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The MiniBIOS model (version 1A4) at the RIVM

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PREFACE

In this report we describe the biosphere model, MiniBIOS, in its operation at the RIVM's Laboratory of Radiation Research. We used MiniBIOS in calculations for the research project, PROSA (**PRO**babilistic **S**afety **A**ssessment). PROSA studies the safety consequences of the disposal of radioactive waste in rock-salt formations. The study has resulted in the determination of radiological effects on humans and the characteristics of the disposal concepts relevant to safety. PROSA, one of the studies in phase 1a of the OPLA research programme, is a follow-up to the VEOS project of OPLA phase 1. The PROSA project differs from VEOS in the systematic approach used in the scenario selection and the inclusion of uncertainties.

The PROSA project was 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). Each institute had its own topics of study: ECN modelled the repository and executed the risk calculations; RIVM modelled the groundwater transport in the geosphere (Laboratory of Soil and Groundwater Research) and the transport of the radionuclides in the biosphere, along with the radiological effects (Laboratory of Radiation Research). Finally, the RGD provided the necessary geological expertise.

While this report describes the model used in the biosphere calculations, another RIVM report, no. 715204005, describes the results of the calculations [La93a]. The model and the results are also described in condensed form in the final report of the PROSA project [PROSA93].

VOORWOORD

Dit rapport beschrijft het model MiniBIOS, zoals het operationeel is bij het Laboratorium voor Stralingsonderzoek. MiniBIOS is een rekenmodel voor de biosfeer en toegepast in berekeningen voor het project PROSA. PROSA heeft als doel het bepalen van het gezondheidsrisico voor de mens ten gevolge van de opberging van radioactief afval in zoutformaties alsmede het bepalen van een aantal relevante kenmerken, die voor een verdere selectie van mogelijk geschikte zoutformaties gebruikt kunnen worden. Het onderzoek wordt uitgevoerd in het kader van het Fase-1A onderzoeksprogramma van de commissie OPLA (OPberging te LAnd). PROSA is een vervolg op de in fase 1 uitgevoerde veiligheidsstudie VEOS, en kenmerkt zich door een meer systematische benadering van de scenario selectie en het meenemen van onzekerheden door middel van probabilistische rekentechnieken.

Het project PROSA is een gemeenschappelijk project van het ECN, het RIVM en de RGD. Het ECN draagt zorg 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 en het Laboratorium voor Stralingsonderzoek de modellering van de biosfeer. Daarnaast levert de RGD expertise met betrekking tot de geologische aspecten.

Dit rapport beschrijft uitgebreid de modellering van de biosfeer in het model MiniBIOS. De resultaten van de berekeningen met MiniBIOS zijn beschreven in het RIVM rapport 715204005. De resultaten van het project PROSA en de gevolgde methodiek zijn beschreven in het PROSA-eindrapport.

SUMMARY

This report is to function as the user's guide of the MiniBIOS model, version 1A4 (MiniBIOS_1A4). MiniBIOS is a dynamic simulation model for calculating the transport of radionuclides in the biosphere and the consequential radiation dose to humans. MiniBIOS, a compartment model, consists of a number of terrestrial compartments, subdivided into compartments for water, sediment and soil. A simple ocean model also forms a part of MiniBIOS. The transport of radionuclides in the biosphere is described with transfer coefficients between the compartments. The radiation dose to humans is calculated via various exposure pathways, including ingestion of water, fish, vegetables, meat and milk, inhalation of suspended soil and external irradiation. MiniBIOS has been developed by the National Radiological Protection Board (NRPB) for use in probabilistic assessments of the radiological impacts in disposing radioactive waste. The Laboratory of Radiation Research used the model in PROSA, a study on the safety of the disposal of radioactive waste in salt formations.

This report describes the MiniBIOS_1A4 model. The mathematical description of the model, the organization of the computer code with the input- and output data files (of which examples are shown in the report), and the quality system associated with the model are given in succession. Finally, the report includes a description of the EXPO computer model, which is derived from MiniBIOS. EXPO is designed to calculate the radiation dose to humans residing in a salt desert contaminated with radionuclides. The exposure pathways in EXPO are external irradiation and inhalation of suspended soil. The model was also used in the PROSA study.

SAMENVATTING

Dit rapport vormt de gebruikershandleiding voor het model MiniBIOS, versie 1A4 (MiniBIOS_1A4). MiniBIOS is een dynamisch simulatiemodel voor het berekenen van het transport van radionucliden in de biosfeer en de daaruit volgende stralingsbelasting van de mens. MiniBIOS is een compartimenten model. Het model bevat een aantal terrestrische compartimenten, onderverdeeld in water-, sediment- en bodemcompartimenten, en een aantal zeecompartimenten. Het transport van radionucliden in de biosfeer wordt beschreven met transferfactoren tussen de verschillende compartimenten. In de berekening van de stralingsdosis van de mens zijn verschillende belastingspaden opgenomen, zoals ingestie van water, vis, groente, vlees, melk, inhalatie van stofdeeltjes en externe straling.

Het model MiniBIOS is ontwikkeld door de National Radiological Protection Board (NRPB) voor toepassing in studies naar de veiligheid van de opberging van radioactief afval. Het model is specifiek geschikt voor het uitvoeren van een probabilistische studie, waarbij veel modelberekeningen uitgevoerd moeten worden. Het Laboratorium voor Stralingsonderzoek heeft MiniBIOS_1A4 toegepast in het project PROSA, een studie naar de veiligheid van de opslag van radioactief afval in geologische zoutformaties.

Dit rapport beschrijft het model MiniBIOS_1A4. Achtereenvolgens worden beschreven de wiskundige beschrijving van het model MiniBIOS_1A4, de organisatie van de computer code met de invoer- en uitvoerbestanden, en het kwaliteitssysteem, verbonden met het model. In het rapport zijn tevens voorbeelden opgenomen van invoer- en uitvoerbestanden.

Tenslotte geeft dit rapport een beschrijving van het computer model EXPO. Dit model is afgeleid uit MiniBIOS, en is specifiek voor de berekening van de stralingsbelasting van de mens ten gevolge van een verblijf op een zoutwoestijn, verontreinigd met radionucliden. De belastingspaden in EXPO zijn externe straling en inhalatie van stofdeeltjes. Het model EXPO is ook toegepast in de studie PROSA.

1 INTRODUCTION

The PROSA (PRObabilistic Safety Assessment) project on the safety of the disposal of radioactive waste in rock-salt formations [PROSA93] has two objectives: the determination of the radiological effects on humans and the derivation of the parameters, which influence the radiological effects the most and can be influenced by the choice of the disposal concept.

The methodology used in PROSA is the scenario type of analysis. A scenario is a combination of events and processes which results in the release of radionuclides from the disposal facility into the biosphere. In this type of analysis, various scenarios are composed from an extensive list of features, events and processes. Next, for all selected scenarios the radiological consequences are determined with calculation models; different scenarios may require different calculation models. To accommodate uncertainties PROSA uses probabilistic calculations. In PROSA, three compartments are distinguished: the rock-salt formation, the overburden and the biosphere. The models therefore consist of three successive modules. The REPOS module describes the behaviour of the rock-salt formation and calculates the release of radionuclides from the repository. The MASCOT module describes the groundwater transport of the radionuclides in the overburden and calculates the flux of radionuclides to the biosphere. Finally, the module EXPOS calculates the radiation dose to humans.

In probabilistic assessments multiple model runs are required. To reduce the computing time, the models are usually considerably simplified. In the EXPOS module, the radiation dose to humans is simply calculated by multiplying the flux of a radionuclide to the biosphere by a nuclide-dependent dose conversion factor [PROSA93,St90]. The input parameters for EXPOS are those dose conversion factors. As a consequence, a complete biosphere model, describing the transport of the radionuclides in the biosphere and calculating the radiation dose to humans via the various exposure pathways, is required to determine the input parameters for EXPOS. The various selected scenarios in PROSA lead to two different types of biospheres, each described with a set of dose conversion factors.

In the first type, radionuclides enter the biosphere via the discharge of groundwater, contaminated with radionuclides, into a river. Humans are exposed to radiation via the use of the contaminated river water as drinking water and as irrigation water for agricultural land. The dose conversion factors for this biosphere are calculated with the biosphere model, MiniBIOS [Ma91a]. The MiniBIOS model is a dynamic biosphere transport model developed by the National Radiological Protection Board (NRPB). The model is designed to calculate the radiation dose to humans following the release of radionuclides from a repository of radioactive waste. MiniBIOS is a simplified version of the BIOS model [Ma91b], to be used specifically in probabilistic risk assessments. The model consists of compartments representing soils, rivers, lakes and oceans. The exchange of activity is modelled with transfer coefficients, which encompass a variety of processes. The individual dose is calculated for several exposure pathways, including the intake of contaminated drinking water, ingestion of agricultural products and seafood, external irradiation and inhalation of suspended soil. In the application of the MiniBIOS model to PROSA, the original NRPB version (called MiniBIOS_1A) was slightly adapted. The version of MiniBIOS, operational at the RIVM and used in the calculation of the dose conversion factors, is MiniBIOS_1A4.

In the second type of biosphere, rock salt contaminated with radionuclides reaches the biosphere through a geological upward movement (diapirism). Since the soil consists of rock salt, no agricultural practices are possible. Humans are only exposed to radiation via external exposure and inhalation of suspended soil. Therefore a different set of dose conversion factors is required. The dose conversion factors for this type of biosphere are calculated with the EXPO model. This model is largely based on the description in MiniBIOS of the exposure pathways external irradiation and inhalation of suspended soil.

This report describes the MiniBIOS_1A4 and EXPO models. In Chapter 2 the mathematical formulation of MiniBIOS_1A4 is given, and in Chapter 3 the organization of the MiniBIOS_1A4 model. Chapter 4 describes the quality system associated with the use of the MiniBIOS model. Finally, Chapter 5 describes the EXPO model. For the use of these models in the PROSA project, the reader is referred to the PROSA final report and the RIVM report [PROSA93, La93a].

2 THE MINIBIOS MODEL (MINIBIOS_1A4 VERSION)

2.1 Introduction

The MiniBIOS model is a dynamic biosphere transport model for use in the assessment of the radiological impacts in disposal of radioactive waste [Ma91a]. The model calculates the time-dependent environmental concentrations and radiation dose to humans from a flux of radionuclides from the geosphere. The model, developed by the NRPB, is based on the BIOS model [Ma91b]. MiniBIOS, specifically designed for probabilistic risk assessments, is considerably simplified with respect to BIOS to reduce the amount of computing time.

The MiniBIOS model is a compartment model. Each biosphere component, like rivers and soil layers, is represented by a box. The transport of radionuclides in the biosphere is described with transfer coefficients between the boxes, whereas within a box homogenous mixing is assumed. The transfer of radionuclides in the biosphere is described with a set of first-order linear differential equations:

$$\frac{dN_i}{dt} = \sum_{j \neq i} \lambda_{ji} N_j(t) - \sum_{j \neq i} \lambda_{ij} N_i(t) + S_i(t) - \lambda_0 N_i(t) + \lambda_p N_i^P(t)$$

N_i	number of a given radionuclide in compartment *i*
N_i^p	number of the parent nuclide in compartment *i*
S_i	source term in compartment *i*
λ_{ij}	transfer coefficient from compartment *i* to compartment *j*
λ_0	decay constant of the radionuclide
λ_p	decay constant of the parent nuclide

The radiation dose is determined in three consecutive steps. First, the transfer coefficients between the biosphere compartments are computed from the parameters describing the biosphere. Second, the set of differential equations is solved, resulting in the time-dependent inventories in the compartments. Third, the radiation dose to humans is calculated from the inventories in the relevant compartments.

MiniBIOS is a dynamic model: a flux of radionuclides varying with time results in a time-dependent radiation dose. However, the parameters which define the biosphere are constant in time, with values usually equal to annual averages. Therefore the time resolution of the model is at least one year.

In this chapter the MiniBIOS model, version MiniBIOS_1A4, is described. Section 2.2 describes the structure of the biosphere and the transfer coefficients. The calculation of the radiation dose is described in Section 2.3. Finally, in Section 2.4 the differences between the original NRPB model (MiniBIOS_1A) and the RIVM version (MiniBIOS_1A4) are summarized. The description of the model is largely based on the user's guide for MiniBIOS_1A [Ma91a]. For more detailed information the reader is referred to [Ma91a].

2.2 Compartment structure

The biosphere in MiniBIOS_1A4 consists of a river system with adjacent agricultural land, along with an ocean model (Figure 2.1). The river system is subdivided into a number of river or lake sections. A single river section is composed of seven boxes: one river-water box, three boxes representing river-sediment layers and three boxes representing agricultural land adjacent to the river section. The different river sections are connected sequentially, and activity flows downstream with the river water and the river-sediment bed. The last river section flows into a local marine compartment.

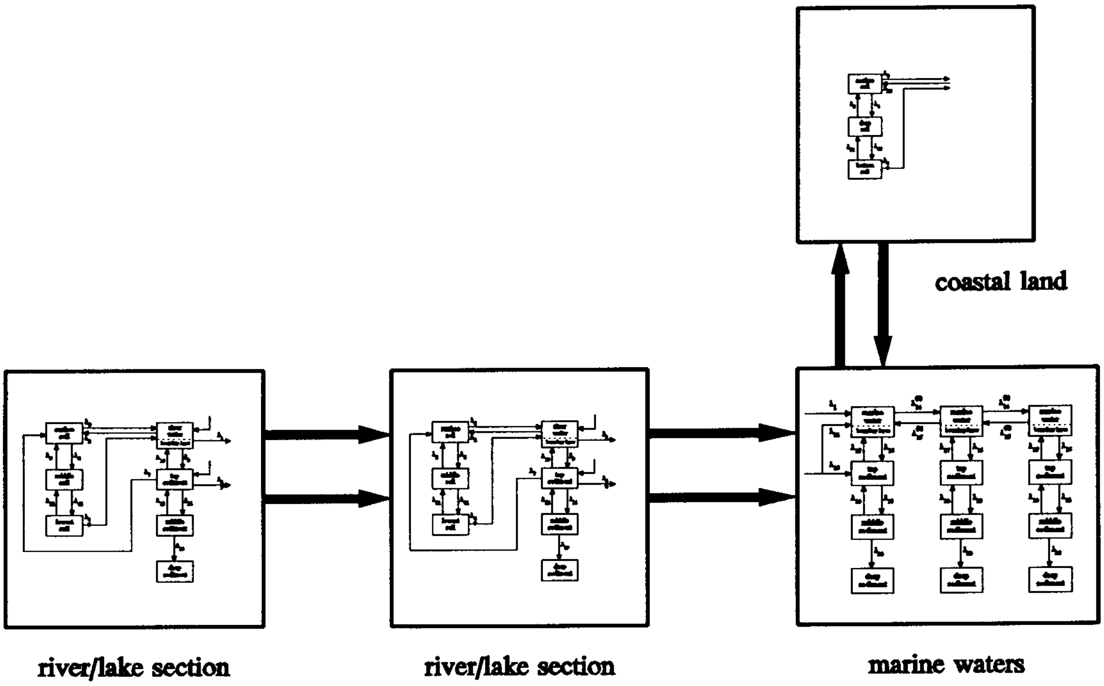

Figure 2.1 Overview of the general compartment structure in MiniBIOS_1A4. The various boxes are given in more detail in Figure 2.2 (river/lake section), Figure 2.3 (marine waters) and Figure 2.4 (coastal land).

The marine biosphere is subdivided into a number of ocean sections. Each section contains four boxes: one marine water box and three boxes representing the marine sediment layers. Activity is exchanged between adjacent marine water boxes. Agricultural land, adjacent to the coast, may become contaminated by seaspray. Therefore the first marine compartment is connected with three soil boxes representing agricultural land near the coast.

A single source of activity is located in the biosphere; six different release locations are possible:

1. release to the river-water box, first river section
2. release to the lowest soil box, first river section
3. release to the surface soil box, first river section
4. release to the middle river-sediment box, first river section
5. release split between the river-water box and the lowest soil box, first river section
6. release to the marine water box, local marine compartment

In this section the transfer factors, which govern the exchange of radionuclides in the biosphere, are described for the terrestrial biosphere (2.2.1), the marine biosphere (2.2.2) and the agricultural land near the coast (2.2.3).

2.2.1 *Terrestrial transfer coefficients*

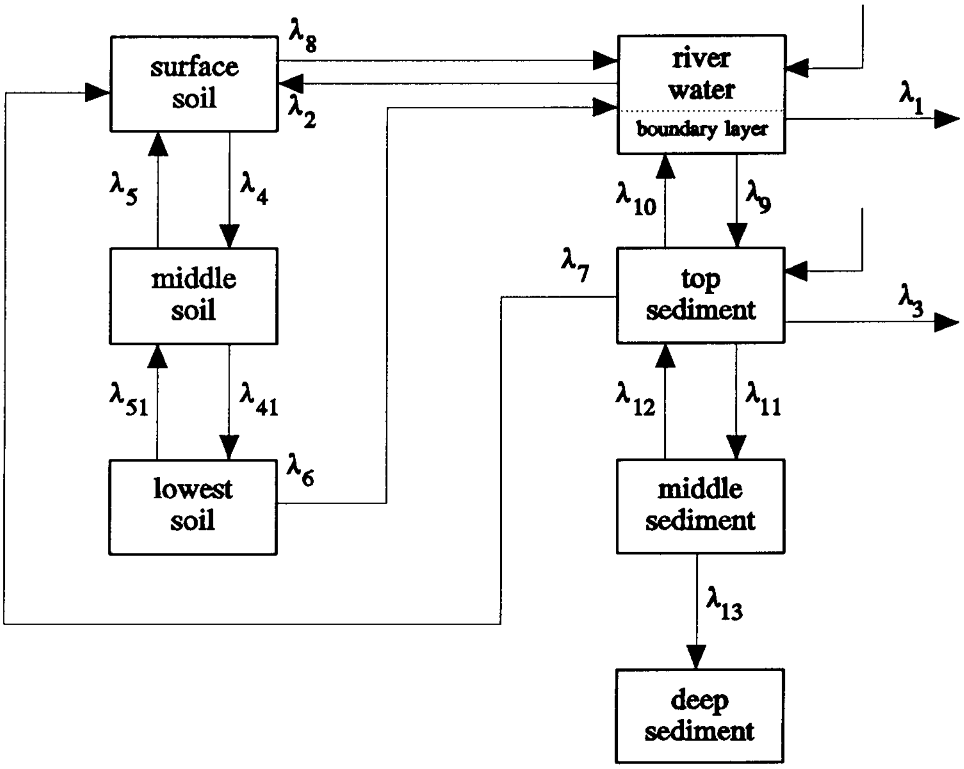

Figure 2.2 Overview of the terrestrial model in MiniBIOS_1A4.

