factors. To determine the possible contribution of these parameters to the uncertainty of the dose conversion factors they are taken stochastically into account in the uncertainty analyses of MiniBIOS (version MiniBIOS_1A4). The parameters involved are indicated in Sections 5.3.1 and 5.4.3.
- Test analyses made it clear that if the volume and flow of the river are taken stochastically into account, the fit of the regression model is not sufficient ($R^2_{adj} <$ 70%) for a useful analysis. Therefore, we decided to take the river volume and river flow deterministically into account in the uncertainty analyses. The volume and flow in the surface-water box in the uncertainty analyses correspond with the volume and flow of the smallest river included in the calculations of the dose conversion factors.
- There are no correlations between the parameters taken into account in the uncertainty analyses as no correlations are permitted [Ja91].
- Test calculations showed that the mobility of the radionuclides in the biosphere, reflected in the distribution coefficient (K_d), will have a significant influence on the resulting inventory of the surface soil (Figure 5.2). The test calculations are carried out for Tc-99 with a hypothetical range of the distribution coefficient. Therefore, the uncertainty analyses are done for an immobile radionuclide (Th-229, no ingrowth of decay products included) and a mobile radionuclide (Tc-99). The soil distribution coefficient is taken deterministically into account in the analyses. For Th-229, the

maximum value of the distribution is chosen, i.e. K_d = 2.0e+5. For Tc-99, the minimum value of the distribution is chosen, i.e. K_d = 1.0e-3 (Appendix A). We assumed the results of the uncertainty analyses for Tc-99 and Th-229 to be representative of all other radionuclides.

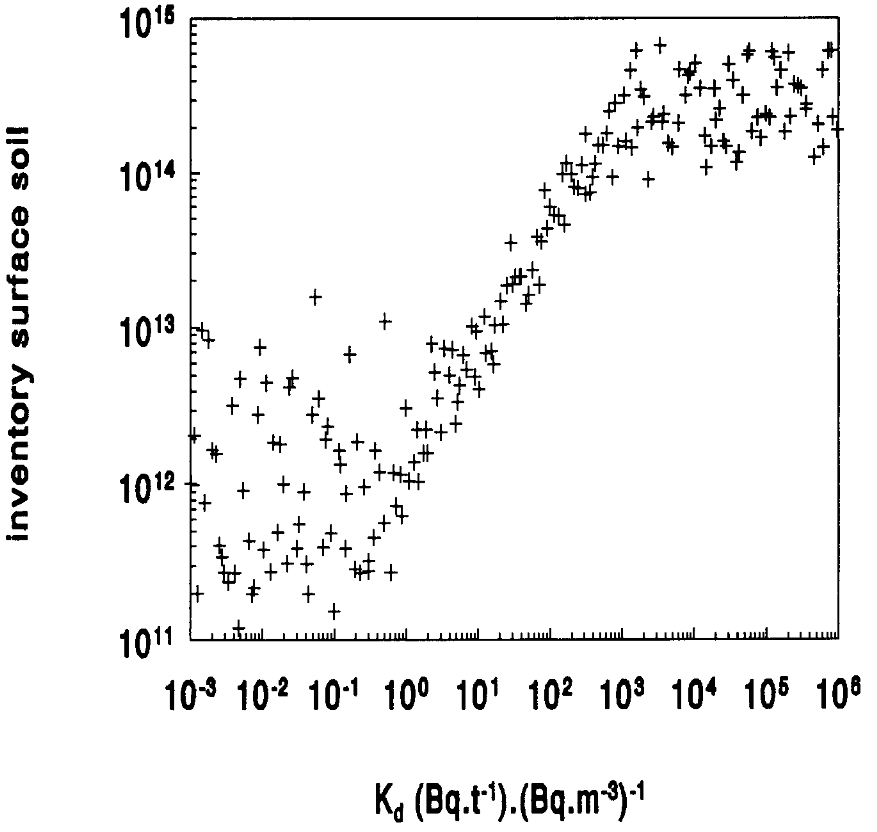

Figure 5.2 Effect of the distribution coefficient (hypothetical range) on the inventory of Tc-99 in the surface soil.

5.3.1 *Inventory calculations*

The parameters used in the calculations of the inventory in the terrestrial and marine boxes of MiniBIOS are all included in the transfer coefficients, see Appendix E. Table 5.1 lists parameters of which the distribution or value used in the uncertainty analyses is different from the distribution or value used in the calculations of the dose conversion factors. It is indicated if the parameter is stochastically (stoch.) included in the uncertainty analyses with UNCSAM.

Table 5.1 Parameters of which the distribution or value used in the uncertainty analyses is different from the distribution or value used in the calculations of the dose conversion factors

parameter	stoch.	parameter	stoch.
soil distribution coefficient	no	volume freshwater box	no
groundwater velocity	yes	volumetric flow	no
depth of river	no		

In Appendix F the distributions or deterministic values for the parameters used in the uncertainty analyses are described. In the calculations one terrestrial compartment and two marine compartments are included. The uncertainty analysis of the inventory calculation is executed for the inventory after 10,000 years of a continuous release of 1 Bq a^{-1}, since the dose conversion factors are calculated for this time. After this period concentration equilibrium in the surface water and surface soil is reached (Chapter 4). The results of the analyses are only valid for this time period of release. For other time periods the results will probably be different.

5.3.2 *Dose calculations*

The most important parameters of the various contamination pathways are determined. As described in Chapter 3, parameters specifically related to the ingestion of seafood, inhalation and external radiation are taken deterministically into account in the calculations of the dose conversion factors. Therefore, only for the ingestion of water, fish, crops and animal produce, the most important parameters are determined.

The value used for the concentration in the river water or surface soil is equal to the mean value determined in the uncertainty analysis for the inventories (Appendix G). It is expected that both the concentration in the surface water and surface soil will contribute strongly to the uncertainty in the dose conversion factors. Therefore, the results of the uncertainty analyses will only give a relative contribution of the several parameters to the uncertainty in the dose conversion factors.

5.4 Results

5.4.1 *Inventory calculations for Tc-99*

Figure 5.3 gives the mean inventory (Bq) of Tc-99 in the terrestrial boxes and mean values of the transfer coefficients. As the dose conversion factor is mainly determined by the inventories of the surface-water box and the surface-soil box, the analyses are limited to these two boxes.

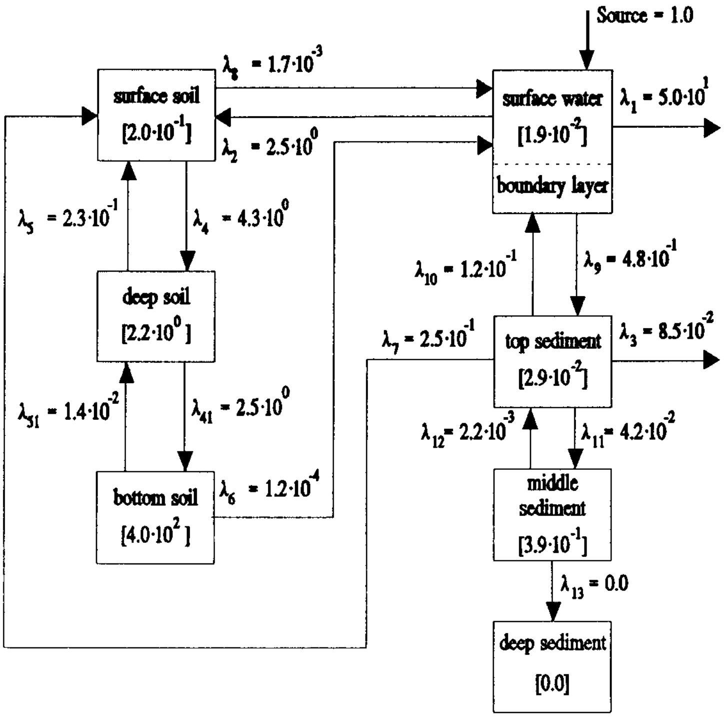

Figure 5.3 Mean inventory (Bq) of Tc-99 in the several boxes and mean transfer coefficients (a^{-1}) after a continuous release of 10,000 years.

The inventory in the surface water will mainly be determined by λ_1, which is governed by the volumetric flow and the volume of the box. These two parameters are not stochastically included in the analyses as described in Section 5.3.

Table 5.2 Results of the uncertainty analysis for the inventory in the surface-water box (R^2_{adj} = 67.3%)

parameter	SRC	NRC	t-stat.
v_g	0.72	0.008	17.3
I_i	- 0.34	- 0.027	- 8.4
D	- 0.13	- 0.004	- 3.1
D_r	- 0.11	- 0.004	- 2.7
κ	- 0.10	- 0.0007	- 2.3

An uncertainty analysis for the surface-water box indicates, although R^2_{adj} is lower than

70%, that none of the other stochastic parameters has an important influence on the inventory of the surface water (Table 5.2). The sensitivity (NRC) of the model to the various model inputs is low. Therefore, the inventory in the surface water is concluded to be mainly determined by the river flow and volume (Figure 5.3).

The parameters predominantly influencing the inventory in the surface soil are: the irrigation rate (I_i), the annual infiltrated rainfall (r), the heightening of the surface soil by river sediment (S), the diffusion coefficient (D), the porosity of the soil (φ_s) and the groundwater velocity (v_g) (Table 5.3).

Table 5.3 Results of the uncertainty analysis for the inventory in the surface-soil box (R^2_{adj} = 73.9%)

parameter	SRC	NRC	t-stat.
D	0.77	1.41	19.9
I_i	0.22	1.16	5.9
r	- 0.08	- 1.58	- 2.2
S	0.08	0.21	2.0
φ_s	0.19	1.75	5.0
v_g	- 0.27	- 0.21	- 7.3

Important processes involved in the transport of mobile radionuclides towards the surface soil (positive NRC) are diffusion, irrigation and sediment transfer to land. The transport of mobile radionuclides out of the surface soil (negative NRC) is governed by infiltrating rainfall and groundwater transport. The contribution of both processes to the uncertainty of the inventory in the surface soil is low.

To check these conclusions, the influence of these parameters on the related transfer coefficients is determined by doing an uncertainty analysis on the transfer coefficients. The results are listed in Table 5.4 (see also Appendix E).

The diffusion coefficient (D) is a dominant parameter in λ_4 and λ_5. Transfer coefficient λ_4 describes the transport from the surface soil towards the deep soil and includes three processes: infiltration of water (rainfall and irrigation), pore-water diffusion and bioturbation. In the downward transport the diffusion coefficient is of minor importance (Table 5.4). Transfer coefficient λ_5 describes the transport from the deep soil towards the surface soil and includes two processes: pore-water diffusion and bioturbation. The upward transport is totally governed by diffusion (Table 5.4). The diffusion coefficient will have a positive influence on the inventory of the surface soil as the inventory of Tc-99 increases with increasing depth (Figure 5.3). This also corresponds with the results of Table 5.3. In reality, a positive inventory gradient in the soil with a strong upward transport by diffusion is not to be expected. Because of the low distribution coefficient of mobile radionuclides the adsorption to soil particles will be relatively low. Therefore, the transport by bioturbation will be low.

Table 5.4 Results of the uncertainty analysis for the several transfer coefficients

	parameter	SRC	NRC	t-stat.
λ_2 (R^2_{adj} = 100%)	I_i	0.99	1.00	1348.1
λ_4 (R^2_{adj} = 98.1%)	φ_s	- 0.85	- 0.92	- 82.3
	r	0.35	0.77	33.9
	I_i	0.20	0.13	20.3
	D	0.41	0.09	39.2
λ_5 (R^2_{adj} = 100%)	D	0.99	0.99	> 10,000
λ_{51} (R^2_{adj} = 100%)	D	0.99	0.99	> 10,000
λ_6 (R^2_{adj} = 97.3%)	v_g	0.98	1.01	82.7
λ_7 (R^2_{adj} = 100 %)	S	1.00	1.00	> 10,000
λ_8 (R^2_{adj} = 100 %)	E_{ss}	1.00	1.00	> 10,000

In λ_{51}, the diffusion coefficient is also the dominant parameter. Diffusion is not only of importance in the transport of mobile radionuclides from the deep soil layer to the surface soil layer but also in the transport from the deepest soil layer to the surface soil layer. This explains the (negative) influence of the groundwater velocity (v_g) on the inventory of the surface soil. The inventory in the deepest soil box is influenced by λ_6 (Figure 5.3), with the groundwater velocity as the dominant parameter (Table 5.4). In the calculations of the dose conversion factors the groundwater velocity is taken deterministically into account at its maximum value, so the contribution of the deepest soil layer to the inventory of the surface soil will be less.

The irrigation rate (I_i) is included in λ_2 and λ_4. Transfer coefficient λ_2 describes the radionuclide transport from the river water to the surface soil through irrigation (Appendix E). In λ_2, the irrigation rate is the dominant parameter. In λ_4, the irrigation rate is of minor importance. As the irrigation rate has a positive influence on the inventory of the surface soil (Table 5.3) the amount of radionuclides transported from the surface water towards the surface soil by irrigation will be greater than the amount of radionuclides transported towards the deeper soil layers by the infiltrating irrigation water.

The heightening of the soil (S) is the dominant parameter in λ_7, which describes the transport of the river sediment to the surface soil by meandering of the river, flooding and dredging. We are not sure if the result in Table 5.3 is significant because the t-statistic is near its value of significance, i.e. 2. However, from Figure 5.3 the importance of λ_7 could be concluded.

The infiltrating rain water (*r*) is of importance in λ_4. So the downward transport in the soil will be governed by the infiltration of water, both rain water and irrigation water. The downward transport in the soil by infiltration water is influenced by the porosity of the soil (φ_s) (Table 5.4 and Appendix E). As the porosity of the soil increases the transport of radionuclides decreases. In this way, the positive influence of the porosity on the inventory of the surface soil is explained.

5.4.2 *Inventory calculations for Th-229*

Figure 5.4 shows the mean inventory (Bq) of Th-229 in the terrestrial boxes and mean values of the transfer coefficients.

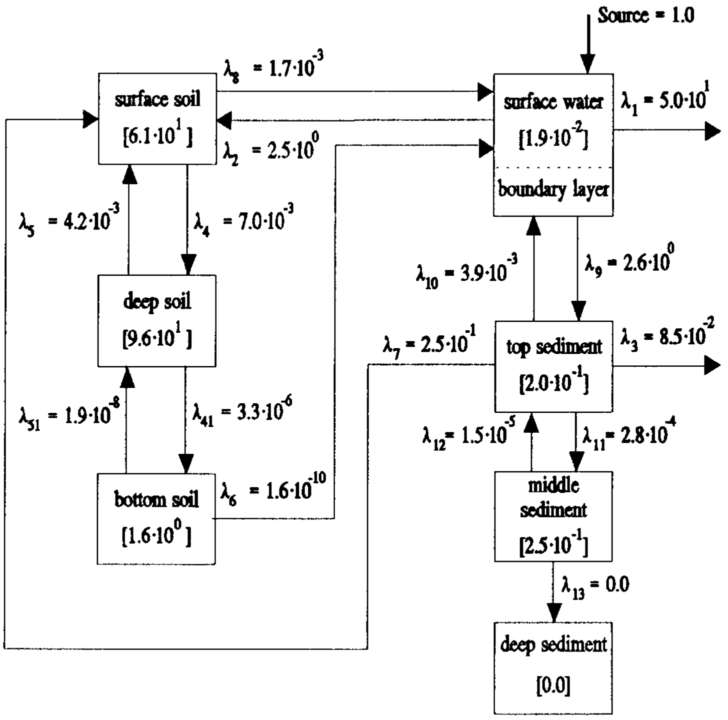

Figure 5.4 Mean inventory (Bq) of Th-229 in the several boxes and mean transfer coefficients (a^{-1}) after a continuous release of 10,000 years.

As for Tc-99, the analyses are limited to the surface-water box and surface-soil box. Equal to Tc-99 (Section 5.4.1), the inventory of Th-229 in the surface water is mainly determined by λ_1 (Figure 5.4 and Table 5.5).

Table 5.5 Results of the uncertainty analysis for the inventory of Th-229 in the surface-water box (R^2_{adj} = 75.1%)

parameter	SRC	NRC	t-stat.
E_{ss}	0.54	0.02	14.9
κ	- 0.54	- 0.03	- 14.5
S	0.20	0.01	5.4
v_{sed}	- 0.18	- 0.01	- 5.1
I_i	- 0.14	- 0.01	- 4.0
φ_s	- 0.07	- 0.01	- 2.1

The most important parameters of immobile radionuclides for the inventory in the surface-soil box are: the irrigation rate (I_i), the Schaeffer sedimentation (κ), the sediment transfer to land (S) and the erosion rate (E_{ss}) (Table 5.6).

Table 5.6 Results of the uncertainty analysis for the inventory of Th-229 in the surface-soil box (R^2_{adj} = 75.7%)

parameter	SRC	NRC	t-stat.
E_{ss}	- 0.74	- 1.04	- 20.5
I_i	0.21	0.58	5.7
κ	0.28	0.50	7.7
S	0.17	0.25	4.7

Important processes involved in the transport of immobile radionuclides towards the surface soil (positive NRC) are therefore irrigation and sediment transfer to land. Both processes contribute to the same extent to the uncertainty of the inventory in the surface soil. The transport of immobile radionuclides towards other compartments (negative NRC) is governed by erosion.

To check these conclusions, the influence of these parameters on the transfer coefficients involved is determined by doing an uncertainty analysis on the transfer coefficients. The results are listed in Table 5.7 (Appendix E).

The erosion rate (E_{ss}) is included in λ_8, which describes the transport from the surface soil to the surface water by erosion. It is the only parameter of importance in this transfer coefficient, so the transport of immobile radionuclides from the surface soil towards other boxes is governed by erosion.

The irrigation rate (I_i) is included in λ_2 and λ_4. Transfer coefficient λ_2 describes the radionuclide transport from the river water to the surface soil through irrigation. Transfer coefficient λ_4 describes the transport from the surface soil towards the deep soil and includes three processes: infiltration of water (rainfall and irrigation), pore-water diffusion and bioturbation. The irrigation rate is only of importance in λ_2 (Table 5.7). The transport to the deeper soil layers is governed by bioturbation. In agreement with the results of Table 5.6, irrigation with contaminated water will have a positive influence on the inventory in the surface soil.

Bioturbation has no influence on the inventory in the surface soil because it is also the governing parameter in λ_5, which describes the transport from the deep soil towards the surface soil. As seen in Figure 5.4, there will be no effective transport between the surface soil and deep soil layer.

