IAEA-BIOMASS-7

Testing of environmental transfer models using data from the remediation of a radium extraction site

Report of the Remediation Assessment Working Group of BIOMASS Theme 2

March 2004

IAEA
International Atomic Energy Agency

The originating Section of this publication in the IAEA was:

Waste Safety Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

TESTING OF ENVIRONMENTAL TRANSFER MODELS USING DATA FROM THE
REMEDIATION OF A RADIUM EXTRACTION SITE
IAEA, VIENNA, 2004
ISBN 92–0–109103–6

Printed by the IAEA in Austria
March 2004

FOREWORD

The IAEA Programme on *BIO*sphere *M*odelling and *ASS*essment (BIOMASS) was launched in Vienna in October 1996. The programme was concerned with developing and improving capabilities to predict the transfer of radionuclides in the environment. The programme had three themes:

Theme 1: Radioactive Waste Disposal. The objective was to develop the concept of a standard or reference biosphere for application to the assessment of the long-term safety of repositories for radioactive waste. Under the general heading of "Reference Biospheres", six Task Groups were established:

Task Group 1: Principles for the Definition of Critical and Other Exposure Groups.

Task Group 2: Principles for the Application of Data to Assessment Models.

Task Group 3: Consideration of Alternative Assessment Contexts.

Task Group 4: Biosphere System Identification and Justification.

Task Group 5: Biosphere System Descriptions.

Task Group 6: Model Development.

Theme 2: Environmental Releases. BIOMASS provided an international forum for activities aimed at increasing the confidence in methods and models for the assessment of radiation exposure related to environmental releases. Two Working Groups addressed issues concerned with the reconstruction of radiation doses received by people from past releases of radionuclides to the environment and the evaluation of the efficacy of remedial measures.

Theme 3: Biosphere Processes. The aim of this Theme was to improve capabilities for modelling the transfer of radionuclides in particular parts of the biosphere identified as being of potential radiological significance and where there were gaps in modelling approaches. This topic was explored using a range of methods including reviews of the literature, model inter-comparison exercises and, where possible, model testing against independent sources of data. Three Working Groups were established to examine the modelling of: (1) long-term tritium dispersion in the environment; (2) radionuclide uptake by fruits; and (3) radionuclide migration and accumulation in forest ecosystems.

This report describes results of the studies undertaken by the Remediation Assessment Working Group under Theme 2. The participants are listed at the end of the publication. The Working Group Leader Ms. Lieve Sweeck (Belgium) was responsible for drafting the main text of the report and was assisted by Mr. Theo Zeevaert (Belgium). The IAEA Scientific Secretary for this publication was initially K.-L. Sjoeblom and subsequently C. Robinson of the Division of Radiation and Waste Safety.

CONTENTS

SUMMARY

This BIOMASS Theme 2 report has been produced by the Remediation Working Group. The main aim of this group was to test the accuracy of predictions of environmental assessment models that form part of the assessment of the radiological impact of remediation decisions. The other aspects of such decisions, such as the technical feasibility, economic and social factors were beyond the scope of this group.

Two scenarios were constructed and applied based on the contamination around the site of a former radium extraction plant in Olen, Belgium, which arose due the discharge of liquid effluents into a local brook; waste disposal practices and the use of waste material as a road surfacing material. This group considered the situation in an area of approximately 100 ha, contaminated as a result of the frequent flooding of a local river and the dredging of bed sediment out of the river onto the riverbanks. The results of a number of environmental surveys in this area were available, giving modellers the opportunity to compare model predictions with actual measurements in the first scenario (known as Type A). The second scenario (Type B) was hypothetical. It was designed to allow modellers to consider the impact of possible future remediation actions, based on input data for a real site.

Olen Scenario Type A considered the influence of a past remedial action, particularly the effect of deep ploughing of land subsequently used as pasture for dairy cows. Five modellers submitted results. The effects on radium concentrations in cow's milk during the period 1971–1972 were assessed and compared with post-remediation measurements. Simplified modelling approaches were used to assess the impact of deep ploughing, partly due to the lack of information on the radium heterogeneity in soil as a function of depth, partly because of the lack of information on the technical details of the deep ploughing. The radium concentration in milk was in general overestimated by around one order of magnitude, but the observed values were usually within the confidence interval of predicted values.

Differences between model predictions were mainly due to differences in user interpretation of the scenario description. The main sources of uncertainty were the radium distribution in the root zone before deep ploughing and the effectiveness of deep ploughing.

Olen scenario Type B considered the effectiveness of potentially feasible remedial actions on the doses experienced by the local population. Two possible remedial actions were identified; the removal of surface soil in the most contaminated areas and the covering with a clean soil layer. The aim of the scenario was to assess the possible influence of these remediation measures on the radiological impact to the local population. The model predictions from six participants were compared with one another. From the analysis of the model predictions, it was derived that rather the different interpretations of the scenario than the differences in modelling approaches were responsible for the differences among the model predictions.

The calculation of the radon concentration in- and outdoors and the lead concentration in soil were the main challenges. There are several parameters that influence radon concentrations in- and outdoors, for example, the current state of buildings, the ventilation rate, the type of soil, the homogeneity of the soil, and differences in treatment of these factors may lead to very different results.

1. INTRODUCTION

1.1. BACKGROUND AND OVERALL OBJECTIVES OF BIOMASS

BIOMASS (*BIO*sphere *M*odelling and *ASS*essment Methods) is the fourth in a series of international programs aimed at the improvement of methods for assessing the impact of radionuclides in the environment; the first three were the VAMP program, sponsored by the International Atomic Energy Agency (IAEA), and BIOMOVS (*BIO*spheric *MO*del *V*alidation *S*tudy) Phases I and II, supported by organisations from Canada, Spain and Sweden. These programs have served to provide forums to promote international collaboration, information exchange, and peer review in the area of modelling and assessment of the movement of radionuclides and other pollutants in the environment.

The scope of the BIOMASS program is the scientific, experimental, and technical aspects related to the analysis and assessment of the behaviour of radionuclides in the environment and their associated impacts. Special emphasis is being placed on the improvement of the accuracy of model predictions, on the improvement of modelling techniques, and on the promotion of experimental activities and field data gathering to complement assessments.

The program is designed to address important radiological issues associated with accidental and routine releases and with solid waste management. Three important areas involving environmental assessment modelling are being covered: Theme 1, Radioactive waste disposal (emphasis on reference biospheres); Theme 2, Environmental Releases (including remediation of areas contaminated as a result of nuclear accidents, unrestricted releases or poor management practices, and reconstruction of radiation doses received due to accidental or poorly controlled releases); and Theme 3, Biosphere Processes (current emphases on tritium fruit trees, and forests).

The general goals of the BIOMASS program can be summarised as follows:

(1) To provide an international focal point in the area of biospheric assessment modelling for the exchange of information and in order to respond to biospheric assessment needs expressed by other international groups (within and outside IAEA).

(2) To develop methods (including models, computer codes and measurement techniques) for the analysis of radionuclide transfer in the biosphere for use in radiological assessments.

(3) To improve models and modelling methods by model testing, comparison and other approaches.

(4) To develop international consensus, where appropriate, on biospheric modelling philosophies, approaches, and parameter values.