Figure 2.2 shows a river/lake section of the model with the transfer coefficients. A single river/lake section consists of a river-water box with three river-sediment boxes, along with agricultural land subdivided in three soil boxes. The flow of activity downstream the river is described by the transfer coefficients λ_1 (flow of the river water) and λ_3 (flow of river sediment).

The transport of radionuclides between the terrestrial compartments is described by the transfer coefficients λ_1 - λ_{13}. Each transfer coefficient represents a number of processes.

The transfer coefficient λ_1 describes the transport between two adjacent river sections and represents the flow of the river water:

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

F	volumetric flow of the river ($m^3\ a^{-1}$)
V	volume of the river compartment (m^3)

The volumetric flow F of the river water transports the radionuclides downstream to the next river section. The last river section discharges into the local sea.

The transfer coefficient λ_2 describes the transport of radionuclides from the river water to the surface soil and represents the irrigation of agricultural land:

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

A	area of contaminated land (m^2)
I	annual irrigation rate ($m\ a^{-1}$)
V	volume of river compartment (m^3)

It is assumed that an area A of land is annually irrigated with river water, with an irrigation rate I.

The transfer coefficient λ_3 describes the transport between two adjacent river sections and represents the movement of the river sediment:

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

v_{sed}	velocity of river sediment ($m\ a^{-1}$)
l_r	length of river section (m)

The transfer coefficient is expressed directly in terms of the velocity of the river sediment v_{sed}. The last river section discharges into a local marine box.

The transfer coefficient λ_4 describes the transport from the surface soil layer to the middle soil layer and represents the processes: infiltration of water, pore-water diffusion and bioturbation:

$$\lambda_4 = \frac{r + f_{in} \cdot I}{R\, l_{ss}\, \varphi_s} + \frac{D + (R - 1)\, B}{R\, l_{ss}\, \min(l_{ss}, l_{ds})}$$

B	bioturbation coefficient in soil ($m^2\ a^{-1}$)
D	diffusion coefficient in soil ($m^2\ a^{-1}$)
I	annual irrigation rate ($m\ a^{-1}$)
R	retardation coefficient in soil (-)
f_{in}	infiltrated fraction of irrigation water, equal to 0.5 (-)
l_{ss}	depth of surface soil box (m)
l_{ds}	depth of middle soil box (m)
r	infiltrated rainfall ($m\ a^{-1}$)
φ_s	porosity of the soil (-)

The surface soil layer is provided with water by rainfall and irrigation. The soluble fraction of the radionuclides in the surface soil layer can be transported to lower soil layers by the infiltrating rainfall r and the infiltrating irrigation water $f_{in} \cdot I$. It is assumed that the fraction of infiltrated irrigation water is one-half the supplied irrigation water. Like infiltrating water, pore-water diffusion (diffusion coefficient D) transports only the radionuclides in solution. The fraction of activity in the solution is given by R^{-1} and the fraction of activity sorbed onto soil particles is consequently $(1 - R^{-1})$. In this, the retardation factor R is defined as:

$$R = 1 + \frac{\rho_s}{\varphi_s} K_d$$

K_d	soil-groundwater distribution coefficient ($(Bq\ t^{-1})\ (Bq\ m^{-3})^{-1}$)
ρ_s	density of the dry soil ($t\ m^{-3}$). The density of the dry soil, ρ_s, is related to the mineral density of the soil ρ_{min} by $\rho_s = (1-\varphi_s) \cdot \rho_{min}$
φ_s	porosity of the soil (-)

Bioturbation is the process of soil particle transport by biotic species in the soil. Hence, this process transports only the radionuclides attached to soil particles. The sorbed fraction is given by $(1 - R^{-1})$. Bioturbation is expressed as a diffusive process, with a bioturbation coefficient B (in $m^2\ a^{-1}$), which can be calculated from the annual amount of transported soil M (in kg dry soil $m^{-2}\ a^{-1}$) by bioturbation with:

$$B = \frac{M \cdot \min(l_{ss}, l_{ds}) \cdot N_{tpk}}{\rho_s}$$

B	bioturbation coefficient in soil (m^2 a^{-1})
M	annual amount of transported soil (kg dry soil m^{-2} a^{-1})
N_{tpk}	conversion factor 0.001 t kg^{-1}
l_{ss}	depth of surface soil box (m)
l_{ds}	depth of middle soil box (m)
ρ_s	density of the dry soil (t m^{-3})

The transfer coefficient λ_{41} describes the transport of radionuclides from the middle soil box to deeper soil layers and represents the processes of infiltration of water and pore-water diffusion:

$$\lambda_{41} = \frac{r + f_{in} \cdot I}{R\ l_{ds}\ \varphi_s} + \frac{D}{R\ l_{ds}\ \min(l_{ds}, l_{bs})}$$

D	diffusion coefficient in soil (m^2 a^{-1})
I	annual irrigation rate (m a^{-1})
R	retardation coefficient in soil (-)
f_{in}	infiltrated fraction of irrigation water, equal to 0.5 (-)
l_{ds}	depth of middle soil box (m)
l_{bs}	depth of lowest soil box, equal to 5 m
r	infiltrated rainfall (m a^{-1})
φ_s	porosity of the soil (-)

The definition of the various terms in the transfer coefficient λ_{41} is similar to λ_4. It is assumed that the bioturbation process does not occur in the deeper soil layers (at a depth of approximately 80 - 100 cm). The soil is assumed to be homogeneous at all depths. Parameters like the diffusion coefficient D, the retardation coefficient R and porosity ρ_s are therefore identical to the corresponding parameters in the transfer coefficients λ_{41} and λ_4.

The transfer coefficient λ_5 describes the upward transport of radionuclides from the middle soil box to the surface soil box and represents the processes of pore-water diffusion and bioturbation:

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

B	bioturbation coefficient in soil (m^2 a^{-1})

D	diffusion coefficient in soil (m^2 a^{-1})
R	retardation coefficient in soil (-)
l_{ds}	depth of middle soil box (m)
l_{ss}	depth of surface soil box (m)

The definition of the various terms is similar to the description in λ_4. Comparison of the transfer coefficients λ_4 and λ_5 shows that the definition of these transfer coefficients satisfies the condition of no net transport of radionuclides by the processes of bioturbation and diffusion if the radionuclides are uniformly distributed in the soil.

The transfer coefficient λ_{51} describes the transport of radionuclides from the lowest soil box to the middle soil box and represents the processes of pore-water diffusion and upward groundwater flow:

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

D	diffusion coefficient in soil (m^2 a^{-1})
R	retardation coefficient in soil (-)
U_p	fraction of groundwater flow to middle soil box (-)
V_g	groundwater flow out of the lowest soil box (m^3 a^{-1})
V_{bs}	volume of the lowest soil box (m^3)
l_{ds}	depth of middle soil box (m)
l_{bs}	depth of lowest soil box, equal to 5 m
φ_s	porosity of the soil (-)

The diffusion term is similar to the description in λ_4 and it is assumed that the process of bioturbation does not occur in the deeper soil layers. The groundwater level is assumed to be at approximately 0.8 - 1 m below surface level [La93a]. Consequently the groundwater flows through the lowest soil box. The movement of the groundwater is able to transport the radionuclides in solution. The groundwater flow makes a small angle with the horizontal, and U_p is the fraction of the total flow directed into the middle soil box. The remaining fraction (1 - U_p) is directed into the river. The groundwater flow is described with two input parameters, θ, the angle of the flow with the horizontal and v_g, the velocity of the groundwater. The parameters U_p and V_g are easily derived from θ, v_g and the dimensions of the soil boxes [Ma91a].

The transfer coefficient λ_6 describes the transport of radionuclides from the lowest soil box to the river water and represents the process of groundwater flow:

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

R	retardation coefficient in soil (-)
U_p	fraction of groundwater flow to middle soil box (-)
V_g	groundwater flow ($m^3\ a^{-1}$)
V_{bs}	volume of lowest soil box (m^3)
φ_s	porosity of the soil (-)

The groundwater transport is already described in transfer coefficient λ_{51}. An important feature of the model is that the groundwater transport in transfer coefficient λ_6 represents the only mechanism, besides the erosion of the surface soil, to remove radionuclides from the soil system. In reality, however, other processes, like diffusion towards lower soil layers, may remove radionuclides from the top soil layers. Also, immobilization of radionuclides in the deeper soil layers by chemical reactions may effectively prevent radionuclides diffusing upwards again. If the groundwater flow is low, an unwanted accumulation of mobile radionuclides in the soil layers may occur. In these circumstances it is advisable to take λ_6 as an effective removal mechanism for radionuclides from the surface soil layers, consisting of both groundwater movement, diffusion processes and immobilization processes.

The transfer coefficient λ_7 describes the transport of radionuclides from the river sediment to the surface soil and represents a variety of processes, like meandering of the river, dredging and sedimentation during flooding periods.

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

A	area of contaminated land (m^2)
A_r	area of river compartment (m^2)
S	heightening of soil by river sediment ($m\ a^{-1}$)
l_{ts}	depth of top sediment (m)

The transfer coefficient is devised with the thickness of the layer of sediment S, deposited annually on the soil by the aforementioned processes. The transfer factor λ_7 is calculated using the dimensions of the surface soil box and top sediment soil box. It is assumed that the total inventory of the river-sediment box is, at most, deposited annually on the agricultural land. The maximum value of λ_7 is therefore set at 1.0 a^{-1}.

The transfer coefficient λ_8 describes the transport of radionuclides from the surface soil towards the river water and represents the processes of surface water runoff and wind erosion:

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

E_{ss}	erosion rate (m a^{-1})
l_{ss}	depth of surface soil (m)

The transfer coefficient is stated directly in terms of the removed depth of soil, E_{ss}.
In the calculations the transfer coefficients are constant over a long time period. It is implicitly assumed that there is no net mass transport, and that the removal of soil by erosion is compensated by the heightening of the soil with sediment (parameter S in transfer coefficient λ_7) and the deposition of uncontaminated soil particles from elsewhere.

The transfer coefficient λ_9 describes the transport of radionuclides from the river water to the first sediment layer and represents the processes of bioturbation, diffusion and sedimentation.

$$\lambda_9 = \frac{l_b}{l_w} F_b \frac{\left(\frac{1}{F_b} - 1\right) B_r + D_r}{l_b \min(l_b, l_{ts})} + \kappa v_{rw} + (1 - F_r) \frac{S_r}{\alpha_r}$$

B_r	bioturbation coefficient in sediment (m^2 a^{-1})
D_r	diffusion coefficient freshwater (m^2 a^{-1})
F_b	unsorbed fraction in boundary layer (-)
F_r	unsorbed fraction in river water (-)
S_r	sedimentation rate (only for lakes) (t m^{-3} a^{-1})
l_w	depth of river (m)
l_b	depth of boundary layer (m)
l_{ts}	depth of top sediment layer (m)
v_{rw}	velocity of river water (m a^{-1})
α_r	suspended sediment load (t m^{-3})
κ	Schaeffer sedimentation (only for rivers) (m^{-1})

In the model the river water contains a boundary layer (thickness l_b) with an enhanced suspended sediment load (10 times the suspended sediment load in the river water). Exchange of activity occurs only between the boundary layer and the upper bed sediment layer by diffusion and bioturbation. The description of these processes is identical to the description in the transfer coefficient λ_4. However, a correction factor $l_b \cdot l_w^{-1}$ is applied to account for the fact that the diffusion and bioturbation processes operate on the radionuclides in the boundary layer only, whereas the transfer factor operates on the total amount of radionuclides in the surface water box. It is important to note that this correction factor is only (approximately) valid if the fraction of radionuclides in solution, F_b, is large. Otherwise an additional correction factor has to be applied to account for the difference in suspended sediment load between the river water and boundary layer.

The fraction F_b of radionuclides in solution in the boundary layer is given by:

$$F_b = \frac{1}{1 + \alpha_b \, K_{sr}}$$

K_{sr}	freshwater-sediment distribution coefficient ((Bq t^{-1}) (Bq m^{-3})$^{-1}$)
α_b	suspended sediment load in the boundary layer (t m^{-3})

A similar description applies to F_r, with the suspended sediment load in the river water being α_r. As stated before, the relationship $\alpha_b = 10 \cdot \alpha_r$ is assumed.

The sedimentation process is described differently for a river than for a lake. The sedimentation rate in the river is assumed directly proportional to the river-water velocity, with a proportionality constant κ, called Schaeffers parameter [NRPB79]. This description is derived for the dispersion of a plume of activity in the water. It is not clear yet to what extent this description can be applied to the sedimentation in a homogeneously mixed river compartment.

For stagnant waters, like a lake, the sedimentation process is described with an annual sedimentation rate S_r (in t m^{-3} a^{-1}, with $S_r = 0$ for a river). The annual deposited fraction of the suspended sediment in the river water is $S_r \cdot \alpha_r^{-1}$, and consequently the fraction of radionuclides annually transferred to the sediment bed $S_r \cdot \alpha_r^{-1} \cdot (1-F_r)$, with $(1-F_r)$ being the fraction sorbed to the suspended sediment.

The transfer coefficient λ_{10} describes the transport of radionuclides from the surface bed sediment to the river water and represents the processes of bioturbation and diffusion.

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

B_r	bioturbation coefficient in sediment (m^2 a^{-1})
D_r	diffusion coefficient freshwater (m^2 a^{-1})
R_s	retardation coefficient in sediment (-)
l_b	depth of boundary layer (m)
l_{ts}	depth of top sediment (m)

It is assumed that the surface sediment bed interacts only with the boundary layer in the surface water. The description of the processes is analogous to the description in the soil layers. However, the retardation factor R_s is given in terms of the porosity of the bed sediments φ_{sed} and the mineral density of bed sediments ρ_{sed}:

$$R_s = 1 + \frac{(1 - \varphi_{sed})}{\varphi_{sed}} \rho_{sed} K_{sr}$$

K_{sr}	freshwater-sediment distribution coefficient ((Bq t^{-1}) (Bq m^{-3})$^{-1}$)
φ_{sed}	porosity of the sediment (-)
ρ_{sed}	mineral density of the sediment (t m^{-3})

The transfer coefficient λ_{11} describes the transport of radionuclides from the top sediment layer to lower sediment layers, and represents the processes of diffusion and (in a lake only) sedimentation.

$$\lambda_{11} = \frac{D_s}{R_s\, l_{ts} \min(l_{ts}, l_{ms})} + \frac{(R_s - 1)}{R_s} \frac{S_r\, l_w}{l_{ts}\, (1 - \varphi_{sed})\, \rho_{sed}}$$

D_s	diffusion coefficient in bed sediment (m^2 a^{-1})
R_s	retardation coefficient in sediment (-)
S_r	sedimentation rate (only for lakes) (t m^{-3} a^{-1})
l_{ts}	depth of top sediment layer (m)
l_{ms}	depth of middle sediment layer (m)
l_w	depth of river (m)
φ_{sed}	porosity of the sediment (-)
ρ_{sed}	mineral density of the sediment (t m^{-3})

The description of the diffusion term is again analogous to the description in the soil. For stagnant waters, like a lake, the transfer coefficient λ_{11} is extended with a term representing the burial by continued sedimentation. The sedimentation process results in an annual mass flux towards the top sediment bed, magnitude $S_r \cdot V_{lake}$, with V_{lake} the volume of the lake water box. Since the biosphere conditions are assumed to be constant with time, the same amount of mass must be transported towards the deeper sediment layers. The total mass of the solid fraction in the top sediment box equals:

$$(1-\varphi_{sed}) \cdot \rho_{sed} \cdot V_{top\ sediment}$$

with $V_{top\ sediment}$ as the volume of the top sediment box. Consequently, the fraction of mass transported annually from the top sediment box towards the middle sediment box equals:

$$(S_r \cdot V_{lake})\ [(1-\varphi_{sed}) \cdot \rho_{sed} \cdot V_{top\ sediment}]^{-1}$$

Since the fraction of radionuclides sorbed to the solid fraction is given by $(1-R_s^{-1})$, this results in the last term in the description of transfer coefficient λ_{11}.

The transfer coefficient λ_{12} describes the transport of radionuclides from the middle sediment layer to the top sediment layer and represents the process of diffusion.

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

D_s	diffusion coefficient in bed sediment ($m^2 \, a^{-1}$)
R_s	retardation coefficient in sediment (-)
l_{ts}	depth of top sediment (m)
l_{ms}	depth of middle sediment (m)

The description of the transfer coefficient is again analogous to the description in the soil.

The transfer coefficient λ_{13} describes the transport of radionuclides from the middle sediment layer to the lowest sediment layer and represents the burial of sediment.

$$\lambda_{13} = \frac{(R_s - 1)}{R_s} \, \frac{S_r \, l_w}{l_{ms} \, (1 - \varphi_{sed}) \, \rho_{sed}}$$

R_s	retardation coefficient in sediment (-)
S_r	sedimentation rate (only for lakes) ($t \, m^{-3} \, a^{-1}$)
l_{ms}	depth of middle sediment layer (m)
l_w	depth of river (m)
ρ_{sed}	mineral density of the sediment ($t \, m^{-3}$)
φ_{sed}	porosity of the sediment (-)

The transfer coefficient is only of importance in stagnant waters. In rivers λ_{13} is equal to zero.

2.2.2 *Marine transfer coefficients*

The ocean model of MiniBIOS consists of a number of sea compartments, exchanging activity. A sea compartment consists of a single marine water box with three marine sediment boxes. The model allows a choice in the number of sea compartments. In Figure 2.3, three compartments are defined. Activity enters the marine biosphere through the flow out of the last river section, with transfer coefficients λ_1 (flow of the river water, see Section 2.2.1), λ_{21} and λ_{23}. The transfer coefficients λ_{21} and λ_{23} represent the movement of the river sediment out of the last river compartment. In the transition from freshwater to salt water, the chemical conditions alter. It is assumed that a fraction f_{desorb} of the activity in the sediment box is transferred to the marine water compartment, while the remaining fraction is transferred to the marine sediment compartment.

