Dose Assessment Model for use in site restoration

General methodology and site-specific aspects

Restoration Strategies for Radioactively Contaminated
Sites and their Close Surroundings
RESTRAT

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1 Introduction

This report is submitted as Technical Deliverable 'TD6' against the requirements of Work Package 4 for the Restoration Strategies for Radioactive Sites and their Close Surroundings, RESTRAT, project.

The RESTRAT project, which is funded by the European Commission under the Nuclear Fission Safety Programme, has the overall objective of developing generic methodologies for ranking restoration techniques as a function of contamination and site characteristics. The development of this generic methodology is based on an analysis of existing remediation methodologies and contaminated sites, and is structured in the following steps:

1 Characterisation of relevant contaminated sites
2 Identification and characterisation of relevant restoration techniques
3 Assessment of the radiological impact
4 Development and application of a selection methodology for restoration options
5 Formulation of generic conclusions and development of a manual

This work package, which is also funded by the Swedish Radiation Protection Institute, is concerned with the dose assessments for selected contaminated sites and restoration techniques. The radiological impact on population and on workers, individually (average members of the critical groups) and collectively, has been assessed. Uncertainty analysis was carried out and the parameters contributing most to the uncertainty, were identified.

2 Background

In order to demonstrate a generic approach for evaluating effects of different restoration options five radioactively contaminated sites were selected representing five different categories of contaminated ecosystems:

- Contaminated freshwater river, Molse Nete river, Belgium
- Low-level waste disposal site, BNFL Drigg site, Great Britain
- Contaminated estuary, Ravenglass estuary, Great Britain
- Restored uranium mining and milling site, Ranstad tailing site, Sweden
- Contaminated fresh water lake, former open pit mine, lake Tranebärssjön, Sweden

In this working package a method is developed for assessing the radiological impact on man as a major attribute in the ranking and selection procedure of the restoration options for radioactively contaminated sites. The impact on the public, as well as the impact on the restoration workers, is to be taken into account. When the radiological impact is brought about by an event or a scenario that is -probable, it is expressed in terms of doses; when the event or scenario shows only a limited probability of occurrence, the impact is expressed in terms of risk. In this study the scenarios considered all show a high probability of occurrence and therefore only doses are considered.

A dose assessment model was developed for each site. Individual doses to average members of a critical group and committed collective doses as a measure of the total health detriment are calculated.

Impact scenarios were developed separately for workers and public. For workers the dose impact is brought about during the restoration works through inhalation of resuspended dust and through external irradiation. The doses are calculated as a function of exposure times and from the contamination levels.

For public the radiological consequence of a restoration is a dose reduction (aversion); i.e. the dose impact without restoration minus the dose impact with restoration. In order to calculate these dose impacts a more comprehensive system, the biosphere, is to be considered and the exposure also takes place through consumption of contaminated food, next to inhalation and external irradiation.

Since the important issue for the RESTRAT project is to show how different restoration options affect the dose to public and workers, the focus has not been to make detailed studies of all processes considered. Simplifications have been made both concerning the number of compartments used and details in the transport processes.

3 General approach

Radioactive sources may be situated in these compartments and expose man directly or indirectly, after transfer to other media as explained hereafter.

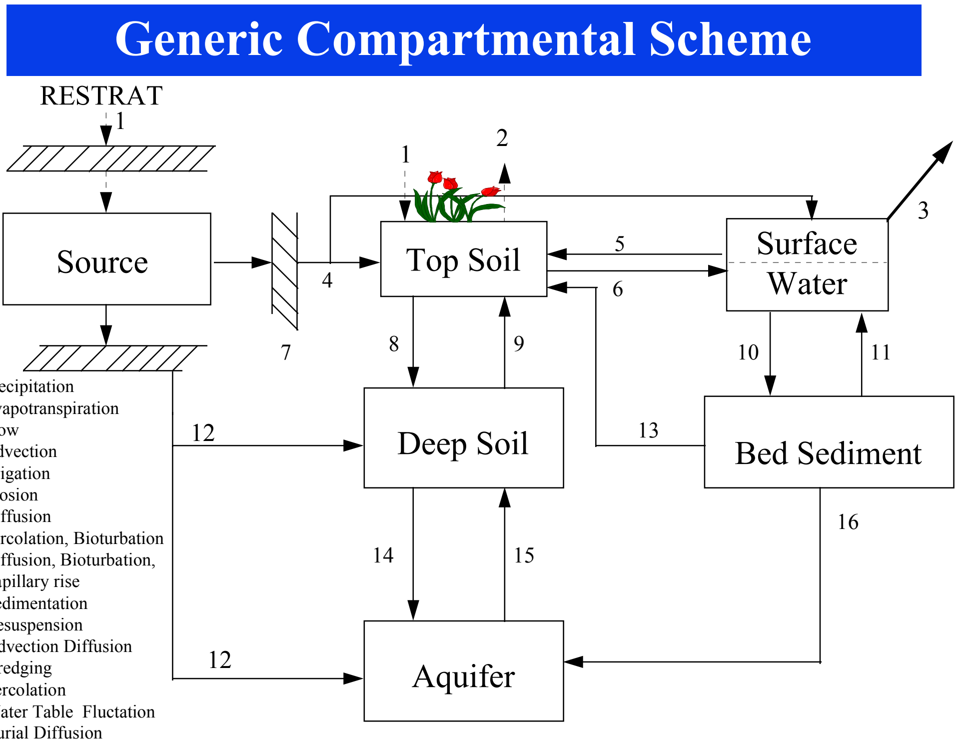

Figure 1 Generic Compartment Scheme.

There are different types of biosphere systems: terrestrial ones (e.g. in the case of contamination of soils) and aquatic ones (contamination of surface waters). For the former type important compartments are topsoil (root zone), deep soil, aquifer, air (see generic scheme in Figure 1). For the latter type basic compartments are the water column (aqueous/solid phases), bed sediment, deep sediment, banks (or shores). Major processes to be considered for calculating the transfers of radionuclides between the compartments are also indicated in Figure 1.Interactions between the terrestrial and aquatic biosphere systems may be important.

3.1 Selection of the exposure scenarios

The first thing to do for every site is to develop an exposure scenario. For this reason information about the different sites have been used. A relevant compartment scheme has been put together for each site. For all sites simplifications have been made in order to get a usable compartment scheme, this is most obvious for the Ravenglass estuary.

3.2 Time periods

The dose calculations are performed at year 1, for the restoration workers and the individual dose, and for the committed collective doses at 100 and 500 years. During this time period the public are supposed to behave in the same way as they do today, with the same living habits and the same consumption of foodstuffs. Furthermore the climate is assumed not to change in a drastic way either.

3.3 Transfer processes

Radionuclides appearing in the biosphere will be involved in the ecological cycle. This implies that they will be transported and exchanged between various biosphere components, such as water, sediments, soil and biota. How effective the transport is and which pathways dominate are among other things dependent on their physical/chemical properties. A short description follows on the processes, which will be considered when developing these dose assessments for the different sites. Emphasis will then be on how they can be calculated and considered in order to develop models for dose assessment of earlier contaminated areas as well as a continuos leakage of radionuclides.

There are three main processes for decreasing the amount of radionuclides or other elements transferred to surface waters. These are transfer out due to water turnover, transfer to the sediments and transfer to land by use of the water for irrigation. The first two are the most effective for depletion of the levels in the water. In general it is only a small fraction of surface water that is used for irrigation. However, radionuclides in sediments may be transferred back to the water column as well as radionuclides in soils migrate to groundwater which is drained into the surface waters. In addition erosion of soil particles to which radionuclides are attached may cause a transfer back to surface waters.

3.3.1 Water turnover

Water turnover causes a transport out of the system of nuclides in soluble as well as in particulate form. The flows have in general seasonal fluctuations with maximum values during spring and autumn. In these calculations annual mean values are used when symbolising the transfer.

3.3.2 Transfer to sediments

Elements in water will attach on particulate matter causing a transport to the sediments. They may also be transferred to the sediments by diffusion or bioturbation. Earlier studies have however pointed out that particle settling is the main transport for relatively immobile radionuclides to the sediments (Bergström and Nordlinder, 1991). This is therefore the only pathway considered in the models, as all studied radionuclides can be classed as relatively immobile radionuclides. The effectiveness of this process is among other things dependent on the element's properties and mass sedimentation rates. The adsorption to suspended matter is described by use of a Kd-parameter which expresses the fraction of element in solid form relative to the fraction in soluble form. This implies that an immediate steady–state condition is achieved, the circumstances of which can be discussed. There are large variations for Kd-values found in the literature.

3.3.3 Transfer to top soil

When surface waters containing radionuclides are used for irrigation, the radionuclide fraction which is taken up and put on the soils leads to contamination.

Sediments taken away, being dredged, and put on soil are also a way of contaminating the soil.

3.3.4 Transfer from sediments

The behaviour of radionuclides in sediments is among other things dependent on the conditions in them. All the chemical processes were simplified so that all radionuclides transferred to the sediments were assumed to be effectively retained. The losses of radionuclides were only due to physical processes like resuspension and growth of sediments. Resuspension has been shown to be a major transport process for maintaining increased levels of radionuclides in water (Sundblad *et al*., 1991).

The addition of new sediments results in a transfer of radionuclides to deeper layers in compartment models, while the top layer remains constant. However, this was not always the case for the models described below because dredging was regularly applied. The sediments taken up were put on soils leading to an effective transfer of radionuclides to the soils.

3.3.5 Transfers from top soil

Nuclides deposited on soils migrate downwards at various rates due to the soil properties as well as the effectiveness of the element's sorption on solid matter. Diffusion and bioturbation lead to a transport from upper soils to deeper situated layers from which they can be transported back to surface water by ground water runoff. Erosion by wind and water may cause a transport to surface water as well. In the models set up only advection due to percolating water with a minor amount of dissolved radionuclide was taken into account as a process for decreasing the concentration of radionuclides in upper soils. It is expected that neglecting the other processes may lead to conservative estimates of the concentrations in soil.

3.4 Identification of the relevant exposure pathways and exposure groups

Radionuclides emanating from a contaminated area will, by different exposure pathways, reach man. The exposure pathways can be of different kinds, external or internal. External exposure is due to radiation from nuclides in the vicinity of the exposed individual while internal exposure is due to radiation from nuclides within the body.

External exposure can be due to contamination of surfaces of different types e.g. soil/sediment or surface water, by direct contamination of the surface of human bodies or by contaminated particles in the air. The external doses usually plays a minor role compared to the internal doses. For contamination with Co-60 and Cs-137 however, external irradiation is often the major, realistic pathway.

The internal doses are due to radiation from nuclides within the human body. The nuclides reach the body via intake of food and water, or via the repository system due to inhalation. The element will be either eliminated or will participate in metabolism in the body, due to its chemical and physical properties.

Exposure pathways considered are

- Consumption of contaminated water
- Consumption of milk and meat contaminated through the watering of the cattle
- Consumption of milk and meat contaminated through the grazing of the cattle on contaminated pasture
- Consumption of fish from contaminated surface waters
- Consumption of cereals, potatoes and vegetables, contaminated through irrigation or amendments to the soil
- Inhalation of contaminated aerosol (also for the restoration workers)
- External irradiation on contaminated fields or banks of surface waters, or in contaminated water or air (also for the restoration workers)

The exposure pathways were calculated, using steady state factors, for the uptake in biota and the further transfer along the food chains.

A critical group, concerned for individual dose, should by definition consist of a real or fictitous group of individuals, which due to their location and living habits obtain the highest exposure.

The collective dose has been derived from the magnitude of the production of different food-crops from production data. The exposure group considered here are farmers living in the area. They are eating the whole agricultural production of the region considered and their annual consumption of milk and meat is produced from cattle on the contaminated site. When fish is included in the diet, fish production data related to normal consumption is considered.

3.5 Influences of restoration options

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

3.6 Dose calculations

The doses calculated consist of individual and committed collective doses. This applies to the restoration workers as well as to the general public. However, for the latter doses are to be assessed with and without restoration operations carried out, in order to evaluate the dose reductions associated with the various restoration options.

The individual doses are the annual effective doses to average members of the critical group during the year 1, first year of the actual situation. The individual doses are expressed in Sv/a.

The collective doses assessed are collective effective dose commitments to the population truncated at the time periods of 100 and 500 years and the collective effective doses to the restoration workers. The collective dose is by definition the sum of each individual dose to a group of individuals and is expressed in manSv. The basis for the assessment of the collective dose to the population has been the yield of different food-crops derived from production data. For the collective dose assessments it does not matter who consumes the contaminated food. So it is not necessary to assume that all contaminated food is consumed by the critical group.

Collective doses to the restoration workers will be derived from the labour volumes and contamination levels on the contaminated site.

3.7 Uncertainties

Uncertainties due to specification of the scenario involve the whole methodology applied for the assessments. One simplification is that the scenarios describe constant conditions over time, i.e. no evolution of the biosphere is considered. There are high uncertainties coupled to any prognoses of future states of the biosphere and also of future behaviour of man.

A basic concept in all the models is that the ecosystems are divided into compartments between which there is an annual transfer of water and thereby material. Each compartment was assumed to comprise a physical area with uniform properties, e.g. chemistry. Radionuclides are also assumed to be homogeneously distributed within the compartments. This is not always the case in reality. Simplifications and assumptions in process descriptions have to be made.

There are two terms of major importance concerning the confidence in model results; verification and validation. The former applies to the accuracy in the numerical methods, which are used in the mathematical codes applied in the models. The codes need to be verified before entering the step of validation when the model results are compared and evaluated against independent data. Verification is a necessity to avoid programming mistakes etc.

The solution methods applied in BIOPATH have been subject to several verifications. Both BIOPATH and PRISM, see chapter 4, have been parts of a total model intercomparison where all models used the same expressions and parameter values for all rate constants and for calculating the doses to man from a variety of exposure pathways in Klos *et al*. (1993). The verification tests showed that uncertainties due to computational errors are of much lower importance than uncertainties due to conceptual modelling and parameter values.

In contrast to uncertainties in results due to conceptual modelling, the uncertainties due to selection of parameter values are easier to quantify by use of error propagation methods. Such an approach was used in the calculations, i.e. parameter values, were randomly generated from predescribed distributions.

4 Compartment modelling and numerical tools

The reason for choosing the BIOPATH/PRISM-codes in the RESTRAT project was that these codes have been used in a lot of international studies within BIOMVS1, BIOMVS2, VAMP and BIOMASS. Both verification and validation has been carried out within these studies. Verification of the PRISM code, i.e. the process of checking that the numerical methods applied give reliable results concerning the precision in numerical results, has been carried out. Validation is the process of testing that the models give a satisfactory description of the system they are applied for. This has been done for compartment modelling.

4.1 BIOPATH

BIOPATH is a general tool (Bergström *et al.*, 1982), which can be used for varying types of compartment models, as long as they are based upon first-order differential equations.The modelling approach of the biosphere in this project is based on compartment theory. The system is divided into a number of physically defined areas or volumes, i.e. compartments. Exchange between these compartments is described by rate constants expressed as number of turnovers per unit of time. Mathematically, this is expressed by a set of first order linear differential equations with constant or time varying transfer coefficients (rate constants).

The general assumptions for compartment models are that

- The outflow from a compartment is solely dependent upon the quantity of the element in that particular compartment
- The compartment is instantaneously well mixed
- All elements have the same probability of leaving the compartment

In general, the assumption that compartments fulfil the condition of instantaneous and homogeneous mixing with satisfactorily precision can be done. This is especially valid in cases where the time studied is long compared with the turnover rate of nuclides within the compartment.

The amount of radioactivity in a given compartment is dependent on:

- The source term for the compartment system, such as the direct release to one or several compartments, or generation within them by decay from the parent nuclide
- The outflow to and inflow from other compartments
- Radioactive decay

In the BIOPATH code the relationship between the amounts of activity in the reservoir system is expressed mathematically in vector form by

$$\dot{Y}(t) = K \cdot Y(t) + Q(t) - \lambda \cdot Y(t)$$

The vectors $\dot{Y}$ and Y refer to activity and activity changes per unit time in the different reservoirs of the system at time t. The coefficient matrices K (year^{-1}) and Q(t) (activity year^{-1}) describe the transfer rates between the reservoirs and source-term to the reservoir, respectively. The decay constant is

$$\lambda = \ln 2/t_{1/2}$$

where $t_{1/2}$ is the physical half-life of the nuclide.

The BIOPATH code includes different methods, EULER, IMPEX and LINDIF, to solve the equation systems.

LINDIF in Forssen and Smith (1974) is a semianalytic solution method, when the eigen vector of the coefficient matrix is obtained, the solution is given. In theory, this method will give an exact solution. This is valid if the source term is constant, this implies in practise a single nuclide. Furthermore, if the coefficients of the matrix vary to much, the differential equation system will be stiff and the rounding errors will give too big contribution. If the time-step in the calculation is short compared to the half-life of the nuclides it will give acceptable results even for chains. This method have been used in the RESTRAT project.

4.2 PRISM

PRISM is a general tool for addressing the uncertainties in any model due to the uncertainty or variability in parameter values, in Gardner *et al*., (1983). The PRISM system consists of three main subprograms, each one described below:

- In PRISM 1, random parameter values are generated by using a systematic sampling method, Latin Hyper Cube. As input to PRISM 1, the mean values or best estimate, type of distributions, standard deviations and the upper and lower limits are given for each parameter. These data are then used to define probability density functions. The Latin Hyper Cube method, used to generate the sets of values from the given distributions, is an efficient Monte Carlo sampling technique which produces random values within the whole desired range. In addition, correlation between model parameters can be taken into account, no matter what type of distributions respective parameter is drawn from.
- In PRISM 2 the model is executed for each set of generated input parameter values by PRISM 1.
- PRISM 3 statistically evaluates and summarises the joint set of model parameters and predictions. The general statistics for the distribution of each parameter and the response of the model to this distribution contain the following: arithmetic mean, standard deviation, coefficient of variation, geometric mean, percentiles (5, 25, 50, 75, and 95 %), and the five highest and five lowest values, respectively. Correlations between the model parameters and the responses as well as between the responses themselves are also obtained from this last part of the analysis. Two correlation coefficients are calculated: the simple Pearson correlation coefficient, and Spearman Rank, which is the correlation of the ranked values of the parameters and model responses. Associated with each correlation coefficient is their percent covariation (COVAR). This represents the percent variance that one variable accounts for in another variable or response. In the cases of correlated model parameters and responses, percent COVAR indicates the amount of variability in the model response that is explained by the variability of that particular model parameter. The regression procedures are used to obtain the relationship between model parameters and model responses. The parameters to be entered into the regression analysis are selected from those, which give the greatest improvement on the sum of squares of regression. From these analyses the relative contribution to the total uncertainty from each parameter is obtained. Furthermore, parameters and processes contributing to the uncertainty in results can be identified. Another important point to address is to look upon what parameters that are the most sensitive ones and this is performed by making sensitivity analysis.

5 Molse Nete River

Mol is located in the northeastern part of Belgium. Since 1956, controlled releases of low-level radioactive effluents have been made by the nuclear facilities in the region of Mol into the small river Molse Nete.

The compartment scheme for Molse Nete river is based on site description given in Sweeck *et al.* (1998). Parameter values used in the dose assessment are taken from L.Sweeck *et al* (1998).

The source, the radioactive effluents from a water treatment facility for the nuclear activities in the Mol region, principally the nuclear research centre SCK CEN, is released into the river and transported further downstream. About 7 km further down the river confluences with the Grote river. This distance is quite far and this is the reason for dividing the river into two boxes, upper and lower part. The same reason goes for dividing the soil into two compartments.

The critical radionuclides, discharged into the Molse Nete are Co-60, Cs-137, Pu-239 and Am-241. Over the period 1961 to 1990, about 130 GBq/a Co-60, 37 GBq/a Cs-137, 1.3 GBq/a Pu-239 and 0.68 GBq/a Am-241 were released. Nowadays, the discharges of radionuclides are much lower.

5.1 Compartment scheme

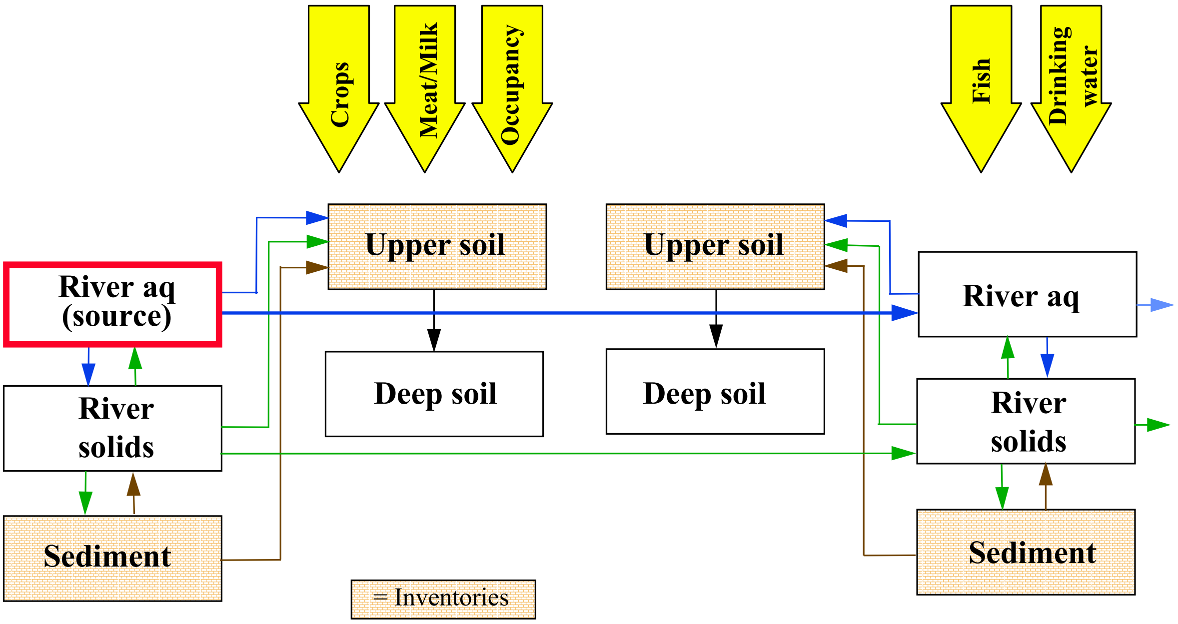

Figure 2 Compartment structure for the Molse Nete river and considered exposure pathways.

Since the releases have been going on for over forty years a lot of activity can be found in the sediments and in the soil next to the river. This is due to dredging of sediment and its application onto agricultural soil aswell as irrigation from the river.

5.2 Processes, exposure pathways and exposure groups

The river is dredged every five years and the sediment is then put on the banks. Some of the dredged sediment is subsequently applied onto agricultural soil. Irrigation with water from the river is normally occurring a few times every year.

Each transfer coefficient can consist of several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the Molse Nete river. The equations and data used are given in Appendix A.