1.2. THEME 2: ENVIRONMENTAL RELEASES

Theme 2 of BIOMASS, Environmental Releases, focuses on issues of dose reconstruction and remediation assessment. Many national agencies and authorities have a growing interest in:

- addressing concerns about the effects of historic releases, both planned and accidental;
- gaining information to improve understanding of processes of migration, accumulation, exposure and exposure consequences;

- making better informed decisions about remediation requirements at contaminated sites, through the assessment of future impacts; and
- guiding decisions on alternative technologies and techniques available for remediation of contaminated sites.

Dose reconstruction and evaluation of remediation alternatives both involve assessment of radionuclide releases to the environment. Such assessments make use of a great variety of information gained from site characterisation studies, source term evaluation, and so on. Ultimately, however, this information has to be combined in some sort of assessment model involving assumptions about how the system has behaved (or will behave). Mathematical modelling of this type is required because it is simply not possible today to measure directly what has happened in the past or what will happen in the future.

The overall objective of BIOMASS Theme 2 is to provide an international forum to increase the credibility of and confidence in methods and models for the assessment of radiation exposure in the context of dose reconstruction and remediation activities. Consideration is being given to assessment of concentrations of radionuclides in relevant environmental media and the associated radiation doses and risks to humans.

Secondary objectives of BIOMASS Theme 2 include the following:

(1) To provide a forum for review, independent scrutiny and intercomparison of methods and models used in dose reconstruction and remediation assessment.

(2) To provide a forum for model testing, and where possible, validation.

(3) To develop the consideration and presentation of conceptual and parameter uncertainties within dose reconstruction and remediation assessment.

(4) To test the transparency and adequacy of modelling assumptions in the context of specified assessment objectives.

(5) To identify assessment shortcomings in terms of model structure and data and hence identify critical research areas.

(6) To identify those components of assessment assumptions that are arbitrary, matters of policy, or simple value judgements, as opposed to those which are objectively verifiable.

Two Working Groups have been established within BIOMASS Theme 2:

(1) Working Group 1 is concerned with the evaluation of the reliability of methods used for dose reconstruction for specific individuals and members of specific population subgroups.

(2) Working Group 2 is concerned with the evaluation of the reliability of dose and risk assessment methodologies applied in support of decisions to determine the cost-effectiveness of risk-reduction measures within an environmental remediation programme.

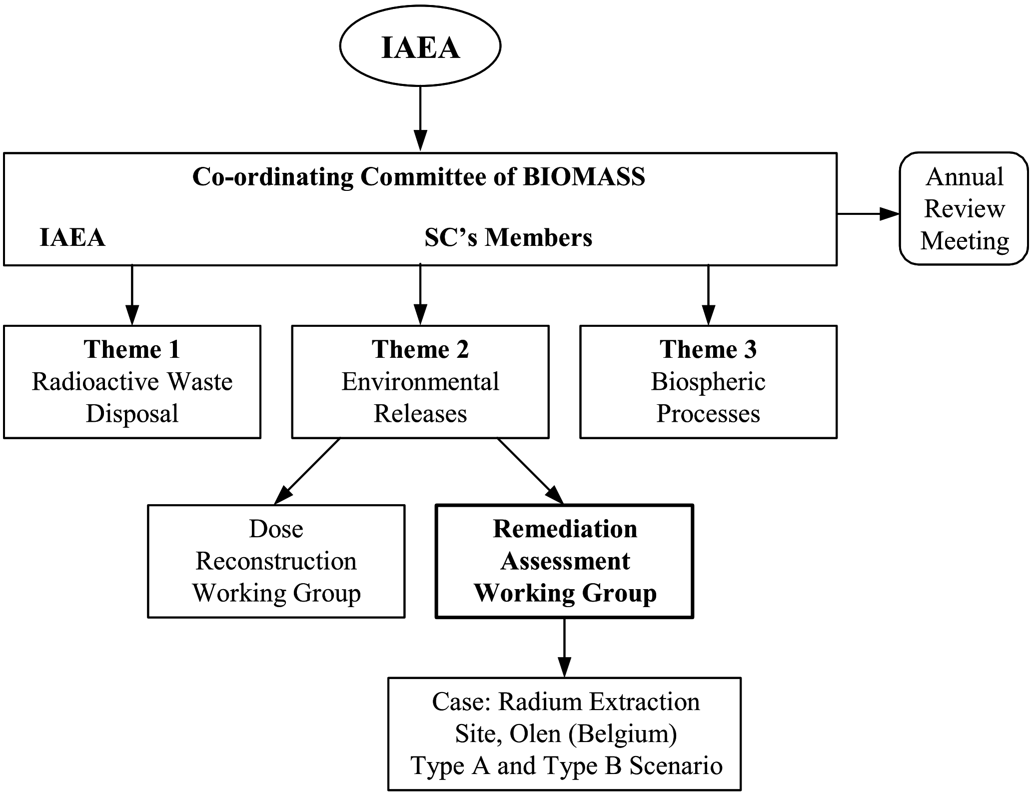


FIG. 1. Position of the remediation assessment working group in organisational structure of BIOMASS.

1.3. REMEDIATION ASSESSMENT WORKING GROUP: AIMS AND POSITION WITHIN BIOMASS

The major aim of the remediation assessment working group is to test the accuracy of predictions of environmental assessment models when remedial actions are involved and to enhance the confidence in the models.

The selection of an appropriate remediation technique is a quite complicated decision because several factors such as the radiological relevance, technical feasibility, economical costs, social factors have to be taken into account. In this study, the radiological impact is the primary criterion and the reliability of assessment models as decision-aiding tools will be evaluated.

The effectiveness of the remedial actions will be assessed in terms of dose savings, whereby the influence of remedial actions on the radiological impact is to be expressed in the appropriate way, e.g. by adapting the source term or parameter values (for example changes in adsorption capacity, transfer factors). These adaptations may have to be carried out in a time-dependent way in order to allow for "degradation" of remediation measures. It was decided not to evaluate the economical aspects of remedial actions within the framework of remediation assessment working group. This decision is in agreement with general scope of BIOMASS project.

Two types of approaches can be envisaged (called type A and B as according to the BIOMOVS I study):

- approach A in which a real past or present situation will be evaluated and model predictions are compared against independent experimental or measured data sets. The aim is to explain the differences between the model predictions and the observed values as well as the differences in the predictions of the different models;
- approach B in which the predictions of different models for specific hypothetical (but realistic) test scenarios are compared. The aim of this exercise is to explain the differences in model predictions.

1.4. STRUCTURE OF THE REPORT

In Section 1, the scope of the BIOMASS Programme, the purpose of the Remediation Assessment Working Group in Theme 2 and its place in the organisational structure of BIOMASS is given. Section 2 gives a description of the test exercises and the modelling tasks. In Section 3, the participants and the main features of their models are summarised. Section 4 contains the results and conclusions of the modelling tasks and in Appendix I and Appendix II the Scenario Description, respectively the model descriptions and detailed results as submitted by the individual participants are given.

2. TEST CASE: RADIUM EXTRACTION SITE, OLEN

2.1. CASE HISTORY

This remediation case concerns the radioactive contamination of a site (Olen-Belgium), brought about by a former radium plant, which was shut down in 1960.

The discovery of very rich ores with a uranium oxide content of 50% in Shaba (in former Belgian Congo) in 1915 led to the development of the radium industry in Olen-Belgium. In 1921 the first ore arrived in Belgium and in 1922 the radium production began in a factory in Olen, where also copper and cobalt (not radioactive) were being produced. Within one year, Belgium dominated the world market and this until the mid 1930's when comparable high grade ore was discovered in Canada. In 1938 the Belgians and the Canadians divided the world market to stabilise the price. The production continued in Canada until the mid 1950's and in Belgium until 1960. The total radium production in Olen was above 500 grams. The exact amount is not known because the annual radium production was kept secret from 1937 for military reasons, radium being a by-product in the fabrication of nuclear weapons. The rapid growth of the gamma of artificial radioisotopes led to a rapid decrease of the importance of radium as a radiation source. This is the reason why the radium extraction in Olen was stopped in 1960 and the radium factory was dismantled in 1977.