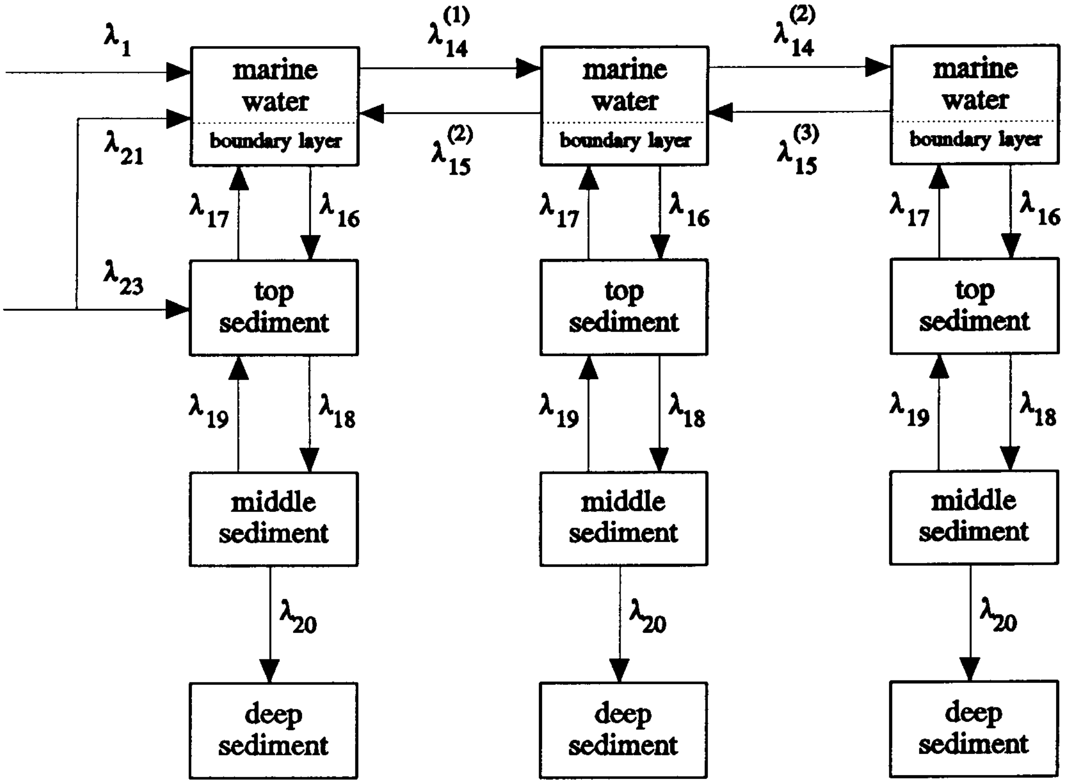

Figure 2.3 The ocean model in MiniBIOS_1A4.

$$\lambda_{21} = f_{\mathrm{desorb}} \cdot \lambda_3$$

$$\lambda_{23} = (1 - f_{\mathrm{desorb}}) \cdot \lambda_3$$

f_{desorb}	fraction of nuclides bound to river sediment, desorbed in salt waters (-)

The transport of radionuclides in the marine biosphere is described with the transfer coefficients λ_{14} - λ_{20}. Each transfer coefficient represents a number of processes. The exchange of activity between the oceans is governed by the transfer coefficients λ_{14} and λ_{15}.

$$\lambda_{14}^{(i)} = \frac{1}{V_{\mathrm{m}}^{(i)}} F_{\mathrm{m,outwards}}^{(i)}$$

$$\lambda_{15}^{(i)} = \frac{1}{V_{\mathrm{m}}^{(i)}} F_{\mathrm{m,inwards}}^{(i)}$$

$V_{\mathrm{m}}^{(i)}$	volume of marine compartment (i) (m^3)
$F_{\mathrm{m,inwards}}^{(i)}$	inward volumetric flow of marine compartment (i) ($m^3\ a^{-1}$)
$F_{\mathrm{m,outwards}}^{(i)}$	outward volumetric flow of marine compartment (i) ($m^3\ a^{-1}$)

The transfer coefficients λ_{14} and λ_{15} represent the flow of marine water, with λ_{14} the flow from the local sea to the global oceans and λ_{15} the flow in reversed direction. Conservation of flux demands that there is no net transport of mass out of a marine compartment. Therefore $F_{\mathrm{m,inwards}}^{(i)}$ and $F_{\mathrm{m,outwards}}^{(i)}$ have to satisfy the conditions (*nmar* equals the number of oceans in the model):

$$F_{\mathrm{m,inwards}}^{(i)} = F_{\mathrm{m,outwards}}^{(i-1)}$$
$$F_{\mathrm{m,inwards}}^{(1)} = 0$$
$$F_{\mathrm{m,outwards}}^{(nmar)} = 0$$

The contribution of the flow of the river water is assumed to be negligible.

The interaction between the marine water and the marine sediments is analogous to the description of the interaction between the river water and the river sediments: the river transfer coefficients λ_9 - λ_{13} correspond directly to the marine transfer coefficients λ_{16} - λ_{20}. The description of the sedimentation process in the marine environment is the same as the description for stagnant waters. Therefore Schaeffers sedimentation parameter is not used.

Since the descriptions of the transfer factors are almost identical to the river section, only the formulas are given here (more information in [Ma91a]).

$$\lambda_{16} = K_{\mathrm{m}} \, S_{\mathrm{m}} \, F_{\mathrm{m}} + \frac{l_{\mathrm{mb}}}{l_{\mathrm{m}}} \, F_{\mathrm{mb}} \frac{(\frac{1}{F_{\mathrm{mb}}} - 1) \, B_{\mathrm{m}} + D_{\mathrm{m}}}{l_{\mathrm{mb}} \, \min(l_{\mathrm{mb}}, l_{\mathrm{mu}})}$$

B_{m}	bioturbation coefficient in marine sediment (m^2 a^{-1})
D_{m}	diffusion coefficient marine sediment (m^2 a^{-1})
F_{mb}	unsorbed fraction in marine boundary layer (-)
F_{m}	unsorbed fraction in marine water (-)
K_{m}	marine water - sediment distribution coefficient [(Bq t^{-1}) (Bq $m^{-3})^{-1}$]
S_{m}	marine sedimentation rate (t m^{-3} a^{-1})
l_{m}	depth of marine water (m)
l_{mb}	thickness of marine boundary layer (m)
l_{mu}	depth of marine upper sediment layer (m)

The fraction F_{mb} of radionuclides in solution in the boundary layer is defined as:

$$F_{\mathrm{mb}} = \frac{1}{1 + \alpha_{\mathrm{mb}} \, K_{\mathrm{m}}}$$

K_{m}	marine water - sediment distribution coefficient [(Bq t^{-1}) (Bq $m^{-3})^{-1}$]

α_{mb}	suspended sediment load in the marine boundary layer (t m^{-3})

The suspended sediment load in the boundary layer is assumed to be ten times the suspended sediment load in the marine water: $\alpha_{mb} = 10 \cdot \alpha_m$. Furthermore, two different values are used for the distribution coefficient K_m for shallow and deep waters. If the water column is less than 100 m, the distribution coefficient for shallow sea waters is used. The same approach is used in the definition of the bioturbation coefficient.

$$\lambda_{17} = \frac{D_m + (R_{ms} - 1)\, B_m}{R_{ms}\, l_{mu}\, \min(l_{mu}, l_{mb})}$$

B_m	bioturbation coefficient in marine sediment (m^2 a^{-1})
D_m	diffusion coefficient in marine sediment (m^2 a^{-1})
R_{ms}	retardation coefficient in marine sediment (-)
l_{mu}	depth of marine upper sediment layer (m)
l_{mb}	depth of marine boundary layer (m)

with the retardation factor R_{ms}:

$$R_{ms} = 1 + \frac{(1 - \varphi_{ms})}{\varphi_{ms}}\, \rho_{ms}\, K_m$$

K_m	marine water-sediment distribution coefficient [(Bq t^{-1}) (Bq $m^{-3})^{-1}$]
φ_{ms}	porosity of the marine sediment (-)
ρ_{ms}	mineral density of the sediment (t m^{-3})

$$\lambda_{18} = \frac{D_m}{R_{ms}\, l_{mu}\, \min(l_{mu}, l_{mm})} + \frac{(R_{ms} - 1)}{R_{ms}}\; \frac{S_m\, l_m}{l_{mu}\, (1 - \varphi_{ms})\, \rho_{ms}}$$

D_m	diffusion coefficient marine sediment (m^2 a^{-1})
R_{ms}	retardation coefficient in marine sediment (-)
S_m	marine sedimentation rate (t m^{-3} a^{-1})
l_m	depth of marine water (m)
l_{mm}	thickness of marine middle sediment layer (m)
l_{mu}	depth of marine upper sediment layer (m)
φ_{ms}	porosity of the marine sediments (-)
ρ_{ms}	the mineral density of the bed sediments (t m^{-3})

$$\lambda_{19} = \frac{D_m}{R_{ms}\, l_{mm}\, \min(l_{mu}, l_{mm})}$$

D_m	diffusion coefficient in marine sediment ($m^2\ a^{-1}$)
R_{ms}	retardation coefficient in marine sediment (-)
l_{mm}	thickness of marine middle sediment layer (m)
l_{mu}	depth of marine upper sediment layer (m)

$$\lambda_{20} = \frac{(R_{ms} - 1)}{R_{ms}}\ \frac{S_m\, l_m}{l_{mm}\,(1 - \varphi_{ms})\, \rho_{ms}}$$

R_{ms}	retardation coefficient in marine sediment (-)
S_m	marine sedimentation rate ($t\ m^{-3}\ a^{-1}$)
l_m	depth of marine water (m)
l_{mm}	thickness of marine lowest sediment layer (m)
φ_{ms}	porosity of the marine sediments (-)
ρ_{ms}	the mineral density of the bed sediments ($t\ m^{-3}$)

2.2.3 *Seaspray model*

Agricultural land near the sea may be contaminated with radionuclides via seaspray. In general, this contamination pathway is only of importance if the release of activity in the biosphere occurs in the local marine compartment [Kö89]. To calculate the consequences of this exposure pathway the MiniBIOS model contains an additional terrestrial compartment adjacent to the local marine compartment. The dimensions of the terrestrial compartment is 500 m inland by the length l_c of the local marine box. The structure is depicted in Figure 2.4. The transfer coefficients λ_4, λ_{41}, λ_5, λ_{51}, λ_6 and λ_8 were defined previously (see Section 2.2.1).

The transfer coefficient λ_{22} describes the transport from the local marine water box to the surface soil box by the seaspray, and is straightforwardly defined as:

$$\lambda_{22} = \frac{l_c\, W_{sea}}{V_m^{(1)}}\, K_{ss}$$

K_{ss}	seaspray concentration factor (-)
$V_m^{(1)}$	volume of local marine compartment (m^3)
W_{sea}	amount of marine water annually transferred to land per unit coastal length ($m^3\ a^{-1}\ m^{-1}$)
l_c	coastal length of local marine compartment (m)

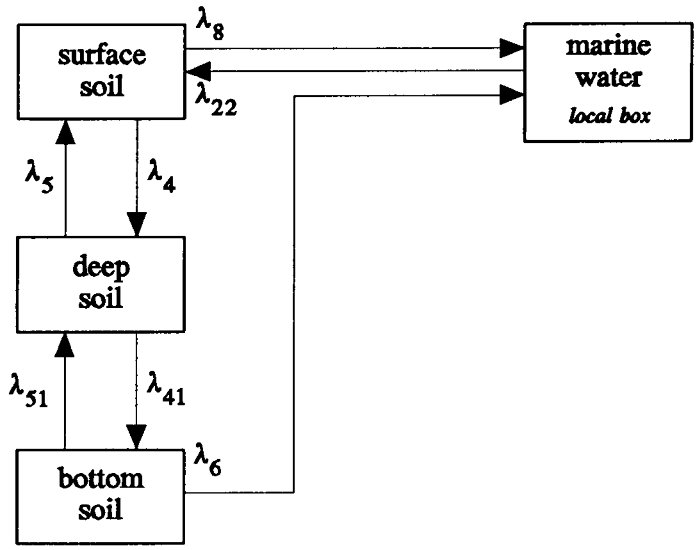

Figure 2.4 The seaspray model in MiniBIOS_1A4.

It is assumed that the concentration of radionuclides in the seaspray may differ from the concentration in the marine water. Therefore a nuclide-dependent concentration factor K_{ss} is defined.

2.3 Exposure pathways

After calculating the number of radionuclides in the compartments for the required output times, the concentrations are determined by dividing the number of radionuclides by the volume of the compartment. Next, MiniBIOS calculates the radiation dose to individuals via various exposure pathways from the concentrations. Three important exposure pathways are distinguished: ingestion, inhalation and external irradiation. In this section the calculation of the radiation dose for each exposure pathway is given.

2.3.1 *Ingestion of drinking water*

MiniBIOS assumes that filtered river water is used as drinking water. Only the soluble fraction of radionuclides in the river water is present in the drinking water, whereas the fraction of radionuclides sorbed to the suspended particles is filtered out. Ingestion of drinking water results in an annual individual radiation dose of D_w, given by

$$D_w = \frac{C_{rw}}{1 + \alpha_r K_{sr}} D_{ing} I_w$$

C_{rw}	concentration in river water ($Bq\ m^{-3}$)
D_{ing}	dose factor for ingestion ($Sv\ Bq^{-1}$)
K_{sr}	freshwater sediment distribution coefficient ($Bq\ t^{-1}$) ($Bq\ m^{-3}$)$^{-1}$
I_w	consumption of drinking water ($m^3\ a^{-1}$)
α_r	suspended sediment load ($t\ m^{-3}$)

2.3.2 *Ingestion of freshwater fish*

In calculating the radiation dose D_{ff} due to the ingestion of freshwater fish, MiniBIOS calculates the concentration of radionuclides in freshwater fish with an equilibrium concentration factor. As in the calculation of the radiation dose for drinking water, it is assumed that uptake of radionuclides in the fish is restricted to the soluble fraction.

$$D_{ff} = \frac{C_{rw}}{1 + \alpha_r K_{sr}} K_{ff} D_{ing} N_{tpk} I_{ff}$$

C_{rw}	concentration in river water ($Bq\ m^{-3}$)
D_{ing}	dose factor for ingestion ($Sv\ Bq^{-1}$)
I_{ff}	consumption of freshwater fish ($kg\ a^{-1}$)
K_{sr}	freshwater sediment distribution coefficient ($Bq\ t^{-1}$) ($Bq\ m^{-3}$)$^{-1}$
K_{ff}	concentration factor of freshwater fish. The concentration factor refers to the fraction of radionuclides in solution only [($Bq\ t^{-1}$) ($Bq\ m^{-3}$)$^{-1}$]
N_{tpk}	conversion factor 0.001 $t\ kg^{-1}$
α_r	suspended sediment load ($t\ m^{-3}$)

2.3.3 *Ingestion of crops*

MiniBIOS distinguishes three different types of crops: green vegetables, grains and root vegetables, and three sources of contamination: (1) root uptake, (2) attached soil particles and (3) interception of spray irrigation water. The calculation of the radiation dose D_c due to the ingestion of crop type *c* is straightforward.

$$D_c = D_{c,int} + D_{c,soil} + D_{c,irri}$$

$D_{c,\ int}$	dose for ingestion of crop type *c*, contaminated via root uptake ($Sv\ a^{-1}$)
$D_{c,\ soil}$	dose for ingestion of crop type *c*, contaminated via attached soil particles ($Sv\ a^{-1}$)
$D_{c,\ irri}$	dose for ingestion of crop type *c*, contaminated via interception of irrigation water ($Sv\ a^{-1}$)

The root uptake for all three crop types is simply described with an equilibrium concentration factor K_c.

$$D_{c,\,int} = \frac{C_{ss}\,K_c}{\rho_s}\,D_{ing}\,I_c$$

C_{ss}	concentration in surface soil (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
I_c	consumption of crops (fresh weight) (kg a^{-1})
K_c	concentration factor of crops [(Bq kg^{-1} fresh weight crops) (Bq kg^{-1} dry weight soil)$^{-1}$]
ρ_s	density of dry soil (kg m^{-3})

The contamination of crops with attached soil for green vegetables and grains is described with an equilibrium soil contamination factor, S_c, whereas root vegetables are assumed not to be contaminated with attached soil after processing. Part of the attached soil is assumed to be removed in the processing of the food.

$$D_{c,\,soil} = \frac{C_{ss}\,S_c}{\rho_{wet}}\,D_{ing}\,I_c\,f_c$$

C_{ss}	concentration in surface soil (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
I_c	consumption of crops (kg a^{-1})
S_c	soil contamination factor, the weight of attached wet soil as a fraction of the fresh crop weight (-)
f_c	fraction of external contamination remaining after processing (-)
ρ_{wet}	density of the wet soil (kg m^{-3}). The density of the wet soil ρ_{wet} equals $\rho_s + \varphi_s \cdot \rho_{water}$, with ρ_s the density of the dry soil and ρ_{water} the density of water
φ_s	porosity of soil (-)
ρ_w	density of water (kg m^{-3})

The interception of contaminated spray irrigation water is described with an interception factor $[1 - \exp(-\mu_c \cdot Y_c)]$. The annual supply of radionuclides to the crops in an area of 1 m^2 is therefore equal to the supply of radionuclides to the land with irrigation water, multiplied by the interception factor:

$$I \cdot C_{rw} \cdot (1 - \exp(-\mu_c \cdot Y_c))$$

with C_{rw} equal to the concentration in river water and I equal to the annual irrigation rate. Removal of radionuclides results from the harvesting of crops and the process of weathering. The annual removal of radionuclides from an area of 1 m^2 of crops is equal to:

$$Y_c \cdot W_c + Y_c \cdot H_c$$

with Y_c equal to the yield of crops per square metre (kg m^{-2}), H_c, the harvesting rate of crops (a^{-1}) and W_c, the weathering rate of crops (a^{-1}). In equilibrium, the annual supply equals the annual removal, and the equilibrium concentration in crops is given by the ratio of the supply to the removal. For the crops green vegetables and grains this results directly in:

$$D_{c,\,irri} = \frac{C_{rw}\, I\, (1 - e^{-\mu_c Y_c})}{Y_c\, (W_c + H_c)}\, D_{ing}\, I_c\, f_c$$

C_{rw}	concentration in river water (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
H_c	harvesting rate of crop (a^{-1})
I	irrigation rate (m a^{-1})
I_c	consumption of crops (kg a^{-1})
W_c	weathering rate of crop (a^{-1})
Y_c	yield of crop (kg m^{-2})
f_c	fraction of external contamination remaining after processing (-)
μ_c	interception constant of crops (m^2 kg^{-1})

Root vegetables are treated differently, since the parts of the crops with intercepted contamination are not usually eaten. However, radionuclides can be translocated from the outer to the edible parts of the plant. This process is modelled with a translocation factor between the contaminated parts above ground to the edible parts. The ingestion dose for root vegetables $D_{rv.,\,irri}$ is then given by:

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

C_{rw}	concentration in river water (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
H_{rv}	harvesting rate of root vegetables (a^{-1})
I	irrigation rate (m a^{-1})
I_{rv}	consumption of root vegetables (kg a^{-1})
T_{rv}	translocation rate to the internal parts (a^{-1})
W_{rv}	weathering rate of root vegetables (a^{-1})
Y_{rv}	yield of root vegetables (kg m^{-2})
μ_{rv}	interception constant of root vegetables (m^2 kg^{-1})

Like the other crop types, the first factor denotes the equilibrium concentration in the parts contaminated by intercepted irrigation water, with an extra removal rate for the translocation to the inner parts. The second factor is derived similarly: the supply rate of radionuclides to the inner parts due to irrigation is given by the translocation rate T_{rv} times the equilibrium concentration in the outer parts. The removal rate is now equal to the harvesting rate H_{rv}. The equilibrium concentration in the inner parts is equal to the ratio of the supply rate to the removal rate.