Compartment	Processes
Water column	Irrigation Sedimentation Outflow
Sediment	Resuspension Dredging
Surface soil	Infiltration Advection

Exposure pathways considered are:

- Consumption of river water
- Consumption of milk and meat through the watering of cattle at the river
- Consumption of milk and meat contaminated through the pasture eaten by cattle. The soil has been irrigated and dredged upon by sediments from the river
- Consumption of fish from the river
- Consumption of cereals, potatoes and vegetables. The soil has been irrigated and dredged upon by sediments from the river.
- Inhalation of dust from the soil
- External irradiation from contaminated fields

The critical group concerned consists of farmers living in the neighbourhood. They eat locally produced meat and drink milk from cows that graze nearby the river Molse Nete. All food crops are produced locally. The fish is captured in the local river. The drinking water is taken from the river but it is filtered before drinking. The water used for irrigation is not filtered.

The committed collective dose is based on production data. The soil has been irrigated and dredged upon by sediments from the river

For the dose to the workers both inhalation and external exposure from the soil are included.

5.3 Doses to public/remediation workers

The doses calculated consist of annual individual effective doses, first year of actual situation, to an average member of the critical group. Collective effective dose commitments to the population over

100 years and over 500 years and collective dose to the workers performing the restauration actions are also calculated.

5.3.1 Individual doses to critical group: Base case year 1

The results of the dose calculations for the individual doses at year 1 are shown in Table 1.

Table 1 Individual dose (Sv/a) at Molse Nete River at year 1.

Exposure pathway	Co-60 Mean	Cs-137 Mean	Pu-239 Mean	Am-241 Mean	Total Mean
Water	1.6E-07	2.8E-07	1.7E-07	7.5E-08	6.8E-07
Fish	5.9E-07	5.4E-06	8.4E-08	1.2E-07	6.2E-06
Milk	3.8E-10	2.6E-08	2.8E-11	2.2E-10	2.7E-08
Meat	8.8E-08	6.4E-05	2.6E-07	1.0E-06	6.6E-05
Root crops	1.2E-06	2.5E-05	1.9E-04	3.5E-05	2.6E-04
Tubers	7.9E-07	1.0E-04	6.8E-06	3.2E-06	1.1E-04
Vegetables	4.7E-07	6.0E-05	3.3E-06	5.4E-06	6.9E-05
Ext.Exposure	3.8E-05	3.9E-05	6.0E-32	1.3E-07	7.7E-05
Inhalation	1.2E-09	8.5E-10	1.5E-05	5.4E-06	2.0E-05
Total dose	4.1E-05	2.9E-04	2.1E-04	5.1E-05	5.9E-04

The contribution to the total dose from different pathways is graphically depicted in Figure 3.

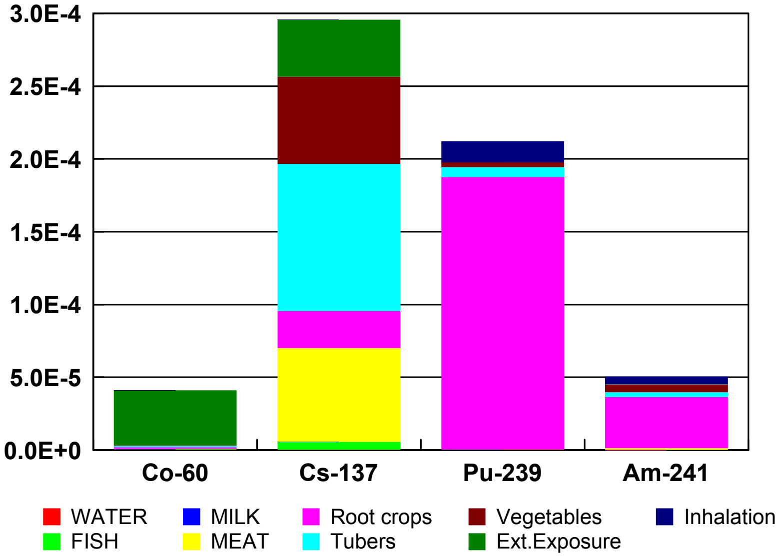

Figure 3 The contribution to the total dose (Sv/a) from different pathways.

For Pu-239 and Am-241 the consumption of root crops dominates the exposure while for Co-60 it is external exposure. Usually the dominating exposure pathway from contaminated soil for Am-241 and especially for Pu-239 is inhalation of resuspended particles. In this case, due to a high value for the root uptake factor, the ingestion of various crops is the dominant exposure pathway. For Cs-137 the ingestion of tubers and vegetables dominates but also ingestion of meat and external exposure play an important role.

5.3.2 Collective doses to public over 100 years and 500 years and to restoration workers

Relevant restoration options for the Molse Nete river have been described in Sweeck *et al.* (1998). The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping is considered, so for this restoration technique the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system.The base case, as the actual situation is without any restoration but with the discharges stopped, is called A.

Table 2 shows the restoration options considered for the Molse Nete River.

Table 2 Restoration options considered for the Molse Nete River.

Case	Restoration option
A	Basecase
B	Source removal
C1	Soil washing
D1	Chemical solubilisation
E1	Capping
F1	Physical immobilisation, *ex-situ*
F2	Physical immobilisation, *in-situ*
G1	Chemical immobilisation, *ex-situ*
G2	Chemical immobilisation, *in-situ*

The capping and immobilisation of the soil makes it of no use for agricultural purposes and no further dose will be obtained via agricultural pathways. The agricultural pathways are dominant compared to intake of fish and water (Table 1). For these options only the doses to the restoration workers are concerned.

The results of the dose calculations for the collective intakes/doses at 100 years and 500 years for the different restoration options are shown in Table 3.

Table 3 Collective doses, (manSv), at the Molse Nete river

Case			Co-60	Cs-137	Pu-239	Am-241	Total
		Year	Mean	Mean	Mean	Mean	Mean
A	Farmers	100	7.3E-03	3.2E+00	1.1E+01	2.0E+00	1.6E+01
		500	7.3E-03	3.6E+00	4.1E+01	6.7E+00	5.1E+01
B	Farmers	100	1.0E-03	3.2E-01	1.1E+00	2.0E-01	1.6E+00
		500	1.0E-03	3.6E-01	4.1E+00	6.7E-01	5.1E+00
	Workers		4.0E-04	1.6E-04	4.0E-05	1.0E-05	6.1E-04
C1	Farmers	100	2.0E-03	9.0E-01	3.0E+00	5.5E-01	4.5E+00
		500	2.0E-03	1.0E+00	1.1E+01	1.9E+00	1.4E+01
	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03
D1	Farmers	100	7.0E-04	3.2E-01	1.1E+00	2.0E-01	1.6E+00
		500	7.0E-04	3.6E-01	4.1E+00	6.8E-01	5.1E+00
	Workers		1.0E-03	5.0E-04	1.0E-04	4.0E-05	1.6E-03
E1	Workers		1.0E-03	1.1E-03	4.0E-04	1.0E-04	2.6E-03
F1	Workers		4.0E-03	2.0E-03	6.0E-04	1.0E-04	6.7E-03
F2	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03
G1	Workers		4.0E-03	2.0E-03	6.0E-04	1.0E-04	6.7E-03
G2	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03

As can be seen in Table 3 Pu-239 gives the largest contribution to the collective dose. The dose to the workers is, on the other hand, dominated by Co-60 and Cs-137, because they give high external exposures.

In Figure 4 the collective dose commitment for the public and for the restoration workers are graphically depicted for Pu-239 for the different restoration options at 100 and 500 years.

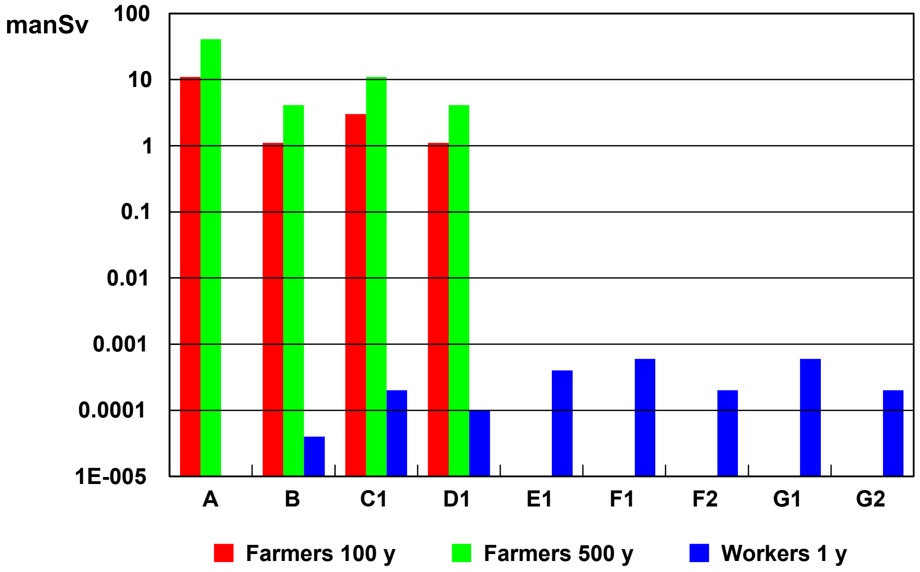

Figure 4 **The total collective dose of Pu-239 (manSv) for the different restoration options at 100 and 500 years.**

As can be seen in Figure 4 the reduction of collective dose commitment is about one order of magnitude for the restoration options when the soil is still usable.

5.4 Uncertainty analysis

The results of the uncertainty analysis are given in Annex A, Table A.4. Here the mean values and the 5 and 95 percentiles are presented for the doses from the different exposure pathways.

5.4.1 Parameter analysis

Parameters that give major contribution to the uncertainty in the dose results are listed below.

1 Concentration factor for uptake from soil to root crops
2 Concentration factor for uptake from soil to tubers
3 Concentration factor for uptake from soil to vegetables
4 Depth of sediment
5 Yield of root crops

For the Molse Nete the concentration factors for uptake from soil to plants dominate the uncertainty in collective dose commitment for all nuclides and for all restoration options concerned when the soil is still usable. The concentration factors used are based on a literature survey for a sandy soil type as in Mol (Sweeck *et al*, 1998).

The effects of different resotration techniques do not give a major contribution to the uncertainty in the dose results because of their small ranges, even though they play an important role for the dose reduction.

6 Drigg Site

The Drigg Site is situated in West Cumbria, Great Britain, about 9 km south of Sellafield, on the coast of the Irish Sea. It lies just west of the village of Drigg, 300 m north of the tidal estuary of the river Irt. Since 1959 the site has been used for the disposal of low-level radioactive waste. Now it is operated by British Nuclear Fuel plc (BNFL) for the shallow burial of solid waste, mostly stemming from the Sellafield site.

The compartment scheme for Drigg site is based on site information in Bousher (1998).

The source is the low-level radioactive waste in solid form deposited at the Drigg site.

The following radioisotopes were to be of most concern Cs-137, U-238, Pu-239 and Am-241.

6.1 Compartment scheme

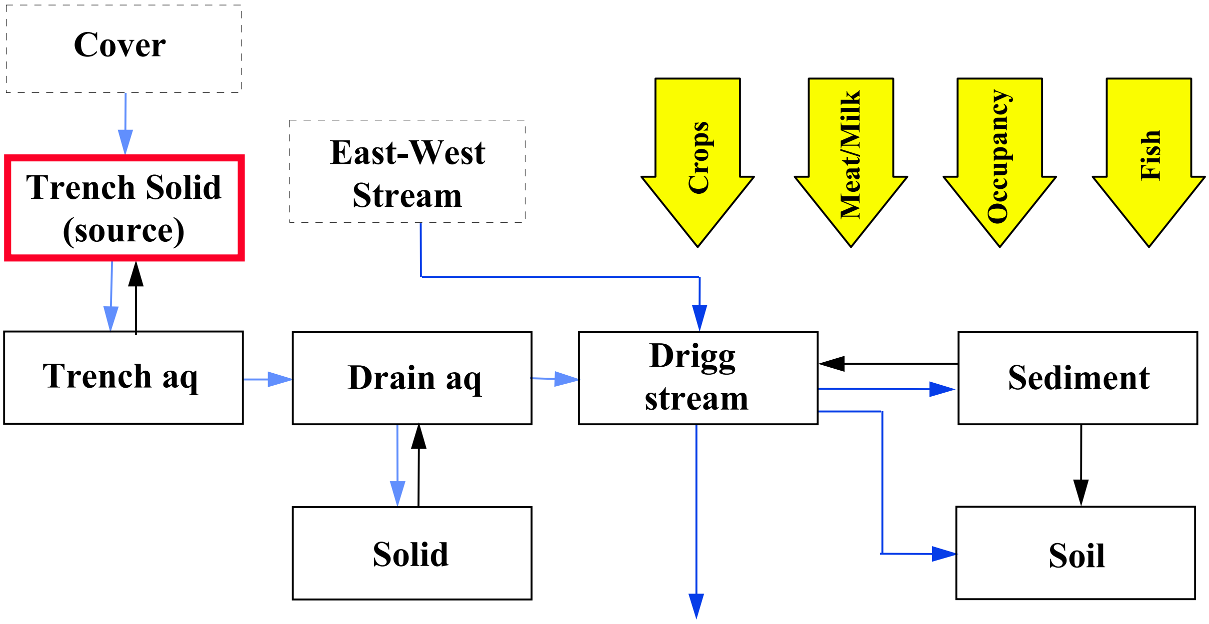

Figure 5 **Compartment scheme for the Drigg site.**

6.2 Processes, exposure pathways and exposure groups

After interaction between the solid phase and the infiltration water the activity is transported as leakage via drains to Drigg stream. Agricultural land was assumed to be irrigated with water from the stream. The sediment in the stream was also dredged annually.

Each transfer coefficient can consist of several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the Drigg site. The equations and data used are given in Appendix B.

Compartment	Processes
Water column	Irrigation Sedimentation of particles Outflow
Sediment	Resuspension Dredging
Surface soil	Infiltration Advection

The exposure pathways for the critical group are indicated in the compartment scheme. The exposure pathways considered are

- Consumption of water
- Consumption of fish
- Consumption of milk and meat via the drinking water of the cattle
- Consumption of milk and meat via the pasturage for the cattle
- Consumption of root crops and vegetables
- Occupancy and inhalation

The critical group concerned consists of farmers living in the neighbourhood. They eat locally produced food and they fish in the Drigg stream.

The committed collective dose is based on production data.

For the dose to the workers both inhalation and external exposure from the soil are included.

6.3 Doses to public/remediation workers

The annual individual effective doses are calculated, first year of actual situation, to an average member of the critical group. Collective effective dose commitments to the population over 100 years and over 500 years and collective dose to the workers performing the restoration actions are also calculated.

6.3.1 Individual doses to critical group: Base case year 1

The results of the dose calculations for the individual doses Sv/a at year 1 are shown in Table 4.

Table 4 Individual dose (Sv/a) at Drigg site at year 1.

Exposure pathway	Cs-137 Mean	U-238 Mean	Pu-239 Mean	Am-241 Mean	Total
Fish	2.4E-04	5.5E-06	1.2E-05	1.4E-05	2.7E-04
Milk	7.5E-06	5.3E-07	1.4E-08	3.6E-08	8.0E-06
Meat	4.4E-06	3.3E-07	2.9E-08	3.9E-08	4.7E-06
Root crops	1.2E-06	3.4E-07	2.0E-06	2.6E-07	3.8E-06
Vegetables	5.5E-07	1.2E-06	1.2E-05	1.6E-06	1.5E-05
Ext.Exposure	5.1E-08	4.7E-35	2.2E-35	1.7E-11	5.1E-08
Inhalation	8.2E-13	5.2E-10	3.9E-09	5.2E-10	4.9E-09
Total dose	2.5E-04	8.0E-06	2.6E-05	1.6E-05	4.1E-04

It should be noted that irrigation is included in the calculations. This may not be so realistic since the Drigg site is situated in the northwestern part of Britain where the precipitation is very high. Furthermore, these calculations were based on the assumption that no restoration technique has been applied to the Drigg site, which is not a true reflection of the current situation. It has been shown that the doses through fish is more important than the doses through irrigation.

Cs-137 is the main contributor to the total dose due to intake of fish. Since Cs-137 is a gamma emitter it is natural that it dominates the external exposure.

The contribution to the total dose from different pathways in Sv/a is graphically depicted in Figure 6.

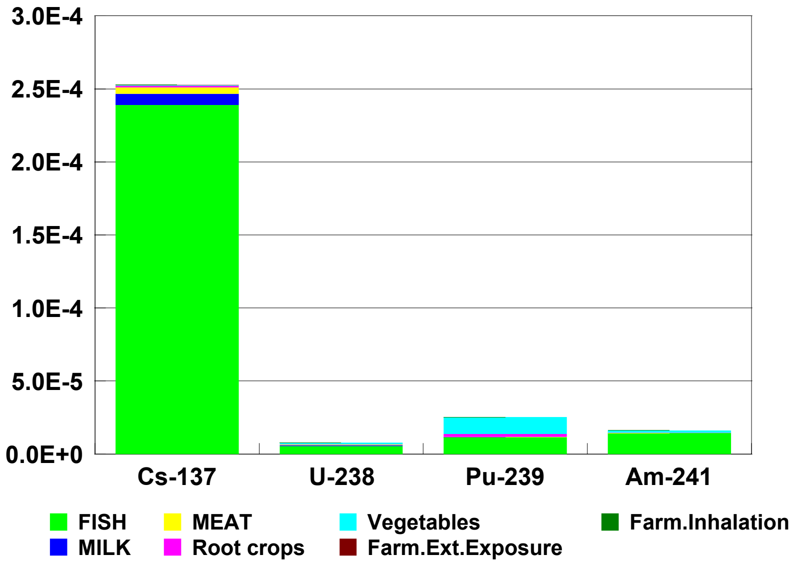

Figure 6 The contribution to the total dose (Sv/a) from different pathways.

Consumption of fish is the main exposure pathway for all nuclides. For Cs-137 fish is the overall dominating exposure pathway. For U-238 and Pu-239 intake of vegetables gives a major contribution to the total dose while for Am-241 root crops play an important role besides the intake of fish.

6.3.2 Collective doses to public over 100 years and 500 years and to restoration workers

Relevant restoration options for the Drigg site have been described in Bousher (1998). The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.The base case, as the situation is without any restoration, is called A.

Table 5 shows the restoration options considered for the Drigg site.

Table 5 Restoration options considered for the Drigg site.

Case	Restoration option
A	Basecase
C2	Filtration
D1	Chemical solubilisation
D2	Ion exchange
D3	Biosorption
E1	Capping
E3	Subsurface barriers
F1	Physical immobilisation, *ex-situ*
F2	Physical immobilisation, *in-situ*
G1	Chemical immobilisation, *ex-situ*
G2	Chemical immobilisation, *in-situ*

The results of the dose calculations for the collective intakes/doses at year 100 and 500 for the different restoration options are shown in Table 6. It should be noted that this refers to a hypothetical situation since restoration methods have already been applied at this site.

Table 6 Collective doses (manSv) at Drigg site at year 100 and 500.

		Year	Cs-137 Mean	U-238 Mean	Pu-239 Mean	Am-241 Mean	Total Mean
A	Farmers	100	8.8E-01	1.2E+01	2.7E+01	9.3E+00	4.9E+01
		500	9.5E-01	2.7E+01	7.6E+01	1.7E+01	1.2E+02
C2	Farmers	100	1.4E-01	2.6E-02	3.9E-01	3.6E-01	9.3E-01
		500	1.6E-01	1.2E-01	1.8E+00	1.2E+00	3.3E+00
	Workers		4.9E-10	3.3E-11	5.0E-10	5.0E-10	1.5E-09
D1	Farmers	100	1.2E-01	2.3E+00	4.9E+00	2.6E+00	9.9E+00
		500	1.3E-01	8.8E+00	1.8E+01	5.9E+00	3.3E+01
	Workers		1.2E-09	1.1E-10	2.0E-10	1.6E-10	1.7E-09
D2	Farmers	100	4.0E-02	4.0E+00	8.4E+00	3.9E+00	1.6E+01
		500	4.4E-02	1.3E+01	2.9E+01	8.4E+00	5.1E+01
	Workers		1.0E-10	6.7E-11	1.0E-10	1.0E-10	3.7E-10
D3	Farmers	100	1.6E-01	3.2E+00	6.6E+00	3.2E+00	1.3E+01
		500	1.8E-01	1.1E+01	2.3E+01	7.0E+00	4.2E+01
	Workers		5.0E-10	4.7E-11	9.0E-11	7.0E-11	7.1E-10
E1	Farmers	100	4.0E-03	8.8E-02	1.9E-01	1.5E-01	4.3E-01
		500	4.4E-03	4.3E-01	9.3E-01	4.9E-01	1.9E+00
	Workers		4.0E-12	3.3E-13	7.0E-13	5.0E-13	5.5E-12
E3	Farmers	100	3.0E-02	6.3E-01	1.4E+00	8.7E-01	2.9E+00
		500	3.3E-02	2.6E+00	5.9E+00	2.1E+00	1.1E+01
	Workers		5.0E-10	4.0E-11	8.0E-11	7.0E-11	6.9E-10
F1	Farmers	100	7.4E-02	1.2E+00	2.2E+00	7.8E-01	4.2E+00
		500	8.0E-02	2.2E+00	6.4E+00	1.4E+00	1.0E+01
	Workers		2.1E-09	1.9E-10	3.6E-10	2.7E-10	2.8E-09
F2	Farmers	100	7.4E-02	1.1E+00	2.2E+00	7.8E-01	4.2E+00
		500	8.0E-02	2.4E+00	6.4E+00	1.4E+00	1.0E+01
	Workers		1.0E-09	6.7E-11	2.0E-10	1.0E-10	1.4E-09
G1	Farmers	100	5.2E-02	7.5E-01	1.6E+00	5.5E-01	2.9E+00
		500	5.6E-02	1.7E+00	4.5E+00	1.0E+00	7.2E+00
	Workers		1.4E-09	1.2E-10	2.3E-10	1.7E-10	1.9E-09
G2	Farmers	100	5.2E-02	7.5E-01	1.6E+00	5.5E-01	2.9E+00
		500	5.6E-02	1.7E+00	4.5E+00	1.0E+00	7.2E+00
	Workers		7.0E-10	6.0E-11	1.0E-10	8.0E-11	9.4E-10

As can be seen in Table 6 the contribution from Pu-239 gives the highest contribution to the total dose.

In Figure 7 the total collective dose for the public and for the restoration workers are graphically depicted for Pu-239 for the different restoration options at 100 and 500 years.