The radium production of the factory in Olen has led to a non-negligible radium contamination of the site in the neighbourhood, made possible through the absence of adequate regulations and control on the discharge of radioactive effluents. This caused:

- the discharge of radioactively contaminated liquid effluents in the brook Bankloop (since 1922), flowing into the Kleine Nete and finally into the river Nete;
- the creation of dumping grounds (5) in the vicinity of the factory, used for discharging radioactive and other waste;
- the use of waste material as a layer for hardening a few roads.

In the late 1950's the authorities established the new Belgian Nuclear Research Centre (SCK·CEN) in the same region. The environmental survey that was required in the authorisation for discharging liquid effluents from the laboratories revealed abnormal Ra-226 levels in some of the small rivers. Then it became clear that the water and the sediments of the Kleine Nete and of the Bankloop were contaminated through the liquid effluents from the radium plant in Olen. The banks of the Bankloop brook were also contaminated because the brook was cleaned regularly and the sediments that were removed were placed on the banks. The Bankloop regularly flooded the land located just before its confluence with the Kleine Nete as a result of heavy rain, contaminating this boggy soil. Because an agricultural organisation wanted to make this land ready for farming, it had acquired the land and had taken some measures to change the water management of this area.

This was the situation at the Olen site in 1960. A first study of the biological cycle of radium was performed from 1960 to 1967. A second phase of measurements followed in 1977. This study included aerial radiological survey, ground measurements, sampling of water, fish, vegetables, agricultural products, etc. As a result of the study, a number of remedial actions were executed.

In 1989 and 1990, a more detailed assessment of the most contaminated parts, including the dumping grounds and the Bankloop was carried out by a mobile survey and a survey on foot. The programme also included an evaluation of the radon exposure in the dwellings of St. Jozef-Olen, the village surrounding the factory, and in open air above the dumping grounds, as well as an evaluation of radium in airborne dust, in surface water, in ground water, in the food chain and in milk teeth of children.

Government, factory, research institute (SCK·CEN), local government, NIRAS (federal nuclear waste agency) and OVAM (non-nuclear waste agency) are working together to define possible remediation strategies taking into account all relevant aspects (radiological evaluation, chemical and toxicological hazards, cost, public acceptance, public concern, ...).

A number of streets with localised contamination were identified. A consensus exists to eliminate the contamination in a controlled way when ground works are done in these streets. The contaminated material will be stored temporarily on the D1 dumping ground. Three streets have been remediated to date.

2.2. SITE CHARACTERISTICS

The site proposed for this remediation study is the area between Kleine Nete and the road Roerdompstraat that has been contaminated through the liquid effluents of the former radium plant of Olen (Figure 2). A detailed site description is given in Appendix I.

Regular floodings and dredging of sediments have led to an important Ra-226 contamination over some tens of ha, especially at the western side of the brook. Around 1960, a canal was constructed to drain the site. The original east to west flow in the marsh was reversed and the drainage water pumped into the Kleine Nete upstream of the confluence with the Bankloop. This has led to a drying of the marsh and a displacement of contamination in the peat from west to east. However in the winter of 1960–1961, because of heavy rainstorms, the verges collapsed at the place of the passage of the drainage canal and a new dispersion of the water of the Bankloop took place.

Radiological studies have been undertaken in order to evaluate the possibility of using the site for agricultural purposes. As a result of the first radiological study carried out in the period 1961–1967, some remedial actions were taken: the Old Bankloop was filled up and deep ploughing was applied to make pastures for dairy cows.

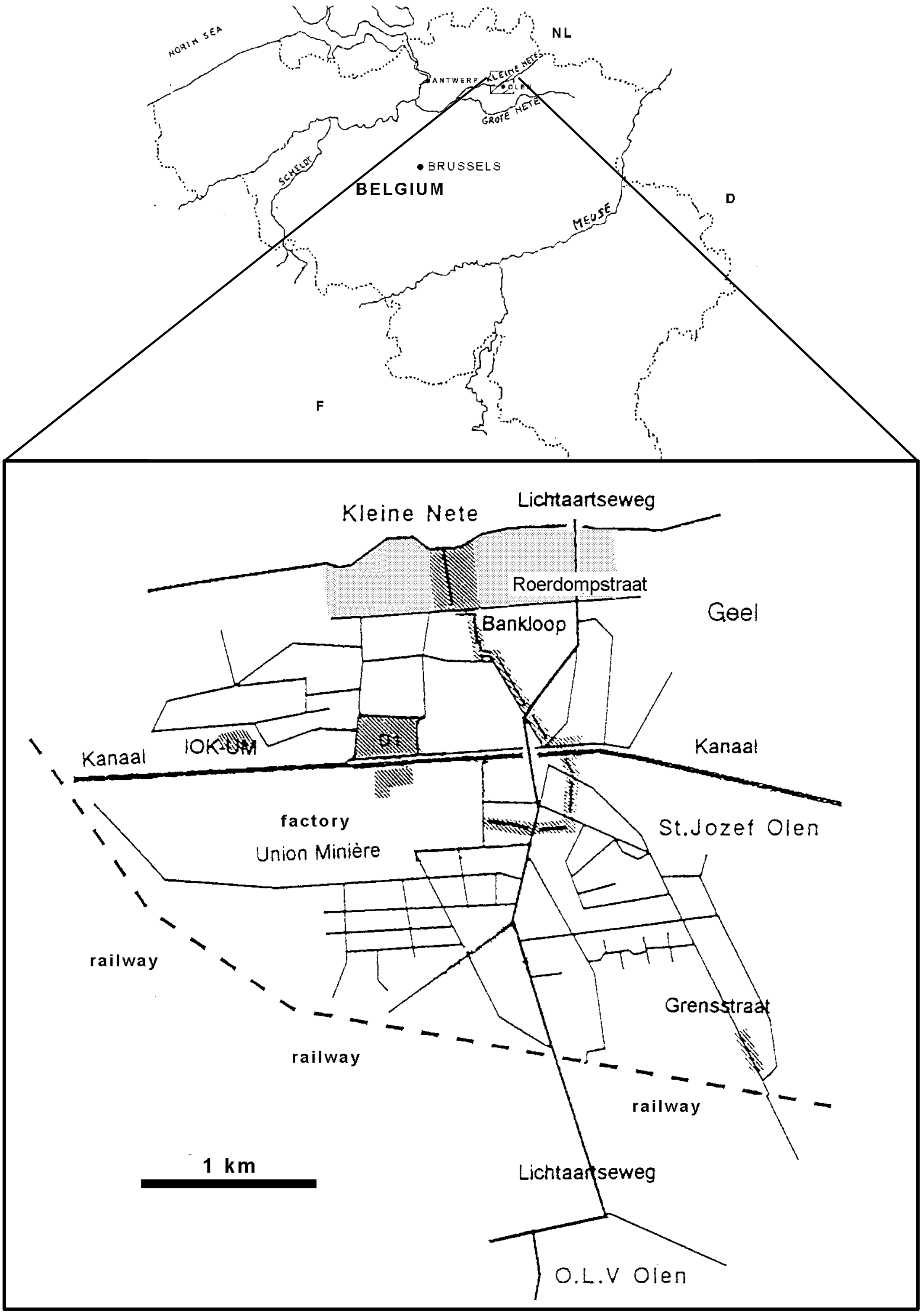


FIG.2. Localisation of the 100 ha test site between Roerdompstraat and Kleine Nete (indicated by the grey shaded part). The factory U.M. is the former Olen plant and the most radium contaminated areas in Olen are indicated by black stripes.

