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Sensitivity analysis for modules for various biosphere types

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Abstract

This study presents the results of a sensitivity analysis for the modules developed earlier /Bergström et al, 1999/ for calculation of ecosystem specific dose conversion factors (EDFs). The report also includes a comparison between the probabilistically calculated mean values of the EDFs and values gained in deterministic calculations. An overview of the distribution of radionuclides between different environmental parts in the models is also presented. The radionuclides included in the study were ^{36}Cl, ^{59}Ni, ^{93}Mo, ^{129}I, ^{135}Cs, ^{237}Np and ^{239}Pu, selected to represent various behaviour in the biosphere and some are of particular importance from the dose point of view.

The deterministic and probabilistic EDFs showed a good agreement, for most nuclides and modules. Exceptions from this occurred if very skew distributions were used for parameters of importance for the results.

Only a minor amount of the released radionuclides were present in the model compartments for all modules, except for the agricultural land module. The differences between the radionuclides were not pronounced which indicates that nuclide specific parameters were of minor importance for the retention of radionuclides for the simulated time period of 10 000 years in those modules. The results from the agricultural land module showed a different pattern. Large amounts of the radionuclides were present in the solid fraction of the saturated soil zone. The high retention within this compartment makes the zone a potential source for future exposure. Differences between the nuclides due to element specific K_d-values could be seen. The amount of radionuclides present in the upper soil layer, which is the most critical zone for exposure to humans, was less then 1% for all studied radionuclides.

The sensitivity analysis showed that the physical/chemical parameters were the most important in most modules in contrast to the dominance of biological parameters in the uncertainty analysis. The only exception was the well module where the physical/chemical and parameters related to human behaviour were of about the same importance. In general the physical/chemical parameters identified in the sensitivity analysis are quite easily estimated and hence can be varied within relatively small interval when site-specific EDFs are calculated. The size of an area which is influenced by groundwater discharge from below as well as soil K_d and bioaccumulation factors are harder to specify. Research resources should therefore be concentrated on studies concerning those parameters.

Sammanfattning

Denna rapport presenterar resultaten från en känslighetsanalys som genomförts för de moduler som utvecklats tidigare /Bergström et al, 1999/ för att erhålla ekosystem-specifika dosomvandlingsfaktorer (EDF). Rapporten innehåller också en jämförelse mellan probabilistiskt beräknade medelvärden för EDF och deterministiskt beräknade värden. En översikt av fördelningen av radionuklider mellan olika delar av biosfären presenteras också. De radionuklider som inkluderades i denna studie var ^{36}Cl, ^{59}Ni, ^{93}Mo, ^{129}I, ^{135}Cs, ^{237}Np och ^{239}Pu. Dessa valdes för att representera olika beteenden i biosfären, dessutom är några av särskilt intresse ur dossynpunkt.

De deterministiska och probabilistiska EDFarna stämde bra överens för de flesta nuklider och moduler. Undantag från detta uppträdde när mycket skeva fördelningar användes för parametrar som var viktiga för resultaten.

Endast en liten del av de utsläppta nukliderna fanns kvar i modellernas delkomponenter med undantag av modulen för jordbruksmark. Skillnaden mellan de olika radionukliderna var inte påtaglig vilket indikerar att nuklidspecifika parametrar hade mindre betydelse för retentionen av radionuklider i dessa moduler under den tidsperiod på 10 000 år som simulerades. Resultaten från jordbruksmarksmodulen visade ett annat mönster. Stora mängder radionuklider fanns i den fasta fraktionen av den grundvatten-mättade jordzonen. Den stora retentionen i denna delkomponent gör denna zon till en potentiell källa för framtida exponering. Skillnader mellan de olika nukliderna på grund av elementspecifika K_d-värden kunde ses. Mindre än 1% av mängden radionuklider fanns i det övre jordlagret som är den mest kritiska zonen för exponering till människor.

Känslighetsanalysen visade att fysikalisk-kemiska parametrar var viktigast i de flesta moduler till skillnad från resultaten från den tidigare utförda osäkerhetsanalysen där biologiska parametrar dominerade. Det enda undantaget var brunnsmodulen där fysikalisk-kemiska parametrar och parametrar relaterade till mänskligt beteende var ungefär lika betydelsefulla. I allmänhet är de fysikalisk/kemiska parametrarna som identifierades i känslighetsanalysen ganska lätta att uppskatta och kan därför varieras inom ett litet intervall när platsspecifika EDFar beräknas. Storleken på det område som påverkas av grundvattenutflöde underifrån liksom K_d i jord och bioackumulations-faktorer är svårare att specificera. Forskningsresurser borde därför koncentreras till studier rörande dessa parametrar.

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1 Introduction

This study is closely related to an earlier study, which provides a basis for illustrations of yearly dose rates to most exposed individual from calculated releases of radionuclides from deep geological repositories /Bergström et al, 1999/. The main aim of this study is to present the sensitivity analysis performed on the modules developed in that study. The report also includes a comparison between the mean values of the ecosystem specific dose conversion factors (EDFs) presented in the former study with values gained in deterministic calculations. An overview of the distribution of radionuclides between different environmental parts used in the modules is also presented.

1.1 Background

A number of models, modules, have been developed as a base for the illustration of dose to humans from calculated releases of radionuclides which have been deposited in deep geological repositories /Bergström et al, 1999/. Results from these modules applied specifically on three sites, Aberg, Beberg and Ceberg /Nordlinder et al, 1999/, are part of the safety analysis SR 97 /SKB, 1999/. All calculations were performed with uncertainty analysis, i.e. all parameters, except the dose conversion factors, were given intervals from which the parameter values used in the model calculations were generated. The chosen intervals represented uncertainties in the determination of parameter values. The intervals were generally relatively wide because the knowledge was insufficient to specify parameter values better. The latter is true especially for those factors which were used to describe sorption of the elements to solid matter (K_d-values) as well as their uptake in biological matter (root uptake and bioaccumulation factors). Some parameters, e.g. the site-specific parameters in the surface water modules generally had smaller intervals as measured data of e.g. volumes and residual times of water were used.

The six modules available are well, lake, running waters, coast, agricultural land and peat bog /Bergström et al, 1999/. The parameters which contributed most to the uncertainty in the values of the calculated factors were identified with the help of regression and correlation analyses. Information about the sensitivity of the models for the parameters used within the models was not achieved. This is instead one of the topics of this report. Sensitivity analysis is an important tool in model improvement and a good help in the planning of how future biosphere studies should be performed within the work of localisation of a deep repository for spent nuclear fuel. The parameters for which the modules are sensitive are important to quantify within a narrow range to give a good illustration of the exposure situation. The identification can therefore point out important areas which need further investigation and also which parameter should be investigated in future site-specific studies.

Seven radionuclides were chosen for this study; ^{36}Cl, ^{59}Ni, ^{93}Mo, ^{129}I, ^{135}Cs, ^{237}Np and ^{239}Pu. These nuclides represent different mobility rates and also dominating exposure pathways. In the result tables the nuclides are sorted after relative mobility.

The comparison between deterministic and probabilistic values of EDFs is treated in Chapter 2. Chapter 3 deals with the distribution of radionuclides within the biosphere model parts and the sensitivity analysis is presented in Chapter 4. The results are discussed in Chapter 5. Values used in the sensitivity analysis can be found in tables in Appendix A.