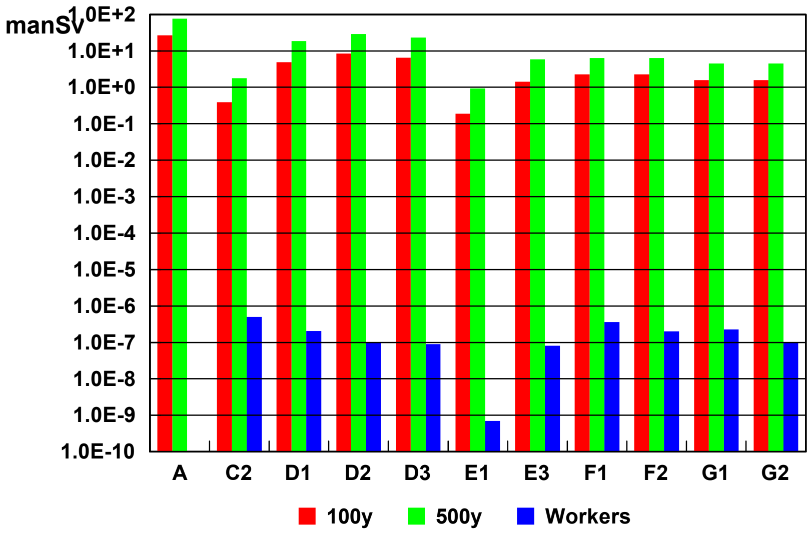

Figure 7 **The total collective dose of Pu-239 (manSv) for the different restoration options at 100 and 500 years.**

As can be seen in Figure 7 the reduction of dose to the public is small to moderate for the different restoration options except for options E1 and, especially, C2. Restoration option C2 is the filtration of the leachate from the waste in the trenches and E1 is the capping of the trenches.

The lowest dose to the remediation workers is obtained when capping the trenches is considered.

6.4 Uncertainty analysis

The results of the uncertainty analysis are given in Annex B, Tables B.4 – B.14. Here the mean values and the 5 and 95 percentiles are presented for the different doses.

6.4.1 Sensitivity analysis

Parameters that are of major importance to the uncertainty in the dose results are listed below

1 Discharge
2 Flow from trenches to drain
3 Flow from Drigg stream out of the system
4 Distribution coefficient in soil between water and particles

For the Drigg site the amount of water flowing from the trenches and out of the system dominates the uncertainty for all nuclides concerned, especially for Cs-137 and U-238. This is due to large ranges applied to the different flows. For Pu-239 and Am-241 the appointed distribution coefficient between solid and soluble fraction in the trenches, the Kd-value, contributes considerably to the uncertainties in the results.

The decontamination factors do not give a major contribution to the uncertainty in the dose results because of their small ranges, even though they play an important role for the dose reduction.

7 Ravenglass Estuary

The Ravenglass estuary is situated in West Cumbria, Great Britain, on the coast of the Irish Sea. It encompasses the tidal reaches of the River Esk, Irt and Mite with a total area of about 7.3 km^2. Its northern part directly borders the Drigg site.

The compartment scheme for Ravenglass is based on site information in Bousher (1998). The Cumbrain coast is representing the Irish Sea in the scheme. Its volumes and turn over are taken from Jefferies *et al.* (1989).

The source originates from the Sellafield nuclear plant, which discharges into the Irish Sea. Sediments are contaminated mainly via the Irish Sea from waste discharges from the Sellafield nuclear fuel reprocessing plant. The discharges have been going on since the beginning of the fifties. Nowadays the discharges are lower than in previous times. The sediments in the estuary became contaminated and nowadays they are the source from which activity is leaking into the Irish Sea. It is assumed that all particulate material in the water mass comes from the Irish Sea.

The main radionuclides under consideration are Cs-137, Pu-239 and Am-241.

7.1 Compartment scheme

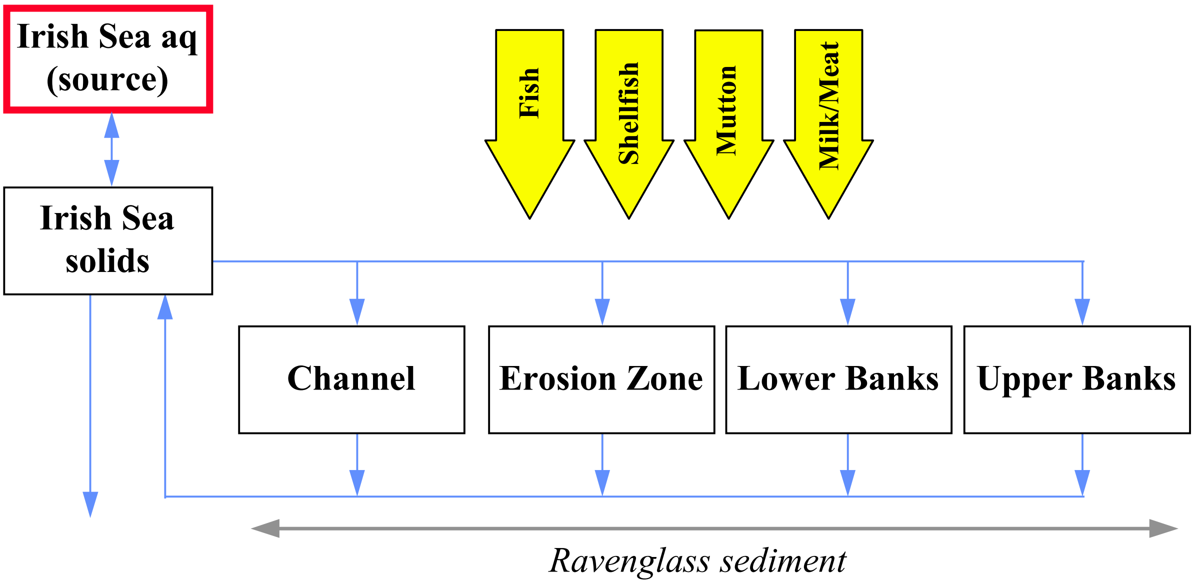

Figure 8 Compartment scheme for the Ravenglass estuary.

7.2 Processes, exposure pathways and exposure groups

Each transfer coefficient can consist of several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the Ravenglass estuary. The equations and data used are given in Appendix C.

Compartment	Processes
Water column	Sedimentation of particles Outflow
Sediment	Resuspension

The important exposure pathways for the critical group are indicated in the compartment scheme. The exposure pathways considered are

- Consumption of fish
- Consumption of shell fish
- Consumption of meat via the drinking water of the cattle and sheep
- Consumption of meat via the pasturage for the cattle and sheep
- Occupancy, only external exposure is considered since the sediments are assumed to be wet

The critical group concerned consists of people living in the neighbourhood. The dose assessment performed considers doses due to consumption of meat from cattle and meat from sheep grassing on the upper banks and drinking water from the river. Consumption of fish and shellfish are also included as pathways.

The committed collective dose is based on production data.

For the dose to the workers both inhalation and external exposure from the sediments are included.

7.3 Doses to public/remediation workers

The annual individual effective doses are calculated, first year of actual situation, to an average member of the critical group. Collective effective dose commitments to the population over 100 years and over 500 years and collective doses to the workers performing the restoration actions are also calculated.

7.3.1 Individual doses to critical group: Base case year 1

The results of the dose calculations for the individual doses Sv/a at year 1 are shown in Table 7.

Table 7 Individual dose (Sv/a) at Ravenglass Estuary at year 1.

	Cs-137	Pu-239	Am-241	Total
Exposure pathway	Mean	Mean	Mean	Mean
Fish	4.25E-05	2.6E-05	4.6E-05	1.1E-04
Shellfish	5.8E-06	2.0E-04	2.7E-04	4.7E-04
Meat	5.3E-04	1.1E-06	8.7E-07	5.3E-04
Sheep	3.8E-04	3.7E-06	5.9E-06	3.9E-04
Ext	2.8E-07	2.5E-10	2.8E-08	3.0E-07
Total	9.1E-04	2.3E-04	3.2E-04	1.5E-03

The contribution to the total dose from different pathways in Sv/a is graphically depicted in Figure 9.

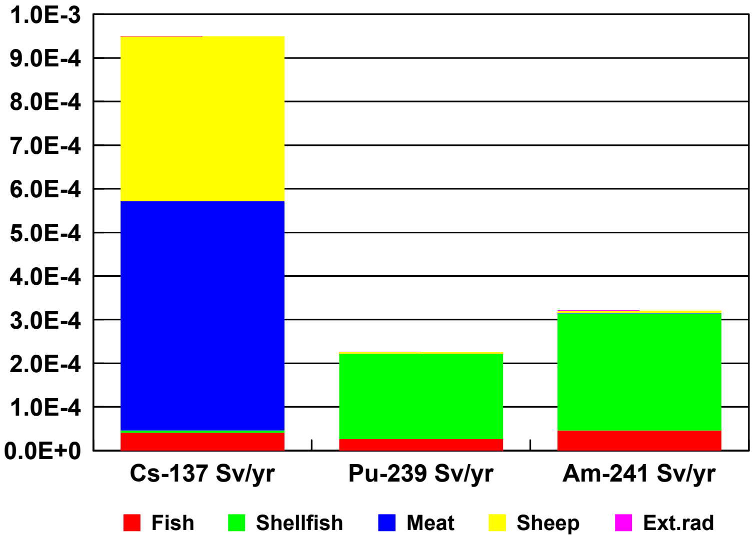

Figure 9 **The contribution to the total dose (Sv/a) from different pathways.**

As can be seen in Figure 9, the overall dominating exposure pathway for Cs-137 is via the ingestion of meat both from sheep and cattle. For Pu-239 and Am-241 the exposure via consumption of shellfish is the dominating one.

7.3.2 Collective doses to public over 100 years and 500 years and to restoration workers

Relevant restoration options for the Ravenglass estuary have been described in Bousher (1998). The effects of different restoration techniques are given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. The base case, as the situation is without any restoration is called A. Only the sediments of the upper banks are considered for restoration.

Table 8 shows the restoration options considered for the Ravenglass estuary site.

Table 8 **Restoration options considered for the Ravenglass estuary.**

Case	Restoration option
A	Basecase
B	Source removal
C1	Soil washing
D1	Chemical solubilisation

The results of the dose calculations for the collective doses at year 100 and 500 for the different restoration options are shown in Table 9.

Table 9 Collective doses (manSv) at Ravenglass estuary at 100 years and 500 years.

Case	Year	Cs-137 Mean	Pu-239 Mean	Am-241 Mean	Total Mean
A	100	2.3E+01	2.3E+00	3.2E+00	2.8E+01
	500	2.3E+01	2.6E+00	3.6E+00	2.9E+01
B	100	1.1E+01	1.6E+00	2.2E+00	1.5E+01
	500	1.1E+01	1.7E+00	2.4E+00	1.5E+01
C1	100	1.8E+01	2.1E+00	3.0E+00	2.3E+01
	500	1.8E+01	2.4E+00	3.3E+00	2.4E+01
D1	100	2.8E+00	2.1E+00	2.8E+00	7.7E+00
	500	2.8E+00	2.2E+00	3.1E+00	8.2E+00

As can be seen in Table 9 Cs-137 gives the highest exposure.

In Figure 10 the total collective doses from Cs-137 for the public and for the restoration workers are graphically depicted for the different restoration options at 100 and 500 years.

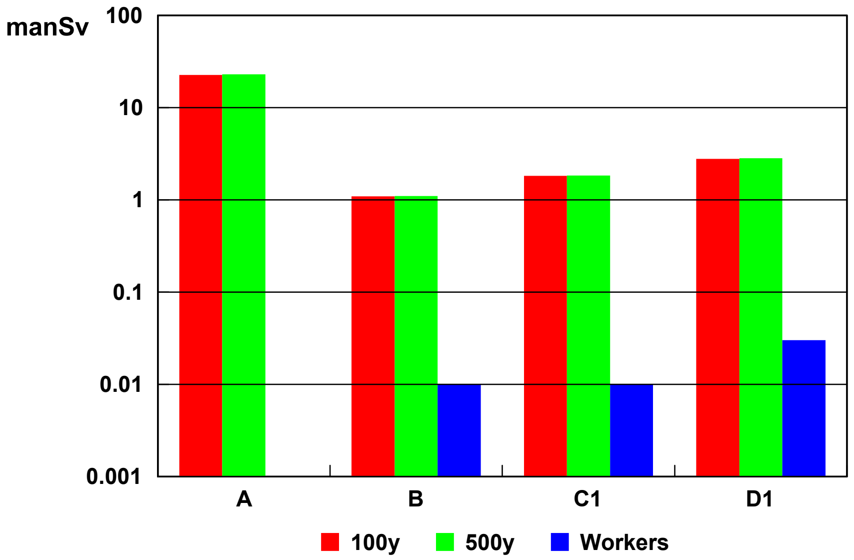

Figure 10 The total collective dose of Cs-137 (manSv) for the different restoration options at 100 years and 500 years.

As can be seen in Figure 10 the largest reduction of the collective dose is obtained by option B that stands for removal of the sediments in the estuary.

7.4 Uncertainty analysis

The results of the uncertainty analysis are given in Annex C, Tables C.5 - C.6. Here the mean values and the 5 and 95 percentiles are presented for the different doses.

7.4.1 Sensitivity analysis

Parameters that are of major importance to the uncertainty in the dose results are listed below

1. Suspended material in estuary
2. Distribution coefficient from sediment to water
3. Concentration factor from soil to plants
4. Concentration factor for shellfish
5. Shellfish production

For Cs-137 the concentration factor from soil to plants contributes the most to the uncertainty while for Pu-239 and Am-241 suspended material in the estuary, the distribution coefficient for sediment and the concentration factor for shellfish dominate.

The decontamination factors do not give a major contribution to the uncertainty in the dose results because of their small ranges, even though they play an important role for the dose reduction.

8 Ranstad Tailing Site

The Ranstad Tailing Site is situated in the southern part of Sweden, in the Billingen-Häggum district, about 20 km south of the city of Skövde. The tailings stem from a former uranium processing plant of AB Atomenergi, which operated on the uranium mined in a nearby open pit mine. Nowadays this plant processes filter resin from fuel fabrication and waste from incineration handling of low-level radioactive waste at Studsvik.

The major uranium production at the Ranstad site was carried out between 1964 and 1969. The residues from the leaching process were put in a large tailing deposit. The source is in solid form; it consists of crushed alumshale. When water is entering the tailing weathering processes starts and a heavy-metal contaminated leachate is produced. Some of this leachate is collected in a ditch surrounding the tailing; the rest of the leachate is infiltrated into the ground under the tailing.

The contaminants are not only radionuclides, i.e. U-238, but there is also a significant level of manganese and nickel. So any risk assessment should include chemical-toxical effects too.

The compartment scheme for the Ranstad tailing site is based on site information in Stiglund (1999).

8.1 Compartment scheme

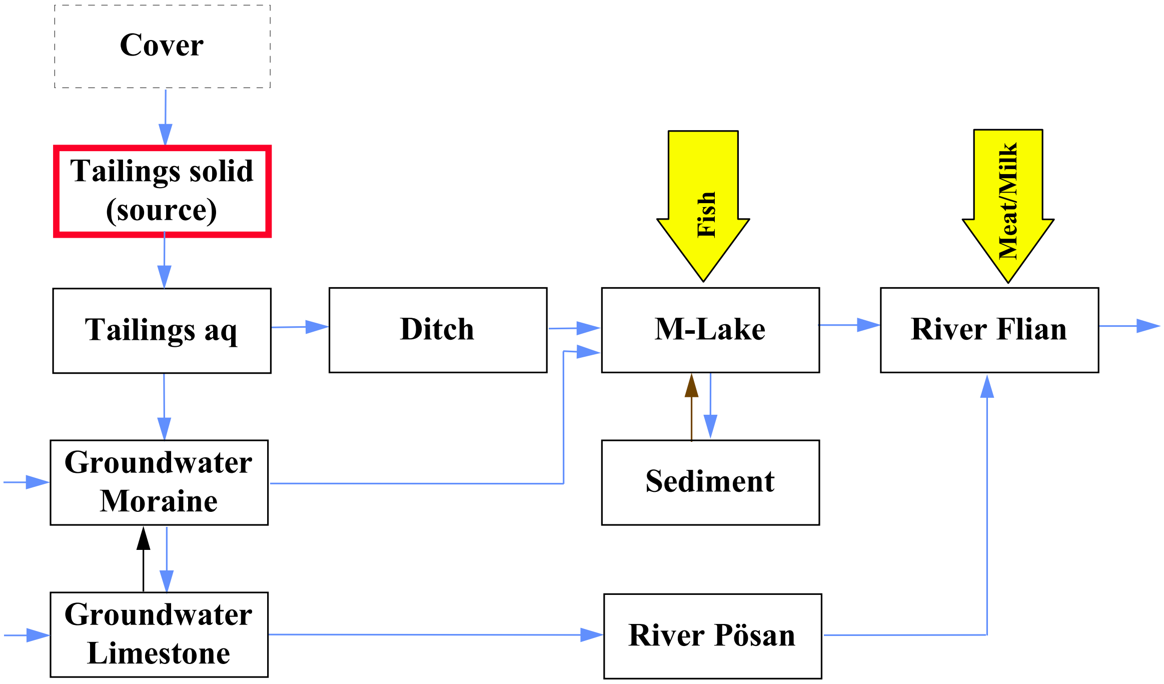

Figure 11 Compartment scheme for the Ranstad tailing site.

8.2 Processes, exposure pathways and exposure groups

The leachate from the tailing is transported both to a sorrounding ditch and down into the moraine underneath the tailing. In the moraine the leachate is diluted and transported further to the M-Lake. Some fraction of the leachate even reach the limestone aquifer.

Each transfer coefficient can consist of several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the Ranstad tailing site. The equations and data used are given in Appendix D.

Compartment	Processes
Water column	Sedimentation of particles Outflow
Sediment	Resuspension
Groundwater	Transfer to deeper groundwater Outflow

The important exposure pathways for the critical group are indicated in the compartment scheme. The exposure pathways considered are

- Consumption of water
- Consumption of fish
- Consumption of milk and meat via the drinking water of the cattle

The critical group concerned consists of farmers living in the neighbourhood. They consume locally produced meat and drink milk from cows. The fish is captured in the M-lake. The drinking water is taken from the limestone aquifer underneath the tailing.

The committed collective intake/dose is based on production data.

8.3 Intakes/doses to public/remediation workers

The doses calculated consist of individual and committed collective intakes/doses. The remediation workers are not supposed to receive any intakes during their work.

8.3.1 Individual intakes/doses to critical group: Base case year 1

The results of the dose calculations for the individual doses at year 1 are shown in Table 10.

Table 10 Individual dose (Sv/a) and intake (kg/a) at Ranstad tailing site at year 1.

Exposure pathway	Manganese kg/a	Nickel kg/a	Uranium kg/a	U-238 Sv/a
	Mean	Mean	Mean	Mean
Water	5.96E-07	3.50E-09	5.57E-09	3.19E-09
Fish	3.88E-04	1.02E-04	6.44E-05	3.68E-05
Milk	5.33E-09	1.28E-08	6.29E-09	3.60E-09
Meat	1.80E-06	1.25E-06	2.20E-07	1.26E-07
Total	3.90E-04	1.03E-04	6.46E-05	3.70E-05

The contribution to the total intake/dose from different pathways is shown in Figure 12.

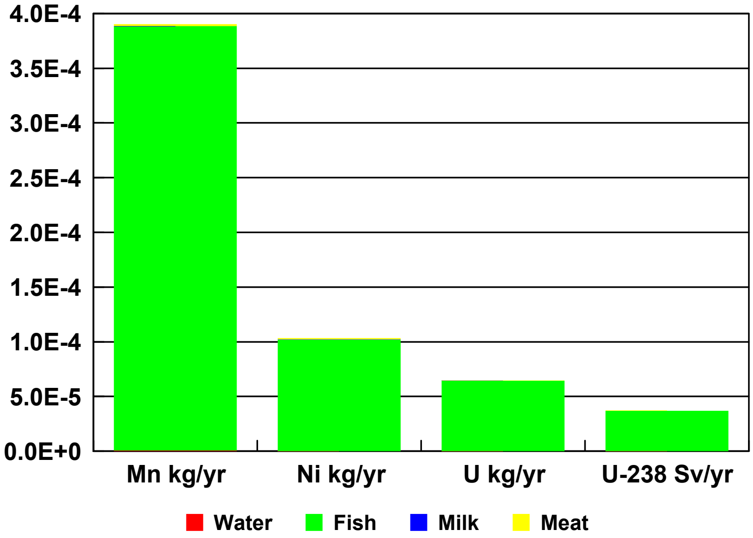

Figure 12 The contribution to the total dose (Sv/a) and intake (kg/a) from different pathways.

The intake of fish from the M-lake is the dominating exposure pathway for all heavy metals as well as for U-238.

8.3.2 Collective intakes/doses to public over 100 years and 500 years

Relevant restoration options for the Ranstad tailing site have been described in Stiglund (1999). The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping is considered, so for this restoration technique the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system. The base case, as the situation is without any restoration, is called A.

Table 11 shows the restoration options considered for the Ranstad tailing site.

Table 11 Restoration options considered for the Ranstad site.

Case	Restoration option
A	Base case
C1	Soil washing
D1	Chemical solubilisation
E1	Capping, 0.5 m moraine
E2	Capping, 1.6 m
F2	Physical immobilisation, *in-situ*
G2	Chemical immobilisation, *in-situ*

The results of the dose calculations for the collective intakes/doses at 100 years and 500 years for the different restoration options are shown in Table 12.

Table 12 Collective intake, (mankg), and doses, (manSv), at the Ranstad tailing site

Case	Year	Manganese mankg Mean	Nickel mankg Mean	Uranium mankg Mean	Uranium manSv Mean
A	100	1.2E+01	8.8E-01	1.0E+00	5.9E-01
	500	2.2E+01	5.8E+01	4.2E+01	2.4E+01
C1	100	6.3E+00	3.5E-01	4.0E-01	2.3E-01
	500	1.3E+01	2.2E+01	1.7E+01	9.4E+00
D1	100	5.1E+00	2.3E-01	2.3E-01	1.3E-01
	500	1.0E+01	1.2E+01	9.6E+00	5.5E+00
E1	100	7.9E+00	5.6E-01	6.5E-01	3.7E-01
	500	1.6E+01	3.5E+01	2.6E+01	1.5E+01
E2	100	4.4E+00	3.1E-01	3.4E-01	1.9E-01
	500	9.4E+00	1.8E+01	1.4E+01	8.1E+00
F2	100	1.3E+00	1.1E-01	8.9E-02	5.1E-02
	500	3.8E+00	4.0E+00	3.1E+00	1.8E+00
G2	100	7.3E-01	7.5E-02	6.0E-02	3.4E-02
	500	2.9E+00	2.5E+00	2.0E+00	1.1E+00

As can be seen in Table 12 the intake of heavy metals and the committed collective dose from U-238 are quite high. This is due to the consumption of water from the limestone aquifer. Since the time of transport for the leachate down to the limestone is rather long, some hundred years will pass before the groundwater in the limestone will be heavily contaminated.

In Figure 13 the collective dose commitment from U-238 for the public is graphically depicted for the different restoration options at 100 and 500 years.