For the contamination of the crops in the agricultural area along the sea coast, the interception of irrigation water is replaced with the interception of seaspray. Details are given in [Ma91a].

2.3.4 *Ingestion of animal produce*

MiniBIOS distinguishes two types of consumption animals, sheep and cattle, and the consumption of five animal products: beef, mutton, cow's liver, sheep's liver and milk. Calculations are straightforward: products are contaminated by the animal's ingestion of contaminated drinking water and contaminated pasture.

The dose $D_{a,dw}$ through the ingestion of an animal product contaminated via the drinking water is calculated with the concentration factor F_a.

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

A_{drink}	fraction of animal drinking water affected (-)
C_{rw}	concentration in river water (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
F_a	concentration factor of animal (Bq kg^{-1}) (Bq d^{-1})$^{-1}$
I_a	consumption of the animal product (kg a^{-1})
I_{wa}	water ingested by animal (m^3 d^{-1})

It is assumed that only a fraction A_{drink} of the drinking water is contaminated. The contaminated fraction of the drinking water consists of unfiltered river water.

The contamination of pasture is calculated analogous to the contamination of crops. The ingestion dose $D_{a,past}$ through the intake of an animal product contaminated via the animal intake of pasture is given by:

$$D_{a,past} = D_{a,int} + D_{a,soil} + D_{a,irri}$$

$D_{a,int}$	dose for ingestion of animal product contaminated via intake of pasture (Sv a^{-1}). Contamination of pasture via root uptake.

$D_{a,soil}$	dose for ingestion of animal product contaminated via intake of pasture (Sv a^{-1}). Contamination of pasture via attached soil particles.
$D_{a,irri}$	dose for ingestion of animal product contaminated via intake of pasture (Sv a^{-1}). Contamination of pasture via interception of irrigation water.

The dose $D_{a,int}$ through the contamination of pasture by root uptake is given as:

$$D_{a,\,int} = \frac{C_{ss}\,K_p}{\rho}\;Z\,I_{pa}\,F_a\,D_{ing}\,I_a$$

C_{ss}	concentration in surface soil (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
F_a	concentration factor in animal part (Bq kg^{-1}) (Bq $d^{-1})^{-1}$
I_a	consumption of animal product (kg a^{-1})
I_{pa}	consumption of pasture by animals (kg dry weight d^{-1})
K_p	concentration factor of pasture (Bq kg^{-1} wet weight of grass) (Bq kg^{-1} dry weight soil$)^{-1}$
Z	weight of wet pasture which gives 1 kg dry pasture (kg wet weight of grass) (kg dry weight of grass$)^{-1}$
ρ	density of dry soil (kg m^{-3})

The dose $D_{a,soil}$ through the contamination of pasture by attached soil particles is given as:

$$D_{a,\,soil} = \frac{C_{ss}\,S_a}{\rho}\;I_{pa}\,F_a\,D_{ing}\,I_a$$

C_{ss}	concentration in surface soil (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
F_a	concentration factor in animal part (Bq kg^{-1}) (Bq $d^{-1})^{-1}$
I_a	consumption of animal produce (kg a^{-1})
I_{pa}	consumption of pasture by animals (kg dry weight pasture d^{-1})
S_a	soil uptake as a fraction of the dry pasture uptake (-)
ρ	density of dry soil (kg m^{-3})

The dose $D_{a,irri}$ through the contamination of pasture by interception of irrigation water is given as:

$$D_{a,\,irri} = \frac{C_{rw}\,I\,(1 - e^{-\mu_p Y_p})}{Y_p\,(W_p + H_{pa})}\;I_{pa}\,F_a\,D_{ing}\,I_a$$

C_{rw}	concentration in river water (Bq m^{-3})
D_{ing}	dose factor for ingestion (Sv Bq^{-1})
F_a	concentration factor in animal part (Bq kg^{-1}) (Bq $d^{-1})^{-1}$

H_{pa}	harvesting rate of pasture (a^{-1})
I	irrigation rate ($m\ a^{-1}$)
I_a	consumption of animal product ($kg\ a^{-1}$)
I_{pa}	consumption of pasture by animals (kg dry weight d^{-1})
W_p	weathering rate of pasture (a^{-1})
Y_p	yield of pasture (kg dry weight m^{-2})
μ_p	interception constant of pasture ($m^2\ kg^{-1}$)

In this formula the harvesting rate of pasture H_{pa} depends on the density of animals:

$$H_{pa} = \frac{N_a\ I_{pa}\ ndy}{Y_p}$$

I_{pa}	consumption of pasture by animals (kg dry weight d^{-1})
N_a	density of animals (m^{-2})
Y_p	yield of pasture ($kg\ m^{-2}$)
ndy	number of days per year ($d\ a^{-1}$)

2.3.5 *Ingestion of marine food*

MiniBIOS distinguishes four types of marine food: fish, crustaceans, molluscs and seaweed. It is assumed that all marine food comes from the local marine box. The calculation of the individual dose, D_f, to a component of the marine food is straightforward.

$$D_f = \frac{C_{mw}}{1 + \alpha_m\ K_m}\ K_f\ D_{ing}\ N_{tpk}\ I_f$$

C_{mw}	concentration in local marine box ($Bq\ m^{-3}$)
D_{ing}	dose factor for ingestion ($Sv\ Bq^{-1}$)
I_f	consumption of marine food ($kg\ a^{-1}$)
K_m	marine sediment distribution coefficient ($Bq\ t^{-1}$) ($Bq\ m^{-3})^{-1}$
K_f	concentration factor in marine food. The concentration factor refers to the fraction of radionuclides in solution only [($Bq\ t^{-1}$) ($Bq\ m^{-3})^{-1}$)]
N_{tpk}	conversion factor 0.001 $t\ kg^{-1}$
α_m	suspended sediment load ($t\ m^{-3}$)

2.3.6 *Inhalation*

Inhalation of contaminated suspended soil particles results in a radiation dose. This inhalation dose is calculated in MiniBIOS for (1) a member of the public (exposed to a relatively low dust level for a long time period), and (2) a farmer ploughing fields (exposed to a high dust level for a short time period). The inhalation dose D_{inh} is given by:

$$D_{inh} = \frac{C_{ss}}{\rho_s} a_d D_{inh} I_{air} O_{occ}$$

C_{ss}	concentration in the surface soil (Bq m^{-3})
D_{inh}	dose factor for inhalation (Sv Bq^{-1})
I_{air}	air volume inhalation rate (m^3 a^{-1})
O_{occ}	fraction of a year spent in the dust level. Different values are possible for a member of the public and a farmer ploughing fields.
a_d	dust level in air (kg m^{-3}). Different values are possible for a member of the public and a farmer ploughing fields.
ρ_s	density of dry soil (kg m^{-3})

Inhalation of seaspray and suspended beach sediment is modelled in the same way. The dose D_{ss} from the inhalation of seaspray is given by:

$$D_{ss} = C_{mw} K_{ss} I_{ss} D_{inh}$$

C_{mw}	concentration in the marine water (Bq m^{-3})
D_{inh}	dose factor for inhalation (Sv Bq^{-1})
I_{ss}	annual volume of seaspray inhaled (m^3 a^{-1})
K_{ss}	seaspray concentration factor (-)

and the dose D_{sed} from the inhalation of suspended beach sediment by:

$$D_{sed} = \frac{C_{ms}}{\rho_{ms}} D_{inh} I_{sed}$$

C_{ms}	concentration in the top marine sediment layer (Bq m^{-3})
D_{inh}	dose factor for inhalation (Sv Bq^{-1})
I_{sed}	inhalation rate of mass of sediment (kg a^{-1})
ρ_{ms}	density of marine sediment (kg m^{-3})

2.3.7 *External exposure*

The exposure to external irradiation from the contaminated soil is determined for gamma emissions. The dose rate D_{ext} is calculated by multiplying the nuclide concentration in the surface soil C_{ss} by a dose-rate conversion factor G, corrected with the occupancy factor O_{occ}.

$$D_{ext} = C_{ss}\ G\ O_{occ}$$

C_{ss}	concentration in the surface soil (Bq m^{-3})
G	dose-rate conversion factor for a radionuclide (Sv a^{-1}) (Bq $m^{-3})^{-1}$
O_{occ}	fraction of a year spent on the contaminated soil. The value is equal to the occupancy factor in the calculation of the inhalation dose for a member of the public.

The dose-rate conversion factor G is the external dose rate for an individual, occupying contaminated soil with a uniform concentration of radionuclides in the top 30 cm. It is assumed that the soil surface is infinite and the contribution from the radionuclides in the soil beneath 30 cm negligible [NRPB79]. To take account of the energy dependence of the absorption, the photon spectrum of a radionuclide is divided into 12 distinct energies.

$$G = \sum_{i=1}^{12} t_g(i)\ Y_p(i)\ N_{spy}$$

N_{spy}	conversion factor 3.16E7 (s a^{-1})
$Y_p(i)$	yield of γ- or X-ray photons with photon energy E_i per disintegration (-)
$t_g(i)$	dose-rate conversion factor for photon energy E_i (Sv s^{-1}) (Bq $m^{-3})^{-1}$

The dose-rate conversion factor $t_g(i)$ is the dose rate per unit concentration of a mono-energetic source of photons, with photon energy, E_i, in a homogeneous soil layer of 30 cm. In the model 12 discrete photon energies are distinguished. The photon energies E_i and the default values of $t_g(i)$ are given in Table 2.1.

Table 2.1 Dose-rate conversion factors $t_g(i)$ for a mono-energetic source of photons with photon energy E_i

photon energy E_i [MeV]	0.01	0.015	0.02	0.03	0.05	0.1
$t_g(i)$ [Sv s^{-1}/Bq m^{-3}]	2.62e-21	6.97e-20	1.42e-19	2.66e-19	5.21e-19	4.14e-18

photon energy E_i [MeV]	0.2	0.5	1.0	1.5	2.0	4.0
$t_g(i)$ [Sv s^{-1}/Bq m^{-3}]	9.92e-18	2.00e-17	3.97e-17	5.92e-17	7.36e-17	1.30e-16

The default values in Table 2.1 were supplied by the NRPB [Ba92]. However, calculations of the external dose-rate conversion factors for mono-energetic sources can be found in the literature for various source distributions in soil, e.g. [Ko85]. In Figure 2.5 a comparison is made between the default values and the external dose-rate conversion factors calculated for a uniform soil layer of 30 cm according to [Ko85,Ko83].

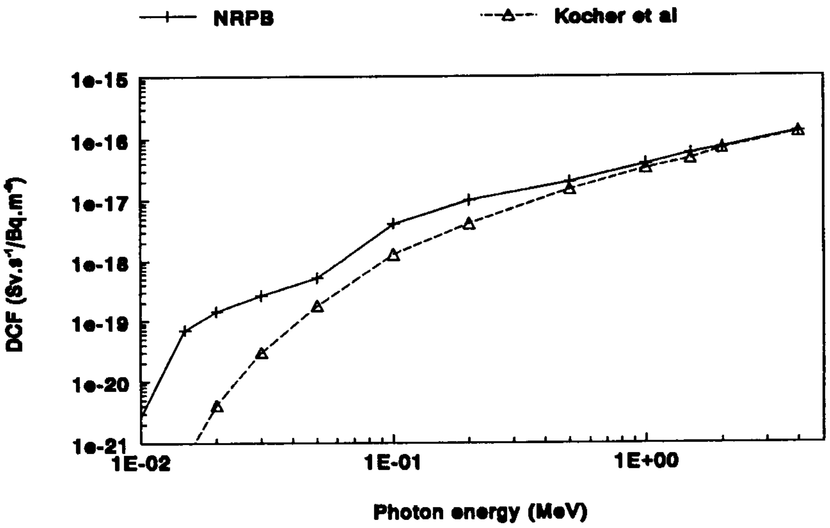

Figure 2.5 Comparison between the default values in MiniBIOS and the derived values [Ko85,Ko83] for the dose-rate conversion factors.

The results are within 25% agreement for photon energies higher than 0.5 MeV but for low photon energies the values deviate considerably. However, the contribution of low energy photons to the radiation dose is very low. The influence choosing the external dose-rate conversion factors will have on the total radiation dose, including ingestion and inhalation, is therefore limited.

The yield of γ- or X-ray photons $Y_p(i)$ with photon energy E_i per disintegration is nuclide dependent and can be calculated with the use of handbooks on radionuclides, e.g. as in [ICRP83]. As an illustration, the yields are calculated for the radionuclides ^{60}Co and ^{137}Cs. Table 2.2 shows the yield of photons for the radionuclide ^{60}Co ([ICRP83]).

Table 2.2 Yield of photons for the radionuclide ^{60}Co ([ICRP83])

designation	photon energy [MeV]	yield
γ 3	1.173	0.999
γ 4	1.332	1.00

The yield of photons with the discrete energies E_i is calculated by linear interpolation. The nearest energies for the photons of ^{60}Co are 1 MeV and 1.5 MeV. The photon yield with an energy of 1.173 MeV is therefore divided between the energies 1 MeV and 1.5 MeV, in the ratio (1.5 - 1.173) : (1.173 - 1). The result for ^{60}Co is listed in Table 2.3.

Table 2.3 The photon yield Y_p at the energies 1 MeV and 1.5 MeV for ^{60}Co

designation	yield Y_p(1 MeV)	yield Y_p(1.5 MeV)
γ 3	0.653	0.346
γ 4	0.336	0.664
Total	0.989	1.010

The decay of the radionuclide ^{137}Cs to ^{137m}Ba and ^{137}Ba, with branch ratios 0.946 and 0.054, results in the emission of electrons without γ-radiation. The nuclide ^{137}Ba is stable, but ^{137m}Ba decays to ^{137}Ba (half-life 153 s) with the emission of γ-radiation. The external irradiation of the radionuclide ^{137}Cs is therefore due to the photon emission in the decay of ^{137m}Ba. In equilibrium, a concentration in the soil of 1 Bq.m^{-3} ^{137}Cs results in 0.946 Bq m^{-3} ^{137m}Ba. The external exposure of 1 Bq m^{-3} ^{137}Cs in the soil is calculated by applying the same procedure as for ^{60}Co to the γ-emission and X-rays of ^{137m}Ba, correcting for the lower concentration. The results are presented in Table 2.4.

Table 2.4 The calculation of the photon yield, Y_p, at discrete photon energies for the radionuclide ^{137}Cs

designation (^{137m}Ba)	photon energy [MeV]	yield	yield Y_p (30 keV)	yield Y_p (50 keV)	yield Y_p (0.5 MeV)	yield Y_p (1.0 MeV)
γ 1	6.616e-1	8.98e-1 · 0.946			5.75e-1	2.75e-1
Kα_1 X-ray	3.219e-2	3.92e-2 · 0.946	3.30e-2	4.06e-3		
Kα_1 X-ray	3.182e-2	2.13e-2 · 0.946	1.83e-2	1.83e-3		
Total			5.13e-2	5.89e-3	5.75e-1	2.75e-1

Next to external exposure from the soil, the MiniBIOS model allows calculation of the external exposure from contaminated beach sediment and the handling of fishing gear. Calculations are done in a similar way, but the dose-rate conversion factor is now expressed as the product of a geometrical factor g and the effective energy of the photon spectrum E_{eff}:

$$D_{beach} = C_{ms}\, g_b\, E_{eff}\, O_b$$

$$D_{fg} = C_{ssed}\, g_{fg}\, E_{eff}\, O_{fg}$$

C_{ms}	concentration in the marine sediment (Bq m^{-3})
C_{ssed}	concentration in the suspended sediment of the local marine water box (Bq m^{-3})

g_b	geometrical dose-rate factor for beach sediment (Sv a^{-1} MeV^{-1}) (Bq $m^{-3})^{-1}$
g_{fg}	geometrical dose-rate factor for fishing gear (Sv a^{-1} MeV^{-1}) (Bq $m^{-3})^{-1}$
E_{eff}	effective energy of the photon spectrum (MeV)
O_b	fraction of a year spent on the beach
O_{fg}	fraction of a year handling fishing gear

The concentration in the suspended sediment is calculated straightforwardly from the concentration in the marine water:

$$C_{ssed} = C_{mw}\,(1 - F_m)\,\frac{\rho_m}{\alpha_m}$$

C_{mw}	concentration in the local marine water box (Bq m^{-3})
F_m	fraction of activity not bound to suspended sediment (-)
ρ_m	mineral density of the sediment (t m^{-3})
α_m	suspended sediment load in marine water (t m^{-3})

The dose-rate factor, g, depends on the geometry of the source. Default values are taken from [Ma91a]:

$g_b = 2.5\ 10^{-9}$ (Sv a^{-1}) (Bq $m^{-3})^{-1}$ MeV^{-1}

$g_{fg} = 1.4\ 10^{-11}$ (Sv a^{-1}) (Bq $m^{-3})^{-1}$ MeV^{-1}

2.4 Differences between MiniBIOS_1A and MiniBIOS_1A4

The MiniBIOS_1A4 model differs from the original version, MiniBIOS_1A. This section gives a summary of the most important modifications. They concern the soil structure and the definition of some parameters in the transfer coefficients.