2.3. SCENARIO MODELLING TASKS

2.3.1. Scenario Type A

The scenario of this type is related to the influence of the deep ploughing of the site between the Roerdompstraat and Kleine Nete on the Ra-226 concentrations in the food chain. The modelling task is to assess the Ra-226 concentrations in the milk of dairy cows (a group of 50–60 cows) that were put on ten different pasture plots arranged on the remediated area. These cows have been followed and their milk sampled and measured over several periods during two years (1971–1972). The input information to this scenario is given in Appendix I.

The endpoints were:

- Ra-226 concentrations in root zone soil (corresponding to the root-zone depth of pasture) for each of the ten pasture plots (averaged over each plot) expressed in Bq/g DW before the remediation and after the remediation over the years 1971 and 1972;
- Ra-226 concentrations in pasture grass for each of the ten plots, expressed in Bq/kg DW during summer of the years 1971 and 1972;
- Ra-226 concentrations in cow's milk, averaged over the total group and over each of the periods indicated in the scenario description, expressed in Bq/l.

For each of the concentrations indicated, estimates of the mean and the 95% confidence interval (2.5% and 97.5% lower and upper bound estimates) were requested. After submitting the predictions (including uncertainty estimates), the observed data were given and revisions of predictions were possible.

2.3.2. Scenario Type B

The modelling tasks for this scenario are the individual doses to an adult farmer, living on the most contaminated area of the site, cultivating vegetables in a kitchen garden with contaminated ground water and keeping dairy and beef cattle on the fields. It is reasonable to assume that the contaminated ground water is not only used for irrigation, but also as drinking water and that a fraction of the food ingested is obtained from the contaminated site.

Locally produced foodstuffs are: milk, meat, vegetables and potatoes.

Participants were asked to take the contribution of ^{210}Pb, the long-lived daughter nuclide of ^{226}Ra into account and give the endpoints separately for Ra and Pb, assuming that ^{210}Pb is in equilibrium with ^{226}Ra at year 1.

The endpoints were:

- external irradiation indoors and outdoors;
- inhalation of resuspended particles indoors and outdoors;
- inhalation of emanated radon indoors and outdoors;
- ingestion of soil;
- ingestion of drinking water obtained from contaminated ground water (well);

- ingestion of leafy vegetables, potatoes grown on the contaminated soil (contribution through root uptake) and irrigated by contaminated ground water (contribution through foliar uptake);
- ingestion of milk, meat (contribution through grass, water and soil intake by the cattle);

after 1, 50, 100, 200 and, if possible 500 years (peak doses, i.e. doses at the time of the maximum may also be given, but are optional). The input information to this scenario is given in Appendix I.

The deterministic calculations of doses were to be carried out for the following three options:

- no remediation;
- removal of most contaminated soil;
- covering with a clean soil layer of 0.5 m.

In this way, the effectiveness of the remedial actions in terms of dose savings and contamination reductions can be evaluated.

In order to be able to analyse the results for the deterministic calculations, the participants were also asked to give the concentrations in different biosphere compartments, such as:

- concentration of radium and lead in soil (in the upper 1 m layer) for pasture, kitchen-garden (irrigated) and farm;
- concentration of radium and lead in dust (in- and outdoors), grass, leafy vegetables, potatoes, drinking water, milk and meat;
- concentration of radon in air (in- and outdoors);

after 1, 50, 100, 200 and, if possible 500 years.

For the stochastic calculations, participants were asked to calculate the arithmetic mean and the 95% confidence interval (2.5% and 97.5% percentiles) of the individual doses and this for the following two options:

- no remediation;
- covering with a clean soil layer of 0.5 m.

The same exposure pathways were to be considered as for the deterministic calculations, with the exception of dust inhalation and soil ingestion, which are optional. The same applies to peak doses. Participants were also asked to perform a sensitivity analysis in order to identify and rank the input parameters, which have a significant effect on the dose results.

3. PARTICIPANTS, MODELS AND APPROACHES

3.1. SCENARIO TYPE A

Five participants, including the scenario author, have performed calculations for the Olen scenario Type A. The participants are listed below in Table I, together with the names of their codes and the main model features. OLENRAD-A and RISKOLEN used the equilibrium approach to estimate the soil to milk transfer of radium whereby their variation of the milk concentration in time is only reflecting the level of radium contamination of the different pasture plots on which the cows were put during certain time periods. The other modellers used a dynamic approach to model the radium transport in the cow whereby TAMDYN code is the only model that considered various subcompartments (bone, GIT, blood, etc.) within the cow compartment. A more detailed description of each model (schematic view, main equations, tables of the estimates, evaluation of the model performance) as presented by the modellers, is given in Appendix II.

3.2. SCENARIO TYPE B

Six models participated in the intercomparison modelling exercise. Their models, together with the main characteristics are given in Table II. For the ingestion pathways from soil and water to the foodstuffs, all models assumed equilibrium approach, but did not necessary take into account all pathways that may lead to the contamination of the foodstuffs. For example, CLRP and OLENRAD-B did not consider the intake of water by cattle (Table III) Different approaches were used for calculating the radium and lead transport in soil and aquifer and the radon concentration in- and outdoors. CLRP-RAD and TAMDYN-UV considered various soil layers and used a dynamic approach to calculate the radium and lead transport while the others like OLENRAD-B assumed only one homogeneous upper soil layer (Table II). OLENRAD-B did not consider different soil layers because the modeller assumed that the ground water level varied, leading to an average radium concentration over the thickness of the contaminated soil layer.

Some modellers, like OLENRAD-B and DOSDIM used measured data directly in the dose calculations while others used the data mainly to validate their model predictions. OLENRAD-B calculated the ingestion of drinking water and inhalation doses of dust using the measured radium concentrations in drinking water and aerosols. Also the external doses were calculated by using the dose rate measurements of the site. CLRP-RAD on the other hand used these dose rates to validate his external dose calculation method.

Also different assumptions were made concerning the radon concentration in air. DOSDIM related the in- and outdoor radon concentration to the radium concentration in soil through a simple site-specific transfer coefficient measured near the site, while others used more dynamic approaches to calculate the radon fluxes from soil to the atmosphere and into the houses. All modellers, except RESRAD (ONSITE), due to the limitations of used computer code RESRAD 5.91, performed stochastic calculations.

TABLE I. SUMMARY OF PARTICIPANTS AND THE MAIN MODEL FEATURES (SCENARIO TYPE A)

Participant/Organisation (Country)	Code name	Type	Uncertainty method
P. Krajewski/CLRP (Poland)	CLRP	Mainly dynamic	Error propagation
L. Sweeck/SCK·CEN (Belgium)	DOSDIM	Partly dynamic, partly equilibrium	Monte Carlo (LHS)[a]
A. Kryshev/Typhoon (Russia)	OLENRAD-A	Equilibrium	Error propagation
P. Lietava/Nuclear Research Institute (Czech Republic)	RISKOLEN	Equilibrium	Monte Carlo (LHS)[a]
B. Kanyár/University of Veszprém (Hungary)	TAMDYN	Mainly dynamic	Monte Carlo (LHS)[a]

[a] Latin Hypercube Sampling.