Table 5.7 Results of the uncertainty analysis for several transfer coefficients

	Parameter	SRC	NRC	t-stat.
λ_2 (R^2_{adj} = 100%)	I_i	1.00	1.00	1335.0
λ_4 (R^2_{adj} = 100%)	B	1.00	0.99	> 10,000
	D	0.0001	0.0001	3.3
	ρ	- 0.0002	- 0.001	- 8.6
	r	0.0001	0.006	2.9
λ_5 (R^2_{adj} = 100%)	B	1.00	0.99	> 10,000
	D	0.0001	0.0001	2.5
λ_7 (R^2_{adj} = 100%)	S	1.00	1.00	> 10,000
λ_8 (R^2_{adj} = 100%)	E_{ss}	1.00	1.00	> 10,000
λ_9 (R^2_{adj} = 98.6%)	κ	0.98	0.98	111.3
	D_r	0.05	0.03	5.5
	K_{sr}	- 0.04	- 0.01	- 4.6

The heightening of the soil (S) is the dominant parameter in λ_7, which describes the transport of the river sediment to the surface soil by meandering of the river, flooding and dredging. If λ_7 is of importance to the inventory in the surface soil, parameters included in λ_9 should also be of importance. This is because the radionuclides are released in the surface water (Figure 5.4). Coefficient λ_9 describes the transport from the river water to the top sediment by sedimentation, diffusion and bioturbation. The dominant parameter in λ_9 is the Schaeffer sedimentation (κ) (Table 5.7). As seen in Table 5.6 this parameter influences also the inventory in the surface soil. Therefore, the pathway sedimentation → sediment transfer to land can be concluded to be of importance to the transport of immobile radionuclides towards the surface soil.

5.4.3 *Sensitivity and uncertainty in the individual exposure pathways*

It is to be expected that the mobility of the radionuclides in the biosphere will have a significant influence on the resulting dose conversion factor. In the uncertainty analyses of the various exposure pathways, it is assumed that the mobility is reflected in the various concentration factors. Therefore, the uncertainty analyses are done for an immobile radionuclide (Th-229, no ingrowth of decay products included) with low concentration factors and a mobile radionuclide (Tc-99) with high concentration factors. The value used for the concentration in the river water or surface soil is equal to the mean value determined in the uncertainty analysis for the inventories. The distributions and values used for the various parameters are listed in Appendix H.

5.4.3.1 Ingestion of drinking water

In the calculations of the dose due to the ingestion of water (D_w, Appendix G) the suspended sediment load (α_r) and freshwater sediment distribution coefficient (K_{sr}) are the only possible stochastic parameters as it was decided to take the human ingestion rates and dose factors deterministically into account (Chapter 2 and Appendix G). Both α_r and K_{sr} are sensitive parameters for immobile radionuclides like Th-229, but not for mobile radionuclides (Table 5.8). For Th-229, we used a smaller range for the distribution of K_{sr} than the range used in the analyses for the inventory calculations because the range, given in Appendix F, is too large for a good regression fit using UNCSAM. Both α_r and K_{sr} are taken stochastically into account in the calculations of the dose conversion factors.

Table 5.8 Results of the uncertainty analysis for the contamination pathway water for Tc-99 (R^2_{adj}=90.7%) and Th-229 (R^2_{adj}=83.1%)

	parameter	SRC	NRC	t-stat.
Tc-99	K_{sr}	- 0.90	- 0.019	- 29.3
	α_r	- 0.21	- 0.017	- 6.9
Th-229	K_{sr}	- 0.36	- 1.01	- 8.8
	α_r	- 0.80	- 1.15	- 19.3

5.4.3.2 Ingestion of freshwater fish

In the calculations of the dose due to the ingestion of freshwater fish (D_{ff}, Appendix G) the suspended sediment load (α_r), the freshwater sediment distribution coefficient (K_{sr}) and the concentration factor for freshwater fish (K_{ff}) are possible stochastic parameters. Table 5.9 gives the results of the uncertainty analysis.

Table 5.9 Results of the uncertainty analysis for the contamination pathway fish for Tc-99 (R^2_{adj}= 99.9%) and Th-229 (R^2_{adj}= 80.1%)

	parameter	SRC	NRC	t-stat.
Tc-99	K_{ff}	0.99	0.99	371.0
	K_{sr}	- 0.02	- 0.014	- 8.9
Th-229	K_{ff}	0.86	0.93	19.2
	α_r	- 0.31	- 1.09	- 6.9
	K_{sr}	- 0.11	- 0.75	- 2.5

The concentration factor (K_{ff}) is for both mobile and immobile radionuclides an important source of uncertainty. For mobile radionuclides it is the only parameter of importance. Immobile radionuclides are also influenced by the suspended sediment load (α_r) and freshwater sediment distribution coefficient (K_{sr}). In the calculations of the dose conversion factors all three parameters are taken stochastically into account.

5.4.3.3 Ingestion of crops

The dose (D_c) due to the ingestion of crops (green vegetables, cereals and root vegetables) is determined by the pathways: internal contamination in the crop through uptake from the soil ($D_{c,\ int}$), external contamination through attached soil on the surface of the crop ($D_{c,\ soil}$) and interception of contaminated irrigation water ($D_{c,\ irri}$) (see Appendix G). An uncertainty analysis for green vegetables shows that for mobile radionuclides (Tc-99) the internal contamination is the dominant contamination pathway (Table 5.10). For immobile radionuclides (Th-229) the interception of irrigation water is also of importance.

In the calculations for root vegetables the translocation of external adsorbed radionuclides to the internal parts of the plant is also included. For mobile radionuclides external contamination is not of importance, t-stat. < 2, therefore the dose will not be influenced by translocation. For immobile radionuclides the translocation rate is small, so it will not contribute to the uncertainty in the ingestion of root crops.

In the calculations of the dose conversion factors the concentration factor of crops (K_c), the irrigation rate (I_i) and the density of the soil (ρ) are taken stochastically into account. All other parameters included in the exposure pathway 'crops' are taken deterministically into account.

Table 5.10 Results of the uncertainty analysis for the contamination pathway crops for Tc-99 (R^2_{adj}=98.1%) and Th-229 (R^2_{adj}=95.0%)

	parameter	SRC	NRC	t-stat.
Tc-99	K_c	0.98	0.94	67.5
	ρ	- 0.17	- 0.93	- 12.0
Th-229	K_c	0.65	0.32	27.7
	I_i	0.48	0.59	20.9
	μ_c	0.47	0.43	19.6
	Y_c	- 0.25	- 0.23	- 10.9
	H_c	- 0.14	- 0.59	- 5.8
	ρ	- 0.11	- 0.30	- 5.0
	S_c	0.06	0.09	2.4

5.4.3.4 Ingestion of animal produce

The dose (D_a) due to the ingestion of animal produce (meat, liver and milk) is determined by the pathways: ingestion of water by the animal ($D_{a,dw}$), internal contamination in pasture ($D_{a,past}$), interception of contaminated irrigation water by pasture ($D_{a,irri}$) and ingestion of soil ($D_{a,soil}$). For a description of these pathways see Appendix G. The contribution of the transfer factor (F_a) to the uncertainty in the dose, will be underestimated because the range for this parameter in respect of the calculations of the dose conversion factors is reduced to achieve a better regression fit using UNCSAM. An uncertainty analysis for meat shows that for mobile radionuclides (Tc-99) the ingestion of pasture by the animal is the most important contamination pathway (Table 5.11). For immobile radionuclides the uptake of water ($D_{a,dw}$) by the animal is the most important source of uncertainty. The interception of contaminated irrigation water by pasture ($D_{a,irri}$) is also of importance. In the calculations of the dose conversion factors only the concentration factor for pasture (K_p), the transfer factor (F_a), the irrigation rate (I_i) and the density of the soil (ρ) are taken stochastically into account.

Table 5.11 Results of the uncertainty analysis for the contamination pathway animal produce for Tc-99 (R^2_{adj}=73.1%) and Th-229 (R^2_{adj}=97.9%)

	parameter	SRC	NRC	t-stat.
Tc-99	K_p	0.68	0.90	12.5
	F_a	0.58	1.09	9.8
	ρ	- 0.19	- 1.68	- 3.4
	Z	0.17	1.43	3.2
Th-229	I_{wa}	0.66	0.61	42.6
	F_a	0.42	1.01	26.3
	I_i	0.27	0.34	17.8
	Y_p	- 0.18	- 0.34	- 11.8
	I_{pa}	0.13	0.42	8.7
	W_p	- 0.09	- 0.40	- 5.8

5.5 Discussion

5.5.1 *Inventory in the surface-water box*

The radionuclide inventory in the water is, for all radionuclides, governed by the flow and volume of the river. In the calculations of the dose conversion factors, the uncertainty in both parameters is high because the radionuclides are assumed to be released in rivers of different sizes. The assumed distributions for the flow and volume of the river include most of the common rivers of the Netherlands. Further investigations will have no influence on the uncertainty of both parameters as the size of the river in which the radionuclides are released is unknown.

5.5.2 *Inventory in the surface-soil box*

The transport pathways towards the surface soil and the transport from the surface soil towards other compartments is strongly influenced by the mobility of the radionuclides. Therefore, the analyses are done for a mobile (Tc-99) and an immobile radionuclide (Th-229). The uncertainty in the distribution coefficients, as found in the literature, is high because of a strong natural variability and experimental uncertainty in the determination [Ha85]. Further investigations will probably reduce the uncertainty. However, in the calculations of the dose conversion factors the physical conditions of the soil under consideration are unknown, so the uncertainty in this parameter will remain high.

For mobile radionuclides the transport towards the surface soil is governed by irrigation with contaminated river water and diffusion out of the deeper soil layers. The uncertainty in the irrigation rate (I_i) is relatively low and is mainly due to natural variability (Chapter 3). A further reduction in the uncertainty of this parameter will be difficult to achieve. The uncertainty in the diffusion coefficient (D) is also due to natural variability. An improvement of the MiniBIOS code is recommended for the transport of mobile radionuclides as the calculated inventory gradient in the soil and consequently upward transport in the soil by diffusion is not likely in reality. The transport of mobile radionuclides from the surface soil towards other boxes is governed by the infiltration of rain and irrigation water. As for the irrigation rate (I_i) the uncertainty in the infiltrating rain water (r) is relatively low and mainly due to natural variability (Chapter 3). A further reduction of the uncertainty will be difficult to achieve. The infiltration of water is influenced by the porosity of the soil (φ_s). The uncertainty in the porosity is low and further investigations are not worthwhile. In conclusion, the investigations for the transport of mobile radionuclides in the biosphere should be concentrated on the determination of the distribution coefficients.

For immobile radionuclides the transport towards the surface soil is governed by irrigation with contaminated river water and the heightening of the soil with contaminated river sediments. As stated above, the uncertainty in the irrigation rate (I_i), mainly caused by natural variability, is relatively low. In the contamination pathway sedimentation → sediment transfer to land, two parameters are of importance: the heightening rate of the soil (S) and the Schaeffer sedimentation (κ). The assumed distribution for the heightening of the soil is a rough estimation because for a time period of 10,000 years no values are available. It is not to be expected that further investigations could reduce the uncertainty of this parameter. The uncertainty in the Schaeffer sedimentation (κ) is high because of incomplete knowledge and only a few values for this parameter are available (Chapter 3). Further, the Schaeffer sedimentation is determined for a point source and the consequences for a more diffuse source [NRPB79], as used in the calculations of the dose conversion factors, are not exactly known. Further investigation is required. The transport of immobile radionuclides from the surface soil towards other boxes is governed by the erosion rate (E_{ss}). The distribution for the erosion rate is determined by the distribution of the heightening of the soil. No net heightening of the soil by flooding or dredging is assumed to occur. As mentioned before, the distribution for the heightening of the soil is a rough estimation and the results of further investigations are expected to be low. The investigations for the transport in the biosphere of immobile radionuclides should be concentrated on the determination of the distribution coefficients and the Schaeffer sedimentation.

5.5.3 *Ingestion of water, fish, crops and animal produce*

The most important sources of uncertainty have been determined for the ingestion of water, fish, crops and animal produce. The uncertainties in the radionuclide concentrations of the surface-water box and surface-soil box are not taken into account in the analyses. Therefore, the results of the uncertainty analyses give only a relative contribution of the parameters stochastic included to the uncertainty in the dose conversion factors.

The ingestion of water is an important exposure pathway for several radionuclides (Chapter 4). For mobile radionuclides the dose due to the ingestion of water will only be determined by the radionuclide concentration in the water as almost no radionuclides are adsorbed at the suspended particles in the water. Immobile radionuclides are partly adsorbed to suspended particles in the water; as a result the distribution coefficient (K_{sr}) and the suspended sediment load (α_r) are also of importance. The uncertainty in the distribution coefficients, as found in the literature, is high because of a strong natural variability and experimental uncertainty in the determination (Chapter 3). Further investigations will probably give a reduction in the uncertainty. However, in the calculations of the dose conversion factors the physical conditions of the sediments under consideration are unknown, so the uncertainty in this parameter will remain high. The uncertainty in the suspended sediment load is mainly due to natural variability and a further reduction of the uncertainty in this parameter will be difficult to achieve.

The ingestion of fish is also an important exposure pathway for several radionuclides (Chapter 4). The uncertainty in this exposure pathway is mainly caused by the uncertainty in the concentration factor (K_{ff}). The uncertainty in this parameter is due to natural variability and experimental uncertainty in the determination. Both sources of uncertainty are included in the values found in the literature. It is not known which of either is the dominant source of uncertainty and therefore we are not sure if the uncertainty in this concentration factor can be reduced.

Another important exposure pathway is the ingestion of crops (Chapter 3). The uncertainty in this exposure pathway is mainly due to the uncertainty in the concentration factor (K_c). We are not sure if the uncertainty in this concentration factor can be reduced because the uncertainty in the concentration factors for crops will, like the concentration factor for fish (K_{ff}), depend on both natural variability and experimental uncertainty. For immobile radionuclides, the uncertainty is influenced also by the interception of irrigation water. For this exposure pathway not all parameters, and especially not the interception constant (μ_c), are taken stochastically into account in the calculations of the dose conversion factors. Further investigations should give information about the uncertainty in these parameters.

The ingestion of animal produce is only of importance for a few radionuclides (Chapter 4). For mobile radionuclides, the uncertainty in this exposure pathway is mainly determined by the concentration factors in pasture (K_p) and by the transfer factor in the animal (F_a). Here also, we are not sure if the uncertainty in the concentration factor or transfer factor can be reduced. For immobile radionuclides the ingestion of contaminated water by animals and the interception of irrigation water by pasture are the most important sources of uncertainty. Parameters included only in these two exposure pathways are taken deterministically into account in the calculations of the dose conversion factors. As the relative importance of the ingestion of animal produce on the total dose conversion factor for most radionuclides is small (Chapter 4), it is not necessary to take these parameters stochastically into account in the calculations of the dose conversion factors.

5.5.4 *Conclusions and recommendations*

The most important sources of uncertainty in the dose conversion factors of a mobile radionuclide (Tc-99) and an immobile radionuclide (Th-229) have been determined. First, parameters significantly influencing the radionuclide inventory in the water and the surface soil were determined and second, the most important parameters within the various contamination pathways were determined. Because the uncertainty analyses of the water and surface soil are done independently of those of the various exposure pathways, the analyses will only give a relative contribution of the parameters to the uncertainty in the dose conversion factors.

The uncertainty analyses of the soil inventory were done for the time period after 10,000 years of a continuous release of 1 Bq a^{-1}. The results of the analyses are only valid for this time period of release. For other time periods the results will probably be different.

Table 5.12 gives an overview of the most important parameters determining the inventory in the water and surface soil. In the calculations of the dose conversion factors they are, except for the groundwater velocity, taken stochastically into account. The various concentration factors are important parameters for the exposure pathways included (Table 5.8 - 5.11).

To reduce the uncertainty in the dose conversion factors, the investigations should be concentrated on the distributions of the several distribution coefficients and concentration factors. The correlation between these two parameters should also be investigated. Further, the uncertainty in the Schaeffer sedimentation should be studied. The uncertainty of most other relevant parameters is mainly due to natural variability, which cannot be reduced.

Table 5.12 Overview of the most important sources of uncertainty in the inventories of the water and soil

mobile radionuclide (Tc-99)	immobile radionuclide (Th-229)
F: flow of river	F: flow of river
V: volume of river compartment	V: volume of river compartment
K_d: soil distribution coefficient	K_d: soil distribution coefficient
D: diffusion coefficient in soil	E_{ss}: erosion rate
I_i: infiltrated irrigation rate	I_i: infiltrated irrigation rate
r: infiltrated rainfall	κ: Schaeffer sedimentation
S: heightening of soil by river sediment	S: heightening of soil by river sediment
φ: porosity of soil	
v_g: groundwater flow	

The MiniBIOS code should be improved for the transport of mobile radionuclides as the calculated inventory gradient in the soil and consequently upward transport in the soil by diffusion is not likely in reality.

6 VARIOUS RELEASE POINTS

In the calculations of the dose conversion factors the radionuclides are released in a river according to the preceding project VEOS [Kö89]. As described in Chapter 2, it is difficult to select a proper release point because the salt concentration and the area of the biosphere in which the radionuclides are released are unknown. It is possible that the radionuclides are released into other parts of the biosphere like a coastal sea, a lake, a water well or deeper soil layers due to processes like groundwater transport, coastal erosion or climatic changes. The effect of different release points is not included in the calculations of the dose conversion factors, although it may considerably contribute to the uncertainty. To indicate the possible contribution to the uncertainty caused by different release points, deterministic calculations with MiniBIOS are made for both a mobile (Tc-99) and an immobile radionuclide (Th-229, no decay products). First, the assumptions we made for the biosphere related to the different release points are described. Second, the results are discussed.

6.1 Assumptions made for the different release points

The biosphere and the exposure pathways for the other release points are, unless otherwise stated, equal to the biosphere and exposure pathways used for release in a river (Chapter 2).

6.1.1 *Release in a river*

For the deterministic calculation of the dose conversion factor, the same biosphere is assumed as for the probabilistic calculations (Chapter 3). From the distributions for the stochastic input parameters of MiniBIOS the 50 percentile value has been selected (Appendix J).

6.1.2 *Release in a lake*

For a release into a lake we assumed the volume of the lake to be equal to the volume of the river compartment (5.65×10^5 m^3, see Appendix J). There is no flow of water out of the lake except from its use as an irrigation source. Irrigation is also the only contamination pathway for the surface soil because we assumed that no sediment is transferred from the lake to the land by flooding or dredging. The sedimentation rate is kept minimal to ensure that the concentration in the water is maximal. Appendix K gives the parameters which differ from the calculations for release in a river.

6.1.3 *Release in deeper soil layers*

For releases into the deeper soil layers the soil model of MiniBIOS [Ui93] is used. The radionuclides are released into the lowest soil box. We assumed that the radionuclides are also transported downwards by diffusion. In λ_{51}, the transport to the surface soil is possible via diffusion and an upward groundwater flow. The downward transport by diffusion is simulated, assuming that transfer coefficient λ_6 is equal to λ_{51} [Ui93]. The influence of the upward groundwater flow in λ_{51} is neglected.

6.1.4 *Release in a well*

The dose conversion factor as a result of the release into a water well is determined for a farmer who uses groundwater as drinking water and for the irrigation of crops. We assumed that the total flux to the biosphere is released into the water well of a single farmer. The area of irrigated land (1.5×10^5 m^2) equals the area of an average Dutch farm [LEI88]. We made the following assumptions:

- o in a river, the most important source of removal is the flow of the river
- o in a well, the most important source of removal is irrigation
- o the use of irrigation water from a well and from a river is identical
- o the contribution of the sediment transfer to the dose is low if the radionuclides are released in a river. Test calculations confirmed this assumption.

Under these assumptions, the dose conversion factor for a well (D_w) is calculated from the dose conversion factors for a release into a river (D_r) with:

$$D_w = \frac{F}{N_{di}} D_r$$

F	:	flow of river	(m^3 a^{-1})
N_{di}	:	extraction of drinking and irrigation water	(m^3 a^{-1}).