2 Comparison between deterministic and probabilistic values

In Bergström et al /1999/ the EDF values were calculated probabilistically as most of the parameters were set to vary within a given range. The EDF mean values presented in that study and values gained in deterministic calculations (i.e. when the parameters are given a specific value, in this case the mean value of the parameter ranges used in the other study) were compared, see Table 2-1.

Generally there was a good agreement between the results. Lower EDF values were gained in the deterministic calculations for ^{237}Np in the lake and running waters module (~ 3 times lower) and for ^{239}Pu in the agricultural module (also ~ 3 times lower). This can be explained by the uneven distribution of important parameters used in the module of concern, which is further discussed in section 5.1.

Table 2-1. Comparison between EDFs (Sv/year) gained in deterministic (D) calculations (this study) and the EDF mean values gained in the probabilistic (P) calculations /Bergström et al, 1999/ respectively. Values differing most are shaded. The radionuclides are sorted with respect to relative mobility as nuclides to the left have lower K_d-values than those to the right.

Module		EDF ^{36}Cl	EDF ^{93}Mo	EDF ^{237}Np	EDF ^{129}I	EDF ^{59}Ni	EDF ^{135}Cs	EDF ^{239}Pu
Well	D	7.6E-13	2.8E-12	5.5E-11	8.6E-11	7.1E-14	2.4E-12	2.7E-10
	P	4.4E-13	4.5E-12	7.1E-11	1.5E-10	9.2E-14	2.8E-12	2.8E-10
	Ratio D/P	1.73	0.62	0.77	0.57	0.77	0.86	0.96
Lake	D	3.3E-16	6.0E-16	1.3E-14	5.7E-14	2.3E-17	2.2E-14	2.5E-14
	P	4.8E-16	7.5E-16	3.8E-14	5.7E-14	2.8E-17	2.2E-14	3.1E-14
	Ratio D/P	0.69	0.80	0.34	1.00	0.82	1.00	0.81
Running waters	D	2.0E-15	3.5E-15	7.7E-14	3.4E-13	1.3E-16	1.3E-13	1.4E-13
	P	2.8E-15	4.4E-15	2.3E-13	3.8E-13	1.7E-16	1.3E-13	1.8E-13
	Ratio D/P	0.71	0.80	0.34	0.90	0.77	1.00	0.78
Coast	D	1.3E-16	6.5E-17	1.3E-15	1.8E-14	3.0E-17	7.3E-16	8.7E-15
	P	1.6E-16	9.2E-17	2.0E-15	1.8E-14	2.2E-17	7.8E-16	6.4E-15
	Ratio D/P	0.81	0.71	0.65	1.00	1.36	0.94	1.36
Agricultural land	D	3.2E-13	1.2E-12	2.6E-12	6.0E-11	1.6E-14	3.8E-13	3.6E-13
	P	4.0E-13	8.7E-13	2.1E-12	5.0E-11	1.1E-14	3.1E-13	1.2E-12
	Ratio D/P	0.80	1.38	1.24	1.20	1.45	1.23	0.30
Peat bog	D	1.8E-11	2.8E-12	1.2E-10	3.9E-11	3.2E-13	2.4E-12	4.2E-10
	P	2.2E-11	2.5E-12	1.1E-10	3.0E-11	2.7E-13	2.7E-12	4.1E-10
	Ratio D/P	0.82	1.12	1.09	1.30	1.19	0.89	1.02

3 Radionuclide distribution in the module compartments

In the calculations of EDFs the major environmental components are represented by ”compartments” between which the radionuclides are transferred. The distribution of amounts of the seven radionuclides (^{36}Cl, ^{59}Ni, ^{93}Mo, ^{129}I, ^{135}Cs, ^{237}Np and ^{239}Pu) between the different compartments in the modules were investigated at the end of the studied time period, i.e. after 10 000 years.

3.1 Well module

In the well module the radionuclides from a deep repository for spent nuclear fuel are assumed to reach the biosphere within a well which was assumed to be used as a source for consumption and irrigation water. The compartments used were groundwater, irrigated soil (top soil) and deep soil. The water used for irrigation was assumed to reach the well again through downward migration in the soil. The fraction of the annually supplied water amount in the well which was not used for irrigation was assumed to leave the system /Bergström et al, 1999/.

For all studied radionuclides the amount of radionuclides lost from the system was more than 90% (see Table 3-1). The most mobile nuclide, ^{36}Cl, was almost totally absent in the system after the study time period of 10 000 years whereas 93% of the ^{239}Pu, which has low mobility, has been transported out of the system and 5.6% remained in the deep soil. Almost 2% of the supplied amount were present in the top soil, which is important for the exposure to humans.

Table 3-1. The distribution (in %) of radionuclides between different compartments in the well module after 10 000 years. Out is the amount of the radionuclides that has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Well water	0.011	0.023	0.011	0.011	0.011	0.011	0.011
Top soil	0.002	0.308	0.157	0.479	0.749	1.112	1.821
Deep soil	0.007	1.047	0.570	1.651	2.512	3.635	5.612
Out	99.980	98.622	99.262	97.859	96.727	95.242	92.555

3.2 Lake module

The lake module contains compartments for water and sediment. The sediments are divided into three different sediment types; transport, accumulation, and deep sediment respectively, which are all represented by a specific compartment. The radionuclides reach the system directly in the lake water and outflow from the system occurs from the water as well as from the accumulation sediment due to turnover of lake water as well as burial in deep sediment. The lake water was assumed to be used as irrigation water implying additional compartments for top and deep soils /Bergström et al, 1999/.

As can be seen in Table 3-2 there was a very low build up of radionuclides in sediments over centuries because of the large fraction leaving the system with the out-flowing water.

Table 3-2. The distribution (in %) of radionuclides between different compartments in the lake module after 10 000 years. Out represents the fraction which has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Water	0.003	0.007	0.003	0.003	0.003	0.003	0.004
Transport sediment	0.001	0.000	0.005	0.000	0.006	0.005	0.056
Accumulation sediment	0.002	0.000	0.022	0.001	0.023	0.022	0.231
Top soil	0.000	0.002	0.001	0.002	0.004	0.005	0.008
Deep soil	0.000	0.007	0.004	0.009	0.014	0.019	0.029
Out	99.994	99.985	99.965	99.984	99.951	99.945	99.672

3.3 Running waters module

The running waters was assumed to be used for irrigation and therefore the module consists of three compartments representing the water in the stream, the irrigated soil (top soil) and the deep soil. In- and outflow of radionuclides from the system occur from the water compartment /Bergström et al, 1999/.

Minor amounts of the radionuclides remained within the system (see Table 3-3).

Table 3-3. The distribution (in %) of radionuclides between different compartments in the running waters module after 10 000 years. Out represents the fraction which has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
River	0.010	0.022	0.010	0.010	0.010	0.010	0.011
Top Soil	0.000	0.011	0.005	0.014	0.021	0.030	0.048
Deep Soil	0.000	0.039	0.021	0.055	0.081	0.113	0.173
Out	99.990	99.929	99.964	99.921	99.887	99.847	99.768

3.4 Coast module

The coast module describes a bay in connection with the open sea. Two different compartments therefore represent the water, one for the bay and one for the open sea. The sediments in the bay are represented by two compartments, the deeper one functioning as a sink where radionuclides enter but do not leave. The sediment in the open sea area was represented by one compartment. The inflow of radionuclides to the system was to the bay whereas the outflow occurred from the water and sediment of the open sea region due to water turnover and sediment burial /Bergström et al, 1999/.