TABLE II. SUMMARY OF PARTICIPANTS AND MAIN MODEL FEATURES (SCENARIO TYPE B)

Participant/Organisation (Country)	Code name	Type	Uncertainty method
P. Krajewski/CLRP (Poland)	CLRP-RAD	Dynamic soil transport model (upper 2 m soil layer divided into 7 soilcompartments). Time-dependent soil processes: diffusion and leaching. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	Monte Carlo (LHS)[a]
L. Sweeck/SCK·CEN (Belgium)	DOSDIM	One soil compartment. Time-dependent soil processes: leaching and bioturbation. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	Monte Carlo (LHS)[a]
T. Sazykina/ Typhoon (Russia)	OLENRAD-B	One soil compartment. Time-dependent soil processes: leaching, bioturbation and erosion. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	Error propagation
P. Lietava/Nuclear Research Institute (Czech Republic)	RESRAD (ONSITE) v.5.91	Multi soil compartments with one contaminated soil layer . Time-dependent soil processes: leaching, erosion and ground water transport. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	/
Ch. Yu/ANL (USA)	RESRAD-OFFSITE v.1.0	Multi soil compartments with one primary contaminated soil layer and secondary contaminated zone. Time-dependent soil processes: leaching, erosion and ground water transport. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	Monte Carlo (LHS)[a]
B. Kanyár, A. Nényei/University of Veszprém (Hungary)	TAMDYN-UV	Dynamic soil transport model (upper 2.5m soil layer divided into soil layers of 10 cm each). Time-dependent soil processes: diffusion and leaching. Equilibrium approach for external irradiation, ingestion and inhalation pathways.	Monte Carlo (LHS)[a]

[a] Latin Hypercube Sampling.

TABLE III. SUMMARY OF THE ENDPOINTS MODELLED (SCENARIO TYPE B)

	CLRP-RAD	DOSDIM	OLENRAD-B[a]	RESRAD (ONSITE)[b]	RESRAD-OFFSITE	TAMDYN-UV
Inhalation of dust						
Indoors	×	×	×	×	×	×
Outdoors	×	×	×	×	×	×
External irradiation						
Indoors	×	×	×	×	×	×
Outdoors	×	×	×	×	×	×
Inhalation of emanated radon						
Indoors	×	×	×	×	×	×
Outdoors	×	×	×	×	×	×
Ingestion of leafy vegetables						
Contamination via root	×	×	×	×	×	×
Foliar contamination		×		×	×	×
Ingestion of potatoes						
Contamination via root	×	×	×	×	×	×
Foliar contamination		×		×	×	×
Ingestion of drinking water	×	×	×	×	×	×
Ingestion of milk						
Contamination via grass	×	×	×	×	×	×
Contamination via water intake		×		×	×	×
Ingestion of meat						
Contamination via grass	×	×	×	×	×	×
Contamination via water intake		×		×	×	×
Soil ingestion (optional)		×	×	×	×	×
Maximum of endpoints (optional)					×	×

[a] OLENRAD-B did not make calculations for Pb-210.

[b] RESRAD (ONSITE) reports the combined contamination of food crops via root and foliar uptake, however makes a difference between water independent and water dependent pathways. For simplification, it was assumed that the water independent pathways correspond with root uptake and the water dependent pathways with foliar uptake.

4. METHODS AND PARAMETERS

4.1. SCENARIO TYPE A

In Tables IV and V, the main model parameters (best estimate values, uncertainty ranges and probability density function (pdf)), used to calculate the radium transport between and in the soil, grass and cow compartments, are summarised. For most model parameters, given in Table IV, experimental data were reported in the scenario description. Some modellers used the arithmetic or geometric mean of these data as best estimate value, while others used personal judgement to choose the best estimate value. Because for most input parameters, only a limited number of experimental data was given, the uncertainty ranges (and certainly all probability density functions) were mainly defined by personal judgement. To take into account the effect of deep ploughing on the radium concentration in the root zone, a dilution factor was used, defined as the ratio of the radium concentration in the root zone before deep ploughing to the radium concentration in the root zone after deep ploughing. In Table V, the data chosen by DOSDIM, CLRP and TAMDYN to model the radium transfer from grass to milk dynamically are presented. These data were not given in the scenario description. TAMDYN used rate coefficients to model the transfer of radium between the main organs in the cow and considers losses via excretion. CLRP and DOSDIM assume only one cow compartment, taking into account the biological half-life of radium. The milk to grass coefficient used by DOSDIM was calculated from the equilibrium milk to grass factor and the biological half-life.

4.2. SCENARIO TYPE B

Deterministic and stochastic calculations were made. During the course of the exercise, it was agreed upon to consider the main biospheric parameters in the uncertainty and sensitivity analysis and their best-estimate values and uncertainty ranges were included in the scenario description. Table VI summarises the dose factors for which differences have been observed between the models. In Tables VII and VIII, the values of the model parameters considered in the deterministic and stochastic calculations are listed. The values used in the deterministic approach were also taken as best-estimate values (e.g. mean, mode, median of a probability distribution) in the stochastic calculations, unless indicated otherwise.

As seen in Tables VII and VIII, the input data were not the same for all models. Although for most model parameters, values were given in the scenario description, these were not always used because of differences in data requirements of the models and/or differences in personal judgement. Some models like DOSDIM, OLENRAD-B were able to use most of the available information directly. Other models like RESRAD-OFFSITE could not use all data supplied but required additional data, e.g. the infiltration rate is not an input parameter in RESRAD-OFFSITE, but is calculated using the precipitation rate, runoff coefficient, evapotranspiration rate and irrigation rate as input parameters. For the runoff coefficient however no data were given in the scenario description. Personal judgement played an important role in the choice of the parameter values. Especially CLRP-RAD did not use the values of several input parameters given in the scenario, but calculated them (e.g. diffusion coefficient of radon in soil, the infiltration rate, dust concentration in air) from additional information given in the scenario description and other sources. The detailed scenario and model descriptions are given in Appendices I and II.

TABLE IV. SUMMARY OF THE BEST ESTIMATE VALUES USED IN SCENARIO TYPE A FOR THE MODEL PARAMETERS (THE UNCERTAINTY RANGES ARE GIVEN IN PARENTHESES)

Parameter		CLRP	DOSDIM	OLENRAD-A	RISKOLEN	TAMDYN
Soil to grass concentration ratio (dw/dw)	value	0.12 (0.075–0.192)	0.065 (gsd 2.2)	0.05 (sd 0.03)	0.17 (gsd 1.66)	0.05 (0.02–0.15)
	pdf type	lognormal	lognormal	normal	lognormal	triangular
Intake by cattle during grazing period Ic (kg dw/d)	value	15 (12.5–18)	12.5 (10–15)	/	12.5 (10–15)	12.5 (7–20)
	pdf type	lognormal	triangular		uniform	normal
Intake by cattle during stabling period (Bq/d)	value	100 (80–120)	100 (80–120)	100 (50–150)	100 (20–200)	100 (30–300)
	pdf type	lognormal	triangular		triangular	triangular
Equilibrium grass to milk factor Fm (d/l)	value	1.86E-04 (1.16E-04–3E-04)	2.15E-04 (gsd 2)	/	1.19E-04 (8.8E-05–2.85E-04)	4E-04[a]
	pdf type	lognormal	lognormal		triangular	
Grass to milk concentration ratio Ic * Fm (kg/l)	value	/	/	3E-03 (sd 2E-03)	/	/
	pdf type			normal		
Dilution factor due to deep ploughing	value	3 (1.9–4.8)	6.7 (1–100)	10	10 (4.3–20)	1.8 (1.5–3)
	pdf type	lognormal	logtriangular	/	uniform	

[a] TAMDYN only used the equilibrium grass-to-milk transfer factor to derive the coefficients given in Table V.