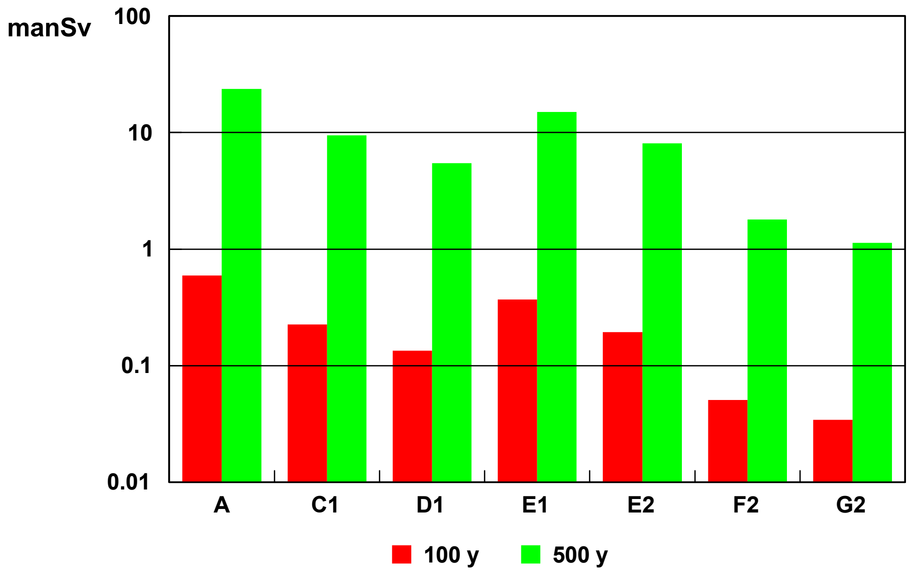

Figure 13 **The total collective dose of U-238 (manSv) for the different restoration options at 100 years and 500 years.**

As can be seen in Figure 13 the reduction of committed dose to the public is quite small for the different restoration options except for options F2 and G2. It seems that the physical and chemical immobilisation is the most effective among the restoration options in order to reduce the dose.

8.4 Uncertainty analysis

The results of the uncertainty analysis are given in Annex D, Tables D.4 - D.7. Here the mean values and the 5 and 95 percentiles are presented for the different doses.

8.4.1 Sensitivity analysis

Parameters that are of major importance to the uncertainty in the dose results are listed below

1 Concentration factor to fish
2 Distribution coefficient from soil to water
3 Groundwater flow from Billingen to the moraine
4 Groundwater flow from Billingen to the limestone
5 Distribution coefficient from sediment to water

The concentration factor to fish dominates the uncertainty for all metals and U-238 radiologically.

The Df-factors do not give a major contribution to the uncertainty in the dose results because of their small ranges, even though they play an important role for the dose reduction.

9 Lake Tranebärssjön

The location of the Lake Tranebärssjön site is approximately 5 km east of the Ranstad tailing site. It is a former uranium mine (open pit mining) which was in operation between 1965 and 1969. The lake has existed only since 1990, when the mine was flooded by water. Its dimensions are 2000 m length, 100 – 200 m width, and 15 m depth, giving an open area of 250 000 m^2.

The compartment scheme for the lake Tranebärssjön site is based on site information in Stiglund (1999).

The input of the substances studied are leaching from the banks around the lake. The backfill in the lake is of the same type of material as in the banks. Furthermore there is a leakage from surrounding alumshale which has been affected by lowering of the groundwater table during the operation of the pit.

The contaminants are not only radionuclides, i.e. U-238, but there is also a significant level of manganese and nickel. So any risk assessment should include classical chemical-toxical effects too.

9.1 Compartment scheme

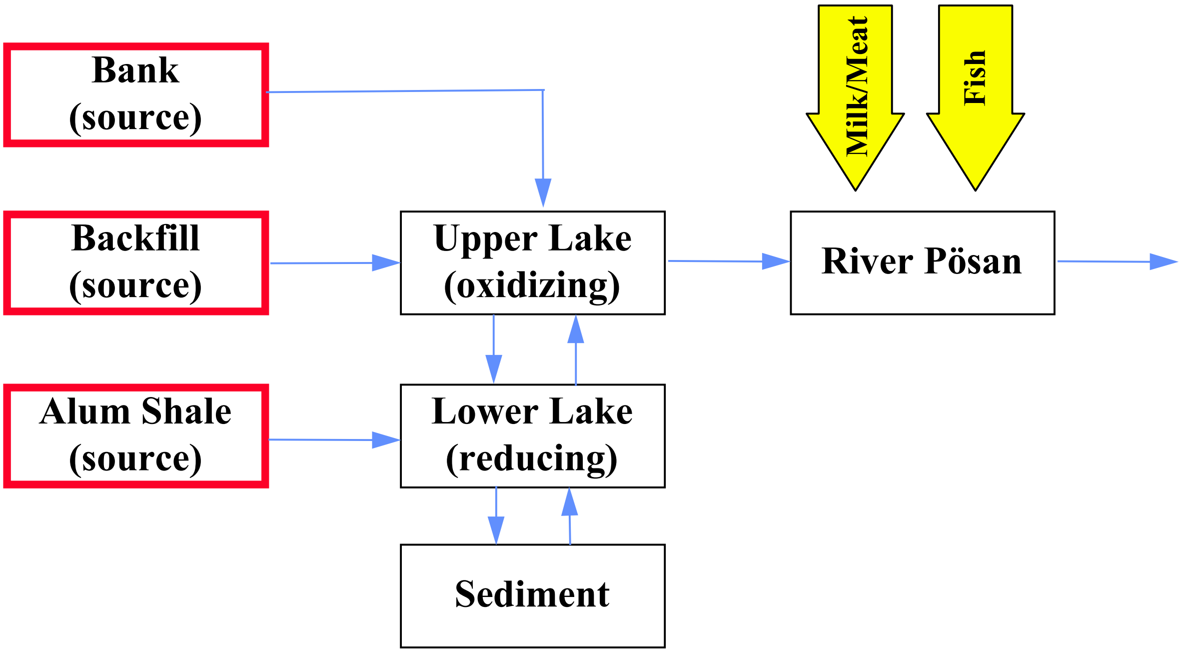

Figure 14 Compartment scheme for the lake Tranebärssjön.

9.2 Processes, exposure pathways and exposure groups

Each transfer coefficient can consist of several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the lake Tranebärssjön. The equations and data used are given in Appendix E.

Compartment	Processes
Water column	Sedimentation of particles Outflow
Sediment	Resuspension
Groundwater	Discharge Transfer to deeper groundwater Outflow

The important exposure pathways for the critical group are indicated in the compartment scheme. The exposure pathways considered are

- Consumption of fish
- Consumption of milk and meat via the drinking water of the cattle
- Consumption of milk and meat via the pasturage for the cattle

The critical group concerned consists of farmers living in the neighbourhood. They are eating locally produced meat and drink milk from cows that graze nearby the river Pösan. The fish is also captured in the river.

The so called committed collective intake is based on production data.

9.3 Intake/dose to public

The individual and committed collective doses/intakes are calculated. The remediation workers are not supposed to receive any intakes during their work.

9.3.1 Individual doses to critical group: Base case year 1

The results of the dose calculations/intakes for the individual doses/intakes at year 1 are shown in Table 13.

Table 13 Individual dose (Sv/a) and intake (kg/a) at Lake Tranebärssjön at year 1.

Exposure pathway	Manganese kg/a	Nickel kg/a	Uranium kg/a	U-238 Sv/a
Exposure	Mean	Mean	Mean	
Fish	1.7E-3	5.0E-5	2.2E-5	1.2E-5
Milk	9.1E-6	2.0E-5	2.1E-6	1.2E-6
Meat	1.8E-5	9.0E-7	2.9E-7	1.7E-7
Total	1.7E-3	7.0E-5	2.4E-5	1.4E-5

The contribution to the total dose/intake from different pathways is graphically depicted in Figure 15.

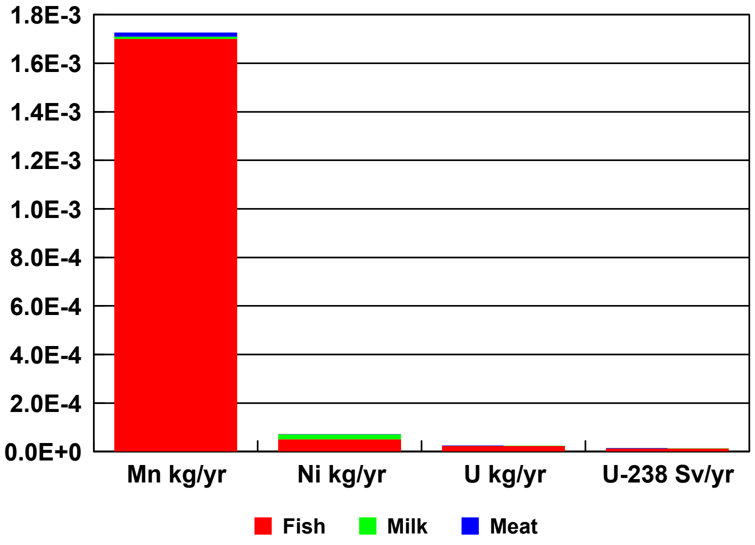

Figure 15 The contribution to the total dose (Sv/a) and intake (kg/a) from different pathways.

The intake of fish from the Pösan river is the dominating exposure pathway for manganese. Even for nickel the intake of fish is dominating but not as clearly. The dominance of exposure via consumption of fish is caused by quite high values of concentration factors for manganese and nickel. For uranium the dominating exposure pathway is via the intake of fish.

9.3.2 Collective doses/intakes to public over 100 years and 500 years.

Relevant restoration options for the lake Tranebärssjön have been described in Stiglund (1998). The effects of different restoration techniques are given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. The base case, as the situation is without any restoration is called A. The case C2 means that the outflowing water from the lake is filtrated through a sand filter and case D3 means that the water is leaving the lake and flows into a wetland.

Table 14 shows the restoration options considered for the lake Tranebärssjön.

Table 14 Restoration options considered for the lake Tranebärssjön.

Case	Restoration option
A	Basecase
C2	Filtration
D3	Biosorption

The results of the dose/intake calculations for the collective doses/intakes at 100 years and 500 years for the different restoration options are shown in Table 15.

Table 15 Collective intake, (mankg), and doses, (manSv), at the lake Tranebärssjön.

Case	Year	Manganese mankg Mean	Nickel mankg Mean	Uranium mankg Mean	Uranium manSv Mean
A	100	1.6E+00	1.4E+00	1.2E-01	6.9E-02
	500	4.4E+00	5.9E+00	4.8E-01	2.7E-01
C2	100	7.2E-01	2.3E-01	1.4E-02	8.1E-03
	500	2.4E+00	1.0E+00	5.7E-02	3.3E-02
D3	100	5.9E-01	1.1E-01	3.5E-03	2.0E-03
	500	2.2E+00	5.5E-01	1.6E-02	8.9E-03

As can be seen in Table 15 the intake of manganese and nickel is dominating the intake for all restoration options.

In Figure 16 the collective dose commitment from U-238 for the public is graphically depicted for the different restoration options at 100 and 500 years.

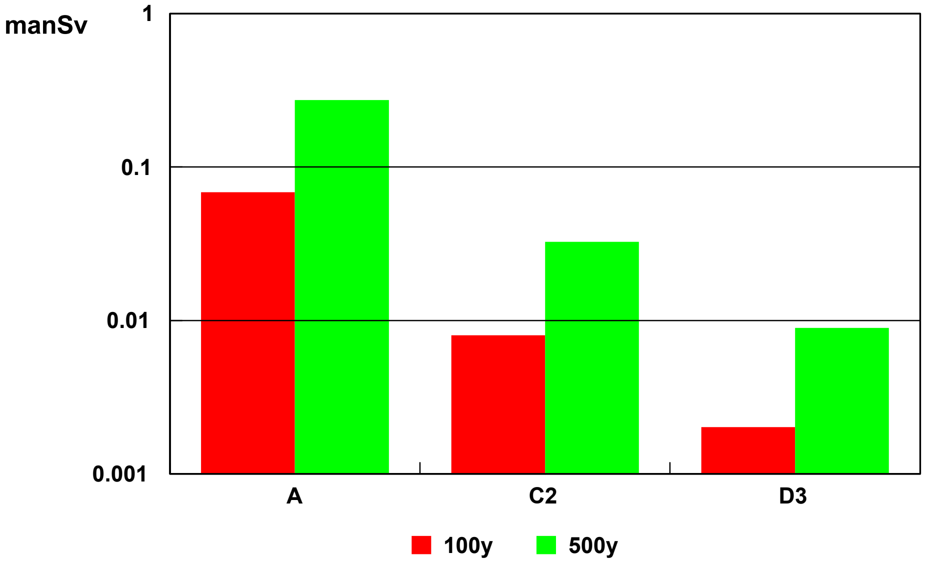

Figure 16 The total collective dose of U-238 for the different restoration options at 100 and 500 years.

As can be seen in Figure 16 the reduction of total committed dose to the public is quite large for the different restoration options. The calculations show that the option C2, sand filter, reduces the dose with one order of magnitude and that the option D3, wetland, reduces the dose with a factor of thirty.

9.4 Uncertainty analysis

The results of the uncertainty analysis are given in Annex E, Tables E.5 - E.6. Here the mean values and the 5 and 95 percentiles are presented for the different doses.

9.4.1 Sensitivity analysis

Parameters that are of major importance to the uncertainty in the dose results are listed below

1 Concentration factor to fish
2 Distribution coefficient beteween sediment and water
3 Transfer coefficient to meat
4 Transfer coefficient to milk
5 Concentration in the backfill of the lake

It seems that for the metals, as well as for U-238, the uncertainty is dominated by the transfer coefficients from cow to milk and meat, the distribution coefficient soil/water and the backfill concentration in the lake.

The decontamination factors do not give a major contribution to the uncertainty in the dose results because of their small ranges, even though they play an important role for the dose reduction.

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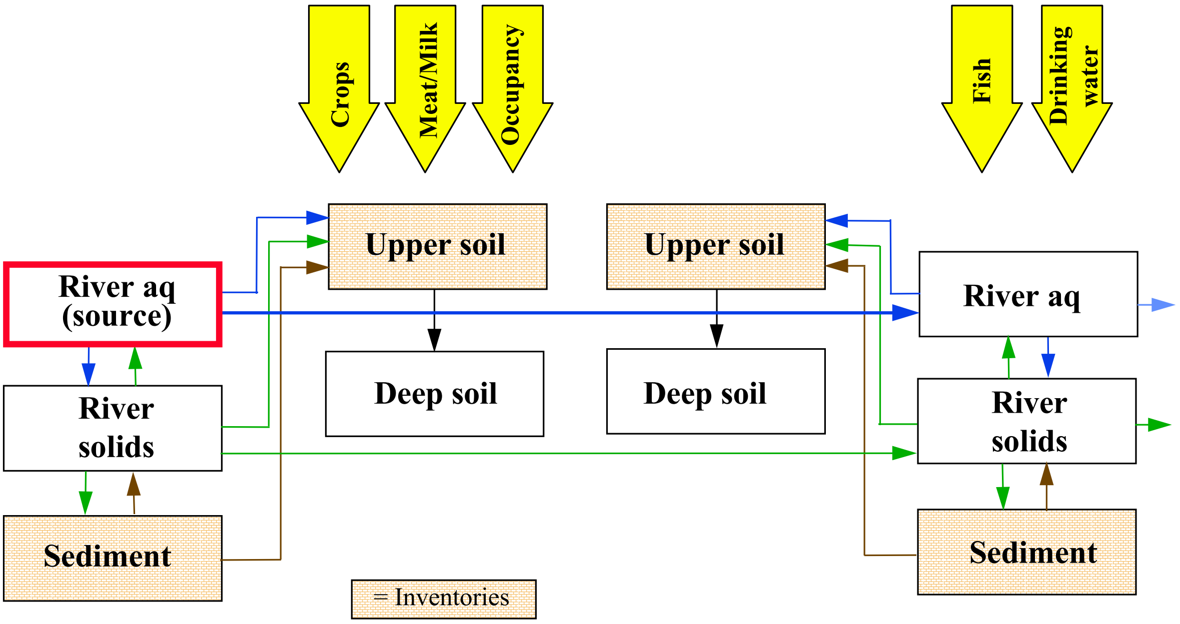
Appendix A – Mol

In this appendix transfer coefficients, used for turnover of radionuclides and dose assessment for the Mol scenario, are given aswell as parameter values used in the assessment. The compartment scheme for Molse Nete river is based on site description given in Sweeck *et al*. (1998).

The compartment scheme is shown below.



Transfer coefficients

Expressions of transfer coefficients (T_c) used in the compartment model are given below. The T_c within each section of the river is treated the same way. Values of the parameters in the calculations are shown below.

Sorption

The nuclides in the water are divided into soluble and suspended matter where the transfer from soluble to suspended fraction becomes:

$$Tc_{\text{soluble to suspended}} = Kd \cdot \ln(2)/Tk) \cdot (M/V)$$

and from suspended to soluble fraction:

$$Tc_{\text{suspended to soluble}} = \ln(2)/Tk$$

where

Kd = Distribution factor between solid and soluble fraction [m^3/kg]
V = Volume of water [m^3]
M = Mass of suspended material in the water [kg]
Tk = Half time of the reaction velocity [a]

Sedimentation

The only major process considered for the transfer coefficient describing the transport of radionuclides from water to sediment is via gravitational settling. The transfer then becomes:

$$Tc_{\text{suspended to sediment}} = S/(Susp \cdot MD)$$

where

S = Sedimentation rate [$kg/(m^2 \cdot a)$]
Susp = Concentration of suspended matter in the water body [kg/m^3]
MD = Mean depth of the water body [m]

Resuspension

Resuspension from the sediment to the water body is assumed to be onto the suspended matter. Data of sedimentation rate and net-sedimentation rate have been used in the expression for transfer coefficient considering only the mass balance, which then becomes:

$$Tc_{\text{sediment to suspended matter}} = (S - netS)/(SedDens \cdot (1 - SedPor) \cdot SedDepth)$$

where

S = Sedimentation rate [$kg/(m^2 \cdot a)$]
netS = Net sedimentation rate [$kg/(m^2 \cdot a)$]
SedDens = Sediment density [kg/m^3]
SedPor = Porosity of sediment [-]
SedDepth = Depth of sediment considered [m]

Outflow

The transport of radionuclides between the water compartments is assumed to be equal to the water flow. Transfer coefficients for the soluble and suspended fractions are assumed to be the same and can then be calculated from the turnover of water

$$Tc_{\text{out of river section}} = Flow/V$$

where

Flow = The flow of water in section i of the river [m^3/a]
V = Volume of section i of the river [m^3]

Data of length, width and depth of respective river section are used for calculation of the volume. The flow from the upper section is to the lower section while the flow from the lower section is out of the system.

Irrigation

Irrigation of agricultural land along each section of the river is considered. The transfer coefficient is given by

$$Tc_{\text{water to soil}} = Q_I \cdot \text{Soilarea}/V$$

where

Q_I = Irrigation amount [m/a]
Soilarea =Area of agricultural soil which is irrigated with water from respective section i of the river [m^2]
V = Volume of respective section i of the river [m^3]

Dredging

Dredging of the lower part of the river is performed every fifth year. In the model the total net-sedimentation is assumed to be dredged and can then be described with a rate constant (per year) which is valid for a period of hundreds of years.

$$Tc_{\text{sediment to soil}} = (\text{NetS} \cdot \text{length} \cdot w)/\text{SedMas}$$

where

netS = Net sedimentation rate, [$kg/(m^2 \cdot a)$]
length = Length of river section [m]
w = Width of river section [m]
SedMas = Mass of sediment in river section [kg]

Turnover in top soil

The dominating process for the turnover in the top soil is the advection

$$Tc_{\text{soil to deep soil}} = (P + Q_I / \text{Soilarea})/(h \cdot (1 + Kd \cdot \text{SoilDens} \cdot (1\text{-SoilPor})/\text{SoilPor}))$$

where

P = Precipitation – Evapotranspiration [$m^3/(m^2 \cdot a)$]
Soilarea = Area of irrigated soil [m^2]
h = Depth of the soil [m]
Kd = Distribution factor between solid and soluble fraction in the soil [m^3/kg]
SoilDens = Density of soil particles [kg/m^3]
SoilPor = Porosity of the soil[-]

Calculation of nuclide concentration in different media

The calculation of nuclide concentration in different media is made by dividing the inventory by the mass or volume for each media considered.

$$C_W = \text{Inventory(water)}/\text{Mass(water)}\ [\text{Bq/kg}]$$

where

Inventory(water) = Inventory in the two parts of the river, given by the compartment model [Bq]
Mass(water) = Mass of water in the two parts of the river[kg]

$$C_S = \text{Inventory(soil)}/\text{Mass(soil)}\ [\text{Bq/kg}]$$

where

Inventory(soil) = Inventory in the two parts of the soil given by the compartment model [Bq]
Mass(soil) = Mass of soil in the two parts next to the river[kg]

$$C_{sed} = \text{Inventory(sediment)}/\text{Mass(sediment)}\ [\text{Bq/kg}]$$

where

Inventory(sediment) = Inventory in the two parts of the sediment, given by the compartment model [Bq]
Mass(sediment) = Mass of sediment in the two parts of the river[kg]

Crops are contaminated from root uptake and surface contamination due to retention of contaminated irrigation water. The mean concentration of surface contamination is calculated.

$$C_{surf} = \frac{C_w}{Y_w} \cdot \frac{I}{t_{tot}} \cdot \sum_n \int_0^{t_n} e^{-\lambda t_n} dt$$

where

C_w = Concentration of radionuclides in irrigation water [Bq/kg]
Y_w = Yield [kg/m^2]
I = Remaining water, retention, on the vegetation after each irrigation occasion [m^3/m^2]
t_{tot} = Irrigation period, growing time [day]
λ = Empirical time constant for retention on vegetation [day^{-1}]
n = Number of irrigation occasions [-]
t_n = t_{tot}/n , Time between each irrigation occasion

Dose assessment

The exposure pathways considered are consumption of filtrated water and fish from the river and agricultural products from the land, which has been contaminated due to irrigation, and sediment from dredging.