Similar to the lake and running water modules very small amounts of the radionuclides were present within the coast module system after the study time period (see Table 3-4).

Table 3-4. The distribution (in %) of radionuclides between different compartments in the coast module after 10 000 years. Out represents the fraction which has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Water, bay	0.001	0.003	0.001	0.001	0.001	0.001	0.001
Top sediment, bay	0.000	0.000	0.013	0.000	0.014	0.013	0.139
Deep sediment, bay	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water, open coast	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sediment, open bay	0.000	0.000	0.000	0.000	0.000	0.000	0.003
Out	99.999	99.997	99.985	99.998	99.984	99.985	99.856

3.5 Agricultural land module

The soil in the agricultural land module was divided into three layers; top soil, deep soil and the saturated zone. Two compartments represent the saturated zone (groundwater and the solid fraction of the soil) whereas the other two are represented by one compartment each. The radionuclides enter the system as solutes in the groundwater of the saturated zone (soluble part). Outflow occurs through erosion of the top soil as well as outflow of groundwater from the saturated zone /Bergström et al, 1999/.

For ^{36}Cl most of the amount (99.5%) had left the system after the time period considered (see Table 3-5), whereas that fraction was much smaller for the other radionuclides. A relation to K_d can be seen as the fraction present in the solid part of the saturated zone increases with increasing K_d-value. A deviation from this pattern was seen for ^{93}Mo, which is due to the short half-time of this nuclide (3 500 years) in relation to the others. The total amount of this nuclide in all compartments after the simulated time period is therefore less than the supplied amount and as the transfer out of the system is quite fast this fraction will be smaller than for other long-lived radionuclides. The relations are therefore somewhat different than for ^{237}Np for which the same K_d-value was used. Very small amounts (less then 1%) of all radionuclides were present in the top soil.

Table 3-5. The distribution (in %) of radionuclides between different compartments in the agricultural land module after 10 000 years. Out represents the fraction which has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Top soil	0.003	0.498	0.394	0.844	0.935	0.850	0.035
Deep soil	0.038	3.641	2.836	4.658	4.741	3.996	0.150
Solid, saturated zone	0.354	43.774	31.970	59.876	70.855	81.619	99.503
Water, saturated zone	0.063	0.078	0.057	0.036	0.025	0.015	0.000
Out	99.542	52.009	64.742	34.586	23.445	13.520	0.312

3.6 Peat bog module

The peat bog module consists of two compartments. The radionuclides reach the biosphere within the pore water of the bog (soluble part) and leave the system through the same compartment. A compartment representing the organic matter (solid fraction) was also included /Bergström et al, 1999/.

Small amounts of radionuclides were left in the peat bog after 10 000 years (see Table 3-6). About 5% of the supplied amount of ^{239}Pu and 2% of the amounts of ^{237}Np and ^{59}Ni can be found in the solid organic fraction of the peat bog.

Table 3-6. The distribution (in %) of radionuclides between different compartments in the peat bog module after 10 000 years. Out represents the fraction which has left the module system.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Water	0.019	0.043	0.019	0.019	0.020	0.019	0.021
Organic matter	0.021	0.143	2.084	0.063	2.176	0.626	4.744
Out	99.960	99.814	97.897	99.919	97.805	99.355	95.234

4 Sensitivity analysis

4.1 Methods

In order to investigate the relative importance of the parameters used in the different modules in Bergström et al /1999/ these parameters (see Appendix A) were assumed to be normally distributed and given a standard deviation of 1% of the mean value. Two parameters, the dose conversion factors and the annual number of irrigation occasions, were constants. If those parameters would also be varied they would dominate the sensitivity totally and thus overshadow the contribution from other parameters. The PRISM system /Gardner et al, 1983/ was used in the analyses. This enabled all parameters to be varied at the same time which reduced the number of "modelling running" considerably.

The selection of radionuclides was based on difference in mobility and exposure pathway /Bergström et al, 1999/. The most mobile of the chosen radionuclides is ^{36}Cl whereas ^{239}Pu is considered to be retarded considerably in soils and sediments. The different behaviour of the nuclides in the environment implies that they reach humans through different exposure pathways, see Table 4-1.

Table 4-1. The dominating exposure pathways for the different radionuclides in the modules. W=well module, L=lake module, R=running waters module, C=coast module, A=agricultural land module, P=peat bog module.

	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Water consumption	W		W	W			
Fish consumption		C	L, R, C	L, R	L, R, C	L, R, C	L, R, C
Milk consumption	L, R, A, C, P	C		L, C, A, P, R	L, R, A, P	A, P	
Meat consumption				C		A, P	
Consumption of cereals	A, P	L, R, A, P		A, P			
Consumption of root crops	W	W		W	W	W	
Inhalation of dust			A, P				W, L, R, A, P

4.2 Results

A summary of the results of the sensitivity analysis is presented in Table 4-2. The parameters were divided into three categories depending on their nature. *Physical/ chemical parameters* described physical properties and included for example adsorption, soil erosion, water transport and sedimentation rates whereas e.g. root uptake factors, transfer factors to milk and meat and accumulation of radionuclides in fish were called *biological parameters*. The third category, *human induced parameters* included for example consumption rates and the annual amount of irrigation water used.

The models were most sensitive to physical/chemical parameters in most modules. The only exception was the well module where the physical/chemical and human induced parameters were of about the same importance. Biological parameters were somewhat less important than the human induced ones in most cases. This is the general pattern for the mean values for the seven radionuclides studied (see Table 4-2). The pattern differs somewhat for the specific nuclides.

A more specified presentation of the results for each module follows.

Table 4-2. Contribution (in %) of the different parameter categories to sensitivity in EDFs for the different radionuclides and average across all radionuclides.

Module	Parameter category	Contribution to sensitivity in EDFs (%)							
		^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{35}Cs	^{239}Pu	Mean
Well	Physical/Chemical	47	52	30	45	67	45	35	46
	Biological	4	5	0	1	7	2	0	3
	Human induced	49	44	71	53	27	52	55	50
Lake	Physical/Chemical	71	78	79	76	68	51	80	72
	Biological	17	7	10	14	16	25	4	13
	Human induced	10	16	11	9	10	24	16	14
Running waters	Physical/Chemical	76	78	79	80	69	53	81	74
	Biological	15	7	10	10	20	24	3	13
	Human induced	10	15	11	9	12	24	15	14
Coast	Physical/Chemical	41	68	62	52	67	69	61	60
	Biological	40	20	18	33	16	18	20	24
	Human induced	19	12	19	15	14	12	21	16
Agricultural land	Physical/Chemical	88	76	82	77	81	89	84	83
	Biological	8	23	1	18	11	8	0	10
	Human induced	3	0	19	6	6	2	15	7
Peat bog	Physical/Chemical	74	71	74	72	77	79	65	73
	Biological	19	14	0	20	15	19	0	12
	Human induced	7	15	26	8	7	4	34	14

4.2.1 Well module

The parameters describing human behaviour and physical/chemical conditions were the ones for which the model in the well module was most sensitive. The biological parameters had a minor influence.