TABLE V. TRANSFER COEFFICIENTS USED IN SCENARIO TYPE A TO DETERMINE THE DYNAMIC TRANSFER OF RADIUM FROM GRASS TO MILK

Parameter	CLRP	DOSDIM	TAMDYN
Excretion coefficient (d^{-1})	/	/	2.0 (0.5–5.0; triangular)
GIT to blood plasma coefficient (d^{-1})	/	/	0.2 (0.05–0.5; triangular)
Urinary excretion coefficient (d^{-1})	/	/	0.5 (0.15–1.5; triangular)
Milk excretion coefficient (d^{-1})	/	/	0.2 (0.05- 0.5; triangular)
Blood to bone surface coefficient (d^{-1})	/	/	10.0 (3.0–25; triangular)
Bone surface to blood coefficient (d^{-1})	/	/	0.5 (0.1–1.5; triangular)
Bone surface to bone coefficient (d^{-1})	/	/	0.3 (0.1–1.0; triangular)
Biological decay coefficient (d^{-1})	1.47E-02	0.3519	/
Grass-to-milk coefficient (l^{-1})	/	9.62E-05	/

TABLE VI. SUMMARY OF DIFFERENCES IN DOSE FACTORS USED IN SCENARIO TYPE B

	Dose factor (in mSv/y per Bq/m^3)					
	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
External irradiation:						
Ra-226	4.19E-6[a]	2.4E-6[c]	n.c. (used measured dose rates)	4.19E-6[a]	3.03[d]	2.4E-6[c]
	2.31E-6[b]			2.31E-6[b]		
Pb-210	1.32E-9[a]	1.5E-9[c]	n.c. (used measured dose rates)	1.32E-9[a]	1.7E-3[d]	1.5E-9[c]
	6.24E-10[b]			6.24E-10[b]		
Inhalation radon:	3.15E-4	3.15E-4	3.15E-4	3.15E-4	7.6 indoors[e]	2.5E-9[f]
					5.7 outdoors[e]	

[a] For soil density of 1000 kg/m^3.

[b] For soil density of 1800 kg/m^3.

[c] Given in scenario description.

[d] In mSv/y per Bq/g

[e] In mSv/WLM (Working Level Month)

[f] In Sv/Bq

n.c. = not considered.

TABLE VII. SUMMARY OF THE BEST-ESTIMATE VALUES USED IN SCENARIO TYPE B FOR THE RADIONUCLIDE-DEPENDENT INPUT PARAMETERS (THE UNCERTAINTY RANGES ARE GIVEN IN PARENTHESES)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
For Ra-226:						
Diffusion coeff. in soil (m^2/y)	1.0E-5 (2E-6–5E-5) triangular	n.c.	n.c.	n.c.	n.c	5E-05 deterministic 1.0E-5 (2E-6–5E-5) triangular
K_d in soil (m^3/kg)	0.5 (0.05–1.5) for upper soil layers 1 (0.05–3) for deeper soil layers exponential	0.5 (0.05–5) loguniform	n.c.	0.5	0.5 (0.05–5) loguniform	0.5 (0.05–5) loguniform
K_d in aquifer (m^3/kg)	40 (20–80), derived from scenario description lognormal	same as for soil		same as for soil	same as for soil	same as for soil
Soil-to-plant TF						
pasture (dw/dw)	0.08 (1E-2–3E-1)	0.08 (1E-2–3E-1)	0.08 (1E-2–3E-1)	0.08	0.08 (1E-2–3E-1)	0.08 (1E-2–3E-1)
leafy veg. (dw/fw)	1.78E-2 (6.7E-3–6.7E-1)	0.01 (1E-3–1E-1)	0.01 (1E-3–1E-1)	0.01	0.01 (1E-3–1E-1)	0.01 (1E-3–1E-1)
potatoes (dw/fw)	7.5E-3 (1E-3–7.5E-2) lognormal	1.5E-3 (2E-4–15E-2) logtriangular	1.5E-3 (2E-4–15E-2) logtriangular	1.5E-3	1.5E-3 (2E-4–15E-2) logtriangular	1.5E-3 (2E-4–15E-2) logtriangular
Grass-to-milk TF (d/l)	2E-4 (5E-5–1E-3) triangular	2E-4 (5E-5–1E-3) triangular	2.15E-4 (5E-5–1E-3) triangular	2E-4	2E-4 (5E-5–1E-3) triangular	2E-4 (5E-5–1E-3) triangular
Grass-to-beef TF (d/kg)	5E-4 (1E-4–2E-3) triangular	5E-4 (1E-4–2E-3) logtriangular	5E-4 (1E-4–2E-3) logtriangular	5E-4	5E-4 (1E-4–2E-3) logtriangular	5E-4 (1E-4–2E-3) logtriangular
Translocation factor potatoes (-)	n.c.	0.1 (0.001–0.15) logtriangular	n.c.	0.1	0.1 (0.001–0.15) logtriangular	0.1 (0.001–0.15) logtriangular
External dose rate (μSv/h)[a]	used for validation	n.c.	1 (0.5–2)	n.c.	n.c.	n.c.
External dose						
shielding factor indoors	0.25 (0.15–0.4)	0.25	0.25	0.25	0.35	0.25
shielding factor outdoors	0.7 (0.4–1) triangular	0.7	0.75	0.7	0.7	1 for ≤ 10 cm depth; 0.5 for every additional 10 cm

[a] Given in the Figures I-13 to I-19 of the Scenario Description (Appendix I).

n.c. = not considered.

TABLE VII. (CONTINUED)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
For Rn-222:						
Diffusion coefficient in soil (m^2/y)	37–44 (depending on the soil layer; calculated from diffusion coeff. in air) lognormal	n.c.	15.8	63.1 contaminated soil 25.2 cover material	63.1 (20–200) triangular	63.1 (20–200) triangular
Emanation fraction ε (-)	0.45 (0.25–0.7) triangular	n.c.	0.2	0.25	0.25 (0.1–0.4) uniform	0.25
Pore diffusion coefficient radon in concrete (m^2/y)	n.c.	n.c.	n.c.	6.3	6.3	6.3
Flux retardation factor in concrete	n.c.	n.c.	0.25 (for concrete layer with small fractures)	n.c.	n.c.	n.c.
Diffusion coefficient in air (m^2/s)	1.1E-05 (sd 1E-05) lognormal	n.c.	n.c.	n.c.	n.c.	n.c.
Radon mixing height (m)	2	n.c.	n.c.	2	n.c.	n.c.
Exhalation factor (Bq Rn/m^3 in air per Bq Ra/g in soil)						
indoors	n.c.	330	330	n.c.	n.c.	330
outdoors	n.c.	20	20	n.c.	n.c.	20

n.c. = not considered.