6.1.5 *Release in a sea*

Due to coastal erosion and development of estuaries the land may be flooded and the radionuclides will be released into a marine environment. Exposure pathways included in the dose conversion factor due to release into a sea are:

- consumption of seafood (fish, crustacea and molluscs). We assumed the human consumption rate of crustacea and molluscs to be 1 kg a^{-1}.
- ingestion of agricultural produce contaminated with seaspray. The seaspray concentration factor (k_{ss}) and the volume of seaspray returned to land (S_{sp}) are in accordance with VEOS [Kö89].

- inhalation of seaspray and beach sediment. We assumed a beach occupancy of 50 h a^{-1}. The inhalation rate of beach sediments (I_{bs}) and the inhalation rate of seaspray (I_{ss}) are in accordance with VEOS [Kö89].

Appendix K gives the parameters which differ from the calculations for release in a river.

6.2 Results and conclusions

The dose of mobile radionuclides released into the deeper soil layers will be comparable to their dose after release into a river (Table 6.1). Immobile radionuclides, which are more strongly adsorbed to the soil, are hardly transported towards the surface soil. This results in a lower dose.

Table 6.1. The influence of the release point on the dose conversion factors $(\text{Sv a}^{-1})(\text{Bq a}^{-1})^{-1}$

release point	Tc-99	Th-229
river	8.42E-18	1.44E-14
deeper soil layers	1.96E-17	9.41E-17
well	3.93E-14	6.72E-11
lake	8.80E-15	4.80E-12
sea	3.78E-21	1.32E-18

Release into a well results in the highest dose conversion factor for all release points. We assumed the total flux of radionuclides to be released in the withdrawn groundwater. Because of the high uncertainty in the amount of groundwater withdrawn the uncertainty in this dose conversion factor will probably be high.

The dilution of the radionuclides in a lake depends largely on the flow of water out of the lake. A conservative option is chosen in which, except for irrigation, no flow of water out of the lake is assumed. Therefore, the dose conversion factor will be high.

The dose conversion factors for release in a sea are several orders of magnitude smaller, compared with release into a river, due to the strong dilution in the sea. The results are in agreement with [Kö89].

The uncertainty in the dose conversion factors due to different release points for Tc-99 and Th-229 exceeds the uncertainty in the calculated dose conversion factors (Chapter 4). However, the calculations described for the different release points only give an indication of the influence of the release point on the dose conversion factor because several assumptions for each release point had to be made. The calculations are expected to be conservative. However, the conservatism in the various assumptions is not the same for the different release points. A comparison is therefore not really possible. The calculations are meant to give only an indication of the possible differences between the various release points. Further investigations should give more detailed information about the uncertainty due to different release points.

7 THE DOSE CONVERSION FACTORS IN THE BIOSPHERE FOR DIAPIRISM WITHOUT SUBROSION

7.1 Introduction

If there is a geological upward movement of the repository field (diapirism) without the subsurface dissolution of rock salt by groundwater (subrosion) it is possible that the repository will reach the surface level [PROSA93]. Because of the dry and saline conditions the biosphere will consist of a salt desert in which vegetation is assumed to be absent. It is very unlikely that people will live continuously on the rather small repository field (about 0.5 km^2 [PROSA93]) since they will have to live on crops grown elsewhere and the circumstances outside this field are probably better. However, for the calculations of the dose conversion factors we chose the most conservative option:

- The dose conversion factors were calculated for an adult who lives continuously on the repository field without protection against radiation or dust.
- There is no protective layer on the repository field as a result of deposition of uncontaminated particles from outside the repository field.

Further, we assumed a uniform distribution of the radionuclides in the repository field and an equal resuspension rate of glass and salt particles. Almost the same approach is used as in the VEOS project [Kö89].

Exposure pathways included in the dose conversion factors are therefore the inhalation of radioactive particles and external radiation. Uncontaminated water and food will come from outside the repository field because of the saline conditions. Because there is no flux of radionuclides to the biosphere, as in the scenario with groundwater transport, and because the concentration in the repository field is known as it reaches the surface, the dose conversion factors are given in $(Sv\ a^{-1})(Bq\ m^{-3})^{-1}$ instead of $(Sv\ a^{-1})(Bq\ a^{-1})^{-1}$ as in the other scenario.

We chose a deterministic approach as the effect of less conservative assumptions can easily be calculated. For example, residence for some time outside the repository field results in a total dose reduction by the same relative amount. A reduction in the dust level gives the same relative reduction in the inhalation dose.

Section 7.2 describes the model and parameter values used. Section 7.3 gives the calculated dose conversion factors and in Section 7.4 the results are discussed.

7.2 The model and input parameters used

7.2.1 *EXPO*

The dose conversion factors for the diapirism without subrosion scenario are calculated with the model EXPO [Ui93]. EXPO is derived from MiniBIOS and processes included are external radiation and the inhalation of radioactive particles.

The external radiation due to gamma and X-ray emission is calculated at a level of 1 m above the ground for radionuclides present in the uppermost 30 cm of the soil. The contribution of external radiation due to contamination in deeper layers is small and can be neglected [NRPB79]. The contributions of short-lived daughters are included, with corrections for attenuation and build-up in the soil and air applied.

The dose due to the inhalation is calculated for dust particles with an activity median aerodynamic diameter (AMAD) of 1 μm and an activity per unit of weight equal to the activity in the repository field.

7.2.2 *Input parameters*

Parameters included in the exposure pathways of EXPO are given in Table 7.1 (inhalation) and Table 7.2 (external radiation).

Table 7.1 Parameters included in the exposure pathway "inhalation" (alphabetical order)

parameter	description	value or distribution used
a_{dust}	Dust concentration in air (t m^{-3}) The dust level used is assumed to be twice the normal median dust level in the Netherlands [Me87].	1.0e-10
C_{soil}	Radionuclide concentration in repository field (Bq m^{-3}) The dose conversion factors are calculated for a unit of concentration.	1.0
D_{inh}	Dose factor for inhalation (Sv Bq^{-1}). The dose factors for inhalation for an adult are taken from [No85]. They are in accordance with ICRP-30 [ICRP82]. If more than one value for a nuclide is available, the highest chosen.	Appendix B
I_{inh}	Inhalation rate of air (m^3 a^{-1}). For light work ICRP-30 [ICRP82] assumes an inhalation rate of 1.2 m^3 h^{-1}.	1.0e+04
O_r	Fractional occupancy (-) We assumed that humans live continuously on the repository field.	1.0
ρ	Density of the repository field (t m^{-3}) The same value as in [Kö89] is chosen.	2.2

Table 7.2 Parameters included in the exposure pathway "external radiation"

parameter	description	value or distribution used
C_{soil}	Radionuclide concentration in repository field (Bq m^{-3}) The dose conversion factors are calculated for a unit of concentration.	1.0
$E_{\mathrm{p}}(\mathrm{i})$	Sum of probabilities for γ- or X-ray disintegration in energy bands (-). The sum of the probabilities for γ- or X-ray disintegration in each energy band included is determined from [ICRP83]. The energy bands (MeV) included are: 0.010 0.015 0.020 0.030 0.050 0.100 0.200 0.500 1.000 1.500 2.000 4.000 The determined probability for a specific energy is proportionally divided over the nearest bands [Ui93]. If the energy of the γ or X-ray disintegration is lower than 0.010 MeV or higher than 4.00 MeV, the probability is totally assigned to the boundary of 0.010 MeV, 4.0 MeV respectively. The contribution of short-lived daughters is included.	Appendix C
O_{r}	Fractional occupancy (-) We assumed that humans live continuously on the repository field.	1.0
t_{soil}	Conversion factor for external radiation for radionuclides homogeneously distributed in a 30-cm deep soil layer for discrete energy bands (Sv s^{-1})(Bq m^{-3})$^{-1}$. The energies (MeV) of the various bands are: 0.010 0.015 0.020 0.030 0.050 0.100 0.200 0.500 1.000 1.500 2.000 4.000 The values used are determined from [Ba92].	Appendix C

7.3 Dose conversion factors

Table 7.3 gives dose conversion factors of all radionuclides which may be present in the repository field [PROSA93].

Table 7.3 Dose conversion factors of all radionuclides possibly present in the repository field

nuclide	dose conversion factors (Sv a^{-1})(Bq m^{-3})$^{-1}$		
	inhalation	external radiation	total
C-14	2.591e-16	0.000	2.591e-16
Co-60	2.682e-14	3.130e-09	3.130e-09
Ni-59	1.636e-16	1.987e-14	2.003e-14
Ni-63	3.818e-16	0.000	3.818e-16
Se-79	1.227e-15	0.000	1.227e-15
Rb-87	3.955e-16	0.000	3.955e-16
Sr-90	1.591e-13	0.000	1.591e-13

nuclide	dose conversion factors $(\mathrm{Sv\ a^{-1}})(\mathrm{Bq\ m^{-3}})^{-1}$		
	inhalation	external radiation	total
Zr-93	3.955e-14	3.407e-13	3.802e-13
Mo-93	3.500e-15	2.274e-12	2.278e-12
Nb-94	5.000e-14	1.982e-09	1.982e-09
Tc-99	1.045e-15	0.000	1.045e-15
Pd-107	1.591e-15	0.000	1.591e-15
Sn-126	1.227e-14	2.523e-09	2.523e-09
AI-129	1.909e-14	6.936e-12	6.955e-12
I-129	1.909e-14	6.936e-12	6.955e-12
Cs-135	5.455e-16	0.000	5.455e-16
Cs-137	3.909e-15	7.089e-10	7.089e-10
Sm-147	9.091e-12	0.000	9.091e-12
Sm-151	3.682e-15	1.492e-15	5.174e-15
Eu-154	3.500e-14	1.557e-09	1.557e-09
Cm-248	2.273e-10	2.121e-13	2.275e-10
Pu-244	5.909e-11	1.624e-09	1.684e-09
Cm-244	3.455e-11	3.104e-13	3.486e-11
Pu-240	6.364e-11	2.071e-13	6.384e-11
U-236	1.545e-11	2.772e-13	1.573e-11
Th-232	2.000e-10	3.195e-13	2.003e-10
Ra-228	5.909e-13	1.219e-09	1.219e-09
Th-228	4.182e-11	1.831e-09	1.872e-09
Ra-224	3.864e-13	1.828e-09	1.828e-09
U-232	8.182e-11	5.592e-13	8.238e-11
Cm-245	6.818e-11	1.173e-10	1.855e-10
Pu-241	1.273e-12	6.142e-15	1.279e-12
Am-241	6.364e-11	1.547e-11	7.910e-11
Np-237	5.909e-11	2.983e-10	3.574e-10
U-233	1.682e-11	5.395e-13	1.736e-11
Th-229	2.636e-10	4.087e-10	6.723e-10
Ra-225	9.545e-13	3.785e-12	4.739e-12
Ac-225	1.318e-12	2.960e-10	2.973e-10
Cm-246	6.818e-11	2.769e-13	6.846e-11
Pu-242	5.909e-11	2.553e-13	5.935e-11
Am-242	6.364e-11	2.302e-11	8.666e-11

nuclide	dose conversion factors $(Sv\ a^{-1})(Bq\ m^{-3})^{-1}$		
	inhalation	external radiation	total
Pu-238	5.909e-11	3.171e-13	5.941e-11
U-238	1.455e-11	6.459e-12	2.100e-11
Th-234	4.318e-15	3.107e-11	3.108e-11
U-234	1.636e-11	3.531e-13	1.672e-11
Th-230	3.909e-11	5.502e-13	3.964e-11
Ra-226	1.045e-12	2.185e-09	2.186e-09
Pb-210	1.682e-12	8.682e-13	2.550e-12
Po-210	1.136e-12	1.070e-14	1.147e-12
Cm-247	5.909e-11	4.392e-10	4.982e-10
Am-243	6.364e-11	2.783e-10	3.420e-10
Pu-239	6.364e-11	1.732e-13	6.381e-11
U-235	1.500e-11	2.456e-10	2.606e-10
Pa-231	1.591e-10	5.078e-11	2.099e-10
Ac-227	8.182e-10	5.223e-10	1.341e-09

7.4 Discussion

The dose conversion factors calculated for a biosphere where there is diapirism without subrosion are comparable with the results of VEOS [Kö89]. Differences are due to the increased residence time (one month in VEOS) and the inclusion of low-energy photons in the calculations of the external radiation.

The dose conversion factors calculated result when using a very conservative approach because it is very unlikely that humans will live on the rather small repository field since the circumstances outside the field are probably better. A considerable reduction in the resulting dose can be achieved if humans reside outside the repository field or inside a house. Uncontaminated particles from outside may be deposited on the repository field, giving the field a protective layer. Both the external radiation and contaminated dust level will decrease. The dose conversion factors can also be influenced by a different resuspension rate between the radioactive glass and salt particles. If the salt particles are more quickly resuspended the radionuclide concentration in the surface layer of the repository field will increase. The dose due to external radiation will increase but the dose due to inhalation of contaminated particles will decrease. In the opposite situation the dose due to inhalation will increase and the external radiation will decrease. The exact consequences of the combined effects for the calculated dose conversion factors are not known.

8 CONCLUSIONS AND RECOMMENDATIONS

Dose conversion factors for various radionuclides were determined for a biosphere where the radionuclides are released via groundwater discharge and for a biosphere where the repository reaches the surface. The calculated dose conversion factors should be interpreted as an indication of possible radiation levels in the future, rather than as a prediction, because of the time scales involved in a safety assessment.

The stochastic dose conversion factors for release via groundwater discharge were calculated with the dynamic environmental transfer model MiniBIOS [Ui93] for a farmer who consumes only the (contaminated) produce of his own land. We assumed this to be a conservative option. The radionuclides were released in a river. For a conservative approach the release in a well is probably better, but because of the uncertainty in the salt concentration of the groundwater and the area of the biosphere in which the groundwater is discharged we chose for release in a river. The radiation dose depends on the time period of the model calculation, since the radionuclides accumulate in the soil with time, whereas the required dose conversion factors for EXPOS are constant with time. We decided to define the dose conversion factors for EXPOS as the radiation dose to humans following a fixed time period of accumulation in the soil. Based on the occurrence of glaciation periods in the Netherlands, once in 100,000 years [PROSA93], a time period of 10,000 years was chosen.

For most nuclides the ratio of the minimum to the maximum value of the calculated distribution is 1000 to 100,000. The ratio of the 10 percentile value to the 90 percentile value, however, is usually less than 500. The most important exposure pathways (drinking of water, ingestion of fish and vegetables) and the most important sources of uncertainty in the calculated dose conversion factors were determined.

The dose conversion factors can be improved in various ways:

o The uncertainty in the calculated dose conversion factors can be reduced by reducing the uncertainty in the various distribution coefficients and concentration factors. The correlation between these two parameters should also be investigated. Further, the uncertainty in the sedimentation should be studied. For most other parameters which contribute to the uncertainty in the dose conversion factors, the uncertainty is mainly due to natural variability, which cannot be reduced.

  The MiniBIOS code should be improved for the transport of mobile radionuclides as the calculated inventory gradient in the soil and consequently upward transport in the soil by diffusion is not likely in reality.

  These improvements will probably only influence the dose conversion factors slightly.

In comparison with the overall uncertainty, caused by the selection of the release point and parameters like the river flow, a large research effort in the parameters may not be worthwhile. However, consistency in modelling of the biosphere will be improved.

- The Features, Events and Processes (FEPs) included in the dose conversion factors are described in the final report of PROSA [PROSA93]. In the model validation study BIOMOVS [BIOMOVS92] a similar method for doing safety assessment studies is in development. Using a list of FEPs compiled by different international institutes, all features, events and processes possibly of influence on the dose conversion factors are determined. After screening all the FEPs which should be included in the safety assessment a conceptual model is developed. As the list of FEPs is more extended than the list used in PROSA, it is worthwhile participating in this international study. The confidence in the calculations will be improved. However, a large improvement in the dose conversion factors is not to be expected.
- The interface between the geosphere and biosphere has received hardly any attention. However, it is of importance in the selection of the release point. If information on the salt concentration in the groundwater and the area of the biosphere in which the groundwater is discharged becomes available it will be possible to investigate release points, other than a river. The contribution of the exposure pathway drinking water to the dose conversion factors is relatively high and the release of the radionuclides into a well used by food industries, like breweries, or by thermal baths is of interest.
- The effects of other types of climate are not included in the calculated dose conversion factors. It should be considered including the effects of different types of climate in the dose conversion factors.

The dose conversion factors for the biosphere if the repository reaches the surface level are determined for a very conservative option, which is not likely to appear. In the calculations the same approach was used as in the preceding VEOS project [Kö89] because no new insights were available. Therefore, for this type of biosphere we recommend only further investigations if new insights are available.

In conclusion, the calculated dose conversion factors give a good impression of future radiation levels. We recommend only further investigations if new information on the groundwater properties, future climatic types or new insights in the biosphere if the repository reaches the surface level become available.

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APPENDIX A Distribution coefficients

Distributions used and values found for various radionuclides (alphabetical order) in the literature for the soil distribution coefficients (K_d, (Bq t^{-1})(Bq m^{-3})$^{-1}$) and freshwater distribution coefficients (K_{sr}, (Bq t^{-1})(Bq m^{-3})$^{-1}$).