The doses are calculated using the mean water concentration from the two river sections (C_w [Bq/litre]). The same is done for the two areas of soil where the mean concentration in the two soils has been used (C_s [Bq/kg]). The dose from consumption of water then becomes:

$$D_{\text{water individual}} = C_w \cdot \text{ConWater} \cdot \text{DosFactIng}$$

$$D_{\text{water collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConWater} \cdot \text{DosFactIng} \cdot \text{Pop} \cdot \text{Soilarea}$$

and from consumption of fish

$$D_{\text{fish individual}} = C_w \cdot \text{Bf-Fish} \cdot \text{ConFish} \cdot \text{DosFactIng}$$

$$D_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{FishProd} \cdot \text{RiverArea} \cdot \text{Bf-Fish} \cdot \text{DosFactIng}$$

where

ConWater	= Consumption of water [kg/a]
T	= Time period for collective dose integration [a]
Pop	= Population density [individuals/m^2]
Soilarea	= Soilarea for humans living in the area, based on food production [m^2]
ConFish	= Consumption of fish [kg/a]
Bf-Fish	= Bioaccumulation factor for fish [m^3/kg]
DosFactIng	= Dose factor for ingestion [Sv/Bq]
FishProd	= Production of fish in river [kg/(m^2·a)]
Riverarea	= Area of river [m^2]

The dose via consumption of milk

$$D_{\text{milk individual}} = (C_w \cdot \text{CoConWa} + \text{CoInt}) \cdot \text{Df-milk} \cdot \text{ConMilk} \cdot \text{DosFactIng} \cdot \text{FrMilkCo}$$

$$D_{\text{milk collective}} = \sum_{i=1}^{T} (\text{CoConWa} \cdot C_{w,i} + \text{CoInt}_i) \cdot \text{NrOfCows} \cdot \text{Milkprod} \cdot \text{Df-milk} \cdot \text{DosFactIng} \cdot \text{FrMilkCo}$$

where

CoConWa	= Cattle's consumption of water [l/a]
CoInt$_i$	= $\text{CoConPa} \cdot [\text{CfSoPl} \cdot C_{S,i} + C_{\text{Surf},i}/\text{PasYield}]+[\text{CoConSoil} \cdot C_{S,i}]$
CoConPa	= Cattle's consumption of pasturage [kg/a]
CfSoPl	= Transfer factor soil to pasturage [kg/kg]
PasYield	= Yield of pasturage [kg/m^2]
CoConSoil	= Cattle's consumption of soil [kg/a]
Df-milk	= Distribution factor for milk [a/kg]
ConMilk	= Consumption of milk [m^3/a]
T	= Time period for collective dose integration [a]
NrOfCows	= Soilarea · PasYield/CoConPa
Soilarea	= Area where cattle graze [m^2]
MilkProd	= Milk production from a cow [m^3/a]
FrMilkCo	= Fraction of milk cows [-]

The expression for dose via consumption of meat will be similar as that for milk

$$D_{\text{meat individual}} = (C_w \cdot \text{CoConWa} + \text{CoInt}) \cdot \text{Df-meat} \cdot \text{ConMeat} \cdot \text{DosFactIng} \cdot (1\text{-FrMilkCo})$$

$$D_{\text{meat collective}} = \sum_{i=1}^{T} (\text{CoConWa} \cdot C_{w,i} + \text{CoInt}_i) \cdot \text{NrOfCows} \cdot \text{MeatProd} \cdot \text{Df-meat} \cdot \text{DosFactIng} \cdot (1\text{-FrMilkCo})$$

where

ConMeat = Consumption of meat [kg/a]
Df-meat = Distribution factor for meat [a/kg]
T = Time period for collective dose integration [a]
MeatProd = Production of meat from one cow [kg/a]

and the other parameters are the same as those for the milk pathway.

The dose pathways for intake of different vegetative food are represented by intake of root crops ($D_{\text{rootcrops}}$), tubers (D_{tubers}), and vegetables ($D_{\text{vegetables}}$). The expressions used for those are:

$$D_{\text{rootcrops individual}} = \text{ConRoot} \cdot \text{DosFactIng} \cdot (\text{CfSoRo} \cdot C_S + C_{\text{Surf}} \cdot \text{TL})$$

$$D_{\text{rootcropscollective}} = \sum_{i=1}^{T} \text{RootYield} \cdot \text{Soilarea} \cdot \text{DosFactIng} \cdot (\text{CfSoRo} \cdot C_{S,i} + C_{\text{Surf},i} \cdot \text{TL})$$

$$D_{\text{tubers individual}} = \text{ConTube} \cdot \text{DosFactIng} \cdot (\text{CfSoTu} \cdot C_S + C_{\text{Surf}} \cdot \text{TL})$$

$$D_{\text{tubers collective}} = \sum_{i=1}^{T} \text{TubYield} \cdot \text{Soilarea} \cdot \text{DosFactIng} \cdot (\text{CfSoTu} \cdot C_{S,i} + C_{\text{Surf},i} \cdot \text{TL})$$

$$D_{\text{vegetables individual}} = \text{ConVege} \cdot \text{DosFactIng} \cdot (\text{CfSoVe} \cdot C_S + C_{\text{Surf}} / \text{VegYield})$$

$$D_{\text{vegetables collective}} = \sum_{i=1}^{T} \text{VegYield} \cdot \text{Soilarea} \cdot \text{DosFactIng} \cdot (\text{CfSoVe} \cdot C_{S,i} + C_{\text{Surf},i} / \text{VegYield})$$

where

RootYield = Yield of root crops [kg/m^2]
Soilarea = Area of root crops, tubers and vegetables, respectively [m^2]
CfSoRo = Transfer factor soil to root crops [kg/kg]
TL = Translocation from surface to edible part of the plant ([Bq/kg]/[Bq/m^2])
T = Time period for collective dose integration [a]
TubYield = Yield of tubers [kg/m^2]
CfSoTu = Transfer factor soil to tubers [kg/kg]
CfSoVe = Transfer factor soil to vegetables [kg/kg]
VegYield = Yield of vegetables [kg/m^2]

Dose due to external exposure $D_{external}$ is obtained by

$$D_{external\ individual} = C_S \cdot SoilDens \cdot ResTime \cdot DosFactExt \cdot ShieldFact$$

$$D_{external\ collective} = \sum_{i=1}^{T} C_S \cdot SoilDens \cdot ResTime \cdot DosFactExt \cdot ShieldFact \cdot Pop \cdot Soilarea$$

where

ResTime = Residence time on the contaminated soil [h/a]
DosFactExt = Dose factor for external exposure [Sv/h]/[Bq/m^3]
SoilDens = Density of the soil [kg/m^3]
ShieldFact = Shielding factor [-]
T = Time period for collective dose integration [a]
Pop = Population density [individuals/m^2]
Soilarea = Area which people occupy, farmland [m^2]

Dose due to inhalation $D_{inhalation}$ is obtained by

$$D_{inhalation\ individual} = C_S \cdot Dust \cdot ResTime \cdot InhalRate \cdot DosFactInhal$$

$$D_{inhalation\ collective} = \sum_{i=1}^{T} C_S \cdot Dust \cdot ResTime \cdot InhalRate \cdot DosFactInhal \cdot Pop \cdot Soilarea$$

where

Dust =Concentration of dust in air [kg/m^3] (the same concentration as in dust particles as in soil)
InhalRate =Inhalation rate [m^3/h]
DosFactInhal =Dose factor for inhalation [Sv/Bq]
T =Time period for collective dose integration [a]

The dose to the restoration workers are including both external irradiation and inhalation and is given by

$$D_{restoration\ workers} = C_{Sed} \cdot Worktimesed \cdot (Dust \cdot InhalRate \cdot DosFactInhal + SedDens \cdot DosFactExt \cdot ShieldFact) + C_S \cdot Worktimesoil \cdot (Dust \cdot InhalRate \cdot DosFactInhal + SoilDens \cdot DosFactExt \cdot ShieldFact)$$

where

WorkTimeSed = Work time with contaminated sediment [h]
WorkTimeSoil = Work time with contaminated soil [h]

The work time considered for the different restoration options are described in Sweeck *et al*. (1998).

Dose calculations for the different restoration techniques

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

The results of the committed collective doses are shown in Tables A.4 – A.7.

Table A.1 General parameters and values for the model of Molse Nete.

Description	Unit	Distr.	Best estimate	Min	Max
Nete river flow	m^3/a	T	3.15E+07	2.15E+07	4.15E+07
Nete river 1 length	m	T	3200	3100	3300
Nete river 2 length	m	T	3600	3500	3700
Nete river depth	m	T	0.5	0.4	0.6
Nete river width	m	T	5	4	6
Sediment density	kg/m^3	T	1600	1500	1700
Sedimentation rate	$kg/m^2 \cdot a$	T	100	70	130
Net sedimentation rate	$kg/m^2 \cdot a$	T	57	47	67
Susp	kg/m^3	LT	0.03	0.01	0.3
Sediment depth	m	T	0.75	0.6	0.9
Sediment porosity		T	0.33	0.26	0.4
Dredging to land	$kg/m^2 \cdot a$	T	3.2	2.7	3.7
Precipitation	m	T	0.36	0.3	0.42
Water density	kg/m^3	C	1000		
Time constant	a	C	0.08		
Soil width	m	T	50	40	60
Soil density	kg/m^3	T	1300	1200	1400
Top soil depth (plough layer)	m	T	0.3	0.25	0.35
Deep soil depth	m	T	10	9	11
Soilarea for cattle grazing	m^2	C	1.36E5		
Soilarea agricultural use	m^2	C	3.4E4		
Soilarea for humans	m^2	C	1.4E6		
Top soil porosity		T	0.4	0.3	0.5
Deep soil porosity		T	0.33	0.23	0.43
Irrigation	m	T	0.1	0.095	0.105
Weathering (from surface of vegetation)	days	T	15	10	20
Amount of water retained on leaf	m^3/m^2	T	0.003	0.002	0.004
Number of irrigations per season		C	4		
Growing time of plants	days	T	90	85	95
Translocation factor, here same for all nuclides	$[Bq/kg]/[Bq/m^2]$	T	0.01	0.005	0.015

Table A.2 Nuclide specific data.

Description	Unit	Distr	Nuclide	Best estimate	Min	Max
Distribution factor to milk	a/m^3	LT	Co-60	0.0055	5.5E-04	0.055
			Cs-137	0.019	0.0019	0.19
			Pu-239	1.4E-06	1.4E-07	0.000014
			Am-241	2.7E-05	2.7E-06	2.7E-04
Distribution factor to meat	a/kg	LT	Co-60	2.7E-06	2.7E-07	2.7E-05
			Cs-137	1.0E-04	1.0E-05	0.001
			Pu-239	2.7E-08	2.7E-09	2.7E-07
			Am-241	2.7E-07	2.7E-08	2.7E-06
Bioaccumulation factor to fish	m^3/kg	LT	Co-60	0.29	0.19	0.39
			Cs-137	1.4	1	1.8
			Pu-239	0.003	0.001	0.005
			Am-241	0.025	0.015	0.035
Transfer factor soil to pasturage	kg/kg	LT	Co-60	0.04	0.004	0.4
			Cs-137	0.13	0.013	1.3
			Pu-239	2.3E-04	2.3E-05	0.0023
			Am-241	0.002	2.0E-04	0.02
Transfer factor soil to root crops	kg/kg	LT	Co-60	0.02	0.002	0.2
			Cs-137	0.051	0.0051	0.51
			Pu-239	0.0041	4.1E-04	0.041
			Am-241	0.0021	2.1E-04	0.021
Transfer factor soil to tubers	kg/kg	LT	Co-60	0.01	0.001	0.1
			Cs-137	0.15	0.015	1.5
			Pu-239	1.1E-04	1.1E-05	0.0011
			Am-241	1.4E-04	1.4E-05	0.0014
Transfer factor soil to vegetables	kg/kg	LT	Co-60	0.01	0.001	0.1
			Cs-137	0.15	0.015	1.5
			Pu-239	9.0E-05	9.0E-06	0.0009
			Am-241	4.0E-04	4.0E-05	0.004
Kd sediment	m^3/kg	LT	Co-60	20	5	100
			Cs-137	50	10	250
			Pu-239	250	100	1000
			Am-241	1000	100	2000
Kd soil	m^3/kg	LT	Co-60	0.5	0.1	0.9
			Cs-137	1	0.1	10
			Pu-239	1	0.1	10
			Am-241	3	0.3	30
Dose factor inhalation	Sv/Bq	C	Co-60	5.9E-08		
			Cs-137	8.6E-09		
			Pu-239	1.2E-04		
			Am-241	1.1E-04		
Dose factor ingestion	Sv/Bq	C	Co-60	7.3E-09		
			Cs-137	1.3E-08		
			Pu-239	9.7E-07		
			Am-241	8.9E-07		
Dose factor external irradiation	(Sv/h)/ (Bq/m^3)	C	Co-60	3.7E-13		
			Cs-137	8.0E-14		
			Pu-239	1.0E-40		
			Am-241	5.3E-16		

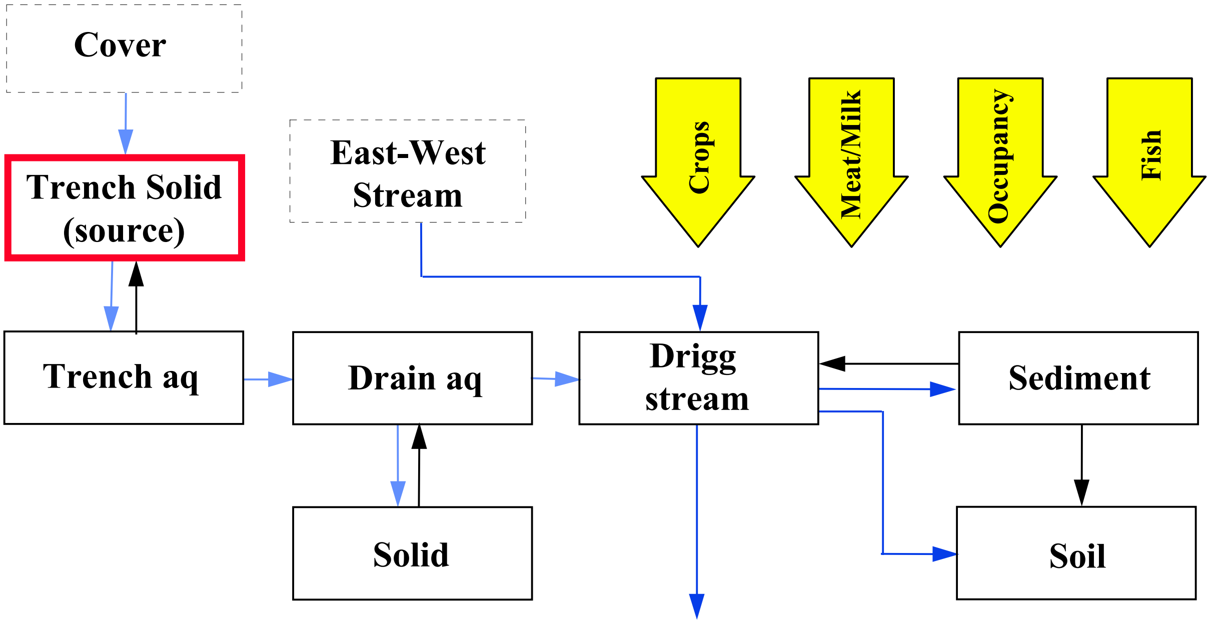
Table A.3 Date used in dose assessment.

Description	Unit	Distr	Best estimate	Min	Max
Population density	Individuals/m^2	T	3.2E-04	3.0E-04	3.4E-04
Shielding factor	-	C	0.7		
Residence time Farmer	h/a	T	1500	1300	1700
Inhalation rate of air	m^3/h	T	1.2	1	1.4
Consumption of water	m^3/a	T	0.4	0.32	0.48
Consumption of fish	kg/a	T	5	4	6
Consumption of milk	m^3/a	T	0.12	0.1	0.24
Consumption of meat	kg/a	T	73	66	80
Consumption of root crops	kg/a	T	70	60	80
Consumption of tubers	kg/a	T	94	84	104
Consumption of vegetables	kg/a	T	56	46	66
Milk production	m^3/a	T	5	4	6
Meat production	kg/a	T	150	100	200
Fish production	kg/m^2	T	0.005	0.004	0.006
Dust concentration	kg/m^3	LT	1E-07	1E-08	1E-06
Yield of root crops	kg/m^2	T	3	2	4
Yield of tubers	kg/m^2	T	3	2	4
Yield of vegetables	kg/m^2	T	2	1.5	2.5
Yield of pasture	kg/m^2	T	1.5	1	2
Cows consumption of water	m^3/a	T	23.7	18.7	28.7
Cows consumption of pasture	kg/a	T	5100	4100	6100
Cows consumption of soil	kg/a	T	200	150	250
Fraction of milk-cows	-	U	0.5		

Appendix B – Drigg trench

In this appendix transfer coefficients, used for turnover of radionuclides and dose assessment for the Drigg site scenario, are given aswell as parameter values used in the assessment. The compartment scheme for Drigg site is based on site description given in Bousher. (1998).

The compartment scheme is shown below



Transfer coefficients

Expressions of transfer coefficients (T_c) used in the compartment model are given below. The T_c within each section of the river is treated the same way. Values of the parameters in the calculations are shown below.

Sorption

The content of nuclides in the trench and the drain is divided into two fractions, a soluble fraction and a solid fraction. The exchange between those fractions obtained from dissolved to solid matter can be given in the expression

$$Tc_{\text{solid to soluble}} = Kd \cdot \ln(2)/Tk \cdot (V \cdot (1 - TrenchPor) \cdot TrenchDens)/(V \cdot TrenchPor)$$

and from particulate to the soluble fraction by

$$Tc_{\text{soluble to solid}} = \ln(2) / Tk$$

where

V = Volume of the trench and drain respectively [m^3]
Kd = Distribution factor between solid and soluble fraction [m^3/kg]
TrenchDens = Density of particles in trench and drain respectively [kg/m^3]
TrenchPor = Porosity [-]
Tk = Half-time of the reaction velocity [a]

Outflow

The water within the trench will leak to the drain and further to the Drigg stream. The expression for those transfer coefficients is:

$$Tc_{\text{trench to drain}} = Q_T / (V_T \cdot Por_T)$$
$$Tc_{\text{drain to stream}} = Q_D / (V_D \cdot Por_D)$$
$$Tc_{\text{stream to out}} = Q_S / V_S$$

where

Q = Flow of water in trench, drain and stream respectively [m^3/a]
V = Volume of the trench, drain and stream respectively [m^3]
Por = Porosity of the trench and drain respectively [-]

The flow of water through the trench is obtained from data of the infiltrating water (precipitation – evaporation) and the area of the trench. For the case with capping as a restoration option (case E) the permeability and the area of the trench are used for the estimation of the amount of water penetrating. Darcy's Law is used to calculate the flow Q that is then given by

$$Q = K \cdot i \cdot A$$

where

K = Hydraulic conductivity [m/sec]
i = Hydraulic gradient [m/m]
A = Area of the trench [m^2]

The hydraulic gradient is set to 1 as the flow is almost vertical and the hydraulic conductivity or permeability is given for each restoration option.

Sedimentation

In the stream there is an exchange between water and sediments, the sedimentation of nuclides is described according to

$$Tc_{\text{water to sediment}} = Kd \cdot S / (Depth \cdot (1 + Kd \cdot Susp))$$

Kd = Distribution factor between solid and soluble fraction in the stream water [kg/m^3]
S = Sedimentation rate in the stream [$kg/(m^2 \cdot a)$]
Depth = Mean depth of the stream [m]
Susp = Suspended material in the stream [kg/m^3]

Resuspension

In the stream there is an exchange between water and sediments, the resuspension of nuclides from sediments, is described according to

$$Tc_{\text{sediment to water}} = \text{Resusp}$$

Resusp = Transfer coefficient describing the resuspension [a^{-1}]

Irrigation

The water in the river is used for irrigation of agricultural land. The transfer coefficient to describe this is obtained from

$$Tc_{\text{river to soil}} = Q_I/V_S$$

where

Q_I = Irrigation amount [m^3/a]
V_S = Volume of Drigg stream [m^3]

Dredging

The river is dredged and the sediment is transferred to the agricultural soil. The transfer coefficient to describe this is obtained from

$$Tc_{\text{sediment to soil}} = \text{Dredg}$$

where

Dredg = Transfer coefficient describing the dredging [a^{-1}]

Turnover in top soil

Leakage of nuclides from the upper soil due to percolation of irrigation and rain water is considered in the model. The transfer coefficient from soil then becomes:

$$Tc_{\text{soil to out}} = (P + Q_I/A)/(\, h \cdot (1 + Kd \cdot \text{SoilDens} \cdot (1\text{-SoilPor})/\text{SoilPor}))$$

where

P = Precipitation – Evapotranspiration [$m^3/(m^2 \cdot a)$]
A = Area of irrigated soil [m^2]
h = Depth of the soil [m]
Kd = Distribution factor between solid and soluble fraction in the soil [m^3/kg]
SoilDens = Density of soil particles [kg/m^3]
SoilPor = Porosity of the soil[-]

Calculation of nuclide concentration in different media

The calculation of nuclide concentration in different media is made by dividing the inventory by the mass or volume for each media considered.

$$C_w = \text{Inventory(water)}/\text{Mass(water)}\ [\text{Bq/kg}]$$

where

Inventory(water) = Inventory in water, given by the compartment model [Bq]
Mass(water) = Mass of water [kg]

$$C_s = \text{Inventory(soil)}/\text{Mass(soil)}\ [\text{Bq/kg}]$$

where

Inventory(soil) = Inventory in soil, given by the compartment model [Bq]
Mass(soil) = Mass of soil [kg]

$$C_{sed} = \text{Inventory(sediment)}/\text{Mass(sediment)}\ [\text{Bq/kg}]$$

where

Inventory(sediment) = Inventory in sediment, given by the compartment model [Bq]
Mass(sediment) = Mass of sediment [kg]

Crops are contaminated from root uptake and surface contamination due to retention of contaminated irrigation water. The mean concentration of surface contamination is calculated.

$$C_{surf} = \frac{C_w}{Y_w} \cdot \frac{I}{t_{tot}} \cdot \sum_n \int_0^{t_n} e^{-\lambda t_n}\, dt$$

where

C_w = Concentration of radionuclides in irrigation water [Bq/kg]
Y_w = Yield [kg/m^2]
I = Remaining water, retention, on the vegetation after each irrigation occasion [m^3/m^2]
t_{tot} = Irrigation period, growing time [day]
λ = Empirical time constant for retention on vegetation [day^{-1}]
n = Number of irrigation occasions [-]
t_n = t_{tot}/n . Time between each irrigation occasion

Dose assessment

The exposure pathways considered are consumption of water and fish from the river and agricultural products from the land which have been contaminated due to irrigation with water from the stream and sediment from dredging.