TABLE VII. (CONTINUED)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
For Pb-210:						
Diffusion coeff. in soil (m^2/y)	5E-6 (1E-6–2E-5) triangular	n.c.	Dose from Pb-210 not calculated	n.c.	n.c.	5E-5 deterministic 5E-6 (1E-6–2E-5) triangular
K_d in soil (m^3/kg)	0.27 (0.025–2.5) loguniform	0.27 (0.025–2.5) loguniform	not done	0.27	0.27 (0.025–2.5) loguniform	0.27 (0.025–2.5) loguniform
Soil-to-plant TF						
pasture (dw/dw)	0.05 (0.02–0.2)	0.05 (0.02–0.2)	not done	0.05	0.05 (0.02–0.2)	0.05 (0.02–0.2)
leafy veg. (dw/fw)	6.09E-2 (2E-2–1.33E-1)	0.01 (3E-3–2E-2)		0.01	0.01 (3E-3–2E-2)	0.01 (3E-3–2E-2)
potatoes (dw/fw)	6.6E-3 (1.5E-3–1.5E-2) lognormal	1E-3 (3E-4–3E-3) triangular		1E-3	1E-3 (3E-4–3E-3) triangular	1E-3 (3E-4–3E-3) triangular
Grass-to-milk TF (d/l)	1.5E-4 (5E-5–1E-3) triangular	1.5E-4 (5E-5–1E-3) triangular	not done	3E-4	1.5E-4 (5E-5–1E-3) triangular	1.5E-4 (5E-5–1E-3) triangular
Grass-to-beef TF (d/kg)	4.0E-4 (1E-4–1E-3) lognormal	4.0E-4 (1E-4–1E-3) triangular	not done	4E-4	4.0E-4 (1E-4–1E-3) triangular	4.0E-4 (1E-4–1E-3) triangular
Translocation factor potatoes (-)	n.c.	0.1 (0.001–0.15) logtriangular	not done	0.1	0.1 (0.001–0.15) logtriangular	0.1 (0.001–0.15) logtriangular
External dose						
shielding factor indoors	0.25 (0.15–0.4)	0.25	0.25	0.25	0.35	0.05
shielding factor outdoors	0.7 (0.4–1) triangular	0.7	0.75	0.7	0.7	0.5 for ≤ 10 cm depth; 0.1 for every additional 10 cm

n.c. = not considered.

TABLE VIII. SUMMARY OF BEST-ESTIMATE VALUES USED IN SCENARIO TYPE B FOR THE RADIONUCLIDE-INDEPENDENT INPUT PARAMETERS (THE UNCERTAINTY RANGES ARE GIVEN IN PARENTHESES)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
Density of soil, after deep ploughing (kg/m^3)	800 (320–1300) for 0–0.5 m depth 1000 (320–1300) for > 0.5 m triangular	800 (320–1300) triangular	1600	800	800 (320–1300) triangular	800 (320–1300) triangular
Moisture of soil (-)	0.3 (0.15–0.5) for 0–0.5 m depth 0.45 (0.4–0.6) for 0.5–1 m depth 0.6 (0.45–0.75) for > 1 m depth triangular	0.3 (0.15–0.5) triangular	n.c.	n.c.	0.3 (0.15–0.5) triangular	0.3
Soil porosity (-)	0.5 (0.35–0.65) triangular	n.c.	0.25	0.5	0.4	0.5
Precipitation rate (m/y)	0.76 (0.53–1) triangular	n.c.	n.c.	0.76		n.c.
Runoff coefficient (-)	0.2	n.c.	n.c.	0.3		n.c.
Evapotranspiration coefficient (-)	n.c.	n.c.	n.c.	0.5		n.c.
Hydraulic conductivity soil (m/y)	4000 (1000–5500) saturated soil triangular	n.c.	n.c.	5361 unsaturated soil 199 saturated soil	5365	n.c.
Hydraulic gradient (-)	n.c.	n.c.	n.c.	n.c.	6.52E-4	n.c.
Darcy velocity (m/y)	n.c.	3.5	n.c.	3.5	3.5	n.c.
Inhalable dust concentration in air (kg/m^3)			n.c., used measured radium conc. in aerosols			
agricultural activities outdoors	2E-7	1E-7 (2E-8–5E-7)		1E-7	1E-7 (2E-8–5E-7)	1E-7
outdoors	2E-7	3E-8 (5E-9–1E-7)		3E-8	1E-7 (2E-8–5E-7)	1E-7
indoors	n.c.	1.5E-8 (2.5E-9–5E-8) triangular		1.5E-8	1.5E-8 (3E-9–7.5E-8) triangular	1E-7
House filtration factor	0.15 (0.05–0.25) triangular	n.c.	n.c.	n.c.	n.c.	0.2
Shielding factor for inhalation indoors	n.c.	n.c.	n.c.	0.4	n.c.	n.c.

TABLE VIII. (CONTINUED)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
Breathing rate (m^3/h)						
indoors	0.75	0.75	0.75	0.75	0.75	0.9
outdoors	1.2	1	1	1	n.c.	1.2
agricultural activities	1.2	1.2	1	1.2	1.2	1.2
Thickness of root zone layer						
pasture	0.15 (0.1–0.3)	0.15 (0.1–0.3)	0.15 (0.1–0.3)	0.15	0.15 (0.1–0.3)	0.15
potatoes, leafy vegetables	0.3 (0.2–0.5) triangular	0.3 (0.2–0.5) triangular	0.3 (0.2–0.5) triangular	0.3	0.3 (0.2–0.5) triangular	0.3
Daily uptake of pasture by cattle (kg/d)	12.5 (10–15) dw triangular	12.5 (10–15) dw triangular	12.5 (10–15) fw for beef cows 40 fw for dairy cows triangular	12.5 dw	12.5 (10–15) fw triangular	12.5 (10–15) triangular
Daily uptake of water by cow (m^3/d)	n.c.	0.06 (0.04–0.08) uniform	n.c.	0.06	0.06 (0.04–0.08) uniform	0.06 (0.04–0.08) uniform
Fractional uptake of soil by cattle (kg dw/kg dw pasture)	n.c.	0.04 (0.01–0.1) triangular	n.c.	0.5	n.c.	0.04 (0.01–0.1) triangular
Soil ingestion rate by cattle (kg/d)	n.c.	n.c.	n.c.	0.5	0.5	n.c.
Yield of vegetation ($kg/m^2/y$)						
leafy vegetables (fresh)	n.c.	2 (0.8–4)	n.c.	2	n.c.	2 (0.8–4)
potatoes (fresh)	n.c.	2 (0.8–4) triangular	n.c.	2	n.c.	2 (0.8–4) triangular
Interception factor food crops (-)	n.c.	0.2 (0.1– 0.5) triangular	n.c.	0.2	0.2 (0.1– 0.5) triangular	0.2 (0.1– 0.5) triangular
Infiltration velocity (mm/y)	365 (calculated)	100 (40–150) uniform	n.c.	computed by code	computed by code	100 (40–150) uniform
Irrigation time (d)	100 (30–150) triangular	100 (30–150) triangular	n.c.	100	100 (30–150) triangular	100 (30–150) triangular
Irrigation rate (m/d)	1E-3 (3E-4–2E-3) triangular	1E-3 (3E-4–2E-3) triangular	n.c.	1E-3	1E-3 (3E-4–2E-3) triangular	1E-3 (3E-4–2E-3) triangular
Erosion rate (mm/y)	n.c.	n.c.	1	1	0	n.c.
Bioturbation rate (kg dw soil/m^2/y)	n.c.	2 (0.5–4) triangular	n.c. separately	n.c.	n.c.	n.c.