Ac

K_d : loguniform distribution: 1.0e+2 2.0e+6
2.0e+6 [Kö89], 1.0e+2 1.0e+3 [Ji85], 1.5e+3 [Ba84], 1.0e+4 [IAEA82]

K_{sr} : loguniform distribution: 6.0e+3 6.0e+5 (this is an assumption)
6.0e+4 [Kö89]

Am

K_d : loguniform distribution: 1.0e+0 4.0e+5
3.0e+3 [Kö89], 2.0e+3, 1.2e+3 8.7e+3 [Co84], 1.0e+2, 1.0e+0 3.0e+2 (clay) [Ji85], 6.2e+3 8.2e+1 4.4e+4 (sandy soils) [Ma90], 6.0e+4, 2.4e+1 4.0e+5 (clay) [Ma90], 7.0e+2, 1.0e+0 4.7e+4 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+3 1.0e+6
3.0e+4 [Kö89] [IAEA82], 1.0e+3 1.0e+6 [Co84]

C

K_d : loguniform distribution: 3.0e-1 1.0e+4
1.0e+0, 3.0e-1 1.0e+4 [Ji85]

K_{sr} : loguniform distribution: 4.0e+2 1.0e+4
4.0e+2 1.0e+4 [Ma90]

Cm

K_d : loguniform distribution: 9.8e+1 5.2e+4
3.0e+3 [Kö89], 9.8e+1 5.2e+4 [Co84], 1.0e+2 [Ji85], 1.9e+3, 9.9e+1 5.2e+4 [Ba84]

K_{sr} : loguniform distribution: 1.0e+3 3.0e+5
3.0e+4 [Kö89] [IAEA82], 1.0e+3 3.0e+5 [Co84]

Co

K_d : loguniform distribution: 2.0e-1 3.8e+3
5.0e+3 [Kö89], 1.0e+1, 1.0e+1 1.5e+1 [Co84], 4.7e+1, 2.0e-1 3.8e+3 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+3 3.0e+4
1.0e+3 [Kö89], 2.0e+3 [Co84], 3.0e+4 [IAEA82]

Cs

K_d : loguniform distribution: 1.0e+1 5.0e+4
3.0e+2 [Kö89], 1.0e+3, 1.0e+3 1.0e+4 [Co84], 1.0e+2, 2.0e+2 1.1e+3 [Ji85], 2.2e+3, 1.0e+1 1.0e+4 (sandy soils) [Ma90], 8.4e+3, 6.5e+1 3.1e+4 (clay) [Ma90], 1.0e+3, 1.0e+1 5.2e+4 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+2 5.0e+5
2.0e+4 [Kö89], 1.0e+2 5.0e+5 [Ma90], 3.0e+4 [IAEA82]

Eu

K_d : loguniform distribution: 6.5e+2 1.0e+3
1.0e+3 [Kö89], 6.5e+2 [Ba84]

K_{sr} : loguniform distribution: 1.0e+4 5.0e+6
1.0e+4 [Kö89], 5.0e+6 [Co84]

I

K_d : loguniform distribution: 0.0e+0 1.0e+1
0.0e+0 [Kö89], 6.0e+0 [Co84], 1.0e+1 [Ji85], 5.5e-1, 2.0e-1 1.2e+0 (sandy soils) [Ma90], 1.3e+0, 1.0e+0 1.8e+1 (clay) [Ma90], 6.0e+1 [Ba84]

K_{sr} : loguniform distribution: 5.0e+0 2.0e+3

2.0e+2 [Kö89] [IAEA82], 5.0e+0 2.0e+3 [Ma90]

Mo

K_d : loguniform distribution: 3.7e-1 4.0e+2

9.0e+0 [Co84], 1.0e+0 [Ji85], 1.8e+1, 3.7e-1 4.0e+2 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 3.0e+1 3.0e+3 (this is an assumption)

3.0e+2 [Co84]

Nb

K_d : loguniform distribution: 3.2e+2 2.1e+3

2.1e+3 [Kö89], 3.2e+2 (clay and sandy soils) [Ma90], 3.5e+2 [Ba84]

K_{sr} : loguniform distribution: 1.0e+2 8.3e+5

1.0e+5 [Kö89], 5.3e+2 8.3e+5 [Co84], 1.0e+2 [IAEA82]

Ni

K_d : loguniform distribution: 1.0e+1 1.5e+1

8.0e+1 [Kö89], 2.0e+1 [Co84], 1.0e+1 [Ji85], 3.2e+1 (sandy soils and clay) [Ma90]

K_{sr} : loguniform distribution: 1.0e+4 1.0e+5

1.0e+4 [Kö89], 1.0e+4 [Co84], 1.0e+4 1.0e+5 [Ma90]

Np

K_d : loguniform distribution: 1.6e-1 3.2e+3

5.0e+1 [Kö89], 5.0e+1, 1.6e-1 9.3e+2 [Co84], 1.0e+1 [Ji85], 3.0e-1 3.0e+2 (clay) [Ji85] 3.8e+1, 1.6e-1 3.9e+2 (sandy soils) [Ma90], 1.3e+3, 4.1e+1 3.2e+3 (clay) [Ma90], 3.0e+2, 1.6e-1 9.3e+2 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 2.0e+1 7.0e+4

3.0e+4 [Kö89], 2.0e+1 7.0e+4 [Ma90]

Pa

K_d : loguniform distribution: 1.0e+2 5.6e+4

6.0e+2 [Kö89], 1.0e+2 [Ji85], 1.0e+3 1.0e+4, 1.6e+4, 6.9e+2 5.6e+4 (clay) [Ma90], 2.5e+3 [Ba84]

K_{sr} : loguniform distribution: 3.0e+3 5.0e+7

3.0e+4 [Kö89], 3.0e+3 5.0e+7 [Ma90]

Pb

K_d : loguniform distribution: 4.5e+0 7.6e+3

5.0e+3 [Kö89], 0.0e+0 1.0e+2 [Ji85], 1.0e+3 (sandy soils) [Ma90], 4.0e+2, 4.5e+0 7.6e+3 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 3.0e+3 3.0e+5 (this is an assumption)

3.0e+4 [Kö89]

Pd

K_d : loguniform distribution: 1.0e+1 6.0e+1

1.0e+1 [Ji85], 3.2e+1 (sandy soils) [Ma90], 6.0e+1 [IAEA82]

K_{sr} : loguniform distribution: 1.0e+4 5.0E+04

1.0e+4 5.0e+4 [Ma90]

Po

K_d : loguniform distribution: 1.9e+2 1.1e+3

1.0e+3 [Kö89], 4.1e+2 (clay) [Ma90], 5.2e+2, 1.9e+2 1.1e+3 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 3.0e+3 3.0e+5 (this is an assumption)

3.0e+4 [Kö89]

Pu

K_d : loguniform distribution: 1.1e+1 3.0e+5
1.0e+3 [Kö89] [Ji85], 5.0e+3, 1.8e+1 1.0e+4 [Co84], 1.0e+3, 3.3e+1 6.9e+3 (sandy soils) [Ma90], 4.3e+4, 3.2e+2 1.9e+5 (clay) [Ma90], 4.5e+3, 1.1e+1 3.0e+5 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+4 1.0e+5
3.0e+4 [Kö89] [IAEA82], 1.0e+4 1.0e+5 [Ji85]

Ra

K_d : loguniform distribution: 1.0e+2 3.8e+4
2.0e+2 [Kö89], 2.0e+2 5.0e+2 [Ji85], 1.0e+4, 1.1e+2 3.8e+4 (sandy soils) [Ma90], 4.5e+2 [Ba84]

K_{sr} : loguniform distribution: 7.0e+1 5.0e+4
5.0e+3 [Kö89], 7.0e+1 3.7e+2 [Ji85], 5.0e+2 5.0e+4 [Ma90]

Rb

K_d : loguniform distribution: 1.0e+2 1.0e+3
1.0e+2 [Ji85], 6.0e+2 [Ba84]

K_{sr} : loguniform distribution: 2.5e+2 1.0e+4
2.5e+2 1.0e+4 [Co84]

Se

K_d : loguniform distribution: 1.0e+1 4.1e+2
1.0e+1 [Kö89], 1.0e+0 [Ji85], 1.5e+2 (sandy soils) [Ma90], 4.1e+2 (clay) [Ma90], 3.0e+2 [Ba84]

K_{sr} : loguniform distribution: 2.0e+2 2.0e+4
4.0e+3 [Kö89], 5.0e+3 [Co84], 2.0e+2 2.0e+4 [Ma90]

Sm

K_d : loguniform distribution: 6.5e+2 1.0e+3
1.0e+3 (sandy soils and clay) [Ma90], 6.5e+2 [Ba84]

K_{sr} : loguniform distribution: 6.0e+3 6.0e+5 (this is an assumption)
6.0e+4 [Kö89]

Sn

K_d : loguniform distribution: 1.0e+2 1.07e+3
1.0e+2 [Ji85], 1.1e+3 (clay and sandy soils) [Ma90], 2.5e+2 [Ba84]

K_{sr} : loguniform distribution: 1.0e+4 2.0e+5
2.0e+5 [Kö89], 1.0e+4 5.0e+4 [Co84]

Sr

K_d : loguniform distribution: 1.5e-1 3.3e+3
3.0e+1 [Kö89], 1.0e+2, 9.0e+0 2.8e+2 [Ji85], 2.6e+1, 2.0e+0 1.1e+2 (sandy soils) [Ma90] 4.5e+2, 8.0e+0 1.2e+3 (clay) [Ma90], 3.7e+1, 1.5e-1 3.3e+3 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 9.0e-1 2.0e+3
1.0e+3 [Kö89], 9.0e-1 1.0e+3 [Co84], 2.0e+3 [IAEA82]

Tc

K_d : loguniform distribution: 1.0e-3 1.1e+1 (maximum [Ma90] and minimum [Kö89] not included)
0.0e+0 [Kö89], 1.1e-1 [Co84], 1.0e+0, 3.0e-1 1.5e+0 [Ji85], 1.4e+0, 1.0e-4 3.9e+2 (sandy soils) [Ma90], 2.9e+1, 1.0e-3 1.1e+1 (clay) [Ma90], 3.3e-2, 2.9e-3 2.8e-1 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+1 4.0e+3
2.0e+2 [Kö89] [IAEA82], 1.0e+1 4.0e+3 [Ma90]

Th

K_d : loguniform distribution: 1.0e+4 2.0e+5 (minimum [Ma90] not included)
6.0e+4 [Kö89], 1.0e+4, 1.6e+5 2.0e+5 (clay) [Ji85], 5.0e+4 8.0e+0 1.0e+5 (clay) [Ma90], 1.5e+5, 2.0e+3 1.5e+5 (agricultural soils) [Ba84]

K_{sr} : loguniform distribution: 1.0e+3 1.0e+7
1.0e+4 [Kö89], 1.0e+3 1.0e+7 [Ma90]

U
K_d : loguniform distribution: 1.3e-1 4.4e+3 (Maximum [Ma90] not included)
4.0e+1 [Kö89], 2.0e+2 4.4e+3 (clay) [Ji85], 8.1e+0, 1.3e-1 1.6e+1 (sandy soils) [Ma90], 2.6e+5, 2.0e+2 7.9e+5 (clay) [Ma90], 4.5e+2, 1.1e+1 4.4e+3 (agricultural soils) [Ba84]
K_{sr} : loguniform distribution: 1.0e+1 1.0e+5
1.0e+3 [Kö89], 1.0e+1 [Ji85], 1.0e+1 1.0e+5 [Ma90]

Zr
K_d : loguniform distribution: 3.0e+0 3.0e+3
2.0e+2 [Kö89], 1.0e+1, 3.0e+0 2.4e+1 (podzol) [Ji85], 3.2e+2 (clay and sandy soils) [Ma90], 3.0e+3 [Ba84]
K_{sr} : loguniform distribution: 6.0e+4 1.0e+6
6.0e+4 [Kö89] [IAEA82], 6.0e+4 1.0e+6 [Ma90]

APPENDIX B Nuclide-specific parameters (alphabetical order)

λ : decay constant (s^{-1})
K_{dm} : shallow marine distribution coefficient ($(Bq\ t^{-1})(Bq\ m^{-3})^{-1}$)
K_{mf} : concentration factor for marine fish ($(Bq\ t^{-1})(Bq\ m^{-3})^{-1}$)
T_{exin} : transfer from external to internal (a^{-1})
D_{inh} : dose factor for inhalation ($Sv\ Bq^{-1}$)
D_{ing} : dose factor for ingestion ($Sv\ Bq^{-1}$)

nuclide	λ	K_{dm}	K_{mf}	T_{exin}	D_{inh}	D_{ing}
Ac-225	8.02E-07	1.0E+04	5.0E+01	1.8E-01	2.9E-06	3.0E-08
Ac-227	1.01E-09	1.0E+04	5.0E+01	1.8E-01	1.8E-03	3.8E-06
Am-241	5.08E-11	5.0E+04	1.6E+02	0.0E+00	1.4E-04	5.9E-07
Am-242m	1.44E-10	5.0E+04	1.6E+02	0.0E+00	1.4E-04	5.7E-07
Am-243	2.98E-12	5.0E+04	1.6E+02	0.0E+00	1.4E-04	5.9E-07
C-14	3.83E-12	1.0E+02	2.0E+04	1.0E+00	5.7E-10	5.7E-10
Co-60	4.16E-09	1.0E+04	1.0E+03	9.5E-01	5.9E-08	7.3E-09
Cm-244	1.21E-09	5.0E+04	5.0E+01	0.0E+00	7.6E-05	3.1E-07
Cm-245	2.58E-12	5.0E+04	5.0E+01	0.0E+00	1.5E-04	6.1E-07
Cm-246	4.64E-12	5.0E+04	5.0E+01	0.0E+00	1.5E-04	6.1E-07
Cm-247	1.41E-15	5.0E+04	5.0E+01	0.0E+00	1.3E-04	5.6E-07
Cm-248	6.48E-14	5.0E+04	5.0E+01	0.0E+00	5.4E-04	2.2E-06
Cs-135	9.55E-15	5.0E+02	1.0E+02	1.0E-01	1.2E-09	1.9E-09
Cs-137	7.32E-10	5.0E+02	1.0E+02	1.0E-01	8.6E-09	1.4E-08
Eu-154	2.50E-09	1.0E+04	3.0E+03	3.7E-01	7.7E-08	2.6E-09
I-129	1.39E-15	1.0E+02	1.0E+01	1.0E-01	4.2E-08	6.7E-08
Mo-93	6.28E-12	1.0E+04	2.0E+01	1.0E+00	7.7E-09	3.3E-10
Nb-94	1.08E-12	1.0E+04	1.0E+02	1.8E-01	1.1E-07	1.9E-09
Ni-59	2.93E-13	1.0E+04	1.0E+03	5.0E-02	3.6E-10	5.7E-11
Ni-63	2.29E-10	1.0E+04	1.0E+03	5.0E-02	8.4E-10	1.6E-10
Np-237	1.03E-14	5.0E+04	1.0E+01	1.0E-04	1.3E-04	1.1E-06
Pa-231	6.70E-13	5.0E+03	5.0E+01	1.0E-02	3.5E-04	2.9E-06
Pb-210	9.85E-10	1.0E+04	2.0E+02	0.0E+00	3.7E-06	1.5E-06
Pd-107	3.38E-15	1.0E+04	3.0E+02	5.0E-02	3.5E-09	4.0E-11
Po-210	5.79E-08	1.0E+04	2.0E+03	1.1E-01	2.5E-06	5.1E-07
Pu-238	2.50E-10	5.0E+04	4.0E+01	0.0E+00	1.3E-04	1.1E-07
Pu-239	9.11E-13	5.0E+04	4.0E+01	0.0E+00	1.4E-04	1.2E-07
Pu-240	3.36E-12	5.0E+04	4.0E+01	0.0E+00	1.4E-04	1.2E-07
Pu-241	1.53E-09	5.0E+04	4.0E+01	0.0E+00	2.8E-06	2.4E-09
Pu-242	5.84E-14	5.0E+04	4.0E+01	0.0E+00	1.3E-04	1.1E-07
Pu-244	2.66E-16	5.0E+04	4.0E+01	0.0E+00	1.3E-04	1.1E-07
Ra-224	2.19E-06	5.0E+02	5.0E+02	1.0E-02	8.5E-07	9.9E-08
Ra-225	5.42E-07	5.0E+02	5.0E+02	1.0E-02	2.1E-06	1.0E-07
Ra-226	1.37E-11	5.0E+02	5.0E+02	1.0E-02	2.3E-06	3.6E-07
Ra-228	3.82E-09	5.0E+02	5.0E+02	1.0E-02	1.3E-06	3.8E-07
Rb-87	4.67E-19	5.0E+02	1.5E+01	1.0E+00	8.7E-10	1.3E-09
Se-79	3.38E-13	1.0E+04	6.0E+03	1.0E-01	2.7E-09	2.4E-09
Sm-147	2.07E-19	1.0E+04	3.0E+03	3.7E-01	2.0E-05	5.0E-08
Sm-151	2.44E-10	1.0E+04	3.0E+03	3.7E-01	8.1E-09	1.0E-10
Sn-126	2.19E-13	1.0E+04	5.0E+04	0.0E+00	2.7E-08	5.3E-09

nuclide	λ	K_{dm}	K_{mf}	T_{exin}	D_{inh}	D_{ing}
Sr-90	7.55E-10	5.0E+02	3.0E+00	1.8E-01	3.5E-07	3.5E-08
Tc-99	1.03E-13	1.0E+04	3.0E+01	1.0E-01	2.3E-09	3.9E-10
Th-228	1.15E-08	5.0E+06	6.0E+02	1.0E-02	9.2E-05	1.1E-07
Th-229	2.99E-12	5.0E+06	6.0E+02	1.0E-02	5.8E-04	9.5E-07
Th-230	2.85E-13	5.0E+06	6.0E+02	1.0E-02	8.6E-05	1.4E-07
Th-232	1.56E-18	5.0E+06	6.0E+02	1.0E-02	4.4E-04	7.4E-07
Th-234	3.33E-07	5.0E+06	6.0E+02	1.0E-02	9.5E-09	3.7E-09
U-232	3.05E-10	5.0E+02	1.0E+00	1.0E-02	1.8E-04	3.5E-07
U-233	1.38E-13	5.0E+02	1.0E+00	1.0E-02	3.7E-05	7.8E-08
U-234	8.96E-14	5.0E+02	1.0E+00	1.0E-02	3.6E-05	7.7E-08
U-235	3.12E-17	5.0E+02	1.0E+00	1.0E-02	3.3E-05	7.2E-08
U-236	9.39E-16	5.0E+02	1.0E+00	1.0E-02	3.4E-05	7.3E-08
U-238	4.91E-18	5.0E+02	1.0E+00	1.0E-02	3.2E-05	6.9E-08
Zr-93	1.44E-14	1.0E+04	2.0E+02	1.0E-02	8.7E-08	4.5E-10

APPENDIX C Parameters for external radiation

Conversion factors (Sv s^{-1})(Bq m^{-3})$^{-1}$ for external radiation (t_{soil}) and sum of probabilities for γ- or X-ray disintegration in each energy band (alphabetical order)

Nuclide	Energies of the various bands (MeV)										
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.5000	2.000	4.000
t_{soil}	2.62E-21	6.97E-20	1.42E-19	2.66E-19	5.21E-19	4.14E-18	9.92E-18	2.00E-17	3.97E-17	5.92E-17	7.36E-17	1.3E-16
Ac-225	5.30E-2	1.81E-1	1.03E-2	0.00E 0	2.42E-2	1.76E-1	2.08E-1	2.49E-1	5.53E-3	1.93E-2	2.81E-3	0.00E 0
Ac-227	1.68E-1	4.45E-1	4.57E-2	2.18E-5	2.87E-1	5.36E-1	6.47E-1	3.32E-1	2.64E-2	2.72E-4	0.00E 0	0.00E 0
Am-241	1.57E-1	2.57E-1	2.28E-1	2.33E-2	2.89E-1	6.81E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Am-242m	2.81E-2	3.30E-1	2.94E-1	1.69E-2	2.71E-3	1.16E-1	7.57E-3	7.75E-5	2.44E-3	6.79E-5	0.00E 0	0.00E 0
Am-243	5.06E-2	4.12E-1	2.76E-1	3.00E-2	3.94E-1	1.00E 0	3.10E-1	6.56E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0
C-14	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cm-244	6.40E-3	5.22E-2	3.94E-2	1.83E-3	1.68E-4	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cm-245	4.56E-2	3.38E-1	2.18E-1	1.17E-2	1.64E-2	6.24E-1	1.07E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cm-246	5.93E-3	4.66E-2	3.49E-2	1.59E-3	2.30E-4	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cm-247	1.21E-2	1.28E-1	8.63E-2	7.67E-3	8.02E-2	1.92E-1	2.84E-1	5.11E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cm-248	4.34E-3	3.55E-2	2.69E-2	1.25E-3	1.41E-4	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Co-60	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	9.89E-1	1.01E 0	0.00E 0	0.00E 0
Cs-135	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Cs-137	0.00E 0	0.00E 0	0.00E 0	5.14e-2	5.90e-3	0.00E 0	0.00E 0	5.75e-1	2.75e-1	0.00E 0	0.00E 0	0.00E 0
Eu-154	0.00E 0	0.00E 0	0.00E 0	8.29E-2	1.68E-1	3.16E-1	1.52E-1	2.37E-1	6.86e-1	2.36E-1	5.54E-3	0.00E 0
I-129	0.00E 0	0.00E 0	1.89E-2	6.96E-1	6.08E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Mo-93	0.00e 0	4.54E-1	2.84E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Nb-94	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	8.53E-1	1.15E 0	0.00E 0	0.00E 0	0.00E 0
Ni-59	2.40E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Ni-63	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Np-237	1.31E-1	6.00E-1	2.90E-1	1.35E-1	7.20E-2	5.07E-1	3.25E-1	1.98E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pa-231	1.33E-1	4.75E-1	1.29E-1	7.07E-2	5.06E-3	1.34E-2	7.22E-2	3.81E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pb-210	1.27E-1	1.07E-1	2.79E-3	7.09E-3	3.34E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0