A few parameters influenced the results for the studied radionuclides. The volume of the well, described as an annual mixing volume, was important for all nuclides (see Table 4-3). The importance of the inhalation exposure pathway for actinides was illustrated by the high contributions from the parameters used for calculating dose by inhalation for ^{239}Pu (inhalation rate, exposure time and air concentration of dust). For this nuclide the parameters annual amount of irrigation water and soil particle density were also of importance. For ^{59}Ni and ^{93}Mo annual amounts of irrigation water, root crop consumption and the root uptake factor for root crops were sensitive parameters. The results were in conformity with the dominant exposure pathways for the well module that are consumption of water and root crops grown on soil irrigated with the contaminated water.

Table 4-3. The major contribution to sensitivity (%), in the model used for the well module. P/C=physical/chemical parameters, B=biological parameters, H=human induced parameter.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Mixing volume	67.6	40.3	45.0	63.8	49.7	67.1	27.0
	Runoff	4.3	4.5	8.8	3.5	1.7	2.1	0.0
	Soil K_d	2.6	5.1	8.5	2.6	1.8	1.4	0.0
	Deep soil depth	0.0	17.5	7.4	6.8	11.6	1.7	5.4
	Soil porosity	0.0	2.5	0.0	0.0	2.7	0.0	4.6
	Soil particle density	0.0	0.0	0.0	0.0	3.5	0.0	10.4
	Air concentration of dust	0.0	0.0	0.0	0.0	0.0	0.0	11.6
B	Root uptake factor, root crops	2.3	6.5	5.3	0.0	4.7	0.0	0.0
	Cow's water consumption	2.2	0.0	0.0	2.0	0.0	0.0	0.0
H	Annual amount of irrigation water	6.4	13.4	11.9	6.7	12.2	3.1	13.2
	Consumption of root crops	4.3	6.7	8.5	0.0	6.6	0.0	0.0
	Water consumption	7.9	3.2	4.8	9.4	2.7	21.7	2.1
	Inhalation rate	0.0	0.0	0.0	0.0	0.0	1.2	12.8
	Exposure time	0.0	0.0	0.0	0.0	0.0	0.0	12.7

4.2.2 Lake module

The model used in the lake module was most sensitive for the physical/chemical parameters.

A few parameters dominated the sensitivity of the model. The runoff and size of the catchment area were the most sensitive parameters for the lake module for all of the studied radionuclides (see Table 4-4). As ^{135}Cs mainly reaches humans through consumption of contaminated fish the bioaccumulation factor for fish and the fish consumption rate were two important parameters. For ^{93}Mo the soil K_d, the annual amount of water used for irrigation, the root uptake factor and consumption of cereals were sensitive parameters.

Table 4-4. The major contribution to sensitivity (%), in the model used for the lake module.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Runoff	46.0	50.9	40.3	44.0	38.5	24.6	35.5
	Catchment area	24.0	19.3	39.2	29.9	30.1	27.0	34.6
	K_d soil	1.6	7.6	0.0	2.0	0.0	0.0	0.0
	Soil particle density	0.0	0.0	0.0	0.0	0.0	0.0	3.9
B	Bioaccumulation factor for fish	0.0	0.0	8.0	4.6	2.3	24.6	3.9
	Cow's consumption of cereals	4.7	0.0	0.0	1.4	0.0	0.0	0.0
	Root uptake factor, cereals	1.2	6.0	0.0	0.0	0.0	0.0	0.0
	Transfer coefficient to milk	0.0	0.0	0.0	0.0	5.9	0.0	0.0
	Cow's consumption of pasturage	0.0	0.0	0.0	3.4	4.9	0.0	0.0
H	Fish consumption	0.0	0.0	7.9	5.4	2.7	23.9	3.5
	Annual amount of irrigation water	3.7	9.8	0.0	2.1	2.5	0.0	3.4
	Milk consumption	4.3	0.0	0.0	0.0	5.9	0.0	0.0
	Consumption of cereals	0.0	6.4	0.0	0.0	0.0	0.0	0.0
	Inhalation rate	0.0	0.0	0.0	0.0	0.0	0.0	4.5
	Exposure time	0.0	0.0	0.0	0.0	0.0	0.0	3.4

4.2.3 Running waters module

Also the model used in the running waters module was most sensitive for the physical/ chemical parameters. As expected the running waters modules behaved very similar to the lake module.

The most sensitive parameters for the results of the studied radionuclides were runoff and size of catchment area (see Table 4-5). For ^{135}Cs, the bioaccumulation factor and consumption rates of fish were sensitive parameters. For ^{93}Mo the soil K_d and the annual amount of water used for irrigation were sensitive parameters as in the lake module.

Table 4-5. The major contribution to sensitivity (%), in the model used for the running waters module.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Runoff	42.9	42.5	37.5	41.1	35.1	25.2	32.0
	Catchment area	22.7	17.8	35.9	26.1	25.1	23.9	31.5
	K_d soil	1.6	6.0	0.0	1.3	1.0	0.0	0.0
	Deep soil depth	0.0	5.6	0.0	2.7	2.0	0.0	1.1
	Soil particle density	0.0	0.0	0.0	0.0	0.0	0.0	3.7
	Resuspension of dust	0.0	0.0	0.0	0.0	0.0	0.0	3.6
B	Bioaccumulation factor for fish	0.0	0.0	6.8	4.2	1.9	21.6	3.2
	Transfer coefficient to milk	3.8	0.0	0.0	1.1	5.5	0.0	0.0
	Cow's consumption of pasturage	3.3	0.0	0.0	2.2	3.5	0.0	0.0
	Root uptake factor, cereals	1.7	5.7	0.0	0.0	0.0	0.0	0.0
H	Fish consumption	0.0	0.0	6.8	4.6	2.5	22.1	2.5
	Annual amount of irrigation water	2.9	9.1	0.0	2.3	1.8	0.0	4.3
	Milk consumption	4.1	0.0	0.0	0.0	5.4	0.0	0.0
	Consumption of cereals	0.0	0.0	0.0	0.0	5.5	0.0	0.0
	Inhalation rate	0.0	0.0	0.0	0.0	0.0	0.0	3.5
	Exposure time	0.0	0.0	0.0	0.0	0.0	0.0	3.5

4.2.4 Coast module

Physical/chemical parameters were the most sensitive ones also for the model used in the coast module.

Three parameters gave about the same contribution to the sensitivity for all radionuclides studied. The parameters were the bay area, the water residence time and the mean depth of the bay (see Table 4-6). All three parameters were considered to be physical/chemical parameters. For some nuclides the length of the time period that the cattle graze at the shoreline was an important parameter whereas the accumulation in fish and consumption rate of this food were more important for other nuclides. This was due to the dominance of various exposure pathways (see Table 4-1). Transpiration of water plants as well as parameters connected to the uptake of radionuclides in cattle were sensitive parameters when modelling ^{36}Cl and ^{129}I.