The doses are calculated using the water concentration in the stream (C_w (Bq/litre)) and the concentration in the soil (C_s (Bq/kg)). The dose from consumption from consumption of fish becomes:

and from consumption of fish

$$D_{\text{fish individual}} = C_w \cdot \text{Bf-Fish} \cdot \text{ConFish} \cdot \text{DosFactIng}$$

$$D_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{FishProd} \cdot \text{RiverArea} \cdot \text{Bf-Fish} \cdot \text{DosFactIng}$$

where

T = Time period for collective dose integration [a]
ConFish = Consumption of fish [kg/a])
Bf-Fish = Bioaccumulation factor to fish [m^3/kg]
DosFactIng = Dose factor for ingestion [Sv/Bq]
FishProd = Production of fish in river [kg/m^2]
Riverarea = Area of river [m^2]

The dose via consumption of milk

$$D_{\text{milk individual}} = (C_w \cdot \text{CoConWa} + \text{CoInt}) \cdot \text{Df-milk} \cdot \text{ConMilk} \cdot \text{DosFactIng} \cdot \text{FrMilkCo}$$

$$D_{\text{milk collective}} = \sum_{i=1}^{T} (\text{CoConWa} \cdot C_{w,i} + \text{CoInt}_i) \cdot \text{NrOfCows} \cdot \text{Milkprod} \cdot \text{Df-milk} \cdot \text{DosFactIng} \cdot \text{FrMilkCo}$$

where

CoConWa = Cattle's consumption of water [l/a]
CoInt_i = CoConPa · [CfSoPl · $C_{S,i}$ + $C_{Surf,i}$/PasYield]+[CoConSoil · $C_{S,i}$]
CoConPa = Cattle's consumption of pasturage [kg/a]
CfSoPl = Transfer factor soil to pasturage [kg/kg]
C_{Surf} = Concentration of nuclide on surface [Bq/m^2]
PasYield = Yield of pasturage [kg/m^2]
CoConSoil = Cattle's consumption of soil [kg/a]
Df-milk = Distribution factor for milk [a/kg]
ConMilk = Consumption of milk [m^3/a]
T = Time period for collective dose integration [a]
NrOfCows = Soilarea · PasYield/CoConPa
Soilarea = Area where cattle graze [m^2]
MilkProd = Milk production from a cow [m^3/a]
FrMilkCo = Fraction of milk cows [-]

The expression for dose via consumption of meat will be similar as that for milk

$$D_{\text{meat individual}} = (C_w \cdot \text{CoConWa} + \text{CoInt}) \cdot \text{Df-meat} \cdot \text{ConMeat} \cdot \text{DosFactIng} \cdot (1\text{-FrMilkCo})$$

$$D_{\text{meat collective}} = \sum_{i=1}^{T} (\text{CoConWa} \cdot C_{w,i} + \text{CoInt}_i) \cdot \text{NrOfCows} \cdot \text{MeatProd} \cdot \text{Df-meat} \cdot \text{DosFactIng} \cdot (1\text{-FrMilkCo})$$

where

ConMeat = Consumption of meat [kg/a]
Df-meat = Distribution factor for meat [a/kg]
T = Time period for collective dose integration [a]
MeatProd = Production of meat from one cow [kg/a]

and the other parameters are the same as those for the milk pathway.

The dose pathways for intake of different vegetative food are represented by intake of root crops (D_{rootcops}) and vegetables ($D_{\text{vegetabels}}$). The expressions used for those are:

$$D_{\text{rootcrops individual}} = \text{ConRoot} \cdot \text{DosFactIng} \cdot (\text{CfSoRo} \cdot C_S + C_{\text{Surf}} \cdot \text{TL})$$

$$D_{\text{rootcrops collective}} = \sum_{i=1}^{T} \text{RootYield} \cdot \text{Soilarea} \cdot \text{DosFactIng} \cdot (\text{CfSoRo} \cdot C_{S,i} + C_{\text{Surf},i} \cdot \text{TL})$$

$$D_{\text{vegetables individual}} = \text{ConVege} \cdot \text{DosFactIng} \cdot (\text{CfSoVe} \cdot C_S + C_{\text{Surf}}/\text{VegYield})$$

$$D_{\text{vegetables collective}} = \sum_{i=1}^{T} \text{VegYield} \cdot \text{Soilarea} \cdot \text{DosFactIng} \cdot (\text{CfSoVe} \cdot C_{S,i} + C_{\text{Surf},i}/\text{VegYield})$$

where

RootYield = Yield of root crops [kg/m^2]
Soilarea = Area of root crops, tubers and vegetables, respectively [m^2]
CfSoRo = Transfer factor soil to root crops [kg/kg]
TL = Translocation from surface to edible part of the plant ([Bq/kg]/[Bq/m^2])
T = Time period for collective dose integration [a]
CfSoVe = Transfer factor soil to vegetables [kg/kg]
VegYield = Yield of vegetables [kg/m^2]

Dose due to external exposure D_{external} is obtained by

$$D_{\text{external individual}} = C_S \cdot \text{SoilDens} \cdot \text{ResTime} \cdot \text{DosFactExt} \cdot \text{ShieldFact}$$

$$D_{\text{external collective}} = \sum_{i=1}^{T} C_{Si} \cdot \text{SoilDens} \cdot \text{ResTime} \cdot \text{DosFactExt} \cdot \text{ShieldFact} \cdot \text{Pop}$$

where

ResTime = Residence time on the contaminated soil [h/a]
DosFactExt = Dose factor for external exposure [Sv/h]/[Bq/m^3]
SoilDens = Density of the soil [kg/m^3]
ShieldFact = Shielding factor [-]
Pop = Population [-]
T = Time period for collective dose integration [a]

Dose due to inhalation $D_{\text{inhalation}}$ is obtained by

$$D_{\text{inhalation individual}} = C_S \cdot \text{Dust} \cdot \text{ResTime} \cdot \text{InhalRate} \cdot \text{DosFactInhal}$$

$$D_{\text{inhalation collective}} = \sum_{i=1}^{T} C_{Si} \cdot \text{Dust} \cdot \text{ResTime} \cdot \text{InhalRate} \cdot \text{DosFactInhal} \cdot \text{Pop}$$

where

Dust = Concentration of dust in air [kg/m^3] (the same concentration in dust particles as in soil particles)
InhalRate = Inhalation rate [m^3/h]
DosFactInhal= Dose factor for inhalation [Sv/Bq]
T = Time period for collective dose integration [a]

The dose to the restoration workers are including both external irradiation and inhalation and is given by

$$D_{\text{restoration workers}} = C_S \cdot \text{WorkTimeSoil} \cdot (\text{Dust} \cdot \text{InhalRate} \cdot \text{DosFactInhal} + \text{SoilDens} \cdot \text{DosFactExt} \cdot \text{ShieldFact})$$

where

WorkTimeSoil = Work time with contaminated soil [h]

The work time considered for the different restoration options are described in Bousher, (1998).

Dose calculations for the different restoration techniques

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

The results of the committed collective doses are shown in Tables B.4 – B.14.

Table B.1 General parameters and values for the model of Drigg site.

Description	Unit	Distr.	Best estimate	Min	Max
Trench length	m	T	700	690	710
Trench width	m	T	25	22	27
Trench depth	m	T	6.5	6	7
Number of trenches	-	C	7		
Porosity of trenches	-	T	0.35	0.3	0.4
Area of cover	m^2	T	1.2E5	1.1E5	1.3E5
Depth of cover	m	T	0.5	0.4	0.6
Porosity of cover	-	T	0.25	0.2	0.3
Length of drains	m	T	800	750	850
Depth of drains	m	T	0.05	0.04	0.06
Width of drains	m	T	0.2	0.15	0.25
Length of Drigg stream	m	T	1100	1000	1200
Depth of Drigg stream	m	T	0.1	0.05	0.15
Width of Drigg stream	m	T	0.5	0.4	0.6
Porosity of sediments		T	0.9	0.85	0.95
Depth of sediments	m	LT	0.05	0.03	0.1
Sedimentation rate	$kg/(m^2 \cdot a)$	T	0.03	0.02	0.04
Suspended material in Drigg stream	kg/m^3	T	0.02	0.01	0.03
Area of agricultural soil	m^2	T	5.0E5	4E5	6E5
Depth of soil	m	T	0.25	0.2	0.3
Porosity of soil		T	0.35	0.3	0.4

Table B.1 cont'd

Description	Unit	Distr.	Best estimate	Min	Max
Flow from trenches to drain	m^3/a	LT	6.4E4	6.4E3	6.4E5
Flow from drain to Drigg stream	m^3/a	LT	1.1E5	1.1E4	1.1E6
Irrigation amount	m^3/a	LT	4.4E4	4.4E3	4.4E5
Flow out from Drigg stream	m^3/a	LT	1.1E6	1.1E5	1.1E7
Density of sediment	kg/m^3	T	1600	1500	1700
Density of soil	kg/m^3	T	1300	1200	1400
Transfer coefficient, sediment to agricultural soil (dredging)	a^{-1}	T	0.05	0.045	0.055
Time constant	a	C	0.08		
lambda_w	days	T	15	10	20
Amount of water retained on leaf	m	T	0.003	0.002	0.004
Number of irritations per season	-	C	4		
Grow time of plants	days	T	90	85	95
Translocation factor, here same for all nuclides	$(Bq/kg)/(Bq/m^2)$	T	0.01	0.005	0.015
Precipitation	m	T	0.49	0.39	0.59
Irrigation	m	LT	0.09	0.01	0.7
Density of trenches	kg/m^2	T	500	400	600

Table B.2 Nuclide specific parameters.

Description	Unit	Distr.		Mean	Min	Max
Distribution factor to milk	a/l	LT	Cs-137	1.9E-5	1.9E-6	1.9E-4
			U-238	1.0E-6	2.0E-7	2.0E-6
			Pu-239	1.4E-9	1.4E-10	1.4E-8
			Am-241	2.7E-8	2.7E-9	2.7E-7
Distribution factor to meat	a/kg	LT	Cs-137	1.0E-4	1.0E-5	1.0E-3
			U-238	3.0E-6	3.0E-7	3.0E-5
			Pu-239	2.7E-8	2.7E-9	2.7E-7
			Am-241	2.7E-7	2.7E-8	2.7E-6
Bioaccumulation factor to fish	m^3/kg	LT	Cs-137	1.4	1	1.8
			U-238	0.01	2.0E-3	0.05
			Pu-239	3.0E-3	1.0E-3	5.0E-3
			Am-241	0.025	0.015	0.035
Transfer factor soil to pasture	kg/kg	LT	Cs-137	0.13	0.013	1.3
			U-238	0.02	0.002	0.2
			Pu-239	2.3E-4	2.3E-5	2.3E-3
			Am-241	2.0E-3	2.0E-4	2.0E-2
Transfer factor soil to root crops	kg/kg	LT	Cs-137	5.1E-2	5.1E-3	5.1E-1
			U-238	3.0E-3	3.0E-4	3.0E-2
			Pu-239	4.1E-3	4.1E-4	4.1E-2
			Am-241	2.1E-3	2.1E-4	2.1E-2
Transfer factor soil to vegetables	kg/kg	LT	Cs-137	0.15	0.015	1.5
			U-238	1.0E-3	1.0E-4	1.0E-2
			Pu-239	9.0E-5	9.0E-6	9.0E-4
			Am-241	4.0E-4	4.0E-5	4.0E-3
Kd sediment	m^3/kg	LT	Cs-137	20	2	200
			U-238	10	1	100
			Pu-239	100	1	600
			Am-241	100	1	600
Kd soil	m^3/kg	LT	Cs-137	0.5	0.05	5
			U-238	0.1	0.01	1
			Pu-239	2	0.01	100
			Am-241	6	0.001	50
Dose factor inhalation	Sv/Bq	C	Cs-137	8.6E-9		
			U-238	7.3E-6		
			Pu-239	1.2E-4		
			Am-241	1.4E-4		
Dose factor ingestion	Sv/Bq	C	Cs-137	1.3E-8		
			U-238	4.5E-8		
			Pu-239	9.7E-7		
			Am-241	8.9E-7		
Dose factor external irradiation	(Sv/h)/ (Bq/m^3)	C	Cs-137	8.0E-14		
			U-238	0		
			Pu-239	0		
			Am-241	5.3E-16		

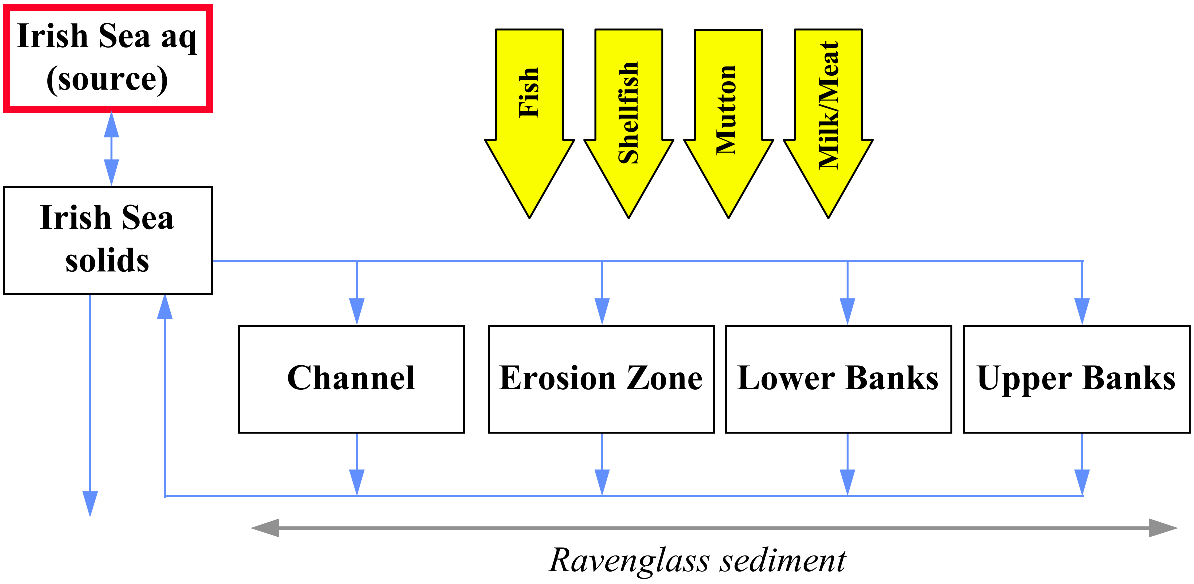
Table B.3 Dose assessment parameters.

Description	Unit	Distr.	Best estimate	Min	Max
Population	ind.	T	50	30	70
Consumption of fish	kg/a	T	5	4	6
Consumption of milk	liter/a	T	260	200	320
Consumption of meat	kg/a	T	30	20	40
Consumption of root crops	kg/a	T	48	38	58
Consumption of vegetables	kg/a	T	22	12	32
Fish production	kg/(m^2·a)	T	0.005	0.004	0.006
Milk production	liter/a	T	5000	4000	6000
Meat production	kg/a	T	150	100	200
Fraction of cattle for milk production	%	U	50	0	100
Intake of water by cattle	litre/a	T	23700	18700	28700
Intake of pasturage by cattle	kg/a	T	5100	4100	6100
Intake of soil by cattle	kg/a	T	200	150	250
Yield of vegetabels	kg/m^2	T	2	1.5	2.5
Yield of root crops	kg/m^2	T	3	2	4
Yield of pasturage	kg/m^2	T	1.5	1	2.5
Residence time on contaminated soil	h/a	T	300	250	350
Inhalation rate	m^3/h	T	1.2	1	1.4
Dust concentration in air	kg/m^3	LT	1E-7	1E-6	1E-7

Appendix C – Ravenglass estuary

In this appendix transfer coefficients, used for turnover of radionuclides and dose assessment for the Ravenglass scenario, are given aswell as parameter values used in the assessment. The compartment scheme for Ravenglass estuary is based on site description given in Bousher, (1998).

The compartment scheme is shown below.



Transfer coefficients

Expressions of transfer coefficients (T_c) used in the compartment model are given below. The T_c within each section of the river is treated the same way. Values of the parameters in the calculations are shown below.

Cumbrian Sea

Sorption

The nuclides in the water is divided into soluble and suspended matter where the transfer from soluble to suspended fraction becomes:

$$Tc_{\text{soluble to suspended}} = Kd \cdot \ln(2)/Tk \cdot M/V)$$

and from suspended to soluble fraction:

$$Tc_{\text{suspended to soluble}} = \ln(2)/Tk$$

where

Kd = Distribution factor between solid and soluble fraction [m^3/kg]
V = Volume of water [m^3]
M = Mass of suspended material in the water [kg]
Tk = Half time of the reaction velocity [a]

Sedimentation

The transfer coefficient describing the transport of radionuclides from water to sediment used in the model, where the major process considered ise gravitational settling, which then becomes:

$$Tc_{\text{suspended to sediment}} = S/(Susp \cdot MD)$$

where

S = Sedimentation rate, Irish Sea [kg/($m^2 \cdot a$)]
Susp = Concentration of suspended matter in the water body [kg/m^3]
MD = Mean depth of the water body [m]

Outflow

The outflow from the compartment system is via the exchange of water between the Cumbrian Sea and the rest of the Irish Sea. The same transfer coefficient for the soluble and suspended fraction is calculated from the turnover of water

$$Tc_{\text{outflow}} = \text{Outflow}/V$$

where

Outflow = The total outflow from Cumbrian coast [m^3/a]

Transport to estuary sediment

The transport of suspended material to the different sediment compartments of Ravenglass estuary is in the model treated as a direct transport of nuclides from the suspended fraction in the Cumbrian coast.

$$Tc_{\text{Irish Sea to channel bottoms}} = S_c \cdot \text{ChanArea}/M$$

$$Tc_{\text{Irish Sea to erosion bottoms}} = S_c \cdot \text{EroArea}/M$$

$$Tc_{\text{Irish Sea to lower banks}} = \text{SedAccLow}/M$$

$$Tc_{\text{Irish Sea to upper banks}} = \text{SedAccUp}/M$$

where

S_c = Sedimentation rate Ravenglass estuary [kg/(m^2·a)]
SedAccLow = Sediment accumulation lower banks [kg/a]
Sed AccUpp = Sediment accumulation upper banks [kg/a]
ChanArea = Area of channels bottoms [m^2]
EroArea = Area of erosion bottoms [m^2]
M = Mass of suspended material in the water in the Cumbrian sea [kg]

Resuspension

Resuspension from the different sediments is calculated differently depending on available data. In the channel area no net sedimentation is considered

$$Tc_{\text{channel bottoms to Irish Sea}} = S_c \cdot ChanArea/M(4)$$

$$Tc_{\text{erosion bottoms to Irish Sea}} = (Sedrat + ResuspEr/1000 \cdot BulkDens) \cdot EroArea/M(5)$$

For upper and lower banks the residence time is given in the site description, which has then been used for the transfer coefficients

$$Tc_{\text{lower banks to Irish Sea}} = (1/RT_{low}) \cdot (1\text{-}FracToEro)$$

$$Tc_{\text{lower banks to erosion bottoms}} = (1/RT_{low}) \cdot FracToEro$$

$$Tc_{\text{upper banks to Irish Sea}} = 1/RT_{upp}$$

where

RT = Mean residence time [a]
FracToEro = Fraction of total outflow of nuclides in sediments from lower banks to sediment in erosion bottoms [-]

Calculation of nuclide concentration in different media

The mean water concentration in the estuary is estimated from the nuclide content in sediment using the distribution coefficient between water and sediment. The assumption is that the suspended particles in the estuary have the same concentration as in the sediment. The solid fraction corresponds to the Kd of the nuclide. The total concentration in water (C_w [Bq/litre]) of both suspended and dissolved matter can then be calculated from sediment concentration according to:

$$C_w = (I(4)+I(5)+I(6)+I(7))/(M(4)+M(5)+M(6)+M(7)) \cdot (Susp+1/Kd)/1000$$

where

I(i) = Inventory of the nuclide in compartment i [Bq]
M(i) = Mass of sediment compartment i [kg]
Kd = Distribution coefficient water to particulates [m^3/kg]
Susp = Concentration of suspended matter in the water body [kg/m^3]

The grazing is assumed to be on the upper banks, the concentration in the upper banks (C_s [Bq/kg]) where vegetation grows which is consumed by the livestock becomes:

$C_s = I(6)/M(6)$

Mean values of reported realeses from Sellafield have been used in the calculations of the concentrations. The calculated concentrations in upper and lower bank are graphically depicted in Figure C.1. The calculated concentrations correspond to observed values. In the figure also the future concentrations are given, with present and 0 releases from Sellafield.

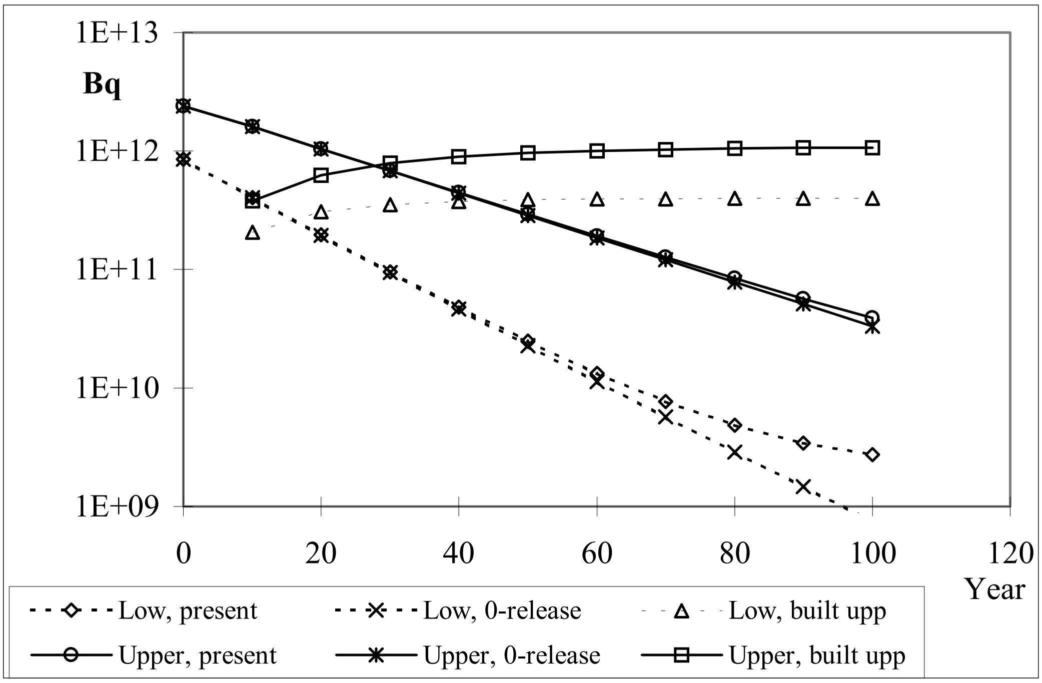


Figure C.1 Calculated concentrations in upper and lower bank of Ravenglass estuary.

Dose assessment

The exposure pathways considered are consumption of fish and shellfish from the estuary and mutton from sheep and meat and milk from cattle grassing on the shore and drinking brackish water. According to present habits cattle are not grassing at the shore.