Nuclide	Boundary of energy band (MeV)											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.5000	2.000	4.000
Pd-107	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Po-210	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	4.20E-6	6.41E-6	0.00E 0	0.00E 0	0.00E 0
Pu-238	1.24E-2	6.31E-2	3.54E-2	4.98E-4	2.62E-4	7.45E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pu-239	4.70E-3	2.39E-2	1.35E-2	1.81E-4	2.34E-4	1.33E-4	4.72E-5	3.49E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pu-240	1.17E-2	6.06E-2	1.19E-2	4.74E-4	3.42E-4	6.72E-5	2.80E-6	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pu-241	8.63E-6	4.41E-5	2.52E-5	7.97E-7	7.72E-6	2.66E-5	6.70E-6	3.43E-7	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pu-242	9.81E-3	4.97E-2	2.82E-2	3.88E-4	2.68E-4	7.58E-5	2.75E-6	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Pu-244	1.16E-1	9.01E-1	6.18E-1	3.33E-2	2.34E-2	3.09E-1	3.28E-1	8.05E-1	7.34E-1	2.47E-2	0.00E 0	0.00E 0
Ra-224	1.32E-1	7.94E-2	9.00E-4	5.55E-3	1.62E-1	2.19E-1	4.68E-1	5.11E-1	1.71E-1	2.99E-2	2.58E-1	1.11E-1
Ra-225	2.83E-2	4.07E-2	1.93E-2	1.45E-1	1.45E-1	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Ra-226	7.33E-2	4.96E-2	3.40E-4	0.00E 0	1.06E-1	1.37E-1	4.18E-1	7.09E-1	3.92E-1	3.08E-1	2.05E-1	1.01E-2
Ra-228	6.11E-2	2.63E-1	4.88E-2	0.00E 0	1.16E-2	1.11E-1	1.97E-1	2.95E-1	5.79E-1	9.84E-2	1.92E-2	0.00E 0
Rb-87	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Se-79	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Sm-147	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Sm-151	0.00E 0	0.00E 0	2.48E-4	4.51E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Sn-126	0.00E 0	0.00E 0	1.44E-1	2.27E-1	1.87E-1	3.72E-1	2.88E-1	2.08E 0	8.37E-1	7.20E-3	0.00E 0	0.00E 0
Sr-90	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Tc-99	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Th-228	1.49E-1	1.45E-1	9.16E-3	5.55E-3	1.66E-1	2.30E-1	4.72E-1	5.11E-1	1.71E-1	2.99E-2	2.58E-1	1.11E-1
Th-229	2.46E-1	7.48E-1	9.01E-2	1.83E-1	3.16E-1	6.91E-1	3.23E-1	2.51E-1	5.53E-3	1.93E-2	2.81E-3	0.00E 0
Th-230	1.54E-2	5.85E-2	7.25E-3	0.00E 0	2.45E-3	1.68E-3	3.66E-4	2.01E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Th-232	1.55E-2	5.76E-2	7.04E-3	0.00E 0	1.59E-3	7.53E-4	1.12E-4	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
Th-234	1.50E-2	6.33E-2	2.79E-2	0.00E 0	3.69E-2	6.67E-2	1.92E-3	4.26E-3	1.22E-2	9.55E-4	4.68E-4	0.00E 0
U-232	1.90E-2	8.10E-2	2.68E-2	0.00E 0	1.80E-3	1.00E-3	2.67E-4	2.34E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0
U-233	1.04E-2	4.19E-2	1.40E-2	4.92E-4	8.41E-4	9.97E-4	5.06E-4	1.21E-4	0.00E 0	0.00E 0	0.00E 0	0.00E 0
U-234	1.61E-2	6.72E-2	2.22E-2	0.00E 0	1.12E-3	4.56E-4	8.31E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
U-235	1.51E-1	6.11E-1	2.99E-1	8.41E-2	4.83E-2	3.55E-1	6.19E-1	1.37E-3	0.00E 0	0.00E 0	0.00E 0	0.00E 0
U-236	1.51E-2	6.30E-2	2.07E-2	2.44E-5	7.53E-4	1.84E-4	2.42E-5	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0
U-238	1.33E-2	5.53E-2	1.82E-2	1.14E-2	1.54E-2	5.07E-5	1.54E-4	2.88E-4	4.04E-3	1.05E-4	9.77E-5	4.28E-5
Zr-93	0.00E 0	6.81E-2	4.25E-2	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E 0	0.00E+0	0.00E 0	0.00E 0

APPENDIX D Concentration factors and transfer factors

Distributions and references used for the various concentration factors and transfer factors (alphabetical order).

F_{be} : Transfer factor to meat (Bq kg^{-1})(Bq d^{-1})$^{-1}$
F_{mi} : Transfer factor to milk (Bq kg^{-1})(Bq d^{-1})$^{-1}$
K_{ff} : Concentration factor for fish (Bq t^{-1})(Bq m^{-3})$^{-1}$
K_{gv} : Concentration factor for green vegetables (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight soil)$^{-1}$
K_{rv} : Concentration factor for root vegetables (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight soil)$^{-1}$
K_{ce} : Concentration factor for cereals (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight soil)$^{-1}$
K_{pa} : Concentration factor for pasture (Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight soil)$^{-1}$

Distributions:

Ac:
F_{be} : loguniform distribution 2.0E-5 6.0E-2
F_{mi} : loguniform distribution 5.0E-6 2.0E-5
K_{ff} : loguniform distribution 4.0E+0 2.5E+1
K_{gv} : loguniform distribution 2.0E-4 3.0E-3
K_{rv} : loguniform distribution 7.7E-5 3.0E-3
K_{ce} : loguniform distribution 1.7E-4 3.0E-3
K_{pa} : loguniform distribution 5.1E-4 3.0E-3

Am:
F_{be} : loguniform distribution 2.0E-5 1.0E-3
F_{mi} : loguniform distribution 4.0E-7 2.0E-5
K_{ff} : loguniform distribution 2.5E+1 2.5E+2
K_{gv} : loguniform distribution 3.6E-7 2.4E-3
K_{rv} : loguniform distribution 1.0E-5 1.0E-3
K_{ce} : loguniform distribution 2.7E-7 1.0E-3
K_{pa} : loguniform distribution 1.7E-6 1.7E-1

C:
F_{be} : loguniform distribution 2.0E-2 4.0E-2
F_{mi} : loguniform distribution 5.0E-3 2.0E-2
K_{ff} : loguniform distribution 5.0E+2 2.0E+5
K_{gv} : loguniform distribution 2.0E-3 2.0E+0
K_{rv} : loguniform distribution 7.3E-3 1.1E+0
K_{ce} : loguniform distribution 1.3E-1 2.6E+1
K_{pa} : loguniform distribution 3.6E-3 6.3E-1

Cm:
F_{be} : loguniform distribution 2.0E-5 2.0E-4
F_{mi} : loguniform distribution 5.0E-6 2.0E-5
K_{ff} : loguniform distribution 2.5E+1 2.5E+2
K_{gv} : loguniform distribution 2.5E-7 1.0E-3
K_{rv} : loguniform distribution 3.3E-6 1.0E-3
K_{ce} : loguniform distribution 4.2E-8 4.1E-3
K_{pa} : loguniform distribution 7.7E-6 1.3E-3

Co:
F_{be} : loguniform distribution 1.0E-3 1.0E-2
F_{mi} : loguniform distribution 1.0E-4 1.0E-2
K_{ff} : loguniform distribution 2.0E+1 1.0E+3
K_{gv} : loguniform distribution 1.0E-3 6.0E-2
K_{rv} : loguniform distribution 1.5E-3 1.1E-1
K_{ce} : loguniform distribution 1.0E-2 4.5E-1
K_{pa} : loguniform distribution 3.5E-3 7.0E-2

Cs:
F_{be} : loguniform distribution 2.0E-2 2.0E-1
F_{mi} : loguniform distribution 5.0E-3 8.0E-3
K_{ff} : loguniform distribution 1.0E+1 1.4E+4
K_{gv} : loguniform distribution 2.4E-4 6.7E+1
K_{rv} : loguniform distribution 4.4E-4 1.2E+1
K_{ce} : loguniform distribution 1.8E-3 5.1E+1
K_{pa} : loguniform distribution 3.5E-4 9.8E+0

Eu:
F_{be} : loguniform distribution 2.0E-3 5.0E-3
F_{mi} : constant 2.0E-5
K_{ff} : loguniform distribution 1.0E+1 3.0E+2
K_{gv} : loguniform distribution 4.8E-6 3.0E-3
K_{rv} : loguniform distribution 8.9E-4 3.0E-3
K_{ce} : loguniform distribution 7.3E-5 3.0E-3
K_{pa} : loguniform distribution 1.7E-5 1.7E-2

I:
F_{be} : loguniform distribution 4.0E-3 4.0E-2
F_{mi} : loguniform distribution 3.0E-3 1.0E-2
K_{ff} : loguniform distribution 5.0E+0 1.0E+2
K_{gv} : loguniform distribution 1.9E-2 4.8E-2
K_{rv} : loguniform distribution 5.6E-3 8.8E-2
K_{ce} : loguniform distribution 2.0E-2 3.6E-1
K_{pa} : loguniform distribution 1.4E-2 1.6E-1

Mo :
F_{be} : loguniform distribution 1.0E-3 1.0E-2
F_{mi} : loguniform distribution 1.0E-3 2.0E-3
K_{ff} : constant 1.0E+1
K_{gv} : loguniform distribution 1.3E-2 6.0E-1
K_{rv} : loguniform distribution 1.3E-2 8.0E-1
K_{ce} : loguniform distribution 5.0E-2 4.8E+0
K_{pa} : loguniform distribution 4.3E-2 1.3E+0

Nb:
F_{be} : loguniform distribution 3.0E-7 3.0E-1
F_{mi} : loguniform distribution 4.0E-7 2.0E-2
K_{ff} : loguniform distribution 3.0E+1 3.0E+4
K_{gv} : loguniform distribution 2.4E-3 1.3E-2
K_{rv} : loguniform distribution 4.4E-3 2.4E-2
K_{ce} : loguniform distribution 1.0E-2 1.0E-1
K_{pa} : loguniform distribution 3.5E-3 1.9E-2

Ni:
F_{be} : loguniform distribution 2.0E-3 5.0E-3
F_{mi} : loguniform distribution 1.0E-3 2.0E-2
K_{ff} : loguniform distribution 1.0E+2 1.0E+3
K_{gv} : loguniform distribution 2.4E-2 5.0E-2
K_{rv} : loguniform distribution 1.3E-2 5.0E-2
K_{ce} : loguniform distribution 9.0E-3 5.9E-1
K_{pa} : loguniform distribution 7.0E-3 1.5E-1

Np:
F_{be} : loguniform distribution 2.0E-4 1.0E-3
F_{mi} : loguniform distribution 5.0E-6 5.0E-5
K_{ff} : loguniform distribution 1.0E-1 5.0E+1
K_{gv} : loguniform distribution 5.5E-5 5.0E-2
K_{rv} : loguniform distribution 1.0E-3 6.0E-2
K_{ce} : loguniform distribution 1.0E-6 4.0E-2
K_{pa} : loguniform distribution 1.0E-4 5.0E-2

Pa:
F_{be} : loguniform distribution 1.0E-3 8.0E-2
F_{mi} : constant 5.0E-6
K_{ff} : loguniform distribution 5.0E-1 2.0E+2
K_{gv} : loguniform distribution 3.0E-3 4.0E-2
K_{rv} : loguniform distribution 3.0E-3 6.0E-2
K_{ce} : loguniform distribution 3.0E-3 4.0E-2
K_{pa} : loguniform distribution 3.0E-3 1.8E-2

Pb:
F_{be} : loguniform distribution 4.0E-4 1.0E-2
F_{mi} : constant 3.0E-4
K_{ff} : loguniform distribution 6.0E+1 3.0E+2
K_{gv} : loguniform distribution 1.8E-3 8.0E-2
K_{rv} : loguniform distribution 2.0E-3 8.0E-2
K_{ce} : loguniform distribution 8.0E-3 8.0E-2
K_{pa} : loguniform distribution 4.5E-3 8.0E-2

Pd: (analogous to Ni [Ji85])
F_{be} : loguniform distribution 2.0E-3 5.0E-2
F_{mi} : loguniform distribution 1.0E-3 2.0E-2
K_{ff} : loguniform distribution 1.0E+2 1.4E+2
K_{gv} : loguniform distribution 2.4E-3 5.0E+0
K_{rv} : loguniform distribution 8.9E-3 5.0E+0
K_{ce} : loguniform distribution 9.0E-3 5.0E+0
K_{pa} : loguniform distribution 1.2E-2 5.0E+0

Po:
F_{be} : loguniform distribution 3.0E-3 5.0E-3
F_{mi} : loguniform distribution 1.0E-4 3.0E-4
K_{ff} : loguniform distribution 1.0E+1 2.0E+3
K_{gv} : loguniform distribution 2.0E-4 9.0E-3
K_{rv} : loguniform distribution 8.9E-5 9.0E-3
K_{ce} : loguniform distribution 9.0E-6 9.0E-3
K_{pa} : loguniform distribution 4.3E-4 9.0E-3

Pu:
F_{be} : loguniform distribution 2.0E-6 1.0E-3
F_{mi} : loguniform distribution 1.0E-7 3.0E-6
K_{ff} : loguniform distribution 4.0E+0 1.0E+3
K_{gv} : loguniform distribution 1.2E-9 1.2E-1
K_{rv} : loguniform distribution 5.0E-6 1.0E-3
K_{ce} : loguniform distribution 9.1E-9 9.1E-1
K_{pa} : loguniform distribution 1.8E-9 1.8E-1

Ra:
F_{be} : loguniform distribution 5.0E-4 3.0E-2
F_{mi} : loguniform distribution 4.0E-4 3.0E-3
K_{ff} : loguniform distribution 3.0E+0 1.0E+3
K_{gv} : loguniform distribution 3.0E-4 9.0E-2
K_{rv} : loguniform distribution 3.0E-4 9.0E-2
K_{ce} : loguniform distribution 3.0E-4 9.0E-2
K_{pa} : loguniform distribution 3.0E-4 9.0E-2

Rb:
F_{be} : constant 1.0E-2
F_{mi} : loguniform distribution 6.0E-3 1.0E-2
K_{ff} : loguniform distribution 2.0E+2 8.6E+3
K_{gv} : loguniform distribution 1.8E-2 2.0E-1
K_{rv} : loguniform distribution 1.5E-2 2.0E-1
K_{ce} : loguniform distribution 6.3E-2 2.7E-1
K_{pa} : loguniform distribution 2.6E-2 9.0E-1

Se:
F_{be} : loguniform distribution 2.0E-2 3.0E-1
F_{mi} : loguniform distribution 4.0E-3 5.0E-2
K_{ff} : loguniform distribution 5.0E+1 1.0E+4
K_{gv} : loguniform distribution 4.2E-2 6.3E+1
K_{rv} : loguniform distribution 4.5E-2 1.2E+1
K_{ce} : loguniform distribution 4.3E-2 7.2E+1
K_{pa} : loguniform distribution 3.0E-1 1.2E+1

Sm:
F_{be} : loguniform distribution 2.0E-3 5.0E-3
F_{mi} : loguniform distribution 2.0E-5 3.0E-5
K_{ff} : constant 3.0E+1
K_{gv} : loguniform distribution 4.8E-6 3.0E-3
K_{rv} : loguniform distribution 4.0E-5 3.0E-3
K_{ce} : loguniform distribution 7.3E-5 3.0E-3
K_{pa} : loguniform distribution 1.7E-5 1.7E-2

Sn:
F_{be} : loguniform distribution 4.0E-4 8.0E-2
F_{mi} : loguniform distribution 6.0E-4 1.0E-3
K_{ff} : loguniform distribution 3.0E+3 5.0E+4
K_{gv} : loguniform distribution 2.5E-3 1.0E+0
K_{rv} : loguniform distribution 1.3E-3 1.0E+0
K_{ce} : loguniform distribution 2.5E-3 1.0E+0
K_{pa} : loguniform distribution 2.5E-3 1.0E+0

Sr:

F_{be}	:	loguniform distribution	3.0E-4	1.0E-1
F_{mi}	:	loguniform distribution	1.0E-3	3.0E-3
K_{ff}	:	loguniform distribution	1.0E+0	1.0E+3
K_{gv}	:	loguniform distribution	1.2E-3	3.0E+0
K_{rv}	:	loguniform distribution	2.2E-3	5.5E+0
K_{ce}	:	loguniform distribution	9.1E-3	2.3E+1
K_{pa}	:	loguniform distribution	1.8E-3	4.0E+0

Tc:

F_{be}	:	loguniform distribution	1.0E-6	4.0E-2
F_{mi}	:	loguniform distribution	1.0E-5	3.0E-2
K_{ff}	:	loguniform distribution	1.0E+1	2.0E+2
K_{gv}	:	loguniform distribution	3.2E+0	5.1E+1
K_{rv}	:	loguniform distribution	1.8E+0	8.7E+1
K_{ce}	:	loguniform distribution	3.0E+0	8.7E+1
K_{pa}	:	loguniform distribution	2.5E+0	7.4E+1

Th:

F_{be}	:	loguniform distribution	6.0E-5	1.0E-4
F_{mi}	:	constant	5.0E-6	
K_{ff}	:	loguniform distribution	1.0E+1	1.6E+3
K_{gv}	:	loguniform distribution	3.8E-4	5.0E-3
K_{rv}	:	loguniform distribution	5.0E-4	5.0E-3
K_{ce}	:	loguniform distribution	5.0E-4	5.0E-3
K_{pa}	:	loguniform distribution	1.7E-4	5.0E-3

U:

F_{be}	:	loguniform distribution	2.0E-4	3.0E-2
F_{mi}	:	loguniform distribution	4.0E-4	6.0E-4
K_{ff}	:	loguniform distribution	1.0E+0	2.0E+1
K_{gv}	:	loguniform distribution	3.8E-4	5.0E-3
K_{rv}	:	loguniform distribution	5.7E-4	5.0E-3
K_{ce}	:	loguniform distribution	1.3E-3	5.0E-3
K_{pa}	:	loguniform distribution	9.5E-4	5.0E-2

Zr:

F_{be}	:	loguniform distribution	1.0E-6	2.0E-2
F_{mi}	:	loguniform distribution	3.0E-5	6.0E-7
K_{ff}	:	loguniform distribution	3.0E+0	3.0E+2
K_{gv}	:	loguniform distribution	1.2E-4	1.2E-1
K_{rv}	:	loguniform distribution	1.1E-4	2.2E-1
K_{ce}	:	loguniform distribution	1.7E-4	9.1E-1
K_{pa}	:	loguniform distribution	8.8E-5	1.8E-1

References used for the determination of the distributions:

Ac:
K_{ff}: 2.5E+1 [Kö89], 4.0E+0 [Ji85]
K_{gv}: 3.0E-3 [Kö89], 2.0E-4 [Ji85], 4.2E-4 [Ba84], 1.0E-3 [IAEA82], 2.5E-3 [Ja85], 3.0E-3 [Ko90]
K_{rv}: 3.0E-3 [Kö89], 3.0E-4 [Ji85], 7.7E-5 [Ba84], 1.0E-3 [IAEA82], 2.5E-3 [Ja85], 3.0E-3 [Ko90]
K_{ce}: 3.0E-3 [Kö89], 1.7E-4 [Ji85], 3.2E-4 [Ba84], 1.0E-3 [IAEA82], 2.5E-3 [Ja85], 3.0E-3 [Ko90]
K_{pa}: 3.0E-3 [Kö89], 5.1E-4 [Ji85], 6.1E-4 [Ba84], 7.0E-4 [IAEA82], 2.5E-3 [Ja85], 3.0E-3 [Ko90]

F_{be}: 2.0E-5 [IAEA82], 4.0E-4 [Si82], 6.0E-2 [Ji85], 6.0E-2 [Ko90]
F_{mi}: 2.0E-5 [IAEA82], 2.0E-5 [Si82], 5.0E-6 [Ji85], 2.0E-5 [Ko90]

Am:
K_{ff}: 5.0E+1 [Kö89], 1.6E+2 [Co84], 3.0E+1 [IAEA82], 2.5E+1 [Ko90], 2.5E+1 2.5E+2 [IAEA93]
K_{gv}: 1.0E-3 [Kö89], 2.0E-4 [Ji85], 1.0E-3 [IAEA82], 5.0E-5 [Ja85], 3.0E-4 [Ko90], 3.6E-7 2.4E-3 [Co84]
K_{rv}: 1.0E-3 [Kö89], 3.0E-4 [Ji85], 5.5E-5 [Ba84], 1.0E-3 [IAEA82], 1.0E-5 [Ja85], 3.0E-4 [Ko90]
K_{ce}: 1.0E-5 [Kö89], 2.2E-5 [Ji85], 1.0E-3 [IAEA82], 5.0E-6 [Ja85], 3.0E-4 [Ko90], 2.7E-7 9.1E-4 [Co84]
K_{pa}: 1.0E-3 [Kö89], 5.0E-4 [Ji85], 7.0E-4 [IAEA82], 1.0E-4 [Ja85], 3.0E-4 [Ko90], 1.7E-6 1.7E-1 [Co84]
F_{be}: 2.0E-5 [IAEA82], 1.0E-4 [Si82], 2.0E-4 [Ji85], 5.0E-4 [Ko90], 4.0E-5 1.0E-3 [IAEA93]
F_{mi}: 4.0E-7 [IAEA82], 2.0E-6 [IAEA93], 3.0E-6 [Si82], 4.0E-7 [Ji85], 2.0E-5 [Ko90]

C:
K_{ff}: 2.0E+4 [Kö89], 8.0E+3 [Ko90], 5.0E+2 2.0E+5 [Ma90]
K_{gv}: 2.0E-3 [Kö89], 2.0E+0 [Ma90]
K_{rv}: 7.3E-3 [Kö89], 1.1E+0 [Ma90]
K_{ce}: 1.3E-1 [Kö89], 2.6E+1 [Ma90]
K_{pa}: 3.6E-3 [Kö89], 6.3E-1 [Ma90]
F_{be}: 2.0E-2 [Si82], 4.0E-2 [Ko90]
F_{mi}: 5.0E-3 [Si82], 2.0E-2 [Ko90]

Cm:
K_{ff}: 5.0E+1 [Kö89], 2.5E+1 [Co84], 3.0E+1 [IAEA82], 2.5E+1 [Ko90], 2.5E+1 2.5E+2 [IAEA93]
K_{gv}: 1.0E-3 [Kö89], 2.0E-4 [Ji85], 1.0E-3 [IAEA82], 5.0E-5 [Ja85], 3.0E-4 [Ko90], 2.5E-7 2.4E-5 [Co84]
K_{rv}: 1.0E-3 [Kö89], 3.0E-4 [Ji85], 3.3E-6 [Ba84], 1.0E-3 [IAEA82], 1.0E-5 [Ja85], 3.0E-4 [Ko90]
K_{ce}: 1.0E-5 [Kö89], 1.1E-3 [Ji85], 1.0E-3 [IAEA82], 5.0E-6 [Ja85], 3.0E-4 [Ko90], 4.2E-8 4.1E-3 [Co84]
K_{pa}: 1.0E-3 [Kö89], 5.0E-4 [Ji85], 7.0E-4 [IAEA82], 1.0E-4 [Ja85], 3.0E-4 [Ko90], 7.7E-6 1.3E-3 [Co84]
F_{be}: 2.0E-5 [IAEA82], 2.0E-5 [Si82], 2.0E-4 [Ji85], 2.0E-4 [Ko90]
F_{mi}: 2.0E-5 [IAEA82], 2.0E-5 [Si82], 5.0E-6 [Ji85], 2.0E-5 [Ko90]

Co:
K_{ff}: 1.0E+3 [Kö89], 1.0E+2 [Ko90], 3.0E+2 [IAEA82], 2.0E+1 3.3E+2 [IAEA93]
K_{gv}: 1.0E-3 [Kö89], 6.0E-2 [Co84], 2.4E-3 [Ba84], 3.0E-2 [IAEA82], 2.0E-2 [Ko90]
K_{rv}: 2.0E-3 [Kö89], 1.1E-1 [Co84], 1.5E-3 [Ba84], 3.0E-2 [IAEA82], 2.0E-2 [Ko90]
K_{ce}: 1.0E-2 [Kö89], 4.5E-1 [Co84], 1.8E-2 [Ba84], 3.0E-2 [IAEA82], 2.0E-2 [Ko90]
K_{pa}: 1.0E-2 [Kö89], 2.0E-2 [Ko90], 3.5E-3 [Ba84], 7.0E-2 [IAEA82]
F_{be}: 1.0E-3 [Si82], 1.0E-2 [Ko90], 3.0E-2 [IAEA82], 1.0E-2 [IAEA93]
F_{mi}: 2.0E-3 [Si82], 2.0E-4 [Ko90], 2.0E-3 [IAEA82], 1.0E-04 1.0E-02 [IAEA93]

Cs:
K_{ff}: 1.0E+2 [Kö89], 1.0E+1 1,4E+4 [Ma90], 2.0E+3 [IAEA82], 1.5E+3 [Ko90]
K_{gv}: 2.0E-2 [Kö89], 2.4E-4 6.7E+1 [Co84], 1.3E-2 [Ji85], 2.0E-2 [Ma90], 3.0E-2 [IAEA82], 3.0E-2 [Ja85], 5.0E-2 [Ko90]
K_{rv}: 1.0E-2 [Kö89], 4.4E-4 1.2E+1 [Co84], 8.0E-3 [Ji85], 5.0E-3 [Ma90], 3.0E-2 [IAEA82], 5.0E-2 [Ja85], 5.0E-2 [Ko90]
K_{ce}: 1.0E-2 [Kö89], 1.8E-3 5.1E+1 [Co84], 1.3E-2 [Ji85], 6.0E-3 [Ma90], 3.0E-2 [IAEA82], 5.0E-2 [Ja85], 5.0E-2 [Ko90]
K_{pa}: 2.0E-2 [Kö89], 3.5E-4 9.8E+0 [Co84], 2.0E-2 [Ji85], 1.4E-2 [Ma90], 1.8E-2 [IAEA82], 1.1E-1 [Ja85], 5.0E-2 [Ko90]
F_{be}: 2.0E-2 [IAEA82], 5E-2 2E-1 [IAEA93], 3.0E-2 [Si82], 3.0E-2 [Ji85], 3.0E-2 [Ko90]
F_{mi}: 8.0E-3 [IAEA82], 8.0E-3 [IAEA93], 7.0E-3 [Si82], 7.0E-3 [Ji85], 5.0E-3 [Ko90]

Eu:
K_{ff}: 3.0E+2 [Kö89], 1.0E+1 1.5E+2 [IAEA93]

K_{gv}: 3.0E-3 [Kö89], 3.0E-3 [Ko90], 4.8E-6 1.0E-4 [Co84]
K_{rv}: 3.0E-3 [Kö89], 8.9E-4 [Ba84], 2.0E-3 [IAEA82], 3.0E-3 [Ko90]
K_{ce}: 3.0E-3 [Kö89], 2.0E-3 [IAEA82], 3.0E-3 [Ko90], 7.3E-5 8.2E-4 [Co84]
K_{pa}: 3.0E-3 [Kö89], 7.0E-3 [IAEA82], 3.0E-3 [Ko90], 1.7E-5 1.7E-2 [Co84]
F_{be}: 2.0E-3 [IAEA82], 5.0E-3 [Si82], 5.0E-3 [Ko90]
F_{mi}: 2.0E-5 [IAEA82], 2.0E-5 [Si82], 2.0E-5 [Ko90]

I:
K_{ff}: 1.0E+1 [Kö89], 4.0E+1 [IAEA82], 5.0E+1 [Ko90], 5.0E+0 1.0E+2 [Ma90]
K_{gv}: 2.0E-2 [Kö89], 4.8E-2 [Co84], 1.9E-2 [Ji85], 2.0E-2 [Ma90], 2.0E-2 [IAEA82], 2.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{rv}: 2.0E-2 [Kö89], 8.8E-2 [Co84], 5.6E-3 [Ji85], 2.0E-2 [Ma90], 2.0E-2 [IAEA82], 2.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{ce}: 2.0E-2 [Kö89], 3.6E-1 [Co84], 3.6E-1 [Ji85], 2.0E-2 [Ma90], 2.0E-2 [IAEA82], 2.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{pa}: 2.0E-2 [Kö89], 7.0E-2 [Co84], 1.0E-1 [Ji85], 1.4E-2 [Ma90], 1.6E-1 [IAEA82], 2.0E-2 [Ja85], 1.0E-1 [Ko90]
F_{be}: 1.0E-2 [IAEA82], 4.0E-2 [IAEA93], 7.0E-3 [Si82], 4.0E-3 [Ji85], 1.0E-2 [Ko90]
F_{mi}: 1.0E-2 [IAEA82], 1.0E-2 [IAEA93], 1.0E-2 [Si82], 1.0E-2 [Ji85], 3.0E-3 [Ko90]

Mo:
K_{ff}: 1.0E+1 [IAEA93]
K_{gv}: 6.0E-2 [Co84], 6.0E-1 [Ji85], 3.0E-2 [Ba84], 1.3E-2 [Ja85], 5.0E-2 [Ko90]
K_{rv}: 8.0E-1 [Ji85], 1.3E-2 [Ba84], 1.3E-1 [Ja85], 5.0E-2 [Ko90]
K_{ce}: 4.5E-1 [Co84], 4.8E+0 [Ji85], 5.4E-2 [Ba84], 1.3E-1 [Ja85], 5.0E-2 [Ko90]
K_{pa}: 8.7E-2 [Co84], 1.3E+0 [Ji85], 4.3E-2 [Ba84], 1.3E-1 [Ja85], 2.0E-1 [Ko90]
F_{be}: 1.0E-3 [IAEA93], 1.0E-2 [Si82], 7.0E-3 [Ji85], 7.0E-3 [Ko90]
F_{mi}: 2.0E-3 [IAEA93], 1.0E-3 [Si82], 1.0E-3 [Ji85], 2.0E-3 [Ko90]

Nb:
K_{ff}: 3.0E+1 [Kö89], 3.0E+2 [IAEA82], 2.0E+2 [Ko90], 1.0E+2 3.0E+4 [IAEA93]
K_{gv}: 1.0E-2 [Kö89], 1.0E-2 [IAEA82], 1.0E-2 [Ja85], 1.0E-2 [Ko90], 2.4E-3 1.3E-2 [Co84]
K_{rv}: 1.0E-2 [Kö89], 1.0E-2 [IAEA82], 1.0E-2 [Ja85], 1.0E-2 [Ko90], 4.4E-3 2.4E-2 [Co84]
K_{ce}: 1.0E-2 [Kö89], 1.0E-2 [IAEA82], 1.0E-2 [Ja85], 1.0E-2 [Ko90], 1.8E-2 1.0E-1 [Co84]
K_{pa}: 1.0E-2 [Kö89], 7.0E-3 [IAEA82], 1.0E-2 [Ja85], 1.0E-2 [Ko90], 3.5E-3 1.9E-2 [Co84]
F_{be}: 3.0E-1 [IAEA82], 3.0E-7 [IAEA93], 5.0E-4 [Si82], 3.0E-1 [Ko90]
F_{mi}: 2.0E-2 [IAEA82], 4.0E-7 [IAEA93], 2.0E-2 [Si82], 3.0E-3 [Ko90]

Ni:
K_{ff}: 1.0E+3 [Kö89], 1.0E+2 1.4E+2 [IAEA93], 1.0E+2 [IAEA82], 1.0E+2 [Ko90]
K_{gv}: 2.0E-2 [Kö89], 2.4E-3 2.4E-2 [Co84], 1.7E-2 [Ji85], 2.0E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{rv}: 2.0E-2 [Kö89], 1.6E-2 [Ji85], 1.3E-2 [Ba84], 2.0E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{ce}: 2.0E-2 [Kö89], 9.0E-3 5.9E-1 [Co84], 4.2E-2 [Ji85], 2.0E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{pa}: 2.0E-2 [Kö89], 1.2E-2 1.5E-1 [Co84], 5.0E-2 [Ji85], 7.0E-3 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
F_{be}: 5.0E-3 [IAEA82], 5.0E-3 [IAEA93], 5.0E-2 [Si82], 2.0E-3 [Ji85], 2.0E-3 [Ko90]
F_{mi}: 1.0E-2 [IAEA82], 2.0E-2 [IAEA93], 7.0E-3 [Si82], 1.0E-3 [Ji85], 1.0E-2 [Ko90]

Np:
K_{ff}: 1.0E+0 [Kö89], 1.0E-1 5.0E+1 [Ma90], 1.0E+1 [IAEA82], 1.0E+1 [Ko90]
K_{gv}: 1.0E-4 [Kö89], 5.5E-5 2.4E-2 [Co84], 2.7E-2 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{ce}: 1.0E-6 [Kö89], 2.7E-5 3.2E-2 [Co84], 1.7E-2 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 1.0E-2 [Ja85], 2.0E-2 [Ko90]
K_{rv}: 1.0E-3 [Kö89], 6.0E-2 [Ji85], 2.0E-2 [Ma90], 4.0E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]

K_{pa}: 1.0E-4 [Kö89], 7.9E-4 3.2E-2 [Co84], 9.3E-3 [Ji85], 7.3E-3 [Ma90], 1.8E-2 [IAEA82], 5.0E-2 [Ja85], 2.0E-2 [Ko90]
F_{be}: 1.0E-3 [IAEA82], 1.0E-3 [IAEA93], 3.0E-3 [Si82], 2.0E-4 [Ji85], 2.0E-4 [Ko90]
F_{mi}: 5.0E-6 [IAEA82], 5.0E-6 [IAEA93], 5.0E-5 [Si82], 5.0E-6 [Ji85], 5.0E-6 [Ko90]

Pa:
K_{ff}: 5.0E+1 [Kö89], 1.0E+1 [IAEA82], 5.0E-1 2.0E+2 [Ma90]
K_{gv}: 3.0E-3 [Kö89], 2.7E-2 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90]
K_{ce}: 3.0E-3 [Kö89], 1.7E-2 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90]
K_{rv}: 3.0E-3 [Kö89], 6.0E-2 [Ji85], 2.0E-2 [Ma90], 4.0E-2 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90]
K_{pa}: 3.0E-3 [Kö89], 9.3E-3 [Ji85], 7.0E-3 [Ma90], 1.8E-2 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90]
F_{be}: 1.0E-3 [IAEA82], 0.0E-0 [Si82], 8.0E-2 [Ji85], 5.0E-3 [Ko90]
F_{mi}: 5.0E-6 [IAEA82], 5.0E-6 [Si82], 5.0E-6 [Ji85], 5.0E-6 [Ko90]

Pb:
K_{ff}: 2.0E+2 [Kö89], 3.0E+2 [IAEA82], 6.0E+1 [Ko90], 1.0E+2 3.0E+2 [IAEA93]
K_{gv}: 7.0E-2 [Kö89], 1.8E-3 [Ji85], 5.4E-3 [Ba84], 1.0E-2 [IAEA82], 6.8E-2 [Ja85], 8.0E-2 [Ko90]
K_{rv}: 7.0E-2 [Kö89], 2.7E-3 [Ji85], 2.0E-3 [Ba84], 1.0E-2 [IAEA82], 6.8E-2 [Ja85], 8.0E-2 [Ko90]
K_{ce}: 7.0E-2 [Kö89], 1.7E-2 [Ji85], 8.0E-3 [Ba84], 1.0E-2 [IAEA82], 6.8E-2 [Ja85], 8.0E-2 [Ko90]
K_{pa}: 7.0E-2 [Kö89], 4.5E-3 [Ji85], 7.8E-3 [Ba84], 1.6E-2 [IAEA82], 6.8E-2 [Ja85], 8.0E-2 [Ko90]
F_{be}: 8.0E-4 [IAEA82], 4.0E-4 [IAEA93], 1.0E-2 [Si82], 4.0E-4 [Ji85], 4.0E-4 [Ko90]
F_{mi}: 3.0E-4 [IAEA82], 3.0E-4 [Si82], 3.0E-4 [Ji85], 3.0E-4 [Ko90]

Pd: (analogous to Ni [Ji85])
K_{ff}: 1.0E+2 1.4E+2 [IAEA93]
K_{gv}: 2.4E-3 2.4E-2 [Co84], 1.7E-2 [Ji85], 5.0E+0 [Ja85], 2.0E-2 [Ko90]
K_{rv}: 1.6E-2 [Ji85], 8.9E-3 [Ba84], 5.0E+0 [Ja85], 2.0E-2 [Ko90]
K_{ce}: 9.0E-3 5.9E-1 [Co84], 4.2E-2 [Ji85], 5.0E+0 [Ja85], 2.0E-2 [Ko90]
K_{pa}: 1.2E-2 1.5E-1 [Co84], 5.0E-2 [Ji85], 5.0E+0 [Ja85], 2.0E-2 [Ko90]
F_{be}: 5.0E-3 [IAEA82], 5.0E-3 [IAEA93], 5.0E-2 [Si82], 2.0E-3 [Ji85], 2.0E-3 [Ko90]
F_{mi}: 1.0E-2 [IAEA82], 2.0E-2 [IAEA93], 7.0E-3 [Si82], 1.0E-3 [Ji85], 1.0E-2 [Ko90]