Soil structure

The MiniBIOS_1A soil model consists of only two soil boxes: a surface soil box and a deep soil box [Ma91a]. The first test calculations for the radionuclide ^{99}Tc revealed that the time period to equilibrium in the surface soil is relatively long: after 1000 years the number of radionuclides in the surface soil box is only a quarter of the equilibrium value at 10,000 years. In the literature it was found that ^{99}Tc reaches equilibrium in the soil much faster [Ja85]. The difference was attributed to the accumulation of radionuclides in the deep soil box due to the relatively low removal rate λ_6.

Therefore it was decided to change the model of two soil boxes (MiniBIOS_1A) into a model with three soil boxes: surface soil box , middle soil box and lowest soil box. The last soil box is very large and supposed to act as a sink. Along with the new soil box, the transfer coefficients λ_{41} and λ_{51} were introduced, and modifications were made to λ_4 and λ_5. As a result, the time period to equilibrium was considerably reduced for ^{99}Tc: after 10 years, 75% of the equilibrium value had already been reached. For an immobile element, like ^{229}Th, hardly any difference was noticed.

Transfer coefficients

The following modifications were made in the definition of the transfer coefficients:

λ_3 The transfer of sediment downstream is defined in terms of the velocity of the river sediment v_{rs} instead of a fraction of the river-water velocity. The transfer factors λ_{21} and λ_{23} are adapted accordingly.

λ_4 The MiniBIOS_1A model makes no distinction between the amount of irrigation water withdrawn from the river (as in transfer coefficient λ_2) and the amount of irrigation water infiltrating the soil (as in transfer coefficient λ_4). In MiniBIOS_1A4 a parameter f_{in}, defined as the fraction of irrigation water infiltrating, is introduced. The parameter value is fixed at 0.5.

λ_5 The upward flow of the groundwater is removed from λ_5, since in the three-box soil model the groundwater flow is present in the lowest soil box.

λ_7 The transfer of river sediment to agricultural land is defined in terms of the annual heightening of the soil instead of the parameter transfer to land.

3 THE MINIBIOS_1A4 COMPUTER CODE

3.1 Introduction

The MiniBIOS_1A4 model is currently operational at the Laboratory of Radiation Research. This chapter describes the organization of the computer code and the input and output data files. Section 3.2 describes the computer code used for a single run of MiniBIOS_1A4. Section 3.3 describes the procedure to use MiniBIOS_1A4 in combination with the software package UNCSAM for probabilistic calculations. For a detailed description of the hardware and the required software, the user is referred to the administration logbook of MiniBIOS [Log93a].

3.2 Structure of the MiniBIOS_1A4 computer code (single run)

The structure of the MiniBIOS_1A4 computer code is given in Figure 3.1, along with the input and output data files.

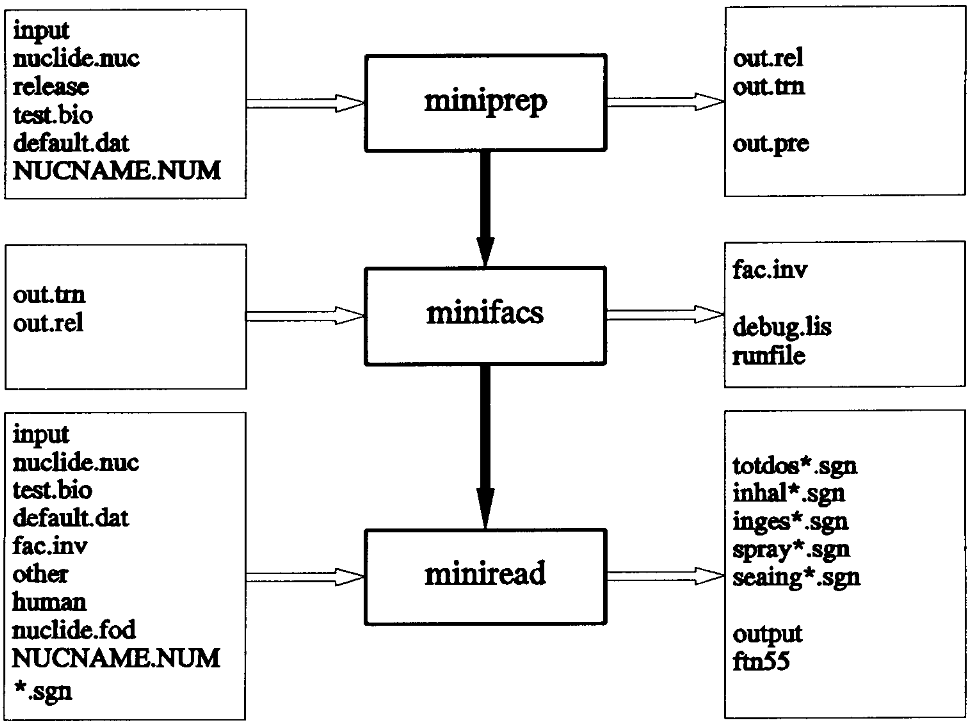

Figure 3.1 Structure of the MiniBIOS_1A4 computer code.

The computer code is subdivided into three sections, called **miniprep, minifacs** and **miniread**. A single run of the model is performed by executing the three sections consecutively. The **miniprep** section is designed to calculate the transfer factors between the various biosphere compartments, the **minifacs** section the inventories in the compartments and the **miniread** section the resulting radiation dose.

3.2.1 *Miniprep*

The **miniprep** section is the executable of a FORTRAN program. In this section the numerical values of the transfer coefficients between the biosphere compartments are calculated from the input data. The executable is compiled from several source files. A list of all the FORTRAN source files in MiniBIOS_1A4 is given in Table 3.1.

Table 3.1 The files with the source code for the MiniBIOS_1A4 computer code.

FORTRAN source code files for MiniBIOS_1A4			
source files	’include’ files		libraries
miniprep.f	minixbio.inc	minixinv.inc	usefil.lib
miniinpu.f	minixcon.inc	minixnuc.inv	
minioutp.f	minixdef.inc	minixoth.inc	
miniread.f	minixdos.inc	minixrel.inc	
miniresu.f	minixfoo.inc	minixsam.inc	
transfer.f	minixhum.inc	minixtra.inc	

The **miniprep** section requires the input data files:

input	A formatted data file with the names of the various input files for MiniBIOS.
nuclide.nuc	A formatted data file with nuclide-dependent data on soil and sediment parameters.
release	A formatted data file with the radionuclide release flux to the biosphere.
test.bio	A formatted data file with site-specific data of the biosphere.
default.dat	A formatted data file with non-site-specific data on the biosphere.
NUCNAME.NUM	A formatted data file with the name of the nuclide and the corresponding identification number, like 43099 ’Tc-99’.

The **miniprep** section produces the output data files:

out.rel	A formatted data file with the release location and the radionuclide release flux; the requested output times are also given here. The data file is an input file for **minifacs**.

out.trn	A formatted data file with the transfer coefficients between the compartments. The data file is an input file for **minifacs.**
out.pre	A formatted log file of the **miniprep** section

The various parameters in the input data files are defined in Appendix A. Examples of the data files for the radionuclide ^{99}Tc are given in Appendix B. The parameter values agree with the parameter values used in the PROSA project for the comparison of different release locations [La93a].

3.2.2 *Minifacs*

The central part of the MiniBIOS_1A4 code is the **minifacs** section, used to calculate the inventories of the radionuclides in the various compartments. The program solves the linear first-order differential equations, which describe the transfer and decay of the radionuclides. The **minifacs** section uses the software tool FACSIMILE, version H008.
FACSIMILE is a large computer program written in FORTRAN 77 and specifically designed to solve numerically linear differential equations [Cu85]. The problems to be solved are stated in the FACSIMILE command language. Calculations are performed by executing the computer program with an input file, which contains the statements in the FACSIMILE command language. The **minifacs** section is a UNIX shell-script with a single command line:

```
exec runfacs < 'PATHNAME'/minibios.fac
```

The **runfacs** program is the executable of the FACSIMILE program. The **minibios.fac** file contains the statements in the FACSIMILE command language.

The **minifacs** section requires the input files:

out.rel	A formatted data file with the release location and the radionuclide release flux. The requested output times are also given here. The data file is an output file of **miniprep.**
out.trn	A formatted data file with the transfer coefficients between the compartments. The data file is an output file of **miniprep.**

The **minifacs** section produces the output files:

debug.lis	A file intended for debugging, produced by the FACSIMILE program.
fac.inv	An unformatted data file with the radionuclide inventories in the biosphere compartments at each output time. The data file is an

	input file of the **miniread** section.
runfile	A formatted log file of the FACSIMILE program.

Examples of the input data files for the radionuclide ^{99}Tc are given in Appendix B. The listed values are calculated with the **miniprep** section with the use of the listed input files.

3.2.3 *Miniread*

The **miniread** section is the executable of a FORTRAN program; it calculates the radiation exposure to humans given the human data and the inventories of the environmental compartments. In this section the MiniBIOS_1A4 output data files are generated. The executable is compiled from several source files. A complete list of the FORTRAN source files is given in Table 4.1. The **miniread** section requires the input data files:

input	A formatted data file with the names of the various input files for MiniBIOS.
nuclide.nuc	A formatted data file with nuclide-dependent data on soil and sediment parameters.
test.bio	A formatted data file with site-specific data of the biosphere.
default.dat	A formatted data file with non-site-specific data of the biosphere.
NUCNAME.NUM	A formatted data file with the name of the radionuclide and the corresponding identification number, like 43099 'Tc-99'.
other	A formatted input file with nuclide-specific data on inhalation and gamma exposure.
human	A formatted data file with agricultural data and data on human behaviour.
nuclide.fod	A formatted data file with nuclide-specific data related to plants and animals.
fac.inv	An unformatted data file with the radionuclide inventories in the biosphere compartments at each output time. This file is an output file of the **minifacs** section.

The output of the MiniBIOS_1A4 computer code is generated in the **miniread** section. This section is specifically adjusted for use of the model in the PROSA project. The output consists of the radiation dose via various exposure pathways at six output times. For a single run of MiniBIOS, the output is appended to files, named totdos*#i*.sgn, inges*#i*.sgn, inhal*#i*.sgn, seaing*#i*.sgn and spray*#i*.sgn. The numbering *#i*, with *#i* = 1..6, denotes the output time. Consequently, these files have to be present before a calculation is started.

The **miniread** section produces the output data files:

output	A formatted logfile of the section **miniread**.
ftn55	A formatted control file with the inventories of the compartments at the output times.

The **miniread** section appends a single line ending with 'F' to the output data files:

totdos*#i*.sgn	Individual doses via (1) all exposure pathways except inhalation of seaspray, (2) all terrestrial ingestion pathways, (3) all terrestrial ingestion pathways of seaspray, (4) all seafood ingestion pathways, (5) all terrestrial inhalation and external irradiation pathways, (6) all terrestrial inhalation and external irradiation pathways of seaspray and (7) all beach inhalation pathways.
inges*#i*.sgn	Individual doses via the exposure pathways of ingestion of (1) drinking water, (2) freshwater fish, (3) beef, (4) cow's liver, (5) milk, (6) mutton, (7) sheep's liver, (8) green vegetables, (9) grain and (10) root vegetables.
inhal*#i*.sgn	Individual doses via the exposure pathways of inhalation and external irradiation: (1) inhalation for a farmer, (2) inhalation for a member of the public, (3) external irradiation from the soil, (4) external irradiation from beach sediment, (5) inhalation of beach sediment, (6) inhalation of seaspray and (7) external irradiation from the handling of fishing gear.
seaing*#i*.sgn	Individual doses via the exposure pathway of ingestion of seafood: (1) fish, (2) crustaceans, (3) molluscs and (4) seaweed.
spray*#i*.sgn	Individual doses for the agricultural land near the coast contaminated by the seaspray. The exposure pathways are ingestion of (1) beef, (2) cow's liver, (3) milk, (4) mutton, (5) sheep's liver, (6) green vegetables, (7) grain, (8) root vegetables, and (9) inhalation for a farmer, (10) inhalation for a member of the public and (11) external irradiation from the soil.

The various parameters in the input data files are defined in Appendix A. Examples of the formatted input files and the output data files for the radionuclide ^{99}Tc are given in Appendix B.

3.3 Structure of the MiniBIOS_1A4 computer code (multiple runs)

In the calculations using MiniBIOS_1A4 for the PROSA project some input parameters have probability distribution functions instead of single values. Therefore probabilistic calculations are done by running the model many times.

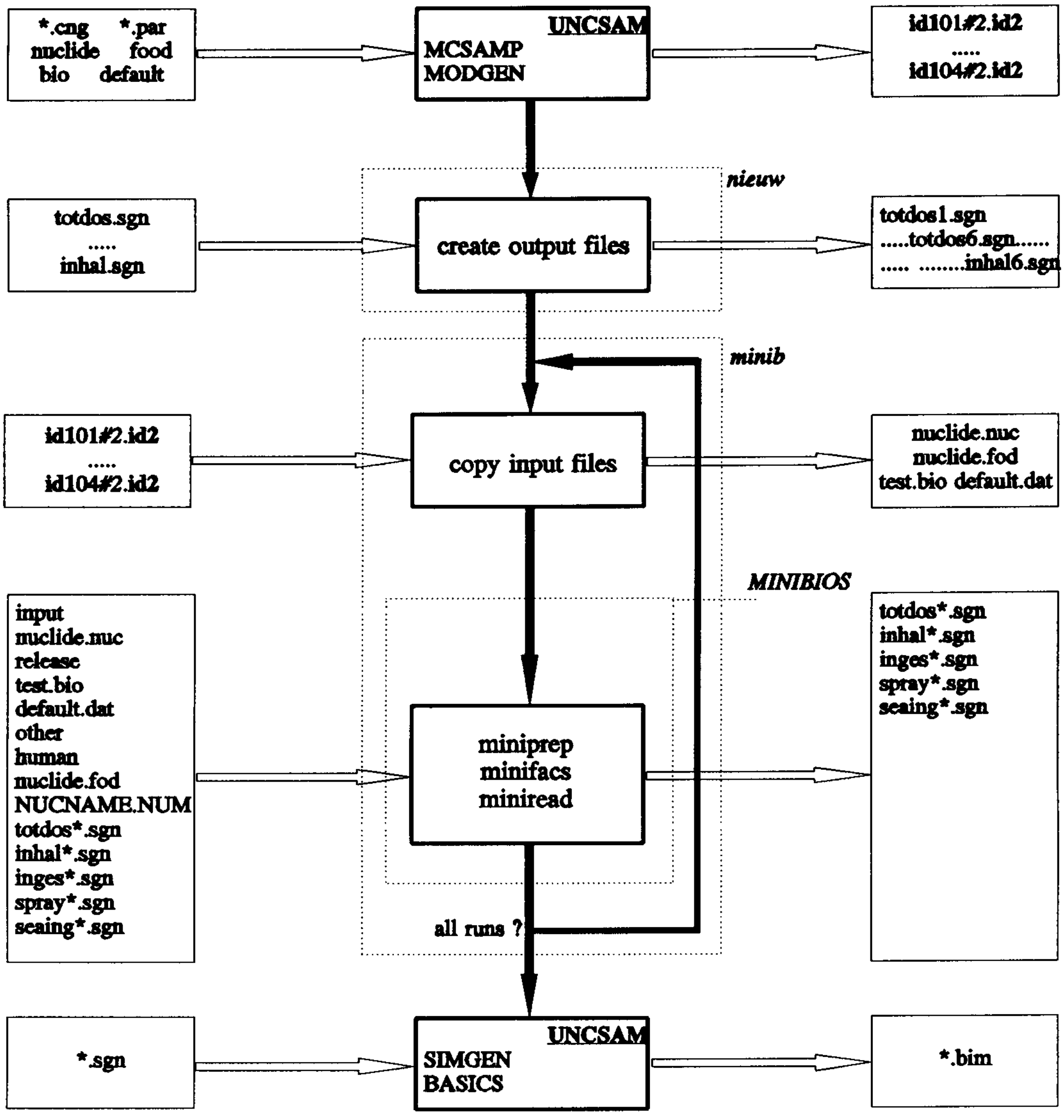

Figure 3.2 Flow diagram of a probabilistic calculation with MiniBIOS_1A4.

In the probabilistic calculations the MiniBIOS_1A4 model was used with the software package UNCSAM [Ja91]. A probabilistic calculation with MiniBIOS consists of a number of consecutive steps, as shown in the flow diagram (Figure 3.2). Three parts can be distinguished: (1) sets of input data files created with UNCSAM, (2) MiniBIOS_1A4 executed for every set of input data files and (3) the output data files combined to clearly present the results. Various UNIX shell-scripts are created to facilitate this procedure, illustrated in this section with the decay chain of the radionuclide ^{229}Th. The input data files and the results correspond to the data files used in the calculations for the PROSA project [PROSA93,La93a]. Examples of the input and output data files are given in Appendix C.

3.3.1 *Creation of sets of input data files*

First, sets of input data files for MiniBIOS are created with UNCSAM [Ja91]. UNCSAM is a software package for performing sensitivity and uncertainty analysis of simulation models. With the use of Monte Carlo sampling techniques UNCSAM generates sets of sampled values from user defined distributions and creates sets of input files containing the sampled data. UNCSAM requires two input files:

Th-229.cng	the names of the input data files with the stochastic parameters for the model and the position of the stochastic parameters in the input data files.
Th-229.par	the probability distribution functions of the parameters.