Table 4-6. The major contribution to sensitivity (%), in the model used for the coast module.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Bay area	13.9	21.9	20.7	16.5	22.9	22.5	20.5
	Mean depth, bay	13.6	23.2	19.9	18.1	21.9	23.8	20.6
	Mean residence time of water in bay	13.6	23.2	21.4	17.8	22.9	22.9	19.1
B	Bioaccumulation factor for fish	0.0	7.1	18.6	0.0	12.0	9.6	19.1
	Transpiration of water plants	10.8	3.7	0.0	9.9	1.5	3.0	0.0
	"Yield" of water plants	10.8	3.6	0.0	8.9	1.5	2.3	0.0
	Cow's consumption of water plants	10.3	4.1	0.0	8.6	1.3	2.2	0.0
	Transfer coefficient to milk	8.3	2.4	0.0	2.4	1.7	0.0	0.0
H	Cow's grazing period	11.1	3.0	0.0	9.7	1.4	2.6	0.0
	Fish consumption	0.0	6.1	19.5	0.0	11.4	8.4	20.7
	Milk consumption	7.7	1.7	0.0	2.3	1.6	0.0	0.0

4.2.5 Agricultural land module

In the agricultural land module physical/chemical parameters dominated the sensitivity totally.

In contrast to the results for the other modules, element specific differences are seen in the agricultural land module (see Table 4-7). This is due to the different mobility of the radionuclides, the high mobility of chlorine makes the results sensitive to the volume of runoff whereas this is not true for Pu. When modelling ^{234}Pu and some of the other nuclides the parameter particle density, which in combination with the porosity and volumes gives the masses of the different soil layers, was important. The model was also sensitive for the runoff for ^{36}Cl, ^{93}Mo, ^{237}Np, ^{129}I and ^{59}Ni. The size of the field area, i.e. the part of the field which is influenced by groundwater discharge from below, was also important. The importance of the inhalation exposure pathway for actinides was shown by the high contributions from the parameters used for calculating dose by inhalation for ^{239}Pu (inhalation rate, exposure time, soil K_d and resuspension of dust). Also for ^{237}Np these parameters were important. The model was sensitive to transfer of contaminated groundwater from below, the depth of the saturated zone and soil K_d for some radionuclides. Root uptake and consumption of cereals were important parameters for ^{93}Mo.

Table 4-7. The major contribution to sensitivity (%), in the model used for the agricultural land module.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Area of field	10.2	18.0	14.0	22.2	21.7	18.2	8.7
	Runoff	60.2	37.1	38.8	19.6	11.8	3.3	0.0
	Depth of saturated zone	0.0	2.6	0.0	8.4	10.8	12.6	8.5
	Soil particle density	0.0	4.6	1.3	16.0	26.8	39.5	36.9
	K_d soil	7.5	10.3	13.6	2.8	0.0	1.5	8.3
	Water transport, deep soil to top soil	5.3	0.0	0.0	0.0	0.0	0.0	0.0
	Water transport, ground water to deep soil	3.2	8.4	5.1	6.4	8.8	4.4	7.9
	Resuspension of dust	0.0	0.0	8.5	0.0	0.0	0.0	8.6
B	Root uptake factor, cereals	5.7	10.3	0.0	4.2	2.7	0.0	0.0
	Transfer coefficient to milk	1.3	0.0	0.0	1.8	4.6	0.0	0.0
	Root uptake factor, pasturage	0.0	0.0	0.0	4.5	2.6	3.4	0.0
	Cow's consumption of pasturage	0.0	0.0	0.0	4.5	2.5	3.5	0.0
H	Exposure time	0.0	0.0	8.5	0.0	0.0	0.0	8.3
	Inhalation rate	0.0	0.0	9.4	0.0	0.0	0.0	7.9
	Consumption of cereals	2.0	10.4	0.0	1.4	0.0	0.0	0.0
	Milk consumption	1.5	0.0	0.0	1.8	5.8	0.0	0.0

4.2.6 Peat bog module

The peat bog module was most sensitive to physical/chemical parameters.

Three parameters contributed to about the same amount of the sensitivity for all studied radionuclides. The parameters were the area of the peat bog, the runoff from the bog and the K_d for peat (see Table 4-8). All three parameters were considered to be physical/ chemical parameters. The importance of the inhalation exposure pathway for actinides was shown by the high contributions from the parameters used for calculating dose by inhalation for ^{239}Pu (inhalation rate and exposure time). Also for ^{237}Np these parameters were important. The uptake in cereals and consumption of this foodstuff were sensitive parameters for ^{93}Mo. Root uptake in cereals was also important for ^{36}Cl.

Table 4-8. The major contribution to sensitivity (%), in the model used for the peat bog module.

	Parameter	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
P/C	Peat bog area	24.2	23.4	20.6	26.0	26.2	25.0	15.7
	Runoff	24.3	22.8	20.4	23.4	25.4	25.0	16.6
	K_d peat	25.5	24.7	19.9	23.0	24.9	26.5	16.1
	Resuspension of dust	0.0	0.0	12.8	0.0	0.0	0.0	17.7
B	Root uptake factor, cereals	13.5	14.2	0.0	4.5	2.8	1.7	0.0
	Transfer coefficient to milk	3.1	0.0	0.0	2.5	5.9	1.7	0.0
	Root uptake factor, pasturage	0.0	0.0	0.0	5.2	3.4	5.3	0.0
	Cow's consumption of pasturage	0.0	0.0	0.0	0.0	3.0	5.1	0.0
	Root uptake factor, root crops	0.0	0.0	0.0	4.7	1.4	0.0	0.0
H	Consumption of cereals	4.4	14.9	0.0	1.6	0.0	0.0	0.0
	Exposure time	0.0	0.0	12.9	0.0	0.0	0.0	17.2
	Inhalation rate	0.0	0.0	13.4	0.0	0.0	0.0	16.7
	Milk consumption	2.7	0.0	0.0	2.6	5.8	1.4	0.0

5 Discussion

5.1 Comparison between deterministic and probabilistic values

For most radionuclides and modules the deterministic and probabilistic EDF values agreed very well. Only for ^{237}Np in the lake and running waters modules and for ^{239}Pu in the agricultural module the deterministic values were about one third of the probabilistic ones. This is due to the uneven distribution of important parameters used in the modules of concern. In the lake and running waters modules the bioaccumulation factor for fish was an important parameter when calculating dose to humans. For ^{237}Np this parameter was set to be logtriangularly distributed between 10 and 3 000 L/kg with an average value of 50 L/kg. In the agricultural land module the soil distribution factor (K_d) was important in the dose calculations. The soil K_d for ^{239}Pu in agricultural land was set to vary logtriangularly between 10 and 100 m^3/kg dw with an average value of 50 m^3/kg dw. As the average values were used in the deterministic calculations those EDFs were somewhat lower than the EDFs gained in the probabilistic calculations.

5.2 Radionuclide distribution in the module compartments

For all modules except the agricultural land module a minor amount of the supplied radionuclides was left in the system after 10 000 years. The differences between different radionuclides were not pronounced which indicates that nuclide specific parameters were of minor importance for the retention of radionuclides over very long time periods in those modules.