Po:
K_{ff}: 2.0E+3 [Kö89], 5.0E+1 [IAEA82], 3.0E+2 [Ko90], 1.0E+1 5.0E+2 [IAEA93]
K_{gv}: 1.0E-3 [Kö89], 3.0E-4 [Ba84], 2.0E-4 [IAEA82], 9.0E-3 [Ko90]
K_{rv}: 6.0E-4 [Kö89], 8.9E-5 [Ba84], 2.0E-4 [IAEA82], 9.0E-3 [Ko90]
K_{ce}: 9.0E-6 [Kö89], 3.6E-4 [Ba84], 2.0E-4 [IAEA82], 9.0E-3 [Ko90]
K_{pa}: 1.0E-3 [Kö89], 4.3E-4 [Ba84], 7.0E-4 [IAEA82], 9.0E-3 [Ko90]
F_{be}: 3.0E-3 [IAEA82], 5.0E-3 [IAEA93], 2.0E-3 [Si82], 5.0E-3 [Ko90]
F_{mi}: 1.0E-4 [IAEA82], 3.0E-4 [IAEA93], 2.0E-4 [Si82], 3.0E-4 [Ko90]

Pu:
K_{ff}: 4.0E+1 [Kö89], 1.0E+3 [Co84], 4.0E+0 [IAEA82], 8.0E+0 [Ko90], 4.0E+0 2.5E+2 [IAEA93]
K_{gv}: 1.0E-4 [Kö89], 1.4E-4 [Ji85], 5.0E-4 [IAEA82], 1.0E-5 [Ja85], 4.0E-4 [Ko90], 1.2E-9 1.2E-1 [Co84]
K_{rv}: 1.0E-3 [Kö89], 3.0E-4 [Ji85], 1.0E-5 [Ba84], 5.0E-4 [IAEA82], 5.0E-6 [Ja85], 4.0E-4 [Ko90]
K_{ce}: 1.0E-6 [Kö89], 1.8E-3 [Ji85], 5.0E-4 [IAEA82], 1.0E-5 [Ja85], 4.0E-4 [Ko90], 9.1E-9 9.1E-1 [Co84]
K_{pa}: 1.0E-4 [Kö89], 3.8E-4 [Ji85], 1.8E-4 [IAEA82], 5.0E-5 [Ja85], 8.0E-5 [Ko90], 1.8E-9 1.8E-1 [Co84]
F_{be}: 1.0E-5 [IAEA82], 1.0E-4 [Si82], 2.0E-6 [Ji85], 3.0E-4 [Ko90], 2E-5 1E-3 [IAEA93]
F_{mi}: 1.0E-7 [IAEA82], 1.0E-6 [IAEA93], 3.0E-6 [Si82], 1.0E-7 [Ji85], 1.0E-7 [Ko90]

Ra:
K_{ff}: 5.0E+2 [Kö89], 5.0E+1 [IAEA82], 1.0E+1 [Ko90], 3.0E+0 1.0E+3 [Ma90]
K_{gv}: 3.0E-4 [Kö89], 1.6E-3 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 1.4E-3 [Ja85], 9.0E-2 [Ko90]
K_{ce}: 3.0E-4 [Kö89], 1.4E-2 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 1.4E-3 [Ja85], 9.0E-2 [Ko90]

K_{rv}: 3.0E-4 [Kö89], 3.0E-3 [Ji85], 1.0E-2 [Ma90], 4.0E-2 [IAEA82], 1.4E-3 [Ja85], 9.0E-2 [Ko90]
K_{pa}: 3.0E-4 [Kö89], 4.0E-3 [Ji85], 7.0E-3 [Ma90], 3.5E-2 [IAEA82], 1.4E-3 [Ja85], 3.0E-2 [Ko90]
F_{be}: 5.0E-4 [IAEA82], 7.0E-3 [Si82], 9.0E-4 [Ji85], 9.0E-4 [Ko90], 3.0E-2 9.0E-4 [IAEA93]
F_{mi}: 6.0E-4 [IAEA82], 1.0E-3 [IAEA93], 4.0E-4 [Si82], 4.0E-4 [Ji85], 3.0E-3 [Ko90]

Rb:
K_{ff}: 2.0E+3 [Ko90], 2.0E+2 8.6E+3 [IAEA93]
K_{gv}: 3.6E-2 [Co84], 3.0E-2 [Ji85], 1.8E-2 [Ba84], 2.0E-1 [Ja85], 9.0E-2 [Ko90]
K_{rv}: 4.5E-2 [Ji85], 1.5E-2 [Ba84], 2.0E-1 [Ja85], 9.0E-2 [Ko90]
K_{ce}: 2.7E-1 [Co84], 2.7E-1 [Ji85], 6.3E-2 [Ba84], 2.0E-1 [Ja85], 9.0E-2 [Ko90]
K_{pa}: 5.2E-2 [Co84], 7.5E-2 [Ji85], 2.6E-2 [Ba84], 2.0E-1 [Ja85], 9.0E-1 [Ko90]
F_{be}: 1.0E-2 [IAEA93], 1.0E-2 [Si82], 1.0E-2 [Ko90]
F_{mi}: 1.0E-2 [IAEA93], 1.0E-2 [Si82], 6.0E-3 [Ko90]

Se:
K_{ff}: 6.0E+3 [Kö89], 5.0E+1 1.0E+4 [Ma90], 2.0E+2 [Ko90]
K_{gv}: 1.0E+0 [Kö89], 2.4E-1 6.3E+1 [Co84], 4.2E-2 [Ji85], 5.0E-1 [Ma90], 1.3E+0 [Ja85], 5.0E-1 [Ko90]
K_{ce}: 1.0E+0 [Kö89], 1.8E+0 7.2E+1 [Co84], 4.3E-2 [Ji85], 5.0E-1 [Ma90], 1.3E+0 [Ja85], 5.0E-1 [Ko90]
K_{rv}: 1.0E+0 [Kö89], 4.4E-1 1.2E+1 [Co84], 4.5E-2 [Ji85], 5.0E-1 [Ma90], 1.3E+0 [Ja85], 5.0E-1 [Ko90]
K_{pa}: 1.0E+0 [Kö89], 3.5E-1 1.2E+1 [Co84], 3.0E-1 [Ji85], 3.5E-1 [Ma90], 1.3E+0 [Ja85], 5.0E-1 [Ko90]
F_{be}: 4.0E-2 [Si82], 3.0E-1 [Ji85], 2.0E-2 [Ko90]
F_{mi}: 4.0E-3 [Si82], 4.0E-3 [Ji85], 5.0E-2 [Ko90]

Sm:
K_{ff}: 3.0E+1 [Kö89]
K_{gv}: 1.0E-4 [Kö89], 2.0E-3 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90], 4.8E-6 1.0E-4 [Co84]
K_{rv}: 4.0E-5 [Kö89], 2.0E-3 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90], 8.9E-4 [Ba84]
K_{ce}: 1.0E-4 [Kö89], 2.0E-3 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90], 7.3E-5 8.2E-4 [Co84]
K_{pa}: 5.0E-3 [Kö89], 7.0E-3 [IAEA82], 3.0E-3 [Ja85], 3.0E-3 [Ko90], 1.7E-5 1.7E-2 [Co84]
F_{be}: 2.0E-3 [IAEA82], 5.0E-3 [Ko90]
F_{mi}: 2.0E-5 [IAEA82], 3.0E-5 [Si82], 2.0E-5 [Ko90]

Sn:
K_{ff}: 5.0E+4 [Kö89], 3.0E+3 [IAEA93], 3.0E+3 [Ko90]
K_{gv}: 1.0E+0 [Kö89], 1.2E-1 [Co84], 4.6E-2 [Ji85], 3.6E-3 [Ba84], 2.5E-3 [Ja85], 2.0E-1 [Ko90]
K_{rv}: 1.0E+0 [Kö89], 2.2E-1 [Co84], 6.0E-2 [Ji85], 1.3E-3 [Ba84], 2.5E-3 [Ja85], 2.0E-1 [Ko90]
K_{ce}: 1.0E+0 [Kö89], 9.1E-1 [Co84], 3.6E-1 [Ji85], 5.4E-3 [Ba84], 2.5E-3 [Ja85], 2.0E-1 [Ko90]
K_{pa}: 1.0E+0 [Kö89], 1.8E-1 [Co84], 1.0E-1 [Ji85], 5.3E-3 [Ba84], 2.5E-3 [Ja85], 2.0E-1 [Ko90]
F_{be}: 4.0E-4 [Ji85], 8.0E-2 [Ko90]
F_{mi}: 6.0E-4 [Si82], 1.0E-3 [Ji85], 3.0E-3 [Ko90]

Sr:
K_{ff}: 2.0E+0 [Kö89], 1.0E+0 1.0E+3 [IAEA93], 6.0E+1 [IAEA82], 3.0E+1 [Ko90]
K_{gv}: 2.0E-1 [Kö89], 1.2E-3 3.0E+0 [Co84], 1.5E-1 [Ji85], 2.9E-1 [Ba84], 3.0E-1 [IAEA82], 5.0E-1 [Ja85], 4.0E-1 [Ko90]
K_{rv}: 6.0E-2 [Kö89], 2.2E-3 5.5E+0 [Co84], 1.4E-1 [Ji85], 5.5E-2 [Ba84], 3.0E-1 [IAEA82], 1.0E-1 [Ja85], 4.0E-1 [Ko90]
K_{ce}: 8.0E-2 [Kö89], 9.1E-3 2.3E+1 [Co84], 1.2E-1 [Ji85], 3.0E-1 [IAEA82], 2.3E-1 [Ba84], 1.5E-1 [Ja85], 4.0E-1 [Ko90]
K_{pa}: 5.0E-2 [Kö89], 1.8E-3 4.4E+0 [Co84], 5.8E-1 [Ji85], 4.3E-1 [Ba84], 3.5E-1 [IAEA82], 4.9E-1 [Ja85], 4.0E-1 [Ko90]
F_{be}: 6.0E-4 [IAEA82], 8E-3 1E-1 [IAEA93], 3.0E-4 [Si82], 8.0E-4 [Ji85], 6.0E-4 [Ko90]
F_{mi}: 1.0E-3 [IAEA82], 3.0E-3 [IAEA93], 1.0E-3 [Si82], 1.0E-3 [Ji85], 2.0E-3 [Ko90]

Tc:
K_{ff}: 3.0E+1 [Kö89], 1.0E+1 2.0E+2 [Ma90], 2.0E+1 [IAEA82], 8.0E+1 [Ko90]
K_{gv}: 1.0E+1 [Kö89], 3.2E+0 5.1E+1 [Co84], 1.2E+0 [Ji85], 3.0E+0 [Ja85], 3.0E+0 [Ko90], 5.0E+0 [Ma90]+[IAEA82]
K_{ce}: 1.0E+1 [Kö89], 3.3E+1 3.1E+2 [Co84], 4.5E+0 [Ji85], 5.0E+0 [Ma90], 5.0E+0 [IAEA82], 3.0E+0 [Ja85]+[Ko90]
K_{rv}: 1.0E+1 [Kö89], 6.0E+0 8.7E+1 [Co84], 1.8E+0 [Ji85], 5.0E+0 [Ma90], 5.0E+0 [IAEA82], 3.0E+0 [Ja85]+[Ko90]
K_{pa}: 1.0E+1 [Kö89], 9.5E+0 7.4E+1 [Co84], 2.5E+0 [Ji85], 3.5E+0 [Ma90], 3.5E+0 [IAEA82], 3.0E+0 [Ja85]+[Ko90]
F_{be}: 1.0E-2 [IAEA82], 1.0E-4 1.0E-6 [IAEA93], 1.0E-2 [Si82], 1.0E-3 [Ji85], 4.0E-2 [Ko90]
F_{mi}: 1.0E-2 [IAEA82], 1.0E-3 1.0E-5 [IAEA93], 1.0E-2 [Si82], 3.0E-2 [Ji85], 1.0E-5 [Ko90]

Th:
K_{ff}: 6.0E+2 [Kö89], 3.0E+1 [IAEA82], 3.0E+1 [Ko90], 1.0E+1 1.6E+3 [Ma90]
K_{gv}: 4.0E-3 [Kö89], 3.8E-4 [Ji85], 5.0E-4 [Ma90], 5.0E-4 [IAEA82], 4.2E-3 [Ja85], 5.0E-3 [Ko90]
K_{ce}: 4.0E-3 [Kö89], 7.1E-4 [Ji85], 5.0E-4 [Ma90], 5.0E-4 [IAEA82], 4.2E-3 [Ja85], 5.0E-3 [Ko90]
K_{rv}: 4.0E-3 [Kö89], 5.7E-4 [Ji85], 5.0E-4 [Ma90], 5.0E-4 [IAEA82], 4.2E-3 [Ja85], 5.0E-3 [Ko90]
K_{pa}: 4.0E-3 [Kö89], 9.5E-4 [Ji85], 1.7E-4 [Ma90], 1.8E-4 [IAEA82], 4.2E-3 [Ja85], 5.0E-3 [Ko90]
F_{be}: 1.0E-4 [IAEA82], 6.0E-5 [Si82], 2.0E-4 [Ji85], 2.0E-4 [Ko90]
F_{mi}: 5.0E-6 [IAEA82], 5.0E-6 [Si82], 5.0E-6 [Ji85], 5.0E-6 [Ko90]

U:
K_{ff}: 1.0E+0 [Kö89], 1.0E+1 [IAEA82], 2.0E+0 [Ko90], 2.0E+0 2.0E+1 [Ma90]
K_{gv}: 3.0E-3 [Kö89], 3.8E-4 [Ji85], 3.0E-3 [Ma90], 2.0E-3 [IAEA82], 2.5E-3 [Ja85], 5.0E-3 [Ko90]
K_{ce}: 3.0E-3 [Kö89], 1.3E-3 [Ji85], 3.0E-3 [Ma90], 2.0E-3 [IAEA82], 2.5E-3 [Ja85], 5.0E-3 [Ko90]
K_{rv}: 3.0E-3 [Kö89], 5.7E-4 [Ji85], 3.0E-3 [Ma90], 2.0E-3 [IAEA82], 2.5E-3 [Ja85], 5.0E-3 [Ko90]
K_{pa}: 3.0E-3 [Kö89], 9.5E-4 [Ji85], 2.1E-3 [Ma90], 1.8E-3 [IAEA82], 2.5E-3 [Ja85], 5.0E-2 [Ko90]
F_{be}: 3.0E-2 [IAEA82], 3.0E-4 [IAEA93], 2.0E-4 [Si82], 3.0E-4 [Ji85], 4.0E-4 [Ko90]
F_{mi}: 6.0E-4 [IAEA82], 4.0E-4 [IAEA93], 6.0E-4 [Si82], 4.0E-4 [Ji85], 5.0E-4 [Ko90]

Zr:
K_{ff}: 2.0E+1 [Kö89], 3.0E+0 3.0E+2 [IAEA93], 3.0E+2 [IAEA82], 2.0E+2 [Ko90]
K_{gv}: 2.0E-4 [Kö89], 1.2E-4 1.2E-1 [Co84], 3.4E-3 [Ji85], 2.4E-4 [Ba84], 5.0E-3 [IAEA82], 1.7E-4 [Ja85], 3.0E-3 [Ko90]
K_{rv}: 2.0E-4 [Kö89], 2.2E-4 2.2E-1 [Co84], 2.1E-3 [Ji85], 1.1E-4 [Ba84], 5.0E-3 [IAEA82], 1.7E-4 [Ja85], 3.0E-3 [Ko90]
K_{ce}: 2.0E-4 [Kö89], 9.1E-4 9.1E-1 [Co84], 2.7E-2 [Ji85], 4.5E-4 [Ba84], 5.0E-3 [IAEA82], 1.7E-4 [Ja85], 3.0E-3 [Ko90]
K_{pa}: 2.0E-4 [Kö89], 1.8E-4 1.8E-1 [Co84], 2.1E-2 [Ji85], 8.8E-5 [Ba84], 7.0E-3 [IAEA82], 1.7E-4 [Ja85], 1.0E-3 [Ko90]
F_{be}: 2.0E-2 [IAEA82], 1.0E-6 [IAEA93], 5.0E-4 [Si82], 2.0E-2 [Ji85], 2.0E-2 [Ko90]
F_{mi}: 3.0E-5 [IAEA82], 6.0E-7 [IAEA93], 3.0E-5 [Si82], 3.0E-5 [Ji85], 5.0E-6 [Ko90]

APPENDIX E Description of the transfer coefficients in a terrestrial compartment

$$\lambda_1 = \frac{F}{V}$$

$$\lambda_2 = \frac{A\, I}{V}$$

$$\lambda_3 = \frac{v_{sed}}{l_r}$$

$$\lambda_4 = \frac{r + I_i}{R\, l_{ss}\, \varphi_s} + \frac{D + (R - 1)\, B}{R\, l_{ss}\, l_{ss}}$$

$$\lambda_{41} = \frac{r + I_i}{R\, l_{ds}\, \varphi_s} + \frac{D}{R\, l_{ds}\, l_{ds}}$$

$$\lambda_5 = \frac{D + (R - 1)\, B}{R\, l_{ds}\, l_{ss}}$$

$$\lambda_{51} = \frac{U_p\, V_g}{R\, V_{bs}\, \varphi_s} + \frac{D}{R\, l_{ds}\, l_{bs}}$$

$$\lambda_6 = \frac{(1 - U_p)\, V_g}{R\, V_{bs}\, \varphi_s}$$

$$\lambda_7 = \frac{S\, A}{A_r\, l_{ts}}$$

$$\lambda_8 = \frac{E_{ss}}{l_{ss}}$$

$$\lambda_9 = F_b \frac{\left(\frac{1}{F_b} - 1\right) B_r + D_r}{l_w\, l_b} + \kappa\, v_{rw}$$

$$\lambda_{10} = \frac{D_r + (R_s - 1)\, B_r}{R_s\, l_{ts}\, l_b}$$

$$\lambda_{11} = \frac{D_s}{R_s\, l_{ts}\, l_{ts}}$$

$$\lambda_{12} = \frac{D_s}{R_s\, l_{ts}\, l_{ms}}$$

A : area of contaminated land (m^2)
B : bioturbation coefficient in surface soil ($m^2\ a^{-1}$)
D : diffusion coefficient in surface soil ($m^2\ a^{-1}$)
D_s : diffusion coefficient in bed sediment ($m^2\ a^{-1}$)
F : flow of river ($m^3\ a^{-1}$)
I : annual irrigation rate ($m\ a^{-1}$)
l_b : depth of boundary layer (m)
l_{ds} : depth of deep soil (m)
l_{ss} : depth of surface soil (m)
l_{ts} : depth of top sediment (m)
r : infiltrated rainfall ($m\ a^{-1}$)
R_s : retardation coefficient in sediment (-)
U_p : fraction of groundwater flow to deep soil (-)
V_{bs} : volume of deepest soil layer (m^3)
v_{rw} : velocity of river water ($m\ a^{-1}$)
κ : Schaeffer sedimentation (m^{-1})

A_r : area of river compartment (m^2)
B_r : bioturbation coefficient in sediment ($m^2\ a^{-1}$)
D_r : diffusion coefficient sediment ($m^2\ a^{-1}$)
E_{ss} : erosion rate ($m\ a^{-1}$)
F_b : unsorbed fraction in boundary layer (-)
I_i : infiltrated irrigation water ($m\ a^{-1}$)
l_{bs} : depth of deepest soil layer (m)
l_r : length of river (m)
l_{ms} : depth of middle sediment (m)
l_w : depth of river (m)
R : retardation coefficient in soil (-)
S : heightening of soil by river sediment ($m\ a^{-1}$)
V : volume of river compartment (m^3)
V_g : groundwater flow ($m^3\ a^{-1}$)
v_{sed} : velocity of river sediment ($m\ a^{-1}$)
φ_s : porosity of the soil (-)

APPENDIX F Parameter values or distributions used in uncertainty analyses of the inventory calculations

Distributions or deterministic values of the parameters used in the uncertainty analyses of the inventory calculations.