In the ^{229}Th example, the input data files containing stochastic parameters are called nuclide.nuc, nuclide.fod, test.bio and default.dat. Before a probabilistic calculation is executed, the corresponding standard input data files called nuclide, food, bio and default have to be present. These data files show empty spaces at the locations of the stochastic parameters.

UNCSAM creates a set of input data files by opening the standard input file and writing the sampled values on the required positions. The sets of input data files created are identified by two codes, **id1** and **id2**, to be defined by the user. If four different input data files are created and 400 model runs have to be done, UNCSAM generates 1600 data files, subdivided in 400 sets of four input data files, named:

id1*#1#2*.id2 where *#1* = 01..04 (number of input data files with stochastic parameters)
#2 = 001..400 (number of model runs).

3.3.2 *MiniBIOS_1A4 runs*

Subsequent to the creation of the input data file sets, a UNIX shell-script entitled **minib** is executed. First, output data files (*.sgn) with a header are created with the shell-script **nieuw**. Next, the following steps are repeated 400 times, i.e. the number of model runs:

1. the input files are copied to the corresponding names for MiniBIOS:

```
cp id101#2.id2 nuclide.nuc
cp id102#2.id2 nuclide.fod
cp id103#2.id2 test.bio
cp id104#2.id2 default.dat
```

2. the MiniBIOS_1A4 code is executed

   With a complete set of input data files, the MiniBIOS_1A4 code is executed, and the output is appended to the output data files *.sgn. This is done in the shell-script, **MINIBIOS.**

Following these steps the data files with intermediate results and the MiniBIOS log files are removed. After 400 runs the output files of MiniBIOS (*.sgn) contain a header and 400 lines, each line the result of a single execution of MiniBIOS.

3.3.3 *Presentation of results*

Finally, UNCSAM can be used to present the radiation dose in a clear manner. UNCSAM requires the *.sgn files to produce statistical information on the model output, like mean and percentile values. The results can also be presented in histogram or cumulative distribution plots. Appendix C gives an example of the file, totdos4.bim, with the statistical information on the model output in the file totdos4.sgn. UNCSAM also gives the opportunity to perform sensitivity and uncertainty analyses. The reader is referred to [Ja90,Ja91] for general information on the model analysis with UNCSAM and to [La93a] for the results of the model analysis of MiniBIOS.

4 QUALITY ASSURANCE

4.1 Introduction

An important aspect of model development and model application is the use of a quality assurance system. Quality assurance is necessary to ensure the reliability of the conceptual model, the correctness of the implementation of the conceptual model in the computer code and the reducibility of the model results. An important demand is to clearly separate the stage of model development and the application of the model [Sm93]. After a period of model development, a version of the model is made operational and used in a project. This version is documented and fixed for a prolonged period of time. After some time a new version of the model is developed and made operational. However, at all times a single, well-defined version of the model is operational, and all results are reducible to that version of the model.

In the development and use of the MiniBIOS_1A4 model in the PROSA project three stages can be identified:

1. acquisition and acceptance of the MiniBIOS_1A model of the NRPB
2. modification of MiniBIOS_1A to MiniBIOS_1A4
3. application of the MiniBIOS_1A4 model to the PROSA project

These stages are elucidated in the following sections. Finally, in Section 4.5 the use of the model in international model validation studies is described.

4.2 Acquisition and acceptance of the MiniBIOS_1A model

In the PROSA project a biosphere model was required to calculate the transport of radionuclides in the biosphere and the conseqquent radiation dose to humans. The MiniBIOS_1A model (MiniBIOS, version 1A) of the NRPB was selected for several reasons:

1. The model is based on the BIOS model of the NRPB, but considerably simplified. In this way a reduction in computing time is achieved. MiniBIOS_1A is therefore suited to probabilistic calculations, as required in PROSA.

2. The BIOS model was used in the preceding project, VEOS [Kö89]. Since the MiniBIOS model is similar to the BIOS model, comparison of the results of the VEOS project to the PROSA project is less difficult.

3. Since the structure and formulas of the MiniBIOS model resemble the structure and formulas of the BIOS model, some experience in the use of the model was available. This was expected to be advantageous in modifying the FACSIMILE part of the code.

4. The MiniBIOS model is used in the international model validation study, BIOMOVS [BIOMOVS90]. The model is also used with good results in the international code verification exercise PSAC (Probabilistic Systems Assessment Code) level 1b of the NEA [Ma91a,Kl91].

After acquisition the MiniBIOS_1A model was installed at the RIVM. Along with the model, examples of input files and output files (inventories in the boxes for two output times and two radionuclides, ^{99}Tc and ^{135}Cs) were delivered by the NRPB. In order to make the model operational, some minor modifications had to be made, resulting in a new version, MiniBIOS_1A1. The MiniBIOS_1A1 version was subjected to an acceptation test. With the use of the same input files we have calculated the inventories in the boxes and compared them to the results of the NRPB. The results of the RIVM and NRPB versions were identical (format of the output was E7.2), with the exception of the inventory of the box 'seaspray' box. The results for this box differ by 30% with the results of the NRPB [Log93a]. It was, however, not possible to trace the origin of this difference. Since the inventory of the 'seaspray' box is not used in the calculations of the radiation dose in the PROSA project, it was decided to consider this deviation as an unimportant drawback. Based on the results of the acceptation test, the model was accepted [Log93a].

4.3 Modification of MiniBIOS_1A1 to MiniBIOS_1A4

During the period of familiarizing ourselves with the model we had some modifications made:

1. The NRPB delivered a few corrections to the input file with FACSIMILE statements. Furthermore, the descriptions of the transfer coefficients λ_4 and λ_7 were changed. The implementation of these modifications resulted in a new version, MiniBIOS_1A2.

2. Calculations with MiniBIOS_1A2 revealed that even for mobile radionuclides like ^{99}Tc reaching equilibrium in the surface soil takes a long time (see Section 2.4). This effect was attributed to the slow removal of radionuclides from the lowest terrestrial box. It was therefore decided to replace the two-layered soil compartment structure with a three-layered soil compartment structure, in which the lowest soil box would act as a sink. The description of the transfer coefficients λ_3, λ_5, λ_6, λ_{21}

and λ_{23} was also modified. The new soil structure was checked in two ways:

- the structure with three soil boxes was used to simulate the old structure with two soil boxes via an appropriate choice of the transfer coefficients. The results proved to be in agreement.
- the time period to equilibrium was checked for the new compartment structure. After a release period of 100 years for the mobile radionuclide ^{99}Tc, the inventory in the top soil box with the old structure was only 3% of the equilibrium value, while in the new compartmental structure over 80% of the equilibrium value had been reached. For an immobile radionuclide, like ^{229}Th, the time-dependent inventories of the top soil box had hardly changed, as was expected.

Details of these test calculations can be found in the administration logbook of the model [Log93a]. The new model structure resulted in a new version, MiniBIOS_1A3. With this version part of the calculations were done for the PROSA project.

3. Since the calculations with MiniBIOS_1A3 showed a discrepancy between the external irradiation module of MiniBIOS_1A3 and the computer program, EXPO (see Chapter 5), the external irradiation module was investigated, resulting in a modification in the external irradiation calculation. After testing of the new module with a calculation done by hand, a new version of MiniBIOS, MiniBIOS_1A4, was installed. With this version new calculations were done for radionuclides with a non-negligible external irradiation contribution to the total radiation dose.

A logbook of the MiniBIOS model is in use to keep track of the modifications to the model [Log93a]. For more detailed information on the modifications from MiniBIOS_1A to MiniBIOS_1A4 the reader is referred to this logbook.

4.4 Application of the MiniBIOS_1A4 model

A calculation using the MiniBIOS_1A4 model is standardized. Each action for a model run is described clearly in a Standard Operating Procedure (SOP) [La92]. Model runs are documented in the logbook of MiniBIOS_1A4 [Log93a], with information on:

1. time and date of the model run
2. name of the operator
3. current version of MiniBIOS
4. location of the input and output data files
5. use of the calculations

The logbook registers also the use of the results of a model run in reports. In this way the ability to reproduce results is assured.

4.5 Validation and model intercomparison

An important aspect in the development and application of a simulation model is the validation of the model. Validation of a model is defined here as the application of a model to a real situation and comparison of the model's results with (experimentally determined) **independent** data sets.

MiniBIOS is a simulation model to be used in the assessment of the radiological impacts for the disposal of radioactive waste in geological structures. Consequently, the time scale of the calculations extends to periods of millions of years, and calculations are performed with a minimum time step of one year. It is clear that hardly any data sets are present to validate a biosphere model on such time scales.

Model intercomparison studies are designed to improve the reliability in biosphere models for long-term safety assessments. In these studies simulation models are applied to well-constructed scenarios, and the model results are intercompared. In this way differences in the approach of biosphere modelling are identified and discussed. The model intercomparison study can be used as an expert review of the model, whereas the results give guidance on future research. Furthermore, the study acts as a forum for the exchange of ideas, experience and information.

With these objectives, the MiniBIOS_1A4 model is brought into BIOMOVS II (BIOspheric Model Validation Study), an international study to test models designed to predict the transfer of radionuclides in the environment. The first meeting took place in November 1991 with representatives from about 50 organizations in 20 countries taking part. Within BIOMOVS II, a model intercomparison study for models used in the safety assessment of radioactive waste disposal has been initiated. The MiniBIOS_1A4 model will be one of the models for calculation in this working group. For more detailed information the reader is referred to the progress reports of BIOMOVS II (e.g. [BIOMOVS92]).

5 THE EXPO MODEL

5.1 Introduction

The EXPO model (version 1.0) is used in the PROSA project to calculate the dose conversion factors (Sv a^{-1}) (Bq m^{-3})$^{-1}$ for the scenario when the repository field reaches the surface due to diapirism without subrosion [La93a]. Exposure pathways included in EXPO are the inhalation of radioactive particles and external irradiation. EXPO is derived from MiniBIOS, with the assumption that the radionuclides are uniformly distributed in a soil layer of 30 cm deep. The mathematical description of the model is given in Section 5.2. In Section 5.3, the organization of the computer code is described, and, finally, in Section 5.4 the results of EXPO are compared to the results of VEOS [Kö89]. For default parameter values and the results of the use of the model in PROSA, the reader is referred to [La93a].

5.2 Mathematical description of EXPO

The radiation dose to humans due to residence on a contaminated soil is calculated in EXPO. Two exposure pathways are distinguished: external irradiation and inhalation of suspended soil.

External irradiation

The external irradiation due to photon 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 irradiation due to contamination in deeper layers is small and can be neglected [NRPB79]. The contribution of electron emission is also neglected. The contributions of short-lived daughters are included; corrections for attenuation and build-up in the soil and air are applied. It is assumed that there is no protection from the radiation by buildings and the like, and that the humans reside continuously on the contaminated soil.

The dose due to external irradiation (D_{ext} in Sv a^{-1}) is determined by [Ma91a, NRPB79]:

$$D_{ext} = C_s \cdot G$$

C_s radionuclide concentration in soil, default value 1.0 (Bq m^{-3})

G dose-rate conversion factor for photon emissions (Sv a^{-1}) (Bq m^{-3})$^{-1}$

The dose-rate conversion factor G in EXPO is identical to the definition in MiniBIOS_1A4 (described in Section 2.3.7). In the computer code, a radionuclide concentration of 1.0 Bq m^{-3} is assumed.

Inhalation of suspended soil

The dose due to the inhalation of suspended soil (D_{inh} in Sv a^{-1}) is calculated straightforwardly:

$$D_{inh} = \frac{C_s}{\rho} a_{dust} d_{inh} I_{inh}$$

C_s	radionuclide concentration in soil, default value 1.0 (Bq m^{-3})
I_{inh}	inhalation rate, default value 1.0e+4 (m^3 a^{-1})
a_{dust}	dust concentration in air, default value 1.0e-7 (kg m^{-3})
d_{inh}	dose factor for inhalation (Sv Bq^{-1})
ρ	density of soil, default value 2.2e+3 (kg m^{-3})

Default values for the radionuclide concentration C_s, the inhalation rate I_{inh}, the dust concentration in air a_{dust} and the density of the soil ρ are inserted in the computer code.

5.3 The EXPO computer code

The EXPO computer code (version 1.0) is written in FORTRAN-77. The program requires a single input file, described in Table 5.1; the name of the input file is requested by the program on the screen.

Table 5.1 Description of the EXPO input file

line number	parameter (name as in source code)	
1	Dinh	dose factor for inhalation (Sv Bq^{-1})
2-3	photon(12)	intensity of photons and electrons for each energy band i (-)
4-5	topsoilgam (12)	dose-rate conversion factor for energy E_i (Sv s^{-1})(Bq m^{-3})$^{-1}$

The output of EXPO, written in the file '**result**', consists of:

1 the name of the radionuclide used
2 dose due to inhalation (Sv a^{-1})
3 dose due to external irradiation (Sv a^{-1})
4 sum of the dose due to inhalation and external irradiation

The output is placed on one line in the above-mentioned sequence.

Calculations using the EXPO model are standardized. A Standard Operating Procedure describes each action for a model run, whereas the use of the model is registrated in the logbook [La93b,Log93b]. Modifications to the model are also described in this logbook [Log93b].

5.4 Comparison of EXPO results with VEOS

The calculation of the external irradiation dose in EXPO is identical to that in MiniBIOS_1A4. Comparison of the results of MiniBIOS with values in the literature is described in Section 2.3.7. The calculation of the radiation dose due to inhalation of dust particles is compared with the results of scenario 3 of VEOS [Kö89]. For a number of radionuclides with external irradiation the doses in VEOS after 2×10^6 years are translated to a dose conversion factor. In VEOS the dose was calculated for an occupancy of one month a year, so the derived dose conversion factors were multiplied by a factor of 12. In Table 5.2 the results are given.

Table 5.2 Dose conversion factors due to inhalation (Sv a^{-1}) (Bq $m^{-3})^{-1}$ calculated with EXPO and determined in VEOS [Kö89]

Nuclide	EXPO	VEOS [Kö89]
Se-79	1.29E-15	1.29E-15
Rb-87	4.15E-16	4.14E-16
Tc-99	1.10E-15	1.10E-15
Pd-107	1.67E-15	1.67E-15
Cs-135	5.73E-16	5.71E-16

The results of EXPO are equal to the dose conversion factors derived from VEOS. The results of the calculation of the dose due to the inhalation of dust in EXPO is therefore similar to the results in VEOS.

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APPENDIX A INPUT PARAMETERS FOR MiniBIOS_1A4

The input parameters of MiniBIOS_1A4 are organized in several input data files, the content of which follows. A parameter is indicated both with its name in the MiniBIOS_1A4 source code (first column) and the definition of the parameter in Chapter 2 (second column). The description of the parameter is given in the third column. If more than one parameter value is required, like the identification numbers of the radionuclides in the decay chain, the number of parameter values is indicated in the description of the parameter, e.g. (ni). Finally, the units are given in the fourth column.

nuclide

ni		number of radionuclides in the decay chain	[-]
nid		identification number of the radionuclide (ni)	[-]
lambda	λ_0	decay constant (ni)	$[s^{-1}]$
kd	K_d	distribution coefficient soil (ni)	$[m^3\ t^{-1}]$
ksr	K_{sr}	distribution coefficient river sediment (ni)	$[m^3\ t^{-1}]$
kprime	κ	Schaeffer sedimentation parameter (ni)	$[m^{-1}]$
kdm	K_m	distribution coefficient sea sediment, shallow sea (ni)	$[m^3\ t^{-1}]$
kdd	K_m	distribution coefficient sea sediment, deep sea (ni)	$[m^3\ t^{-1}]$
Kss	K_{ss}	seaspray concentration factor (ni)	[-]
desorb	f_{desorb}	fraction desorbed in estuary (ni)	[-]

food

Ding	D_{ing}	dose factor for ingestion (ni)	$[Sv\ Bq^{-1}]$
kF	K_{ff}	concentration factor fresh fish (ni)	$[m^3\ t^{-1}]$
gvcf	$K_{c,gv}$	concentration factor green vegetables (ni)	$[Bq\ kg^{-1}\ f\ w\ /Bq\ kg^{-1}\ d\ w]$
gvwea	$W_{c,gv}$	weathering rate green vegetables (ni)	$[a^{-1}]$
gvfr	$f_{c,gv}$	fraction remaining after processing green vegetables (ni)	[-]
gvcr	$H_{c,gv}$	cropping rate green vegetables	$[a^{-1}]$
mugv	$\mu_{c,gv}$	interception parameter, green vegetables	$[m^2\ kg^{-1}]$
solgv	$S_{c,gv}$	contamination factor of green vegetables with soil	[-]
grcf	$K_{c,gr}$	concentration factor grains (ni)	$[Bq\ kg^{-1}\ f\ w\ /Bq\ kg^{-1}\ d\ w]$
grwea	$W_{c,gr}$	weathering rate grains (ni)	$[a^{-1}]$
grfr	$f_{c,gr}$	fraction remaining after processing grains (ni)	[-]
grcr	$H_{c,gr}$	grain cropping rate	$[a^{-1}]$
mugr	$\mu_{c,gr}$	interception parameter grain	$[m^2\ kg^{-1}]$
solgr	$S_{c,gr}$	contamination with soil, grain	[-]
rvcf	$K_{c,rv}$	concentration factor root vegetables (ni)	$[Bq\ kg^{-1}\ f\ w\ /Bq\ kg^{-1}\ d\ w]$
rvwea	$W_{c,rv}$	weathering rate root vegetables (ni)	$[a^{-1}]$
rvexin	T_{rv}	translocation rate root vegetables (ni)	$[a^{-1}]$
rvcr	$H_{c,rv}$	root vegetables cropping rate	$[a^{-1}]$
murv	$\mu_{c,rv}$	interception parameter root vegetables	$[m^2\ kg^{-1}]$
pacf	K_p	concentration factor pasture (ni)	$[Bq\ kg^{-1}\ f\ w\ /Bq\ kg^{-1}\ d\ w]$
pwea	$W_{c,pa}$	weathering rate pasture	$[a^{-1}]$
mup	$\mu_{c,pa}$	interception parameter pasture	$[m^2\ kg^{-1}]$