According to the results from these models the element specific behaviour was more pronounced in the agricultural land module then in the other. Most of the mobile radionuclide ^{36}Cl has left the system whereas the presence of the other nuclides was considerable. The most extreme situation was found in the results for ^{239}Pu where 99.5% of the amount “supplied” has been retarded within the compartment representing the solid fraction of the saturated soil zone. Also for the other nuclides this was a major pool. The high retention within this compartment makes the zone a potential source for future exposure. A minor fraction of the radionuclides was also present in the deep soil compartment. The amount present in the upper soil layer was very small, less then 1% for all studied radionuclides. This is the zone most critical for exposure to humans as the roots of crops are situated here. This layer is also relevant for external exposure and inhalation, for natural reasons.

So where are the radionuclides which have left the modelled systems? The outflow from the systems occurs mainly through water. Erosion of soil and burial in deep sediments are also outflow processes. All water systems drain, sooner or latter, in the oceans which will be the final recipient for the radionuclides but retention in soils and sediments may occur on the way. One feature which is not fully understood is what happens with radionuclides transported from the inland when the fresh water reaches brackish or saline water. Some of the nuclides which reach the oceans will accumulate in sediments whereas others will be present in the water phase available for uptake in the biological food webs and thereby lead to exposures.

The radionuclides in the water from the well can be retarded in the soil if the people who drink the water clean their wastewater through infiltration in the ground. As seen in the agricultural land module radionuclides can be present in the soil for long times and function as potential exposure sources.

5.3 Sensitivity analysis

As mentioned before, sensitivity analysis is an important tool in model improvement as it identifies the parameters for which the models are sensitive. In combination with uncertainty analysis, which identifies parameters which contribute much to the uncertainty in the results (which often indicates that information about more precise values are absent), those parameters which should be prioritised in model improvement can be encircled. The improvement can involve further studies to improve the understanding of underlying processes as well as sampling of site-specific data. The most important category of parameters identified in the sensitivity analysis was physical/chemical ones whereas the uncertainty analysis /Bergström et al, 1999/ stressed the biological parameters such as root uptake and bioaccumulation factors. The physical/chemical parameters were often quite well known and did therefore not contribute much to the uncertainty in that study. An exception was K_d for elements in soil and peat which are important contributors to uncertainty as can be seen in section 5.3.2 below.

In the **well** module the volume for mixing was identified as a sensitive parameter. Mixing volumes for radionuclides in groundwater reaching wells have been discussed during many years. The volume has been described in various ways over the years. The annual infiltration amount of water over an area the size of a deep repository has e.g. been used /Bergman et al, 1977/. This approach gave about hundred times larger volumes than the ones used in Bergström et al /1999/. In Bergström et al /1999/ measured capacities were taken from the Swedish Well Archive. These measured capacities were transformed to annual mixing volumes by assuming that they were constant all over the year. This lead to narrow ranges of the mixing volumes, an approach which can be discussed.

In the **lake** module the parameters runoff and catchment area were sensitive parameters. Both parameters were used when calculating the turnover time of the lake water and thereby the outflow of radionuclides from the system. Using the water turnover time as one parameter instead of calculate it from these two parameters did not effect the results of the sensitivity analysis. For ^{135}Cs bioaccumulation to fish and consumption rate of this foodstuff were as sensitive as the other two mentioned. This is due to a high bioaccumulation factor as cesium has a strong tendency to accumulate in fish muscle. The annual amount of irrigation water was a sensitive parameter for ^{93}Mo. The most exposed human was assumed to use water from the lake to irrigate crops during the growing season. In Sweden, however, we have a humid climate with low needs of irrigation. It is mostly performed for some economically valuable crops and in dry areas. In garden-plots people irrigate when necessary and lake water can then be used. During growing season crops need about 3 mm water daily which corresponds quite well with the used value of 150 mm if the precipitation is sparse. These 150 mm must, however, be seen as an upper level as the mean precipitation during normal years mostly is sufficient for the crops.

The **running waters** module behaved very similar to the lake module and hence the runoff and catchment area were the dominant parameters. In that module no sediment was included and the similar results of the two modules indicate that retention of radionuclides in the lake sediment was not a sensitive process. The doses to humans were calculated using the radionuclide concentration in the water. Therefore the concept where the role of the sediment as a sink is neglected will lead to a somewhat overestimated dose as the water concentration will be higher than in reality. The radionuclide concentration within the sediments will be somewhat underestimated, which may lead to an underestimation of dose if the sediments are used when calculating doses. It would also be important if biosphere evolution would be considered, such as land rise transforming former sediments into agricultural land.

The area and mean depth of the bay as well as the residual time of water were the most important parameters in the **coast** module. All three were used in the calculation of water concentration which is used when calculating uptake in aquatic organisms. For all studied radionuclides except ^{36}Cl and ^{129}I the bioaccumulation in and consumption of fish were sensitive parameters. This is not surprising since the main exposure pathway in the coastal module is consumption of contaminated fish.

The results from the **agricultural land** module were somewhat different from those from the other modules as mentioned earlier. A distinct difference between the different radionuclides can be seen here which was not pronounced for the other modules where element specific parameters seem to be of minor importance. For ^{36}Cl, runoff was the most important parameter which is not surprising since chlorine is very mobile in the environment. For the other nuclides the size of the field area, the runoff and density of the soil particles were sensitive parameters. The depth of the saturated zone was also of some importance. This was because these parameters were used when calculating the transfers between the compartments in the module /see Bergström et al, 1999/. The dominant exposure pathway for ^{237}Np and ^{239}Pu was inhalation which can be seen by the sensitivity to the parameters inhalation rate and exposure time.

In the **peat bog** module the most sensitive parameters were peat area size, runoff and the distribution coefficient, K_d. The area was involved in the expressions describing both the transfer between the solid and the soluble fractions and the outflow of the soluble fraction whereas the K_d was included in the first transfer and the runoff in the second. For ^{237}Np and ^{239}Pu the inhalation rate and exposure time were sensitive parameters as inhalation was the dominant exposure pathway.

5.3.1 Comparison with results from other studies

When concerning biosphere models for radionuclides the terms uncertainty analysis and sensitivity analysis are often mixed up, which may led to confusion. In many cases the term sensitivity analysis is used for what we call uncertainty analysis, i.e. for the study of which parameters contribute to the uncertainty in the results for a certain calculation with a specific model. Sensitivity analysis as we call it are not commonly performed. One exception is Davis et al /1993/ which have performed such an analysis for the biospheric model BIOTRAC. This model is a compartment model developed to perform dose assessments and is composed of submodels much like the modules in this study.

Results from the sensitivity analysis of the surface water submodel in BIOTRAC coincide with the results for the lake and running waters modules. In both studies catchment area and runoff are the most important parameters. The other submodels in BIOTRAC are different from the modules and therefore a comparison is not relevant.

5.3.2 Comparison with results from the uncertainty analysis

It was stated that the biological parameters often were dominating in the uncertainty analysis performed earlier /Bergström et al, 1999/. This was, however, not the case for the **well** module. In this module the physical/chemical parameter soil K_d contributes to the uncertainty for ^{36}Cl, ^{59}Ni, ^{93}Mo and ^{237}Np and the concentration of dust in the air was the most important contributor when modelling ^{239}Pu. The root uptake factor for root crops was identified as important in the uncertainty analysis for all radionuclides discussed in this report except for ^{237}Np and ^{239}Pu. This parameter was, however, not identified as that important in the sensitivity analysis.