Nuclide-specific parameters:

Tc-99:

				used value or distribution$^{*)}$
λ	:	decay constant	(s^{-1})	1.0E-13
K_d	:	soil distribution coefficient	($m^3\ t^{-1}$)	1.0E-03
K_{sr}	:	freshwater distribution coefficient	($m^3\ t^{-1}$)	lun: 1.0E+1, 4.0E+3
K_{dm}	:	shallow marine distribution coefficient	($m^3\ t^{-1}$)	1.0E+04
K_{dd}	:	deep marine distribution coefficient	($m^3\ t^{-1}$)	1.0E+04
κ	:	Schaeffer sedimentation	(m^{-1})	lun: 1.0E-15, 2.0E-06
k_{ss}	:	seaspray concentration factor	(-)	1.0
f_{desorb}	:	fraction desorbed in estuary	(-)	0.0

Th-229:

λ	:	decay constant	(s^{-1})	2.99E-12
K_d	:	soil distribution coefficient	($m^3\ t^{-1}$)	2.0E+05
K_{sr}	:	freshwater distribution coefficient	($m^3\ t^{-1}$)	lun: 1.0E+3, 1.0E+7
K_{dm}	:	shallow marine distribution coefficient	($m^3\ t^{-1}$)	5.0E+06
K_{dd}	:	deep marine distribution coefficient	($m^3\ t^{-1}$)	5.0E+06
κ	:	Schaeffer sedimentation	(m^{-1})	lun: 2.0E-06, 1.0E-5
k_{ss}	:	seaspray concentration factor	(-)	1.0
f_{desorb}	:	fraction desorbed in estuary	(-)	0.0

Nuclide-independent parameters:

A	:	area of contaminated land	(m^2)	5.0E+06
B	:	bioturbation coefficient in soil	($m^2\ a^{-1}$)	lun: 1.0E-4, 2.0E-3
B_r	:	bioturbation coefficient in freshwater sediments	($m^2\ a^{-1}$)	nor: 3.16E-5, 6.2E-11
B_{ms}	:	bioturbation coefficient in shallow seas	($m^2\ a^{-1}$)	3.16E-05
B_{md}	:	bioturbation coefficient in deep seas	($m^2\ a^{-1}$)	3.16E-08
D	:	diffusion coefficient in soil	($m^2\ a^{-1}$)	lun: 5.0E-3, 1.1E-1
D_r	:	diffusion coefficient in freshwater sediment	($m^2\ a^{-1}$)	lun: 1.95E-2, 2.9E-1
D_s	:	diffusion coefficient in bed sediment	($m^2\ a^{-1}$)	lun: 5.0E-3, 1.1E-1
D_m	:	marine diffusion coefficient	($m^2\ a^{-1}$)	3.15E-02
d	:	delay before start of release	(a)	0.0E+00
E_{ss}	:	erosion rate	($m\ a^{-1}$)	uni: 0.0E+0, 1.0E-03
F	:	volumetric flow	($m^3\ a^{-1}$)	1.0E+7
I_i	:	irrigation rate	($m\ a^{-1}$)	uni: 5.0E-2, 1.5E-1
l_b	:	depth of freshwater boundary layer	(m)	1.0E-1
l_{mb}	:	depth of marine boundary layer	(m)	5.0E+00
l_c	:	length of local marine coast	(m)	5.0E+04
l_{ds}	:	depth of deep soil layer	(m)	5.0E-01
l_{ms}	:	depth of middle sediment layer	(m)	1.9E+00

l_{mms}	: depth of marine middle sediment layer	(m)	1.9E+00
l_{mw}	: depth of marine boxes	(m)	1.0E+01, 2.0E+01
l_r	: length of river section	(m)	1.0E+04
l_{ss}	: depth of surface soil layer	(m)	3.0E-01
l_{ts}	: depth of top sediment layer	(m)	1.0E-01
l_w	: depth of river	(m)	2.0E+00
l_{us}	: depth of marine top sediment layer	(m)	1.0e-01
r	: depth of infiltrating rainfall	(m a^{-1})	uni: 3.0e-1, 4.0e-1
S	: heightening of soil by river sediment	(m a^{-1})	uni: 0.0E+0, 1.0E-3
S_{sp}	: volume of seaspray returned to land	(m^3 a^{-1} m^{-1})	0.0E+00
S_r	: sedimentation rate in lake	(t m^{-3} a^{-1})	0.0E+00
S_m	: sedimentation rate in marine boxes	(t m^{-3} a^{-1})	2.0E-05
V	: volume of freshwater box	(m^3)	2.0E+05
V_m	: volume of marine box	(m^3)	5.0E+09, 5.0E+15
$V_{m,in}$	: inflow from other marine boxes	(m^3 a^{-1})	1.58E+11
$V_{m,out}$	: outflow to other marine boxes	(m^3 a^{-1})	1.58E+11
v_{sed}	: sediment velocity	(m a-1)	uni: 2.0E+2, 1.5E+3
W	: width of local box	(m)	1.0E+04
v_g	: groundwater velocity	(m a^{-1})	lun: 1.0E-5, 2.0E-1
α_r	: suspended sediment load in freshwater	(t m^{-3})	uni: 1.0E-5, 5.0E-05
α_m	: marine suspended sediment load	(t m^{-3})	1.0E-5, 4.0E-05
φ_s	: soil porosity	(-)	uni: 2.5E-1, 4.5E-1
φ_m	: porosity of marine sediments	(-)	7.5E-01
φ_{fs}	: porosity of freshwater sediments	(-)	uni: 5.0E-1, 8.0E-1
ρ	: dry bulk soil density	(t m^{-3})	uni: 1.0E+0, 1.6E+0
ρ_s	: mineral density of sediments	(t m^{-3})	uni: 2.55, 2.65
ρ_m	: mineral density of marine sediments	(t m^{-3})	2.6E+0
θ	: angle of groundwater flow	(degrees)	1.0E-3

*)
log : lognormal distribution, median, variation coefficient
lun : loguniform distribution, min., max.
nor : normal distribution, mean, variance
uni : uniform distribution, min., max.

APPENDIX G Description of the ingestion pathways of MiniBIOS

$$D_{w} = \frac{C_{rw}}{1 + \alpha_{r} K_{sr}} D_{ing} I_{w}$$

$$D_{ff} = \frac{C_{rw}}{1 + \alpha_{r} K_{sr}} K_{ff} D_{ing} I_{ff}$$

$$D_{c,\,int} = \frac{C_{ts} K_{c}}{\rho} D_{ing} I_{c}$$

$$D_{c,\,soil} = \frac{C_{ts} S_{c}}{\rho + \varphi_{s} \rho_{w}} D_{ing} I_{c} f_{c}$$

$$D_{c,\,irri} = \frac{C_{rw} I_{i} (1 - e^{-\mu_{c} Y_{c}})}{Y_{c} (W_{c} + H_{c})} D_{ing} I_{c} f_{c}$$

$$D_{a,\,dw} = C_{rw} I_{wa} A_{drink} F_{a} D_{ing} I_{a}$$

$$D_{a,\,past} = \frac{C_{ts} K_{p}}{\rho} Z I_{pa} F_{a} D_{ing} I_{a}$$

$$D_{a,\,soil} = \frac{C_{ts} S_{a}}{\rho} I_{pa} F_{a} D_{ing} I_{a}$$

$$D_{a,\,irri} = \frac{C_{rw} I_{i} (1 - e^{-\mu_{p} Y_{p}})}{Y_{p} \left(W_{p} + \frac{N_{a} I_{pa} ndy}{Y_{p}}\right)} I_{pa} F_{a} D_{ing} I_{a}$$

A_{drink}	: fract. of animal drinking water affected	(-)
C_{rw}	: concentration in river water	(Bq m^{-3})
C_{ts}	: concentration in surface soil	(Bq m^{-3})
D_{ing}	: dose factor for ingestion	(Sv Bq^{-1})
F_{a}	: transfer factor animal	(Bq kg^{-1})(Bq d^{-1})$^{-1}$
f_{c}	: fract. of external contamination remaining after processing	(-)
H_{c}	: harvesting rate of crop	(a^{-1})
I_{a}	: consumption of animal produce	(kg a^{-1})
I_{c}	: consumption of crops	(kg a^{-1})
I_{ff}	: consumption of freshwater fish	(t a^{-1})
I_{pa}	: consumption of pasture by animals	(kg d^{-1})
I_{i}	: irrigation rate	(m a^{-1})
I_{w}	: consumption of drinking water	(m^{3} a^{-1})
I_{wa}	: water drunk by animal	(m^{3} d^{-1})
K_{c}	: concentration factor of crops	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$
K_{ff}	: concentration factor of freshwater fish	(Bq t^{-1})(Bq m^{-3})$^{-1}$
K_{p}	: concentration factor of pasture	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$
K_{sr}	: freshwater sediment distribution coefficient	(Bq t^{-1})(Bq m^{-3})$^{-1}$
N_{a}	: density of animals	(m^{-2})
ndy	: number of days per year	(d a^{-1})
S_{a}	: soil uptake as fraction of dry pasture uptake	(-)
S_{c}	: soil contamination, fraction of fresh crop weight	(-)

W_c : weathering rate of crop (a^{-1})
W_p : weathering rate of pasture (a^{-1})
Y_c : yield of crop (kg m^{-2})
Y_p : yield of pasture (kg m^{-2})
Z : weight of wet pasture equivalent to 1 kg dry pasture (-)
α_r : suspended sediment load (t m^{-3})
ρ : density of soil (kg m^{-3})
ρ_w : density of water (kg m^{-3})
φ_s : porosity of soil (-)
μ_c : interception constant of crops (m^2 kg^{-1})
μ_p : interception constant of pasture (m^2 kg^{-1})

APPENDIX H Parameter values or distributions used in the uncertainty analyses

Nuclide-specific parameters:

Tc-99:

			used value or distribution*)
C_{rw}	: concentration in river water	(Bq m^{-3})	con: 9.69E-8
C_{ts}	: concentration in surface soil	(Bq m^{-3})	con: 1.17E-7
D_{ing}	: dose factor	(Sv Bq^{-1})	con: 3.9E-10
F_a	: transfer factor animal	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	lun: 5.0E-4, 5.0E-3
K_c	: concentration factor crops	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	lun: 3.2E 0, 5.1E 1
K_{ff}	: concentration factor freshwater fish	(Bq t^{-1})(Bq m^{-3})$^{-1}$	lun: 1.0E 2, 2.0E 2
K_p	: concentration factor pasture	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	lun: 2.5E 0, 7.4E 1
K_{sr}	: freshwater distribution coefficient	(m^3 t^{-1})	lun: 1.0E 1, 4.0E 3

Th-229:

C_{rw}	: concentration in river water	(Bq m^{-3})	con: 9.72E-8
C_{ts}	: concentration in surface soil	(Bq m^{-3})	con: 3.62E-5
D_{ing}	: dose factor	(Sv Bq^{-1})	con: 9.5E-7
F_a	: transfer factor animal	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	lun: 6.0E-5, 1.0E-4
K_c	: concentration factor crops	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	lun: 3.8E-4, 5.0E-3
K_{ff}	: concentration factor freshwater fish	(Bq t^{-1})(Bq m^{-3})$^{-1}$	lun: 1.0E 1, 1.6E 3
K_p	: concentration factor pasture	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	lun: 1.7E-4, 5.0E-3
K_{sr}	: freshwater distribution coefficient	(m^3 t^{-1})	lun: 5.0E 6, 1.0e 7

Nuclide-independent parameters:

A_{drink}	: fract. of animal drinking water affected	(-)	con: 1.0E+0
f_c	: fract. remaining after processing	(-)	con: 1.0E+0
H_c	: harvesting rate of crop	(a^{-1})	uni: 1.0E 0, 2.0E 0
I_a	: consumption of animal produce	(kg a^{-1})	con: 4.0E+1
I_c	: consumption of crops	(kg a^{-1})	con: 9.6E+1
I_i	: irrigation rate	(m a^{-1})	uni: 5.0E-2, 1.5E-1
I_{ff}	: consumption of freshwater fish	(kg a^{-1})	con: 2.0E+0
I_{pa}	: consumption of pasture by animals	(kg d^{-1})	nor: 1.4E 1, 2.6E0
I_w	: consumption of freshwater	(m^3 a^{-1})	con: 7.5E-1
I_{wa}	: water drunk by animal	(m^3 d^{-1})	uni: 3.0E-2, 1.5E-1
N_a	: density of animals	(km^{-2})	uni: 2.0E 2, 4.0E 2
S_a	: soil uptake as fraction of dry pasture uptake	(-)	uni: 3.0E-2, 5.0E-2
S_c	: soil contamination as fraction of wet crop weight	(-)	uni: 2.8E-4, 6.5E-4
W_c	: weathering rate of crop	(a^{-1})	uni: 1.5E 1, 2.0E 1
W_p	: weathering rate of pasture	(a^{-1})	uni: 1.5E 1, 2.0E 1
Y_c	: yield (wet weight) of crop	(kg m^{-2})	uni: 1.0E 0, 5.0E 0
Y_p	: yield (dry weight) of pasture	(kg m^{-2})	uni: 1.0E 0, 2.0E 0
Z	: weight of wet pasture equivalent to 1 kg dry pasture	(-)	uni: 3.0E 1, 5.0E 1
α_r	: suspended sediment load in freshwater	(t m^{-3})	uni: 1.0E-5, 5.0E-5
μ_c	: interception constant	(m^2 kg^{-1})	uni: 1.0E-1, 5.0E-1

μ_p	: interception constant of pasture	$(m^2\ kg^{-1})$	uni: 2.0E 0, 3.0E 0
φ_s	: soil porosity	(-)	uni: 2.5E-1, 4.5E-1
ρ	: dry bulk soil density	$(t\ m^{-3})$	uni: 1.0E 0, 1.6E 0
ρ_w	: water density	$(t\ m^{-3})$	con: 1.0E+0

*)

log: lognormal distribution, median, variation coefficient
lun: loguniform distribution, min., max.
nor: normal distribution, mean, variance
uni: uniform distribution, min., max.
con: constant

APPENDIX J Parameter values used in the deterministic calculations for different release points

Nuclide-specific parameters:

Tc-99:

			value used
F_l	: transfer factor to liver	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	1.98E-04
F_{me}	: transfer factor to meat	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	1.99E-04
F_{mi}	: transfer factor to milk	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	5.39E-04
K_{ce}	: concentration factor cereals	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.61E+1
K_{ff}	: concentration factor freshwater fish	(Bq t^{-1})(Bq m^{-3})$^{-1}$	4.46E+1
K_d	: soil distribution coefficient	(m^3 t^{-1})	1.04E-01
K_{gv}	: concentration factor green vegetables	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.28E+1
K_p	: concentration factor of pasture	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.35E+1
K_{sr}	: freshwater distribution coefficient	(m^3 t^{-1})	1.98E+2
K_{rv}	: concentration factor root vegetables	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.25E+1
κ	: Schaeffer sedimentation	(m^{-1})	4.44E-11

Th-229:

F_l	: transfer factor to liver	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	7.74E-05
F_{me}	: transfer factor to meat	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	7.74E-05
F_{mi}	: transfer factor to milk	(Bq kg^{-1})(Bq d^{-1})$^{-1}$	5.00E-06
K_{ce}	: concentration factor cereals	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.58E-03
K_{ff}	: concentration factor of freshwater fish	(Bq t^{-1})(Bq m^{-3})$^{-1}$	1.33E+2
K_d	: soil distribution coefficient	(m^3 t^{-1})	4.46E+4
K_{gv}	: concentration factor green vegetables	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.38E-03
K_p	: concentration factor of pasture	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	9.20E-04
K_{sr}	: freshwater distribution coefficient	(m^3 t^{-1})	9.98E+4
K_{rv}	: concentration factor root vegetables	(Bq kg^{-1} wet weight)(Bq kg^{-1} dry weight)$^{-1}$	1.57E-03
κ	: Schaeffer sedimentation	(m^{-1})	4.47E-06

Nuclide-independent parameters:

B	:	bioturbation coefficient soil	(m^2 a^{-1})	4.44E-04
B_r	:	bioturbation coefficient freshwater sediments	(m^2 a^{-1})	3.16E-05
D	:	diffusion coefficient soil	(m^2 a^{-1})	2.34E-02
D_r	:	diffusion coefficient freshwater sediment	(m^2 a^{-1})	7.52E-02
D_s	:	diffusion coefficient bed sediment	(m^2 a^{-1})	2.33E-02
E_{ss}	:	erosion rate	(m a^{-1})	5.00E-04
F	:	volumetric flow	(m^3 a^{-1})	7.00E+7
I_i	:	irrigation rate	(m a^{-1})	1.00E-01
l_w	:	depth of river	(m)	2.67E+0
r	:	depth of infiltrating rainfall	(m a^{-1})	3.50E-01
S	:	heightening of soil by river sediment	(m a^{-1})	5.00E-04
V	:	volume of river compartment	(m^3)	5.65E+5
v_{sed}	:	sediment velocity	(m a-1)	8.48E+2
α_r	:	suspended sediment load in freshwater	(t m^{-3})	3.00E-05
φ_s	:	soil porosity	(-)	3.50E-01
φ_{fs}	:	porosity of freshwater sediment	(-)	6.50E-01
ρ	:	dry bulk soil density	(t m^{-3})	1.30E+0
ρ_s	:	density of freshwater sediment	(t m^{-3})	2.60E+0

APPENDIX K Parameters which differ from the parameters used for release in a river in the calculations of the various release points

Release in a lake

				value used
F	:	volumetric flow	$(m^3\ a^{-1})$	0.00E+00
S	:	heightening of soil by river sediment	$(m\ a^{-1})$	0.00E+00
S_r	:	sedimentation rate in lake	$(t\ m^{-3}\ a^{-1})$	5.00E-06
v_{sed}	:	sediment velocity	$(m\ a^{-1})$	0.00E+00
κ	:	Schaeffer sedimentation	(m^{-1})	0.00E+00

Release in a sea

				value used
b	:	beach occupancy	$(h\ a^{-1})$	5.00E+01
I_{bs}	:	inhalation rate of beach sediments	$(\mu g\ d^{-1})$	5.75E+00
I_{ss}	:	inhalation rate of seaspray	$(m^3\ a^{-1})$	1.00E-11
I_{cr}	:	consumption of crustacea	$(kg\ a^{-1})$	1.00E+00
I_{mo}	:	consumption of molluscs	$(kg\ a^{-1})$	1.00E+00
k_{ss}	:	seaspray concentration factor	(-)	1.00E+00
S_{sp}	:	volume of seaspray returned to land	$(m^3\ a^{-1}\ m^{-1})$	1.00E+00