solcp	$S_{a,c}$	contamination with soil, pasture for cattle	[-]
solsp	$S_{a,s}$	contamination with soil, pasture for sheep	[-]
fabeef	$F_{a,beef}$	concentration factor beef (ni)	[d kg^{-1}]
facliver	$F_{a,cow\ liv.}$	concentration factor cow liver (ni)	[d kg^{-1}]
familk	$F_{a,milk}$	concentration factor milk (ni)	[d kg^{-1}]
famutton	$F_{a,mutton}$	concentration factor sheep meat (ni)	[d kg^{-1}]
fasliver	$F_{a,sheep\ liv.}$	concentration factor sheep liver (ni)	[d kg^{-1}]
KMF	$K_{f,fish}$	concentration factor seafish (ni)	[m^3 t^{-1}]
KC	$K_{f,crus}$	concentration factor crustacea (ni)	[m^3 t^{-1}]
KM	$K_{f,mol}$	concentration factor molluscs (ni)	[m^3 t^{-1}]
KSW	$K_{f,sw}$	concentration factor seaweed (ni)	[m^3 t^{-1}]

other

Dinh	D_{inh}	dose factor inhalation (ni)	[Sv Bq^{-1}]
photon	$Y_p(i)$	yield per disintegration in photon energy E_i (ni·12)	[-]
topsoilgam	$t_g(i)$	dose factor ext. irradiation, energy E_i (12)	[(Sv s^{-1}) (Bq m^{-3})$^{-1}$]

bio

nter		number of terrestrial compartments	[-]
nmar		number of marine compartments	[-]
relpos		release position	[-]
mtime		number of output times	[-]
To		output times (mtime)	[a]
minimum_delay		delay time for start release	[a]
f		fraction to river water if relpos = 0	[-]
V	V	volume river compartment (nter)	[m^3]
Vdot	F	volumetric flow river water (nter)	[m^3 a^{-1}]
Lr	l_r	length river compartment (nter)	[m]
depth_r	l_w	depth river (nter)	[m]
area	A	area of contaminated land (nter)	[m^2]
Sr	S_r	sedimentation rate lake (nter)	[t m^{-3} a^{-1}]
sedland	S	land heightening by sediment (nter)	[m a^{-1}]
irri	I	irrigation rate (nter)	[m a^{-1}]
alpha_r	α_r	suspended sediment load river water (nter)	[t m^{-3}]
vg	v_g	groundwater velocita (nter)	[m a^{-1}]
theta	θ	angle groundwater flow with horizontal (nter)	[degrees]
D	D	diffusion coefficient soil (nter)	[m^2 a^{-1}]
B	B	bioturbation coefficient soil (nter)	[m^2 a^{-1}]
Lc	l_c	length local sea	[m]
Wl		width lokal sea	[m]
Vm	$V_m^{(i)}$	volume marine box (nmar)	[m^3]
Vm_in	$F_{m,outwards}^{(i)}$	volumetric exchange rate flow outwards (nmar)	[m^3 a^{-1}]
Vm_out	$F_{m,inwards}^{(i)}$	volumetric exchange rate flow inwards (nmar)	[m^3 a^{-1}]
Lmw	l_m	depth sea compartments (nmar)	[m]
alpha_m	α_m	suspended sediment load marine waters (nmar)	[t m^{-3}]
Dm	D_m	diffusion coefficient marine water (nmar)	[m^2 a^{-1}]

Sm	S_m	sedimentation rate sea (nmar)	[t m^{-3} a^{-1}]

default

frs	v_{sed}	velocity of river sediment	[m a^{-1}]
bound	l_b	depth freshwater boundary layer	[m]
rho	ρ_s	density dry soil	[t m^{-3}]
epsilon	φ_s	porosity soil	[-]
Dr	D_r	diffusion coefficient freshwater	[m^2 a^{-1}]
Ltopsed	l_{ts}	depth top sediment box	[m]
Lmidsed	l_{ms}	depth middle sediment box	[m]
rho_s	ρ_{sed}	mineral density river sediment	[t m^{-3}]
epsilon_s	φ_{sed}	porosity river sediment	[-]
Lss	l_{ss}	depth top soil box	[m]
Lds	l_{ds}	depth middle soil box	[m]
Br	B_r	bioturbation coefficient river sediment	[m^2 a^{-1}]
Ds	D_s	diffusion coefficient in freshwater sediment	[m^2 a^{-1}]
erosion	E_{ss}	depth of soil layer annually eroded	[m a^{-1}]
rainfall	r	infiltrated rainfall	[m a^{-1}]
rho_m	ρ_{ms}	mineral density marine sediment	[t m^{-3}]
epsilon_m	φ_{ms}	porosity marine sediment	[-]
Lus	l_{mu}	depth marine top sediment box	[m]
Lms	l_{mm}	depth marine middle sediment box	[m]
Lb	l_{mb}	depth marine boundary layer	[m]
seaspray	W_{sea}	volume seaspray to land per unit coastal length	[m^3 a^{-1} m^{-1}]
Bm_s	B_m	bioturbation coefficient in shallow sea	[m^2 a^{-1}]
Bm_d	B_m	bioturbation coefficient in deep sea	[m^2 a^{-1}]

human

A number of parameters not used in the model are not indicated here

ingwat	I_w	consumption drinking water	[m^{-3} a^{-1}]
ingffiss	I_{ff}	consumption freshwater fish	[kg a^{-1}]
ypasture	$Y_{c,past}$	yield pasture (nter)	[kg m^{-2}]
adrink	A_{drink}	contaminated fraction animal drinking water (nter)	[-]
cattledens	$N_{a,cattle}$	density cattle	[km^{-2}]
ipcow	$I_{pa,cattle}$	consumption pasture cattle, dry weight	[kg d^{-1}]
iwcow	$I_{wa,cattle}$	consumption drinking water cattle	[m^3 d^{-1}]
ingbeef	$I_{a,beef}$	consumption beef	[kg a^{-1}]
ingcol	$I_{a,\ cow\ liver}$	consumption cow liver	[kg a^{-1}]
ingmilk	$I_{a,milk}$	consumptie milk	[kg a^{-1}]
sheepdens	$N_{a,sheep}$	density sheep	[km^{-2}]
ipsheep	$I_{pa,sh}$	consumption rate of pasture, sheep	[kg d^{-1}]
iwsheep	$I_{wa,sheep}$	consumption rate of drinking water, sheep	[m^3 d^{-1}]
ingmut	$I_{a,mutton}$	consumption rate of sheep meat	[kg a^{-1}]
ingshl	$I_{a,\ sheep\ liver}$	consumption rate of sheep liver	[kg a^{-1}]
inggv	$I_{c,gv}$	consumption rate of green vegetables	[kg a^{-1}]

ygveg	$Y_{c,gv}$	yield of green vegetables (nter)	[kg m^{-2}]
inggr	$I_{c,gr}$	consumption rate of grain	[kg a^{-1}]
ygrain	$Y_{c,gr}$	yield of grain (nter)	[kg m^{-2}]
ingrv	$I_{c,rv}$	consumption rate of root vegetables	[kg a^{-1}]
yroot	$Y_{c,rv}$	yield root vegetables (nter)	[kg m^{-2}]
wet	Z	fresh weight pasture of 1 kg dry weight pasture	[-]
inhair	I_{air}	inhalation rate air	[m^3 a^{-1}]
adust_r	a_d	dust level in air, public	[t m^{-3}]
adust_f	a_d	dust level in air, ploughing farmer	[t m^{-3}]
foccup	O_{occ}	fraction of a year ploughing	[-]
ingsfis	$I_{f,fish}$	consumption rate seafish	[kg a^{-1}]
ingcrust	$I_{f,crus}$	consumption rate crustacea	[kg a^{-1}]
ingmoll	$I_{f,mol}$	consumption rate molluscs	[kg a^{-1}]
ingweed	$I_{f,sw}$	consumption rate sea weed	[kg a^{-1}]
beachres	O_b	beach occupancy	[h a^{-1}]
beachinh	I_{sed}	inhalation rate beach sediment	[μg d^{-1}]
inhspray	I_{ss}	inhalation rate seaspray	[m^3 a^{-1}]
fgearocc	O_{fg}	fraction of a year handling fishing gear	[h a^{-1}]

release

ntime	number of times the flux is defined	[-]
release	times and fluxes (ntime$\cdot$(1+ni))	[a, Bq a^{-1}]

APPENDIX B INPUT AND OUTPUT DATA FILES FOR MiniBIOS_1A4

Listings of input and output data files are given for a deterministic calculation with the MiniBIOS_1A4 model for the radionuclide ^{99}Tc. The parameter values are equal to the parameter values used in the PROSA project in the comparison of different release points [La93a].

input

```
USEFIL
NUCLIDE NAME : nuclide.nuc
NUCLIDE RAW : release
NUCLIDE FOOD : nuclide.fod
NUCLIDE OTH : other
TEST BIO : test.bio
SAMPLE DAT : sample.dat
DEFAULT DAT : default.dat
HUMAN DATA : human
```

nuclide.nuc

```
 1                        ni
 43099                    nid
 1.031e-13                decay const.
 1.0404e-01
 1.9814e+02
 4.4483e-11
 1.0e+4                   low marine Kd
 1.0e+4                   deep marine Kd
 1.0E+0                   seaspray const.
 0.0E+0                   desorb
```

release

```
3
0.0E0      1.0E+0
1.0E6      1.0E+0
1.0001E6   0.0E+0
```

test.bio

```
1                                            nter
2                                            nmar
1                                            relpos
6                                            mtime & timeout(mtime)
1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06
0.0                                          minimum_delay
1.0                                          fraction to river if relpos=0.
5.6540e+05                                   volume box
6.9969e+07                                   vol. flow
1.0e+4                                       length river
2.6657e+00                                   depth of river
5.0e+6                                       area
0.0                                          sedimentation, Sr
4.9894e-04                                   sedland
9.9875e-02                                   irri
2.9994e-05                                   alpha_r
2.0E-01                                      vg
1.0E-03                                      theta
```

```
2.3405e-02                                  diffusion coefficient
4.4482e-04                                  bioturbation coefficient
5.0E+04                                     Lc
1.0E+04                                     Wl
5.0E+09  5.0E+15                            Vm
0.0E+00  1.58E+11                           Vm_in
1.58E+11 0.0E+00                            Vm_out
10.0     20.0                               Lmw
4.0e-5  1.0e-5                              alpha_m
3.15e-2 3.15e-2                             Dm
2.0e-5  2.0e-5                              Sm
```

default.dat

```
  8.4836e+02                          sediment velocity
  1.0E-01                             bound
  1.2994e+00                          density soil
  3.4985e-01                          porosity soil
  7.5178e-02                          diffusion coefficient freshwater
  0.1                                 depth top sediment
  1.9                                 depth middle sediment
  2.5998e+00                          density of sediments
  6.4937e-01                          porosity of sediments
  0.30                                depth of surface soil layer
  0.50                                depth of deep soil layer
  3.1573e-05                          bioturbation coeff. freshwater sed.
  2.3276e-02                          diffusion coeff. freshwater sed.
  4.9877e-04                          erosion
  3.4988e-01                          infiltrated rainfall
  2.66                                rho_m
  0.75                                epsilon_m
  0.1                                 Lus
  1.9                                 Lms
  5.0                                 Lb
  0.0                                 seaspray
  3.2E-05                             Bm_s
  3.2E-08                             Bm_d
```

NUCNAME.NUM

```
57
06014 'C-14'
17036 'Cl-36'
20041 'Ca-41'
27060 'Co-60'
28059 'Ni-59'
28063 'Ni-63'
34079 'Se-79'
37087 'Rb-87'
38090 'Sr-90'
40093 'Zr-93'
41094 'Nb-94'
42093 'Mo-93'
43099 'Tc-99'
46107 'Pd-107'
50126 'Sn-126'
53129 'I-129'
55135 'Cs-135'
55137 'Cs-137'
62147 'Sm-147'
62151 'Sm-151'
63154 'Eu-154'
82210 'Pb-210'
84210 'Po-210'
88224 'Ra-224'
```

```
88225 'Ra-225'
88226 'Ra-226'
88228 'Ra-228'
89225 'Ac-225'
89227 'Ac-227'
90228 'Th-228'
90229 'Th-229'
90230 'Th-230'
90232 'Th-232'
90234 'Th-234'
91231 'Pa-231'
92232 'U-232'
92233 'U-233'
92234 'U-234'
92235 'U-235'
92236 'U-236'
92238 'U-238'
93237 'Np-237'
94238 'Pu-238'
94239 'Pu-239'
94240 'Pu-240'
94241 'Pu-241'
94242 'Pu-242'
94244 'Pu-244'
95241 'Am-241'
95142 'Am-242MEC'
95242 'Am-242MB'
95243 'Am-243'
96244 'Cm-244'
96245 'Cm-245'
96246 'Cm-246'
96247 'Cm-247'
96248 'Cm-248'
```

other

```
 2.3e-09
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 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 1.30E-16
```

human

```
 0.75                                 ingwat
 0.0                       (not used) fwat
 2.0                                  ingffis
 0.0                       (not used) yffis
 1.1                                  ypasture
 1.0                                  adrink
 200.                                 cattledens
 0.0                       (not used) cattlefrac
 14.0                                 ipcow
 0.024                                iwcow
 40.0                                 ingbeef
 0.0                       (not used) ybeef
 1.0                                  ingcol
 0.0                       (not used) ycowl
 166.                                 ingmilk
 0.0                       (not used) ymilk
 1.0                                  sheepdens
 0.0                       (not used) sheepfrac
 1.5                                  ipsheep
 4.0E-03                              iwsheep
 0.0                                  ingmut
 0.0                       (not used) ymutt
```

```
0.0                                   ingshl
0.0                        (not used) yshel
96.0                                  inggv
3.8                                   ygveg
58.0                                  inggr
0.7                                   ygrain
80.0                                  ingrv
4.0                                   yroot
5.7                                   wet
10000.                                inhair
1.4e-11                               adust_r
4.2e-9                                adust_f
0.0                                   foccup
4.0                                   ingsfis
0.0 0.0                    (not used) ysfish
0.0                        (not used) fishfrac
0.0                                   ingcrust
0.0 0.0                    (not used) ycrust
0.0                        (not used) crustfrac
0.0                                   ingmoll
0.0 0.0                    (not used) ymoll
0.0                        (not used) mollfrac
0.0                                   ingweed
0.0 0.0                    (not used) yweed
0.0                        (not used) weedfrac
0.0                                   beachres
0.0                                   beachinh
0.0                                   inhspray
0.0                                   fgearocc
```

nuclide.fod

```
3.9e-10                                   dose per unit ingestion
4.4692e+01
1.2756e+01
17.98                                     rate for green veg.
1.0                                       fract. remaining after proces.
1.0E+00                                   green veg. cropping rate
0.36                                      interception param. green veg.
4.0e-4                                    contamin. with soil green veg.
1.6111e+01
17.98                                     rate for grain.
1.0                                       fract. remaining after proces.
1.0E+00                                   grain cropping rate
0.13                                      interception parameter grain
2.6e-3                                    contamin. with soil grain
1.2491e+01
17.98                                     rate for root veg.
1.0e-01                                   transf. from ext. to intern.
1.0E+00                                   root veg. cropping rate
0.14                                      interception param. root veg.
1.3526e+01
17.98                                     weathering rate for pasture
2.9                                       interception param. pasture
4.0E-02                                   soil contamin. cow pasture
2.0E-01                       (not used)  soil contamin. sheep pasture
1.9847e-04
1.9986e-04
5.3875e-04
1.0E+0                                    famutton
1.0E+0                                    fasliver
3.0e+1                                    conc. factor marine fish
1.0e+3                                    conc. factor crustacea
1.0e+3                                    conc. factor molluscs
5.0e+3                                    conc. factor seaweed
```

out.rel

```
 1
 43099
 3
 6
 1
 1.0
 .0 1.0
 1.00000000000000E+006 1.0
 1.00010000000000E+006 .0
 10.0
 100.0
 1000.0
 10000.0
 100000.0
 1.00000000000000E+006
```

out.trn

```
 1.0
 2.0
 1.0
 43099.0
  .32536E-05
  .12375E+03
  .88322E+00
  .84836E-01
  .29366E+01  .25934E+01
  .17161E+01  .15102E+01
  .11337E+00  .11337E+00
  .67541E-02  .67541E-02
  .82467E-03  .82467E-03
  .11762E+00
  .16626E-02  .16626E-02
  .26626E+00
  .30078E-01
  .83384E-02
  .43886E-03
  .00000E+00
  .31600E+02  .00000E+00
  .00000E+00  .31600E-04
  .14918E+00  .18970E+00
  .35549E-02  .35549E-02
  .33624E-02  .63696E-02
  .18696E-04  .18696E-04
  .15827E-03  .31655E-03
  .00000E+00
  .00000E+00
  .84836E-01
```

inges4.sgn

```
.........HEADER.........
water      fish       beef       cowliver   milk       mutton
     sheepliver  greenveg   grain      rootveg
4.152E-18  4.949E-19  1.161E-20  2.922E-22  1.308E-19  0.000E+00
     0.000E+00   1.651E-18  1.050E-18  9.221E-19 F
```

totdos4.sgn

```
.........HEADER.........
totaal    totingter  totingss   totsea    tinhter    tinhss     totinhsea
```

```
8.414E-18 8.414E-18  0.000E+00  2.111E-22 7.412E-25  0.000E+00  0.000E+00 F
```

inhal4.sgn

```
.........HEADER.........
farmer    inhal      extsoil   dbeach     dinhsed    dinhss     dfgear
0.000E+00 7.412E-25  0.000E+00 0.000E+00  0.000E+00  0.000E+00  0.000E+00 F
```

seaing4.sgn

```
.........HEADER.........
dfish     dcrust     dmoll      dweed
2.111E-22  0.000E+00  0.000E+00  0.000E+00 F
```

spray4.sgn

```
.........HEADER..........
beef       cowliver   milk       mutton     sheepliver greenveg   grain
  rootveg    farmer     dinhsoil   dextsoil
0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
  0.000E+00  0.000E+00  0.000E+00  0.000E+00 F
```

APPENDIX C INPUT AND OUTPUT DATA FILES FOR A PROBABILISTIC CALCULATION WITH MiniBIOS_1A4

Listings of input and output data files are given for a probabilistic calculation with the MiniBIOS_1A4 model with the use of UNCSAM for the decay chain of the radionuclide ^{229}Th. The parameter values are equal to the parameter values used in the PROSA project [La93a].