The expression of dose for the different exposure pathways then becomes:

$$D_{\text{fish individual}} = \text{ConFish} \cdot \text{DosFaktIng} \cdot \text{Bf\_fish} \cdot C_w$$

$$D_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{FishProd} \cdot \text{TotArea} \cdot \text{Bf-Fish} \cdot \text{DosFactIng}$$

where

ConFish = Consumption of fish [kg/a]
T = Time period for collective dose integration [a]
DosFactIng = Dose factor for ingestion [Sv/Bq]

FishProd = Yield of fish in estuary [kg/(m^2·a)]
TotArea = Area of estuary representative for fish yield [m^2]
Bf-Fish = Bioaccumulation factor to fish [litre/kg]

$$D_{\text{shell fish individual}} = \text{ConSheF} \cdot \text{DosFaktIng} \cdot \text{Bf-ShellFish} \cdot C_w$$

$$D_{\text{shell fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ShellFishProd} \cdot \text{TotArea} \cdot \text{Bf-ShellFish} \cdot \text{DosFactIng}$$

where

ConSheF = Consumption of shellfish [kg/a]
ShellFishProd=Shellfish production in estuary [kg/(m^2·a)]
TotArea = Area of estuary representative for shellfish yield [m^2]
Bf-ShellFish= Bioaccumulation factor to shell fish [litre/kg]

$$D_{\text{mutton individual}} = \text{ConMutt} \cdot \text{DosFaktIng} \cdot \text{Df-sheep} \cdot (C_s \cdot \text{CF-plant} \cdot \text{ShPaCon} + C_w \cdot \text{ShWaCon})$$

$$D_{\text{mutton collective}} = \sum_{i=1}^{T} \text{NrOfSheep} \cdot \text{ShMeatpr} \cdot \text{DosFaktIng} \cdot \text{Df-sheep} \cdot (C_s \cdot \text{CF-plant} \cdot \text{ShPaCon} + C_w \cdot \text{ShWaCon})$$

where

ConMutt = Consumption of mutton [kg/a]
NrOfSheep = UpBaArea · PasYield · FrSheep/(ShPaCon · 365)
UpBaArea = Area upper banks [m^2]
PasYield = Yield of pasturage [kg/m^2]
FrSheep = Fraction of lifestock which is sheep, the rest is cattle
ShPaCon = Daily consumption of pasturage by sheep [kg/day]
ShWaCon = Daily consumption of water by sheep [litre/day]
Df-Sheep = Transfer coefficient for mutton [day/kg]
ShMeatPr = Mean yield of of mutton per sheep [kg/a]

$$D_{\text{meat individual}} = \text{ConMeat} \cdot \text{DosFaktIng} \cdot \text{Df-meat} \cdot \text{CoInt}$$

$$D_{\text{meat collective}} = (\sum_{i=1}^{T} C_{w,i} \cdot \text{NrOfCows} \cdot \text{MeatProd} \cdot \text{CoConWa} + \text{CoInt}) \cdot \text{Df-meat} \cdot \text{DosFactIng} \cdot (1\text{-FrMilkCo})$$

where

NrOfCows = UpBaArea · PasYield · (1-FrCow)/(CoConPa · 365)
CoInt_i = $C_{s,i} \cdot \text{CF-plant} \cdot \text{CoPaCon} + C_{w,i} \cdot \text{CoWaCon}$
CF-plant = Transfer factor for soil to plant [kg/kg]
CoPaCon = Daily consumption of pasturage by cattle [kg/day]
CoWaCon = Daily consumption of water by cattle [litre/day]
ConMeat = Consumption of meat [kg/a]
Df-meat = Transfer coefficient for meat [day/kg]
MeatProd = Mean yield of meat per cattle [kg/a]

Dose due to external exposure $D_{external}$ is obtained by

$$D_{external\ individual} = C_S \cdot ResTime \cdot DosFactExt$$

$$D_{external\ collective} = \sum_{i=1}^{T} C_S \cdot ResTime \cdot DosFactExt$$

where

ResTime = Residence time on the contaminated soil [h/a]
DosFactExt = Dose factor for external exposure [Sv/h]/[Bq/m^3]
T = Time period for collective dose integration [a]

The dose to the restoration workers are including both external irradiation and inhalation and is given by

$$D_{restoration\ workers} = C_S \cdot Worktimesed \cdot (Dust \cdot InhalRate \cdot DosFactInhal + SoilDens \cdot DosFactExt\ )$$

where

WorkTimeSed = Work time with contaminated sediment [h]

The work time considered for the different restoration options are described in Bousher, (1998).

Dose calculations for the different restoration techniques

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

In Table C.1 the general parameters are given for the calculation of the turn over, in Table 2 the general parameters for the dose calculation are given and in Tables C.3 – C.4 the nuclide specific parameters are given for Cs-137, plutonium and Am-241.

The results of the committed collective doses are shown in Tables C.5 – C.6.

Table C.1 General parameters and values for the model of Ravenglass.

Description	Unit	Type of distribution	Best estimate	Min or Std	Max
Cumbrian sea					
Volume	km^3	T	27	26	27
Sedimentation rate	kg/m^2·a	T	10	5	15
Mean depth	m	T	26	24	27
Water turnover	km^3/a	T	355	340	370
Time constant	a	C	0.02	-	-
Ravenglass					
Mass of channel sediment	kg		3.5E8	3E8	4E8
Mass of erosion sediment	kg	T	3.5E8	3E8	4E8
Area of channels	km^2	T	1	0.9	1.1
Area of erosion sediments	km^2	T	1	0.9	1.1
Sediment accumulation low banks	kt/a	T	6	5.5	6.5
Sediment accumulation upper banks	kt/a	T	9.5	9	10
Residence time of sediment in lower banks	a	T	20	10	30
Residence time of sediment in upper banks	a	T	50	40	60
Resuspension from erosion bottoms	mm/a	U		0	6
Sedimentation rate	kg/m^2·a	T	12	10	14
Bulk density of sediments	kg/m^3	T	1100	1000	1600
Fraction of sediment outflow from lower banks to erosion bottoms	-	U		0.1	0.9

Table C.2 Nuclide specific data.

Description	Unit	Distr	Nuclide	Best estimate	Min	Max
Cumbrian Sea						
Concentration in water (soluble)	Bq/litre	LT	Cs-137	12.9	0.05	33.3
			Pu-α	0.019	5E-4	0.041
			Am-241	0.054	0.01	0.097
Concentration in particles	kBq/kg	LT	Cs-137	16.3	0.1	44.9
			Pu-α	11.8	0.6	28.7
			Am-241	22.2	0.1	53.2
Content in sediments	Bq	T	Cs-137	1.5E15	1E15	2E15
			Pu-α	7.5E15	6E15	9E15
			Am-241	7.5E15	6E15	9E15
Ravenglass						
Initial content in channel	Bq	T	Cs-137	6.6E11	6E11	7E11
			Pu-α	3.3E12	1E12	6E12
			Am-241	3.3E12	1E12	6E12
Initial content in banks lower	Bq	T	Cs-137	8.5E11	8E11	9E11
			Pu-α	4.3E12	2E12	7E12
			Am-241	4.3E12	2E12	7E12
Initial content in banks upper	Bq	T	Cs-137	2.4E12	2E12	3E12
			Pu-α	1.2E13	5E12	2E13
			Am-241	1.2E13	5E12	2E13
Initial content in erosion bottoms	Bq	T	Cs-137	5.5E11	5E11	6E11
			Pu-α	2.8E12	1E12	5E12
			Am-241	2.8E12	1E12	5E12
Distribution coefficient water sediment	m^3/kg	LT	Cs-137	6.6	0.4	72
			Pu-α	1017	40	11000
			Am-241	552	30	790

Table C.3 Consumption data used in the dose assessment.

Exposure pathway	Unit	Distr.	Best estimate	Min or Std	Max	Reference
Intake by man						
Meat	kg/a	N	29	6		Char. of Drigg Table 17
Fish	kg/a	N	35	7		”
Shell fish	kg/a	N	16	3		”
Mutton	kg/a	N	20	4		”
Intake by cattle:						
Water	litre/day	T	75	50	100	IAEA 364 Table XI
Pasturage	kg/day	T	16	10	25	
Intake by Sheep						
Water	litre/day	T	2	3	5	
Pasturage	kg/day	T	1.1	0.5	2	
Fish production	kg/(ha·a)	T	10	5	15	
Shellfish production	kg/(ha·a)	T	10	5	15	
Milk production	liter/a	T	5000	4000	6000	
Meat production	kg/a	T	150	100	200	
Mutton production	kg/a	T	10	5	15	
Fraction of cattle for milk production	%	U	50	0	100	
Yield of pasturage	kg/m^2	T	1.5	1	2.5	
Residence time on contaminated soil	h/a	N	1000	1E-10	1E10	

Table C.4 Nuclide specific data for Cs-137 used in the dose assessment.

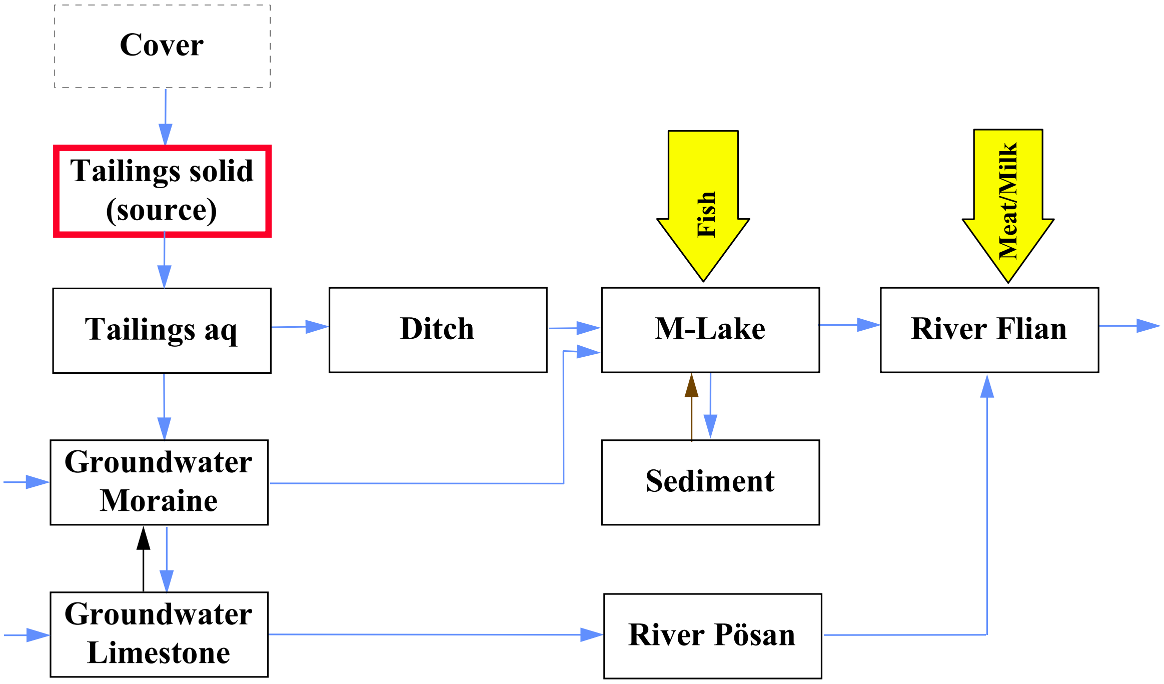
Description	Unit	Distr.	Nuclide	Best est.	Min	Max
Transfer coefficient to milk	day/litre	LT	Cs-137	0.008	0.001	0.027
			Pu-α	1.E-6	3E-9	3E-6
			Am-241	1.5E-6	4E-7	2E-5
Transfer coefficient to meat	day/kg	LT	Cs-137	0.05	0.01	0.06
			Pu-α	1.E-5	2E-7	2E-4
			Am-241	4.E-5	4E-6	1E-4
Transfer coefficient to mutton	day/kg	LT	Cs-137	0.5	0.1	1.6
			Pu-α	4.E-3	2E-5	0.005
			Am-241	3.E-3	3E-4	0.03
Transfer factor soil to plant	kg/kg		Cs-137	0.3	0.03	3
			Pu-α	8.E-4	5E-5	0.6
			Am-241	0.001	2E-4	0.2
Bioaccumulation factor water to fish	litre/kg		Cs-137	100	10	300
			Pu-α	40	0.5	100
			Am-241	50	0.5	200
Bioaccumulation factor water to shell fish	litre/kg		Cs-137	30	10	50
			Pu-α	300	100	1000
			Am-241	500	100	1000
Physical half life	a	C	Cs-137	30		
			Pu-α	10000*		
			Am-241	7380		
Dose factor for man due to intake	Sv/Bq	C	Cs-137	1.4E-8		
			Pu-α	2.5E-7*		
			Am-241	2.1E-7		

* Should be nuclide specific data for each isotope.

Appendix D – Ranstad tailing

In this appendix transfer coefficients, used for turnover of radionuclides and dose/intake assessment for the Ranstad tailing scenario, are given aswell as parameter values used in the assessment. The compartment scheme for Ranstad tailing site is based on site description given in Stiglund, (1999).

The compartment scheme is shown below.



Transfer coefficients

Expressions of transfer coefficients (T_c) used in the compartment model are given below. Values of the parameters in the calculations are shown below.

Sorption

The leakage from solid fraction to the soluble fraction is in the model given as a transfer coefficient corresponding to the leakage rate.

$$Tc_{\text{solid to soluble}} = LR$$

where

LR = Leakage rate of the inventory [1/a]

Outflow

A fraction of the water within the tailing will leach to the underlying moraine and one fraction to the surrounding ditch. The expression for those transfer coefficients are:

$$Tc_{\text{tailing to moraine}} = (F_M \cdot Q_T)/(V_T \cdot R)$$

$$Tc_{\text{tailing to ditch}} = ((1 - F_M) \cdot Q_T)/(V_T \cdot R)$$

where

F_M = Fraction of total leakage to the moraine [-]
Q_T = Flow of water trough the tailing [m^3/a]
V_T = Volume of water in the tailing [kg]
R = Retention
R = $1 + Kd \cdot \rho \cdot [1-\varepsilon]/\varepsilon$
Kd = Distribution factor between solid and soluble fraction [m^3/kg]
ρ = Density [kg/m^3]
ε = Porosity [-]

The flow of water through the trench is obtained from data of the infiltrating water (precipitation – evaporation) and the area of the trench. For the case with capping as a restoration option (case E) the permeability and the area of the trench are used for the estimation of the amount of water penetrating. Darcy's Law is used to calculate the flow Q that is then given by

$$Q = K \cdot i \cdot A$$

where

K = Hydraulic conductivity [m/sec]
i = Hydraulic gradient [m/m]
A = Area of the trench [m^2]

The hydraulic gradient is set to 1 as the flow is almost vertical and the hydraulic conductivity or permeability is given for each restoration option.

For the flow in the ditch no retention is considered and therefore the transfer coefficient becomes

$$Tc_{\text{ditch to lake}} = Q_D / V_D$$

where

Q_D = Flow from ditch to M-lake [m^3/a]
V_D = Volume of water in ditch [m^3]

The transport from the moraine groundwater is either to the limestone aquifer or to the M-lake.

$$Tc_{\text{morain to limestone}} = (Q_T \cdot (1 - F_M) \cdot F_L)/(V_M \cdot R)$$
$$Tc_{\text{morain to lake}} = (Q_T \cdot (1 - F_M) \cdot (1-F_L) + Q_{Mi})/(V_M \cdot R)$$

where

F_L = Fraction of percolating water to limestone aquifer [-]
Q_{Mi} = Inflow of groundwater to moraine [m^3/a]
V_M = Volume of water in the moraine [m^3]
R = Retention [see above]

$$Tc_{\text{limestone to riv. Pösan}} = (Q_T \cdot (1 - F_M) \cdot F_L + Q_{Li})/(V_L \cdot R)$$

where

Q_{Li} = Inflow of groundwater to limestone aquifer [m^3/a]
V_L = Volume of water in the limestone aquifer [m^3]
R = Retention [see above]

$$Tc_{\text{Pösan to Flian}} = Q_P/V_P$$

where

Q_P = Flow from river Pösan to river Flian [m^3/a]
V_P = Mass of water in Pösan [m^3]

$$Tc_{\text{lake to sediment}} = (Kd_L \cdot S)/(Depth \cdot (1+Kd_L \cdot Susp))$$
$$Tc_{\text{lake to riv. Flian}}\ A = Q_L/V_L$$

where

Q_L = Outflow from the lake [m^3/a]
V_L = Volume of the lake [m^3]

Outflow from river Flian is

$$Tc_{\text{Flian to out}} = Q_F/V_F$$

where

Q_F = Flow from river Flian [m^3/a]
V_F = Volume of water in Flian [kg]
Qbill = Inflow of groundwater to limestone [m^3/a]
Ymass(4) = Mass of water in the limestone [kg]
RetL = 1 + (1-PorL)/(PorL · Kds · Dens)

Sedimentation

$$Tc_{\text{lake to sediment}} = (Kd_L \cdot S)/(Depth \cdot (1+Kd_L \cdot Susp))$$

where

Kd_L = Distribution factor between solid and soluble fraction in the lake water [kg/m^3]
S = Sedimentation rate in the lake [kg/[m^2·a]]
Depth = Mean depth of the lake [m]
Susp = Suspended material in the lake [kg/m^3]

Resuspension

$$Tc_{\text{sediment to lake}}\ A = \text{Resusp}$$

where

Resusp = Resuspension from sediment to water body [1/a]

Calculation of nuclide concentration in different media

The calculation of nuclide concentration in different media is made by dividing the inventory by the mass or volume for each media considered.

$$C_W = \text{Inventory(water)/Mass(water) [Bq/kg]}$$

where

Inventory(water) = Inventory in water, given by the compartment model [Bq]
Mass(water) = Mass of water [kg]

Intake and dose assessment

The exposure pathways considered are consumption of groundwater from the limestone aquifer, consumption of fish from the M-lake as well as milk and meat from cattle drinking the water from the river Flian. The intake assessment is based on the concentration in the water in respectively aquifer which is obtained from the expression above.

The expressions for intake and dose then becomes:

$$I_{\text{water individua}} = C_{\text{lime}} \cdot \text{ConWater}$$

$$I_{\text{water collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConWater} \cdot \text{Pop}$$

$$D_{\text{water individual}} = C_{\text{lime}} \cdot \text{ConWater} \cdot \text{DosFactIng}$$

$$D_{\text{water collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConWater} \cdot \text{DosFactIng} \cdot \text{Pop}$$

where

C_{lime} = Concentration in water in the limestone aquifer [kg/m^3]
ConWater = Human consumption of water [m^3/a]
T = Time period for collective dose integration [a]
Pop = Population [-]

DosFactIng = Dose factor for ingestion [Sv/Bq]

$$I_{\text{fish individual}} = C_{\text{lake}} \cdot \text{ConFish} \cdot \text{Cf-fish}$$

$$I_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConFish} \cdot \text{Cf-fish} \cdot \text{Pop}$$

$$D_{\text{fish individual}} = C_{\text{lake}} \cdot \text{ConFish} \cdot \text{DosFactIng} \cdot \text{Cf-fish}$$

$$D_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConFish} \cdot \text{Bf-Fish} \cdot \text{DosFactIng} \cdot \text{Pop}$$

where

C_{Lake} = Concentration in the lake water [kg/m^3]
ConFish = Human consumption of fish [kg/a]
Cf-fish = Concentration factor water to fish [m^3/kg]

$$I_{\text{milk individual}} = C_{\text{Flian}} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk}$$

$$I_{\text{milk collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk} \cdot \text{Pop}$$

$$D_{\text{milk individual}} = C_{\text{Flian}} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk} \cdot \text{DosFactIng}$$

$$D_{\text{milk collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk} \cdot \text{DosFactIng} \cdot \text{Pop}$$

where

C_{Flian} = Concentration in water of river Flian [kg/m^3]
ConMilk = Human consumption of milk [m^3/a]
Df-milk = Distribution factor to milk [a/m^3]
KoConWa = Cow consumption of water [m^3/a]

$$I_{\text{meat individual}} = C_{\text{Flian}} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat}$$

$$I_{\text{meat collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat} \cdot \text{Pop}$$

$$D_{\text{meat individual}} = C_{\text{Flian}} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat} \cdot \text{DosFactIng}$$

$$D_{\text{meat collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat} \cdot \text{DosFactIng} \cdot \text{Pop}$$

where

ConMeat = Human consumption of meat [kg/a]
Df-meat = Distribution factor to meat [a/kg]

Dose calculations for the different restoration techniques

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

The results of the committed collective intakes and doses are shown in Tables D.4 – D.7.

Table D.1 General parameters and values for the model of Ranstad tailing.

	Unit	Type of Distribution	Mean	Min	Max
Leakage from solid to soluble	1/a	C	0.005		
Fraction of flow in tailing to moraine	-	C	0.5		
Fraction of leakage flow from moraine to limestone	-	C	0.87		
Area of the tailing	m^2	C	2.5E5		
Porosity of tailing	-	C	0.3		
Porosity of moraine	-	C	0.2		
Porosity of limestone	-	C	0.05		
Height of cover	m	C	2		
Height of tailing	m	T	6	5	7
Height of moraine	m	T	12	10	14
Height of limestone	m	T	30	20	50
Flow through the tailing	m^3/a	T	1.3E5	1.2E5	1.4E5
Flow from moraine to limestone	m^3/a	LT	5.7E4	5.7E3	5.7E5
Flow from moraine to ditch	m^3/a	LT	8.5E3	8.5E2	8.5E4
Flow from ditch to M-lake	m^3/a	LT	7.4E4	7.4E3	7.4E5
Flow from M-lake	m^3/a	LT	4.7E5	2.5E5	9.0E5
Flow from river Flian	m^3/a	LT	7.9E7	2.0E7	2.0E8
Flow from river Pösan to Flian	m^3/a	LT	1.6E7	5.0E6	5.0E7
Inflow of groundwater to moraine	m^3/a	LT	3.5E5	2.0E5	9.0E5
Inflow of groundwater to limestone	m^3/a	LT	3.2E5	2.0E5	1.0E6
Resuspension in M-lake	1/a	T	0.01	0.005	0.03
Sedimentation rate M-lake	$kg/(m^2 \cdot a)$	T	0.36	0.25	0.5
Depth of M-lake	m	T	1.5	1.3	1.7
Suspension M-lake	kg/m^3	LT	0.03	0.02	0.05
Density	kg/m^3	LT	2650	2150	3100

Table D.2 Nuclide specific parameters.

Description	Unit	Distr.	Nuclide	Best estimate	Min or Std*	Max
Kd in soil	m^3/kg	LN	Mn	0.001	2	
			Ni	0.05	2	
			U	0.015	2	
Kd, water-sediment	m^3/kg	LN	Mn	20	2	
			Ni	10	2	
			U	2	2	
Distribution factor to milk	a/m^3	LT	Mn	3.0E-4	1E-4	1E-3
			Ni	2.6E-3	1.9E-4	0.019
			U	3.7E-3	1.5E-4	0.01
Distribution factor to meat	a/kg	LT	Mn	5.0E-4	1E-4	1E-3
			Ni	7.3E-4	7.3E-5	7.3E-4
			U	3.4E-4	5E-5	1E-3
Concentration factor to fish	m^3/kg	LT	Mn	0.1	0.03	0.3
			Ni	0.1	0.03	0.3
			U	0.1	0.03	0.3

* Geometric standard deviation.