In the **lake** and **running waters** modules the bioaccumulation factor for fish dominates the uncertainty for all radionuclides except ^{36}Cl and ^{59}Ni. For those two nuclides soil K_d was important. In the sensitivity analysis the parameters bioaccumulation factor for fish and soil K_d were important for ^{135}Cs and ^{93}Mo, respectively.

In the uncertainty analysis of the **coast** module the biological parameters dominate totally. The bioaccumulation factor for fish was important for all radionuclides except ^{36}Cl and ^{129}I. For those two nuclides the parameter water plant transpiration was an important contributor to the uncertainty and in the case of ^{129}I the transfer coefficient to milk was also relevant. These parameters were not the most important but were relevant also in the sensitivity analysis.

The area of the field and soil K_d were important parameters in the uncertainty analysis of the **agricultural land** module. For ^{93}Mo and ^{129}I the root uptake factor for cereals was also relevant. Though not the most important, these parameters also showed up in the sensitivity analysis.

In the uncertainty analysis of the **peat bog** module the parameters peat bog area and peat K_d were important parameters. The root uptake factor for cereals was important for ^{93}Mo. These parameters were also important in the sensitivity analysis. The runoff which was a sensitive parameter did not contribute significantly to the uncertainty anyhow.

5.3.3 Conclusions

In general the physical/chemical parameters identified in the sensitivity analysis can quite easily be estimated and hence can be varied within relatively small interval when calculating site-specific EDFs. One exception is the parameter field area size, i.e. the size of an area which is influenced by groundwater coming from below, which, according to our knowledge, is not fully known. The size of the area depends on the flow patterns and varies seasonally. With the current state of knowledge it is hard to model this phenomena correct.

It is also hard to estimate K_d-values and bioaccumulation factors. If site-specific values for the composition of soils could be used the range for the K_d-value could be reduced as this parameter varies between different soil types. The range would anyway be rather large, as the K_d approach is quite rough. It would be preferable if the distribution of radionuclides between the solid and soluble phases could be described in another way considering matters as e.g. surface complexation and ion exchange between the radionuclides and the structures within the soil, and groundwater fluctuations over the year but this is not possible today. The uptake and accumulation of radionuclides in fish are rather complex processes that are described by only one parameter, which value can vary many orders of magnitude for the same element between different water systems. Important factors for the uptake and accumulation of radionuclides in organisms seem to be i.a. water chemistry and also ecological parameters such as the length of the biological food web /Karlsson et al, in manus/. If the values could be expressed as functions of important parameters, which are easy to estimate in nature, site-specific information could reduce the contribution to uncertainty in EDFs considerably. Research resources should therefore be concentrated to studies concerning those parameters.

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Appendix A

In this section the parameter values used in the sensitivity analysis are presented. The general parameters used in the different modules are shown in Table A-1–A-6 whereas the nuclide specific parameters can be found in Table A-7.

Table A-1. General parameters used in the sensitivity analysis of the well module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Mixing volume	2 000	m^3
Cow's water consumption	70	l/day
Water consumption	600	l/year
Milk consumption	200	l/year
Meat consumption	55	kg/year
Consumption of vegetables	40	kg/year
Consumption of root crops	70	kg/year
Soil consumption	0.01	kg/year
Exposure time	100	h/year
Inhalation rate	1	m^3/h
Air concentration of dust	0.0001	kg/m^3
Size of irrigated field	1 000	m^2
Annual amount of irrigation water	150	$m^3/(m^2 \cdot year)$
Number of irrigation occasions	5	–
Top soil depth	0.3	m
Top soil porosity	0.4	m^3/m^3
Deep soil depth	1	m
Deep soil porosity	0.3	m^3/m^3
Soil particle density	2 400	kg/m^3
Bioturbation	2	$kg/(m^2 \cdot year)$
Erosion	0.3	mm/year
Runoff	0.24	$m^3/(m^2 \cdot year)$
Vegetation yield	3	kg/m^2
Retention of irrigated water	3	mm
Weathering constant	0.05	day^{-1}

Table A-2. General parameters used in the sensitivity analysis of the lake module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Lake area	4.3	km^2
Lake max depth	4.1	m
Catchment area	117	km^2
Water conc. of suspended matter	0.001	kg dw/m^3
Sedimentation rate	1	kg $dw/(m^2 \cdot year)$
Sediment density	10	kg/m^3
Resuspension rate	0.9	$year^{-1}$
Resuspension factor	1.5	–
Primary production	0.01	kg $dw/(m^2 \cdot year)$
Fraction of primary production reaching the sediment	0.35	–
Water consumption	600	l/year
Milk consumption	200	l/year
Meat consumption	55	kg/year
Consumption of vegetables	40	kg/year
Consumption of root crops	70	kg/year
Consumption of cereals	80	kg/year
Soil consumption	0.01	kg/year
Fish consumption	30	kg/year
Consumption of crustacean	2	kg/year
Exposure time	100	h/year
Inhalation rate	1	m^3/h
Resuspension of dust	0.0001	kg/m^3
Cow's water consumption	70	l/day
Cow's consumption of pasturage	5	kg/day
Cow's consumption of cereals	12	kg/day
Cow's soil consumption	0.1	kg/day
Cow's grazing period	30	days/year
Size of irrigated field	100 000	m^2
Annual amount of irrigation water	150	$m^3/(m^2 \cdot year)$
Number of irrigation occasions	5	–
Top soil depth	0.3	m
Top soil porosity	0.4	m^3/m^3
Deep soil depth	1	m
Deep soil porosity	0.3	m^3/m^3
Soil particle density	2 400	kg/m^3
Bioturbation	2	$kg/(m^2 \cdot year)$
Erosion	0.1	m/year
Runoff	240	$m^3/(m^2 \cdot year)$
Yield of pasturage	0.5	kg $dw/(m^2 \cdot year)$
Yield of cereals	0.5	kg $dw/(m^2 \cdot year)$
Yield of root crops	3	kg $dw/(m^2 \cdot year)$
Yield of vegetables	3	kg $dw/(m^2 \cdot year)$
Retention of irrigated water	3	mm
Weathering constant	0.05	day^{-1}
Transpiration of water plants	1	$g/(m^2 \cdot h)$

Table A-3. General parameters used in the sensitivity analysis of the running waters module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Catchment area	20	km^2
Water consumption	600	l/year
Milk consumption	200	l/year
Meat consumption	55	kg/year
Consumption of vegetables	40	kg/year
Consumption of root crops	70	kg/year
Consumption of cereals	80	kg/year
Soil consumption	0.01	kg/year
Fish consumption	30	kg/year
Consumption of crustacean	2	kg/year
Exposure time	100	h/year
Inhalation rate	1	m^3/h
Air concentration of dust	0.0001	kg/m^3
Cow's water consumption	70	l/day
Cow's consumption of pasturage	5	kg/day
Cow's consumption of cereals	12	kg/day
Cow's soil consumption	0.1	kg/day
Cow's grazing period	30	days/year
Size of irrigated field	100 000	m^2
Annual amount of irrigation water	150	$m^3/(m^2 \cdot year)$
Number of irrigation occasions	5	–
Top soil depth	0.3	m
Top soil porosity	0.4	m^3/m^3
Deep soil depth	1	m
Deep soil porosity	0.3	m^3/m^3
Soil particle density	2 400	kg/m^3
Bioturbation	2	$kg/(m^2 \cdot year)$
Erosion	0.1	mm/year
Runoff	240	$m^3/(m^2 \cdot year)$
Yield of pasturage	0.5	$kg\ dw/(m^2 \cdot year)$
Yield of cereals	0.5	$kg\ dw/(m^2 \cdot year)$
Yield of root crops	3	$kg\ dw/(m^2 \cdot year)$
Yield of vegetables	3	$kg\ dw/(m^2 \cdot year)$
Retention of irrigated water	3	mm
Weathering constant	0.05	day^{-1}
Transpiration of water plants	1	$g/(m^2 \cdot h)$