Th-229.par

```
#1 21-04-92
#2 UNCSAM
#3 Copyright (c) RIVM/CWM, 1991
TITLE
MiniBIOS nuclide
SAMPLING TECHNIQUE
latin
CORRECTION TECHNIQUE
no
MONTE CARLO INFORMATION
400 51 -16453
PARAMETER DISTRIBUTIONS
kd1
lun
0
1.0e+4  2.0e+5
kd2
lun
0
1.0e+2  3.8e+4
kd3
lun
0
1.0e+2  2.0e+6
ksr1
lun
0
1.0e+3  1.0e+7
ksr2
lun
0
7.0e+1  5.0e+4
ksr3
lun
0
6.0e+3  6.0e+5
kprim1
lun
0
2.0e-6  1.0e-5
kprim2
lun
0
1.0e-15 1.0e-5
kprim3
lun
0
2.0e-6  1.0e-5
kf1
lun
0
1.1e+1  1.6e+3
kf2
lun
0
3.0e+0  1.0e+3
```

```
kf3
lun
0
4.0e+0  2.5e+1
gvcf1
lun
0
3.8e-4  5.0e-3
gvcf2
lun
0
3.0e-4  9.0e-2
gvcf3
lun
0
2.0e-4  3.0e-3
grcf1
lun
0
5.0e-4  5.0e-3
grcf2
lun
0
3.0e-4  9.0e-2
grcf3
lun
0
1.7e-4  3.0e-3
rvcf1
lun
0
5.0e-4  5.0e-3
rvcf2
lun
0
3.0e-4  9.0e-2
rvcf3
lun
0
7.7e-5  3.0e-3
pacf1
lun
0
1.7e-4  5.0e-3
pacf2
lun
0
3.0e-4  9.0e-2
pacf3
lun
0
5.1e-4  3.0e-3
fabeef1
lun
0
6.0e-5  1.0e-4
fabeef2
lun
0
5.0e-4  3.0e-2
fabeef3
lun
0
2.0e-5  6.0e-2
facliver1
lun
0
6.0e-5  1.0e-4
```

```
facliver2
lun
0
5.0e-4  3.0e-2
facliver3
lun
0
2.0e-5  6.0e-2
familk1
con
0
5.0e-6
familk2
lun
0
4.0e-4  3.0e-3
familk3
lun
0
5.0e-6  2.0e-5
vol
his
0
3
0.75 0.20 0.05 0.0 0.0 0.0
2.0e+5 7.5e+5 5.0e+6 1.8e+7
flow
his
0
3
0.75 0.20 0.05 0.0 0.0 0.0
1.0e+7 1.0e+8 1.0e+10 1.0e+11
depth
his
0
3
0.75 0.20 0.05 0.0 0.0 0.0
2.0 3.0 5.0 6.0
sedland
uni
0
0.0 1.0e-3
irri
uni
0
0.05 0.15
alpha_r
uni
0
1.0e-5 5.0e-5
diffu
lun
0
5.0e-3 1.1e-1
bioturb
lun
0
1.0e-4 2.0e-3
frs
uni
0
2.0e+2 1.5e+3
rho
uni
0
1.0 1.6
epsilon
uni
```

```
0
0.25 0.45
D_r
lun
0
1.95e-2 2.9e-1
rho_s
uni
0
2.55 2.65
eps_s
uni
0
0.5  0.8
B_r
nor
2
3.15e-5 6.2e-11 1.0e-15 10.0
D_s
lun
0
5.0e-3 1.1e-1
erosion
uni
0
0.0 1.0e-3
rain
uni
0
0.3 0.4
CORRELATIONS
yes
8
kprim1
ksr1
0.99
kprim2
ksr2
0.99
kprim3
ksr3
0.99
depth
flow
0.9
vol
depth
0.9
vol
flow
0.9
irri
rain
-0.99
erosion
sedland
0.99
```

Th-229.cng

```
4 51
nuclide
99
food
99
bio
99
default
99
kd1
1 4 1 10
(E10.4)
kd2
1 4 12 21
(E10.4)
kd3
1 4 23 32
(E10.4)
ksr1
1 5 1 10
(E10.4)
ksr2
1 5 12 21
(E10.4)
ksr3
1 5 23 32
(E10.4)
kprim1
1 6 1 10
(E10.4)
kprim2
1 6 12 21
(E10.4)
kprim3
1 6 23 32
(E10.4)
kf1
2 2 1 10
(E10.4)
kf2
2 2 12 21
(E10.4)
kf3
2 2 23 32
(E10.4)
gvcf1
2 3 1 10
(E10.4)
gvcf2
2 3 12 21
(E10.4)
gvcf3
2 3 23 32
(E10.4)
grcf1
2 9 1 10
(E10.4)
grcf2
2 9 12 21
(E10.4)
grcf3
2 9 23 32
(E10.4)
rvcf1
2 15 1 10
(E10.4)
```

```
rvcf2
2 15 12 21
(E10.4)
rvcf3
2 15 23 32
(E10.4)
pacf1
2 20 1 10
(E10.4)
pacf2
2 20 12 21
(E10.4)
pacf3
2 20 23 32
(E10.4)
fabeef1
2 25 1 10
(E10.4)
fabeef2
2 25 12 21
(E10.4)
fabeef3
2 25 23 32
(E10.4)
facliver1
2 26 1 10
(E10.4)
facliver2
2 26 12 21
(E10.4)
facliver3
2 26 23 32
(E10.4)
familk1
2 27 1 10
(E10.4)
familk2
2 27 12 21
(E10.4)
familk3
2 27 23 32
(E10.4)
vol
3 8 1 12
(E11.6)
flow
3 9 1 12
(E11.6)
depth
3 11 1 12
(F5.3)
sedland
3 14 1 12
(E11.6)
irri
3 15 1 12
(F5.3)
alpha_r
3 16 1 12
(E11.6)
diffu
3 19 1 12
(E11.6)
bioturb
3 20 1 12
(E11.6)
frs
4 1 1 12
```

```
(E11.6)
rho
4 3 1 12
(F5.3)
epsilon
4 4 1 12
(F5.3)
D_r
4 5 1 12
(E11.6)
rho_s
4 8 1 12
(F5.3)
eps_s
4 9 1 12
(F5.3)
B_r
4 12 1 12
(E11.6)
D_s
4 13 1 12
(E11.6)
erosion
4 14 1 12
(E11.6)
rain
4 15 1 12
(F5.3)
```

nuclide

```
 3                                          ni
 90229 88225 89225                          nucname
 2.99e-12 5.42e-7 8.02e-7                   decay const.



 5.0e+6 5.0e+2 1.0e+4                       low marine Kd
 5.0e+6 5.0e+2 1.0e+4                       deep marine Kd
 1.0E+0 1.0e+0 1.0e+0                       seaspray const.
 0.0E+0 0.0e+0 0.0e+0                       desorb
```

food

```
 9.5e-7 1.0e-7 2.9e-6                      dose per unit ingestion


 17.98 17.98 17.98                         rate for green veg.
 1.0 1.0 1.0                               fract. remaining after proces.
 1.0E+00                                   green veg. cropping rate
 0.36                                      interception param. green veg.
 4.0e-4                                    contamin. with soil green veg.

 17.98 17.98 17.98                         rate for grain.
 1.0 1.0 1.0                               fract. remaining after proces.
 1.0E+00                                   grain cropping rate
 0.13                                      interception parameter grain
 2.6e-3                                    contamin. with soil grain

 17.98 17.98 17.98                         rate for root veg.
 1.0e-2 1.0e-2 1.8e-1                      transf. from ext. to intern.
 1.0E+00                                   root veg. cropping rate
 0.14                                      interception param. root veg.
```

```
 17.98                                         weathering rate for pasture
 2.9                                           interception param. pasture
 4.0E-02                                       soil contamin. cow pasture
 2.0E-01                           (not used)  soil contamin. sheep pasture


 1.0E+0 1.0E+0 1.0E+0                          famutton
 1.0E+0 1.0E+0 1.0E+0                          fasliver
 6.0e+2 5.0e+2 5.0e+1                          conc. factor marine fish
 1.0e+3 1.0e+2 1.0e+3                          conc. factor crustacea
 1.0e+3 1.0e+3 1.0e+3                          conc. factor molluscs
 2.0e+2 1.0e+2 1.0e+3                          conc. factor seaweed
```

bio

```
1                                               nter
2                                               nmar
1                                               relpos
6                                               mtime & timeout(mtime)
1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06
0.0                                             minimum_delay
1.0                                             fraction to river if relpos = 0.
                                                volume box
                                                vol. flow
1.0e+4                                          length river
                                                depth of river
5.0e+6                                          area
0.0                                             sedimentation, Sr
                                                sedland
                                                irri
                                                alpha_r
2.0E-01                                         vg
1.0E-03                                         theta
                                                diffusion coefficient
                                                bioturbation coefficient
5.0E+04                                         Lc
1.0E+04                                         Wl
5.0E+09  5.0E+15                                Vm
0.0E+00  1.58E+11                               Vm_in
1.58E+11 0.0E+00                                Vm_out
10.0     20.0                                   Lmw
4.0e-5  1.0e-5                                  alpha_m
3.15e-2 3.15e-2                                 Dm
2.0e-5  2.0e-5                                  Sm
```

default

```
                                              sediment velocity
  1.0E-01                                     bound
                                              density soil
                                              porosity soil
                                              diffusion coefficient freshwater
  0.1                                         depth top sediment
  1.9                                         depth middle sediment
                                              density of sediments
                                              porosity of sediments
  0.30                                        depth of surface soil layer
  0.50                                        depth of deep soil layer
                                              bioturbation coeff. freshwater sed.
                                              diffusion coeff. freshwater sed.
                                              erosion
                                              infiltrated rainfall
  2.66                                        rho_m
  0.75                                        epsilon_m
```

```
  0.1                                   Lus
  1.9                                   Lms
  5.0                                   Lb
  0.0                                   seaspray
  3.2E-05                               Bm_s
  3.2E-08                               Bm_d
```

input

```
USEFIL
NUCLIDE NAME : nuclide.nuc
NUCLIDE RAW : release
NUCLIDE FOOD : nuclide.fod
NUCLIDE OTH : other
TEST BIO : test.bio
SAMPLE DAT : sample.dat
DEFAULT DAT : default.dat
HUMAN DATA : human
```

release

```
3
0.0E0     1.0E+0  0.0E+0  0.0E+0
1.0E6     1.0E+0  0.0E+0  0.0E+0
1.0001E6  0.0E+0  0.0E+0  0.0E+0
```

other

```
 5.8e-4 2.1e-6 3.0e-8
 2.46E-01  7.48E-01  9.01E-02  1.83E-01  3.16E-01  6.91E-01
 3.23E-01  2.51E-01  5.53E-03  1.93E-02  2.81E-03  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 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 1.30E-16
```

human

```
 0.75                                 ingwat
 0.0                       (not used) fwat
 2.0                                  ingffis
 0.0                       (not used) yffis
 1.1                                  ypasture
 1.0                                  adrink
 200.                                 cattledens
 0.0                       (not used) cattlefrac
 14.0                                 ipcow
 0.024                                iwcow
 40.0                                 ingbeef
 0.0                       (not used) ybeef
 1.0                                  ingcol
 0.0                       (not used) ycowl
 166.                                 ingmilk
 0.0                       (not used) ymilk
 1.0                                  sheepdens
 0.0                       (not used) sheepfrac
 1.5                                  ipsheep
 4.0E-03                              iwsheep
 0.0                                  ingmut
 0.0                       (not used) ymutt
 0.0                                  ingshl
```

```
 0.0                    (not used) yshel
 96.0                              inggv
 3.8                               ygveg
 58.0                              inggr
 0.7                               ygrain
 80.0                              ingrv
 4.0                               yroot
 5.7                               wet
 10000.                            inhair
 1.4e-11                           adust_r
 4.2e-9                            adust_f
 0.0                               foccup
 4.0                               ingsfis
 0.0 0.0                (not used) ysfish
 0.0                    (not used) fishfrac
 0.0                               ingcrust
 0.0 0.0                (not used) ycrust
 0.0                    (not used) crustfrac
 0.0                               ingmoll
 0.0 0.0                (not used) ymoll
 0.0                    (not used) mollfrac
 0.0                               ingweed
 0.0 0.0                (not used) yweed
 0.0                    (not used) weedfrac
 0.0                               beachres
 0.0                               beachinh
 0.0                               inhspray
 0.0                               fgearocc
```

NUCNAME.NUM

```
57
06014 'C-14'
17036 'Cl-36'
20041 'Ca-41'
27060 'Co-60'
28059 'Ni-59'
28063 'Ni-63'
34079 'Se-79'
37087 'Rb-87'
38090 'Sr-90'
40093 'Zr-93'
41094 'Nb-94'
42093 'Mo-93'
43099 'Tc-99'
46107 'Pd-107'
50126 'Sn-126'
53129 'I-129'
55135 'Cs-135'
55137 'Cs-137'
62147 'Sm-147'
62151 'Sm-151'
63154 'Eu-154'
82210 'Pb-210'
84210 'Po-210'
88224 'Ra-224'
88225 'Ra-225'
88226 'Ra-226'
88228 'Ra-228'
89225 'Ac-225'
89227 'Ac-227'
90228 'Th-228'
90229 'Th-229'
90230 'Th-230'
90232 'Th-232'
90234 'Th-234'
91231 'Pa-231'
```

```
92232 'U-232'
92233 'U-233'
92234 'U-234'
92235 'U-235'
92236 'U-236'
92238 'U-238'
93237 'Np-237'
94238 'Pu-238'
94239 'Pu-239'
94240 'Pu-240'
94241 'Pu-241'
94242 'Pu-242'
94244 'Pu-244'
95241 'Am-241'
95142 'Am-242MEC'
95242 'Am-242MB'
95243 'Am-243'
96244 'Cm-244'
96245 'Cm-245'
96246 'Cm-246'
96247 'Cm-247'
96248 'Cm-248'
```

totdos4.sgn (partly)

```
MINIBIOS output data
Input file: river.par
22-01-92
totaal    totingter  totingss   totsea    tinhter   tinhss     totinhsea
8.818E-14 8.098E-14  0.000E+00  1.250E-18 7.197E-15  0.000E+00  0.000E+00 F
5.872E-14 4.988E-14  0.000E+00  1.570E-18 8.846E-15  0.000E+00  0.000E+00 F
5.989E-15 4.647E-15  0.000E+00  1.129E-18 1.341E-15  0.000E+00  0.000E+00 F
2.058E-14 1.625E-14  0.000E+00  1.340E-18 4.328E-15  0.000E+00  0.000E+00 F
8.154E-15 7.152E-15  0.000E+00  1.184E-18 1.001E-15  0.000E+00  0.000E+00 F
5.816E-14 4.865E-14  0.000E+00  1.477E-18 9.510E-15  0.000E+00  0.000E+00 F
5.055E-14 4.378E-14  0.000E+00  1.618E-18 6.768E-15  0.000E+00  0.000E+00 F
6.600E-14 5.586E-14  0.000E+00  1.476E-18 1.014E-14  0.000E+00  0.000E+00 F
9.097E-15 6.658E-15  0.000E+00  1.130E-18 2.438E-15  0.000E+00  0.000E+00 F
1.060E-13 1.006E-13  0.000E+00  1.407E-18 5.437E-15  0.000E+00  0.000E+00 F
.....
```

totdos4.bim

```
#1 11-Jun-93 14:26:56
#2 UNCSAM-BASICS [RIVM] Version 1.00-1.00, [Jun 20, 1792]
#3  Copyright (c) RIVM/CWM, 1991

**** Basic Statistics of file: totdos4.bim

     Title:   simulation data from file: totdos4.sgn

| parameter |      mean     |  st. dev.  |    c.v.    |
=======================================================
 totaal         4.93867E-14  4.31112E-14  8.72931E-01
 totingter      4.31500E-14  3.98270E-14  9.22991E-01
 totingss       0.00000E+00  0.00000E+00  9.99900E+03
 totsea         1.32098E-18  1.82642E-19  1.38263E-01
 tinhter        6.23497E-15  4.56371E-15  7.31954E-01
 tinhss         0.00000E+00  0.00000E+00  9.99900E+03
 totinhsea      0.00000E+00  0.00000E+00  9.99900E+03

| parameter |   abs. dev.   |  variance  |  skewness  |  curtosis  |
====================================================================
 totaal         3.00771E-14  1.85857E-27  2.30113E+00  8.63336E+00
 totingter      2.72062E-14  1.58619E-27  2.55560E+00  1.05700E+01
 totingss       0.00000E+00  0.00000E+00  9.99900E+03  9.99900E+03
 totsea         1.37907E-19  3.33583E-38  9.99910E-01  2.80241E+00
 tinhter        3.48501E-15  2.08275E-29  1.28746E+00  1.74097E+00
 tinhss         0.00000E+00  0.00000E+00  9.99900E+03  9.99900E+03
 totinhsea      0.00000E+00  0.00000E+00  9.99900E+03  9.99900E+03

| parameter |   2.5 perc.   |  25 perc.  |  75 perc.  | 97.5 perc. |
====================================================================
 totaal         3.36800E-15  2.23300E-14  6.33000E-14  1.49500E-13
 totingter      2.63900E-15  1.83400E-14  5.50900E-14  1.38300E-13
 totingss       0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
 totsea         1.03600E-18  1.20200E-18  1.42300E-18  1.66900E-18
 tinhter        6.17500E-16  2.91300E-15  8.10400E-15  1.74900E-14
 tinhss         0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
 totinhsea      0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00

| parameter |  50 perc.     |    mean    |  minimum   |  maximum   |
====================================================================
 totaal         3.86700E-14  4.93867E-14  2.29800E-16  3.38100E-13
 totingter      3.38100E-14  4.31500E-14  1.86900E-16  3.24600E-13
 totingss       0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
 totsea         1.30900E-18  1.32098E-18  1.01400E-18  2.23500E-18
 tinhter        5.15700E-15  6.23497E-15  4.17100E-17  2.48700E-14
 tinhss         0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
 totinhsea      0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
```