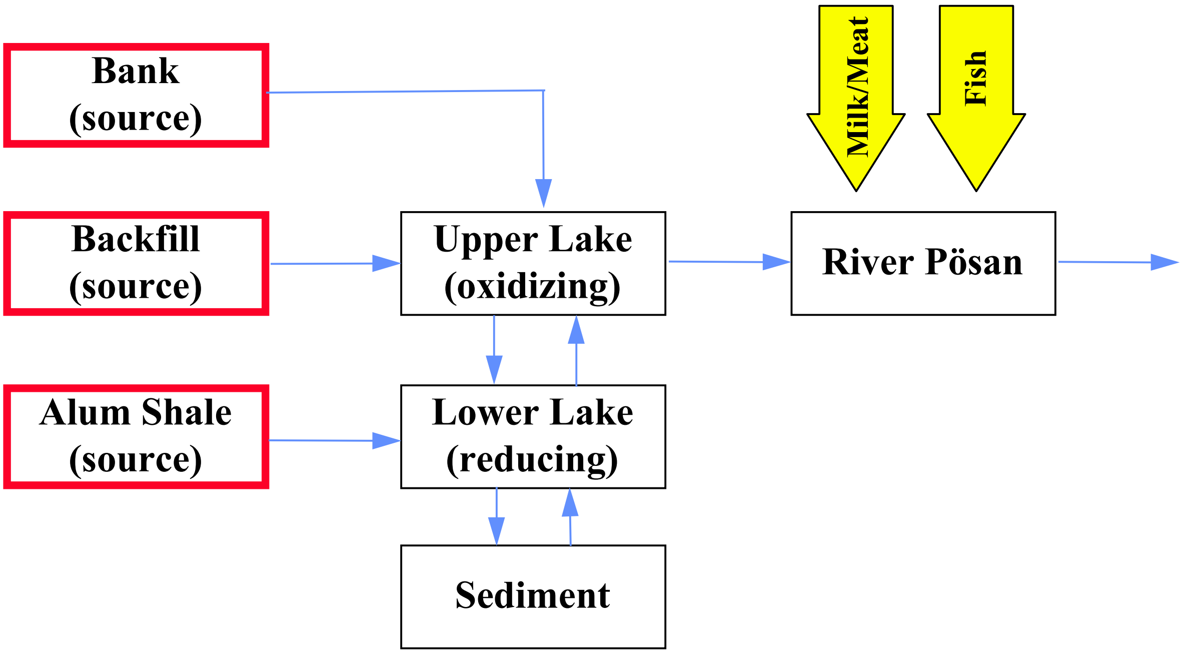
Table D.3 Consumption data used in the dose assessment.

Description	Unit	Distr	Best estimate	Min	Max
Population	-	C	25		
Human consumption of					
- water	m^3/a	T	0.73	0.66	0.8
- fish	kg/a	T	70	16	24
- milk	m^3/a	T	0.33	0.3	0.36
- meat	kg/a	T	95	85	105
Intake of water by cattle	m^3/a	T	32.8	25.8	39.8

Appendix E – Tranebärssjön

In this appendix transfer coefficients, used for turnover of radionuclides and dose/intake assessment for the lake Tranebärssjön scenario, are given aswell as parameter values used in the assessment. The compartment scheme for lake Tranebärssjön site is based on site description given in Stiglund, (1999).

The compartment scheme is shown below.



Transfer coefficients within the lake

The water of the lake is divided into two compartments, surface water and deep water, which are divided by the thermocline. In the model there will be a complete mixing two times a year (spring and autumn) between these. There will be no exchange in spite of the sedimentation process from surface water to deep water.

Expressions of transfer coefficients (T_c) used in the compartment model are given below. Values of the parameters in the calculations are shown below.

Sedimentation

The transfer coefficients describing the transport of nuclides from water to sediment depend on physical-chemical properties of the element. For the transfer coefficient (Tc_{ws}) describing the transport of radionuclides from water to sediment the following expression was used (Hill et al, 1980):

$$Tc_{ws} = Kd_s \cdot S \cdot (h_m \cdot (+ K_d \cdot SS))^{-1}$$

where

Kd_s = Distribution coefficient water to sediment, concentration in solid/concentration in liquid [m^3/kg]

S = Sedimentation growth rate [kg/m^2·a]

h_m = Mean depth of the water body [m]

SS = Concentration of suspended matter in the water [kg/m^3]

This expression will be used for the transfer from surface water to deep water and for deep water to sediment. The sediments above the thermocline are assumed to be erosion or transport bottoms with short residence time and therefore neglected in the model.

Resuspension

$$Tc_{\text{sediment to lake}}\ A = \text{Resusp}$$

where

Resusp = Resuspension from sediment to water body [1/a]

Outflow

The transfer coefficient for the outflow from the lake is set to be the same as the outflow of water, same principle is used for the river were the flow is used. The transfer coefficient for the outflow then becomes:

$$Tc_{\text{L to R}} = Q_L \cdot V_L$$

$$Tc_{\text{R ro O}} = Q_R \cdot V_R$$

where

Q = Outflow from the lake or flow in the river [m^3/a]
V = Volume of the lake or a section of the river [m^3]

Data used in the calculations are given in Tables E.1 and E.2.

Calculation of nuclide concentration in different media

The calculation of nuclide concentration in different media is made by dividing the inventory by the mass or volume for each media considered.

$$C_W = \text{Inventory(water)/Mass(water) [Bq/kg]}$$

where

Inventory(water) = Inventory in water, given by the compartment model [Bq]
Mass(water) = Mass of water [kg]

Intake and dose assessment

The exposure pathways are calculated based upon the concentration in water. Steady state can be assumed to be valid for the biological processes during the time considered. The water bodies in this case is the river Pösan

The concentration in water is the outcome of the compartment model described above. The expressions for intake and dose then becomes:

$$I_{\text{fish individual}} = C_{\text{river}} \cdot \text{ConFish} \cdot \text{Cf-fish}$$

$$I_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{FishProd} \cdot \text{Cf-fish}$$

$$D_{\text{fish individual}} = C_{\text{river}} \cdot \text{ConFish} \cdot \text{DosFactIng} \cdot \text{Cf-fish}$$

$$D_{\text{fish collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{FishProd} \cdot \text{Bf-Fish} \cdot \text{DosFactIng}$$

where

C_{river} = Concentration in water of river Flian [kg/m^3]
ConFish = Human consumption of fish [kg/a]
T = Time period for collective dose integration [a]
FishProd = Total catch of fish in river [kg/a]
DosFactIng = Dose factor for ingestion [Sv/Bq]
Cf-fish = Concentration factor water to fish [m^3/kg]

$$I_{\text{milk individual}} = C_{\text{river}} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk}$$

$$I_{\text{milk collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{MilkProd} \cdot \text{KoConWa} \cdot \text{Df-milk}$$

$$D_{\text{milk individual}} = C_{\text{Flian}} \cdot \text{ConMilk} \cdot \text{KoConWa} \cdot \text{Df-milk} \cdot \text{DosFactIng}$$

$$D_{\text{milk collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{MilkProd} \cdot \text{KoConWa} \cdot \text{Df-milk} \cdot \text{DosFactIng}$$

where

ConMilk = Human consumption of milk [m^3/a]
KoConWa = Cow consumption of water [m^3/a]
Df-milk = Distribution factor to milk [a/m^3]
MilkProd = Milk production from cows in the area [m^3/a]

$$I_{\text{meat individual}} = C_{\text{Flian}} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat}$$

$$I_{\text{meat collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{MeatProd} \cdot \text{KoConWa} \cdot \text{Df-meat}$$

$$D_{\text{meat individual}} = C_{\text{Flian}} \cdot \text{ConMeat} \cdot \text{KoConWa} \cdot \text{Df-meat} \cdot \text{DosFactIng}$$

$$D_{\text{meat collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{MeatProd} \cdot \text{KoConWa} \cdot \text{Df-meat} \cdot \text{DosFactIng}$$

where

ConMeat = Human consumption of meat [kg/a]
Df-meat = Distribution factor to meat [a/kg]
MeatProd = Production of meat from cows in the area [kg/a]

$$I_{\text{pork individual}} = C_{\text{Flian}} \cdot \text{ConPork} \cdot \text{KoConWa} \cdot \text{Df-pork}$$

$$I_{\text{pork collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{PorkProd} \cdot \text{KoConWa} \cdot \text{Df-pork}$$

$$D_{\text{pork individual}} = C_{\text{Flian}} \cdot \text{ConPork} \cdot \text{KoConWa} \cdot \text{Df-pork} \cdot \text{DosFactIng}$$

$$D_{\text{pork collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{PorkProd} \cdot \text{KoConWa} \cdot \text{Df-pork} \cdot \text{DosFactIng}$$

where

ConPork = Human consumption of pork [kg/a]
Df-pork = Distribution factor to pork [a/kg]
PorkProd = Production of meat from porks in the area [kg/a]

$$I_{\text{sheep individual}} = C_{\text{Flian}} \cdot \text{ConSheep} \cdot \text{KoConWa} \cdot \text{Df-sheep}$$

$$I_{\text{pork collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{SheepProd} \cdot \text{KoConWa} \cdot \text{Df-sheep}$$

$$D_{\text{pork individual}} = C_{\text{Flian}} \cdot \text{ConSheep} \cdot \text{KoConWa} \cdot \text{Df-sheep} \cdot \text{DosFactIng}$$

$$D_{\text{pork collective}} = \sum_{i=1}^{T} C_{w,i} \cdot \text{SheepProd} \cdot \text{KoConWa} \cdot \text{Df-sheep} \cdot \text{DosFactIng}$$

where

ConSheep = Human consumption of sheep [kg/a]
Df-sheep = Distribution factor to sheep [a/kg]
SheepProd = Production of meat from sheep in the area [kg/a]

Dose calculations for the different restoration techniques

The effects of different restoration techniques are mainly given by different Df-factors, decontamination factors. The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping and subsurface barriers are considered, so for these restoration techniques the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system/barriers.

The results of the committed collective doses are shown in Tables E.5 – E.6.

Parameter values

Table E.1 Generic parameter to model of lake Tranebärssjön, type of distribution and mean, max and min values used in the uncertainty analysis.

Parameter	Unit		Mean	Min	Max
Lake area	m^2	T	2.7E5	2.6E5	2.8E5
Lake volume	m^3	T	1.2E6	1.1E6	1.3E6
Depth of thermocline in lake	m	T	9	8	10
Outflow from lake	litre/sec	T	27	25	30
Flow in river Pösan	litre/sec	T	80	50	100
Groundwater growth rate	litre/km^2,	T	10	5	15
Area	km^2	T	3	2.5	3.5
Fraction of inflow water via alumshale	-	T	0.01	0.005	0.015
Fraction of inflow water via backfill	-	T	0.5	0.4	0.6
Volume of bank	m^3	T	1.0E6	0.5E6	1.5E6
Depth of bank	m	T	5	4	6
Porosity in bank	-	T	0.3	0.25	0.35
Density of bank	kg/m^3	T	2400	2200	2600
Depth of alumshale	m		0.2	0.1	0.5
Porosity in alumshale	-	T	0.1	0.05	0.15
Density of alumshale	kg/m^3	LT	2400	2200	2600
Backfill volume	m^3	T	3.0E6	2.5E6	3.3E6
Backfill porosity	-	LT'	0.3	0.25	0.35
Backfill density	kg/m^3	LT	2400	2200	2600
Sedimentation rate in lake	$kg/m^2 \cdot a$	LT	2	1	5
Content of suspended matter in lake	kg/m^3		0.02	0.001	0.05
Resuspension from bottom sediments	1/a	LT	0.5	0.01	0.8

Table E.2 Parameter dependent of parameter for manganese, nickel and uranium.

Parameter	Unit			Mean	Min	Max
Kd in lake	m^3/kg	LN	Mn	20	-	-
			Ni	10	-	-
			U	2	-	-
Kd in soil	m^3/kg	LN	Mn	0.001	-	-
			Ni	0.05	-	-
			U	0.015	-	-
Concentration in backfill	kg/kg	T	Mn	5.0E-5	1E-5	4E-4
			Ni	4.0E-5	1E-5	1E-4
			U	6.0E-5	2E-5	1E-4
Concentration in bank	kg/kg		Mn	5.0E-5	1E-5	4E-4
			Ni	4.0E-5	1E-5	1E-4
			U	6.0E-5	2E-5	1E-4
Concentration in alumshale	kg/kg	T	Mn	2.5E-4	1E-4	4E-4
			Ni	2.0E-4	1E-4	3E-4
			U	3.0E-4	2E-4	4E-4
Background concentration in groundwater	ppm	T	Mn	1000	900	11000
			Ni	5	4	6
			U	1	0.5	1.5
Background concentration in river Pösan	ppm	T	Mn	100	50	150
			Ni	2	1	3
			U	1	0.5	1.5

Table E.3

Parameter	Unit		Mean	Min	Max
Cattle's consumption of water	litre/day	T	100	50	150
Cattle's consumption of pasturage	kg d.w./day	T	10	5	15
Pork consumption of water	litre/day	T	8	6	10
Sheep consumption of water	litre/day	T	4	3	5
Consumption of water	litre/a	T	600	400	800
Consumption of fish	kg/a	T	20	16	24
Consumption of milk	litre/a	T	400	250	550
Consumption of meat	kg/a	T	75	50	100
Fish catch in the river	kg/a	T	100	50	150
Milk production in the area		T	1.1E5	1.0E5	1.2E5
Meat production in the area	kg/a	T	9.9E3	9.8E3	1.0E4
Pork production in the area	kg/a	T	6.4E3	6.3E3	6.5E3
Mutton production in the area	kg/a	T	2.1E2	2.0E2	2.2E2

Table E.4

Parameter	Unit			Mean	Min	Max
Distribution factor to milk	day/litre	LT	Mn	2.5E-4	2E-5	3E-3
			Ni	0.02	2E-3	0.2
			U	4.0E-4	4E-5	4E-3
Distribution factor to meat	day/litre	LT	Mn	8.0E-4	8E-5	8E-3
			Ni	5.0E-3	5E-4	0.05
			U	3.0E-4	3E-5	3E-3
Concentration factor to fish	kg/kg	LT'	Mn	100	10	1000
			Ni	100	10	1000
			U	10	2	50

Appendix F – Dose assessment with site-specific Kd-values

The results of the dose assessment given in the main report are obtained using litterature based distribution coefficients. Within the RESTRAT project also site specific Kd-values have been determined (Brendler, 1999).

Additional dose assessments were performed with the site specific Kd-values (Table F.1). For the literature-based Kd values, log-triangular distributions were applied, for the site-specific Kd values, log-normal distributions were obtained.

The dose assessments were performed for Molse Nete river, Drigg and Ranstad tailing site. The collective doses to the public, integrated over 100 years without any restoration measure implemented (case A), were calculated with the site-specific Kd -values and compared to the results obtained with the literature-based Kd- values.

Table F.1 Literature-based and site-specific distribution coefficients (Kd) (m^3/kg).

Site and nuclide	Literature-based data			Site specific data		
	Mean	Low	High	Mean	Log Mean	Std of log
River Mol						
Co-60	20	5	100	0.41	-0.38	0.18
Pu-239	250	100	1000	17	1.23	0.12
Am-241	1000	100	2000	310	2.49	0.09
Drigg						
U-238, drain	0.1	0.01	1	3.63	0.56	0.33
U-238, stream	10	1	100	17	1.23	0.48
Pu-239, drain	2	0.01	100	87	1.94	0.12
Pu-239, stream	100	1	600	240	2.38	0.19
Am-241, drain	6	0.001	50	26	1.42	0.30
Am-241, stream	100	1	600	32	1.49	0.26
Ranstad tailing, U-238						
Tailing layer	0.015*	0.002	0.1	0.034	-1.47	0.35
Moraine layer	0.015*	0.002	0.1	0.29	-0.54	0.26
Limestone layer	0.015*	0.002	0.1	0.0023	-2.63	0.31
Storage pond	2	0.2	20	59	1.77	0.19

* One single parameter was used in the model.

Molse Nete river results

In Figure F.1 the collective doses to the public, truncated at 100 year, with 5th and 95th percentiles are shown. In Table F.2 the main parameters contributing significantly to the uncertainty, are given.

For the Molse Nete river, no significant difference has been observed between the dose values, due to the fact that only site-specific Kd values were available for the river water and not for the soil, which is the main source for human exposure (through root uptake of various crops) at that site.

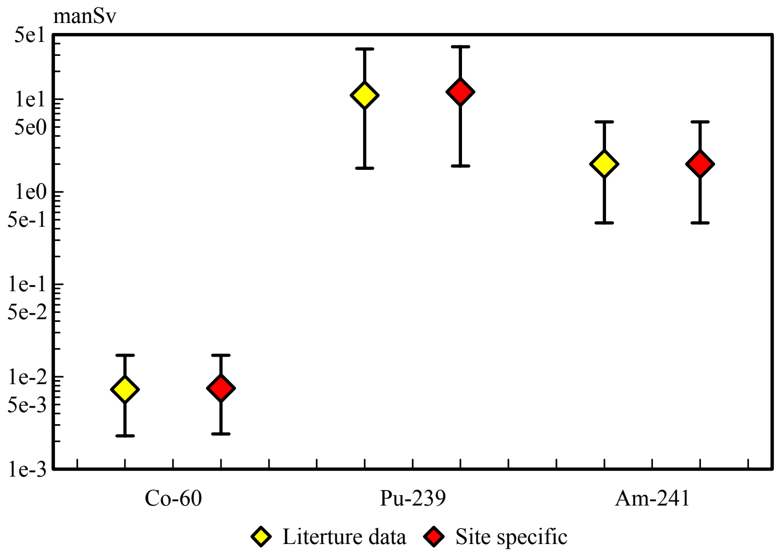


Figure F.1 Collective dose (manSv) to the public at Molse Nete river site truncated at 100 year, with Kd-values from literature and from site specific calculations.

Table F.2 The contribution of main parameters to the overall uncertainty in the collective dose (%) at Molse Nete river site site using ranked regression. (Parameter values are given in Appendix A)

Parameter	Co-60	Pu-239	Am-241
Transfer factor soil to root crops	53	96	89
Transfer factor soil to tubers	18	<1	1
Transfer factor soil to vegetables	9	<1	3
Yield of root crops	1	2	1

Drigg results

In Figure F.2 the collective doses to the public, truncated at 100 year, with the 5th and 95th percentiles are shown. In Table F.3 the main parameters, contributing significantly to the uncertainty, are given.

For the Drigg site, the dose values calculated with the site-specific Kd values are considerably lower than those calculated with the literature-based Kd values. This was due to the fact that the site-specific Kd values for soil (Kd drain) are higher than the ones derived from the literature. For the litterature based values wide ranges were used, especially for Pu-239 and Am-241, down to very low values (associated with high dose values).

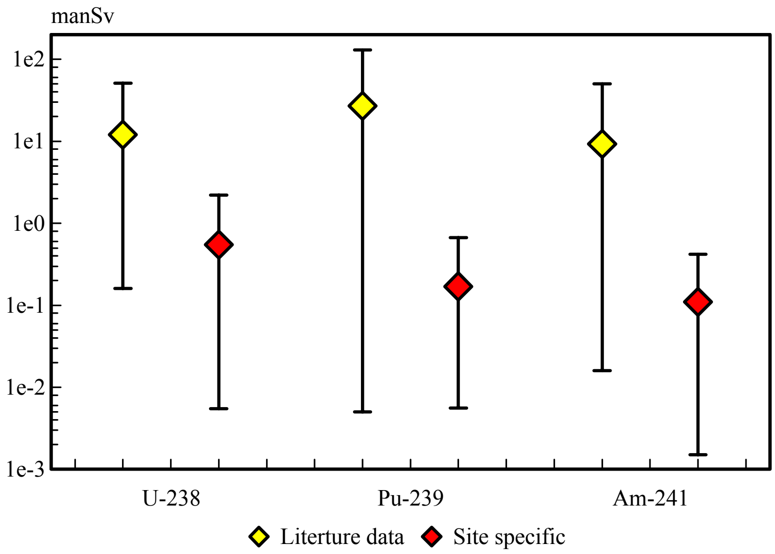


Figure F.2 Collective dose (manSv) to the public at Drigg site, truncated at 100 year, with Kd-values from literature and from site specific calculations.

Table F.3 The contribution of main parameters to the overall uncertainty in the collective dose (%) at Drigg site using ranked regression. (Parameter values are given in Appendix B).

Parameter	U-238		Pu-239		Am-241	
	Lite.	Site sp.	Lite.	Site sp.	Lit.	Site sp.
Kd-drain	18	17	69	3	64	15
Inventory in trenches	30	26	2	5	9	19
Flow of water from trenches to drain	18	26	13	43	10	30
Outflow from Drigg stream	28	25	13	43	13	30

Ranstad

In Figure F.3 the collective doses to the public, truncated at 100 year, with the 5th and the 95th percentiles are shown. In Table F.4 the main parameters, which significantly contribute to the uncertainty, are given.

For the Ranstad tailing site the dose values calculated with the site-specific Kd values are considerably higher than the dose values calculated with the literature-based Kd values. This is due to the low site-specific Kd values in the limestone aquifer with respect to the ones derived from the literature, leading to higher radionuclide concentrations in this aquifer. Since one of the major exposure pathways is considered to be consumption of water taken from the limestone aquifer, the resulting dose to man is higher for the site-specific conditions.

With site specific Kd-values the intake of water totally dominates the dose (more than 99%) while in the other case the consumption of fish is responsible for several percents of the total dose. This also explains the higher contribution to the uncertainty due to the concentration factor to fish for the literature-based case. The model for the Ranstad tailing site was increased with two parameters for the site-specific Kd calculation, three different parameters for the Kd values in each layers in the ground. In the litterature-base case one common Kd was used for all three layers.

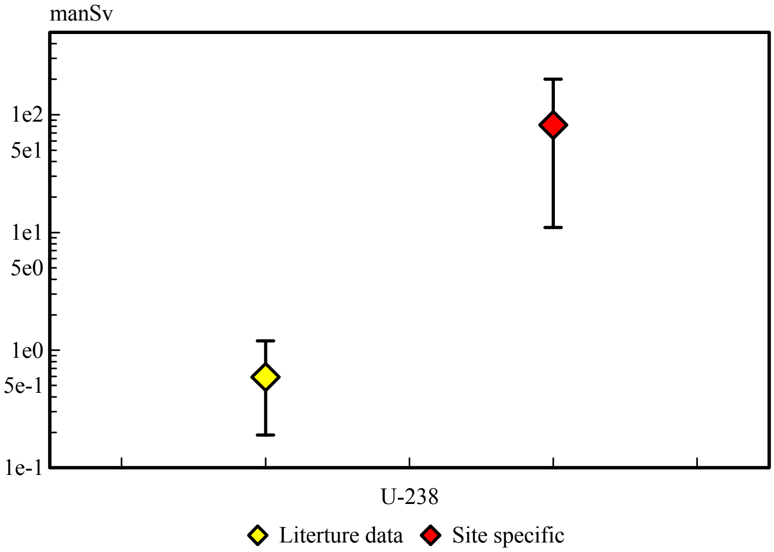


Figure F.3 Collective dose (manSv) to the public at Ranstad tailing site truncated at 100 year, with Kd-values from literature and from site-specific calculations.

Table F.4 The contribution of main parameters to the overall uncertainty in the collective dose (%) at the Ransatd tailing site using ranked regression. (Parameter values are given in Appendix D).

Parameter	Literature	Site specific
Kd in soil	80(1)	27(2)
Flow water from moraine to limestone layer	<1	64
Depth of limestone layer	9	4
Concentration factor to fish	5	<1

1 In the model one single parameter for all ground layers in the was used.
2 Kd in the limestone layer.

References

Brendler V, 1999, Physico-chemical phenomena governing the behaviour of radioactive substances. Site-specific characteristics. RESTRAT-TD.5.