Table A-4. General parameters used in the sensitivity analysis of the coast module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Bay area	1 400 000	m^2
Mean depth, bay	2.3	m
Max depth, bay	8	m
Sedimentation rate, bay	2.0	$kg/(m^2 \cdot year)$
Water concentration of suspended matter, bay	0.001	kg/m^3
Sediment density, bay	10	kg/m^3
Resuspension factor	1.5	–
Water residence time	45	days
Volume, open coast	170 000 000	m^3
Mean depth, open coast	7	m
Sedimentation rate, open coast	0.2	$kg/(m^2 \cdot year)$
Water concentration of suspended matter, open coast	0.001	kg/m^3
Resuspension rate, open coast	0.2	$year^{-1}$
Outflow rate, open coast	44	$year^{-1}$
Milk consumption	200	l/year
Meat consumption	55	kg/year
Fish consumption, bay	30	kg/year
Fish consumption, open coast	1	kg/year
Consumption of algae	2	kg/year
Cow's water consumption	70	l/day
Cow's consumption of pasturage	5	kg/day
Cow's grazing period	30	days/year
Yield of pasturage	0.5	$kg\ dw/(m^2 \cdot year)$
Transpiration of water plants	1	$g/(m^2 \cdot h)$

Table A-5. General parameters used in the sensitivity analysis of the agricultural land module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Depth of saturated zone	5	m
Porosity of saturated zone	0.3	m^3/m^3
Water transport, groundwater to deep soil	200	$mm/(m^2 \cdot year)$
Water transport, deep soil to top soil	100	$mm/(m^2 \cdot year)$
Milk consumption	200	l/year
Meat consumption	55	kg/year
Consumption of vegetables	40	kg/year
Consumption of root crops	70	kg/year
Consumption of cereals	80	kg/year
Soil consumption	0.01	kg/year
Exposure time	100	h/year
Inhalation rate	1	m^3/h
Air concentration of dust	0.0001	kg/m^3
Cow's consumption of pasturage	5	kg/day
Cow's consumption of cereals	12	kg/day
Cow's soil consumption	0.1	kg/day
Area of field	10 000	m^2
Top soil depth	0.3	m
Top soil porosity	0.4	m^3/m^3
Deep soil depth	1	m
Deep soil porosity	0.3	m^3/m^3
Soil particle density	2 400	kg/m^3
Bioturbation	2	$kg/(m^2 \cdot year)$
Erosion	0.1	mm/year
Runoff	240	$m^3/(m^2 \cdot year)$

Table A-6. General parameters used in the sensitivity analysis of the peat bog module. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Mean value	Unit
Peat bog depth	0.5	m
Peat bog area	10 000	m^2
Peat density	100	kg/m^3
Peat porosity	0.9	m^3/m^3
Relative concentration	0.00001	s/m^3
Filtering efficiency	1	–
Fuel consumption	0.0003	kg/s
Milk consumption	200	l/year
Meat consumption	55	kg/year
Consumption of vegetables	40	kg/year
Consumption of root crops	70	kg/year
Consumption of cereals	80	kg/year
Soil consumption	0.01	kg/year
Exposure time	100	h/year
Inhalation rate	1	m^3/h
Exposure time for exhaust	8 000	h/year
Air concentration of dust	0.0001	kg/m^3
Cow's consumption of pasturage	5	kg/day
Cow's consumption of cereals	12	kg/day
Cow's soil consumption	0.1	kg/day
Runoff	240	$m^3/(m^2 \cdot year)$

Table A-7. Nuclide specific parameter values used in the sensitivity analysis. The parameters were assumed to be normally distributed with a standard deviation of 1% of the mean value.

Parameter	Unit	^{36}Cl	^{93}Mo	^{237}Np	^{129}I	^{59}Ni	^{135}Cs	^{239}Pu
Transfer coefficient to milk	day/l	1.7E-02	1.0E-03	5.0E-06	1.0E-02	2.0E-02	8.0E-03	1.0E-06
Transfer coefficient to meat	day/kg	2.0E-02	2.0E-03	1.0E-04	4.0E-02	5.0E-03	5.0E-02	1.0E-05
Root uptake factor, pasturage	kg dw/kg dw	3.0E+01	8.0E-01	7.0E-02	6.0E-01	2.0E-01	2.0E-01	4.0E-04
Root uptake factor, cereals	kg dw/kg ww	2.6E+01	6.8E-01	2.0E-03	1.0E-01	3.0E-02	2.0E-02	7.0E-06
Root uptake factor, vegetables	kg dw/kg ww	3.0E+00	8.0E-02	4.0E-03	3.0E-02	2.0E-02	2.0E-02	2.0E-05
Root uptake factor, root crops	kg dw/kg ww	6.0E+00	1.6E-01	2.0E-03	1.0E-02	4.0E-02	2.0E-02	3.0E-05
Bioaccumulation factor, freshwater fish	l/kg ww	5.0E+01	1.0E+01	5.0E+01	2.0E+02	1.0E+02	1.0E+04	3.0E+01
Bioaccumulation factor, brackish water fish	l/kg ww	1.0E+00	1.0E+01	1.0E+01	3.0E+01	3.0E+02	2.0E+02	3.0E+01
Bioaccumulation factor, algae	l/kg ww	1.0E-01	1.0E+01	6.0E+00	1.0E+03	3.0E+02	5.0E+01	3.0E+02
Bioaccumulation factor, crustacean	l/kg ww	1.0E+02	1.0E+01	4.0E+02	5.0E+00	1.0E+02	1.0E+02	1.0E+02
Translocation	m^2/kg ww	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-02	2.0E-01	2.0E-02
Distribution coefficient (K$_d$), lake sediment	m^3/kg dw	1.0E+00	1.0E-03	1.0E+01	3.0E-01	1.0E+01	1.0E+01	1.0E+02
Distribution coefficient (K$_d$), Baltic Sea sediment	m^3/kg dw	1.0E-03	1.0E-03	1.0E+01	3.0E-01	1.0E+01	1.0E+01	1.0E+02
Distribution coefficient (K$_d$), soil	m^3/kg dw	1.0E-03	1.0E-01	1.0E-01	3.0E-01	5.0E-01	1.0E+00	5.0E+01
Distribution coefficient (K$_d$), peat bog	m^3/kg dw	1.0E-02	3.0E-02	1.0E+00	3.0E-02	1.0E+00	3.0E-01	2.0E+00