TABLE VIII. (CONTINUED)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
Exposure time due to irrigation (y)	n.c.					
potatoes		0.164	n.c.	0.164	0.164	0.164
leafy vegetables		0.164	n.c.	0.25	0.164	0.164
pasture		not irrigated	n.c.	0.08	0.08	not irrigated
Weathering decay constant (d^{-1})	n.c.	0.023 (0.015–0.04) triangular	n.c.	0.082	0.023 (0.015–0.04) triangular	0.023 (0.015–0.04) triangular
Ingestion rate (kg/y)						
leafy vegetables	17	56	56	56	56	56
potatoes	122	122	122	122	122	122
milk	131	131	131	131	131	137
meat	54	54	54	62.2	54	54
water	400	400	400	400	400	400 (180–890) triangular
Ingestion of contaminated soil (g/y)	n.c.	9.125 (50% of ingested soil is not contaminated)	18.25	18.25	18.2	26 deterministic 18.2 (7–40) stochast. triangular
Ventilation of the house (h^{-1})	1 (0.36–1.8) triangular	n.c.	1	0.5	0.5 (0.2–1) triangular	0.5
Building foundation density (kg/m^3)	n.c.	n.c.	n.c.	2400	2400	n.c.
Building foundation porosity	n.c.	n.c.	n.c.	0.2	0.2	0.2
Thickness of basement (m)	0.3 (0.1–0.5) triangular	0.3 (0.1–0.5) triangular	n.c.	0.3	0.3	0.3
Interior surface area of the house floor (m^2)	100 (50–200) triangular	n.c.	n.c.	100		n.c.
Interior volume of the house (m^3)	1000 (800–1500) triangular	n.c.	n.c.	250		n.c.
Height of the room (m)	n.c.	n.c.	n.c.	2.5	2.5	n.c.
Foundation depth (m)	n.c.	3.5	n.c.	3.5	3.5	3
Area of contaminated zone (m^2)	1500 (1000–3000) triangular	n.c.	n.c.	n.c.	n.c.	n.c.
Annual average wind speed (m/s)	3 (sd 0.2) lognormal	n.c.	n.c.	4	n.c.	n.c.

TABLE VIII. (CONTINUED)

Parameter	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
External dose						
shape area factor	0.79 (0.6–1)	n.c.	n.c.	1		n.c.
Average annual time spent (h/y)						
indoors	7000 (5000–8000)	7000	7000	7000	7000	7000
outdoors on fields	1500 (800–1700)	1500	1500	1500	1500	1500
outdoors nearby house	300 (200–400) triangular	300	300	300	300	300
Reduction factor (drink water/ ground water)	n.c.	n.c.	n.c.	n.c.	n.c.	0.5

5. RESULTS AND DISCUSSION

5.1. SCENARIO TYPE A

All modellers, except RISKOLEN and DOSDIM (the scenario author), carried out predictions before the measured data for grass and milk were revealed. During the course of the exercise, two modellers carried out revisions; RISKOLEN carried out revisions after some additional information on the soil profile in the upper 1 m soil layer was given and CLRP revised his predictions after model intercomparisons. These revisions are discussed at appropriate places in the report. The predictions presented in this report are the revised predictions, unless indicated otherwise.

5.1.1. Deterministic calculations

5.1.1.1. Radium concentration in root zone before deep ploughing

The main input information consisted of the location of ten contaminated pasture plots and a map of the spreading of the radium contamination at the site. The modellers had to derive the soil concentration for each plot from concentration ranges given each 50 m by 50 m. The differences in interpretation of these data by the modellers has led to an important variation in the prediction of the soil concentrations before deep ploughing (Table IX and Figure 3); up to a factor 7 for the same pasture plot was found. A trend could not be observed; the lowest or highest radium concentration for each plot was not always derived by the same modeller.

5.1.1.2. Radium concentration in root zone after deep ploughing

The information available about the remedial action was rather limited; only some technical information and one soil profile measurement were given. Possible leaching effects were not considered by most modellers because experimental results demonstrated that the migration of radium to ground water could be neglected. TAMDYN modelled the downward migration of radium and came to the same conclusion. Run-off effects were also neglected by the modellers.

The lack of sufficient information about the deep ploughing has led to different approaches for deriving the dilution factors due to deep ploughing (Table IV). CLRP and TAMDYN used soil profile data reported in the scenario description to estimate the effect of deep ploughing in root zone. The differences in their dilution factors are due to differences in the interpretation of the few reported data. The predictions of the radium concentration in soil after deep ploughing by RISKOLEN are revised results (Figure 4). RISKOLEN initially also used the few soil profile data that are available in the scenario description, but adjusted the dilution factor for deep ploughing after receiving additional information on the current radium distribution in the 1 m upper layer of the soil (Table X). In Figure 5, the revised predictions are shown. Comparison with the initial value shows that a higher dilution factor (best estimate value of 10 instead of 7.5) was used to take into account the effect of deep ploughing (Figure 6).

DOSDIM and OLENRAD-A derived the dilution factor from the ploughing depth, assuming as best estimate homogeneously mixing to a 1m depth. The best estimate value of the dilution factor used in OLENRAD-A however is 50% higher than the one used in DOSDIM. This is due to the fact that OLENRAD-A used a root zone depth of 10 cm instead of 15 cm to calculate the effect of the deep ploughing on the radium concentration in the root zone.

TABLE IX. RADIUM CONCENTRATIONS IN THE ROOT ZONE BEFORE DEEP PLOUGHING (Bq/g dw). THE 95% UNCERTAINTY RANGES ARE GIVEN IN PARENTHESIS

Plot Number	CLRP	DOSDIM	OLENRAD-A	RISKOLEN	TAMDYN
1	0.5 (0.2–1.0)	1.2 (0.3–2.4)	0.6 (0.3–0.9)	1.4 (1.0–1.8)	1.2 (0.8–2.4)
2	1.8 (0.9–3.7)	2.8 (0.8–5.0)	3.6 (1.5–5.7)	4.4 (3.5–5.4)	2.0 (0.8–3.2)
3	2.6 (1.3–5.0)	4.5 (1.1–8.6)	4.6 (1.1- 7.1)	6.6 (5.1–8.0)	2.3 (1.6–3.3)
4	7.7 (3.7–15.5)	9.0 (2.5–18.2)	7.8 (3.1–12.5)	13.5 (11.0–15.9)	3.3 (2.5–4.2)
5	1.0 (0.4–2.4)	2.6 (0.6–5.0)	3.4 (0.7–6.1)	6.8 (5.4–8.2)	1.4 (0.8–1.7)
6	0.2 (0.1–0.4)	0.1 (0.04–0.2)	0.2*	0.7 (0.5–0.9)	0.3 (0.2–0.4)
7	0.3 (0.1–0.6)	0.6 (0.1–1.2)	0.5 (0.2–0.8)	0.6 (0.3–1.0)	1.1 (0.8–1.7)
8	0.2 (0.1–0.4)	0.5 (0.1–1.2)	0.3 (0.2–0.4)	0.3 (0.1–0.4)	0.9 (0.8–1.7)
9	1.3 (0.6–3.7)	2.8 (0.7–5.1)	2.4 (0.6–5.2)	4.4 (3.2–5.6)	1.6 (0.8–3.2)
10	0.7 (0.3–1.5)	0.5 (0.1–1.2)	0.3 (0.2–0.4)	0.8 (0.4–1.1)	1.0 (0.8–1.7)

* No range available.

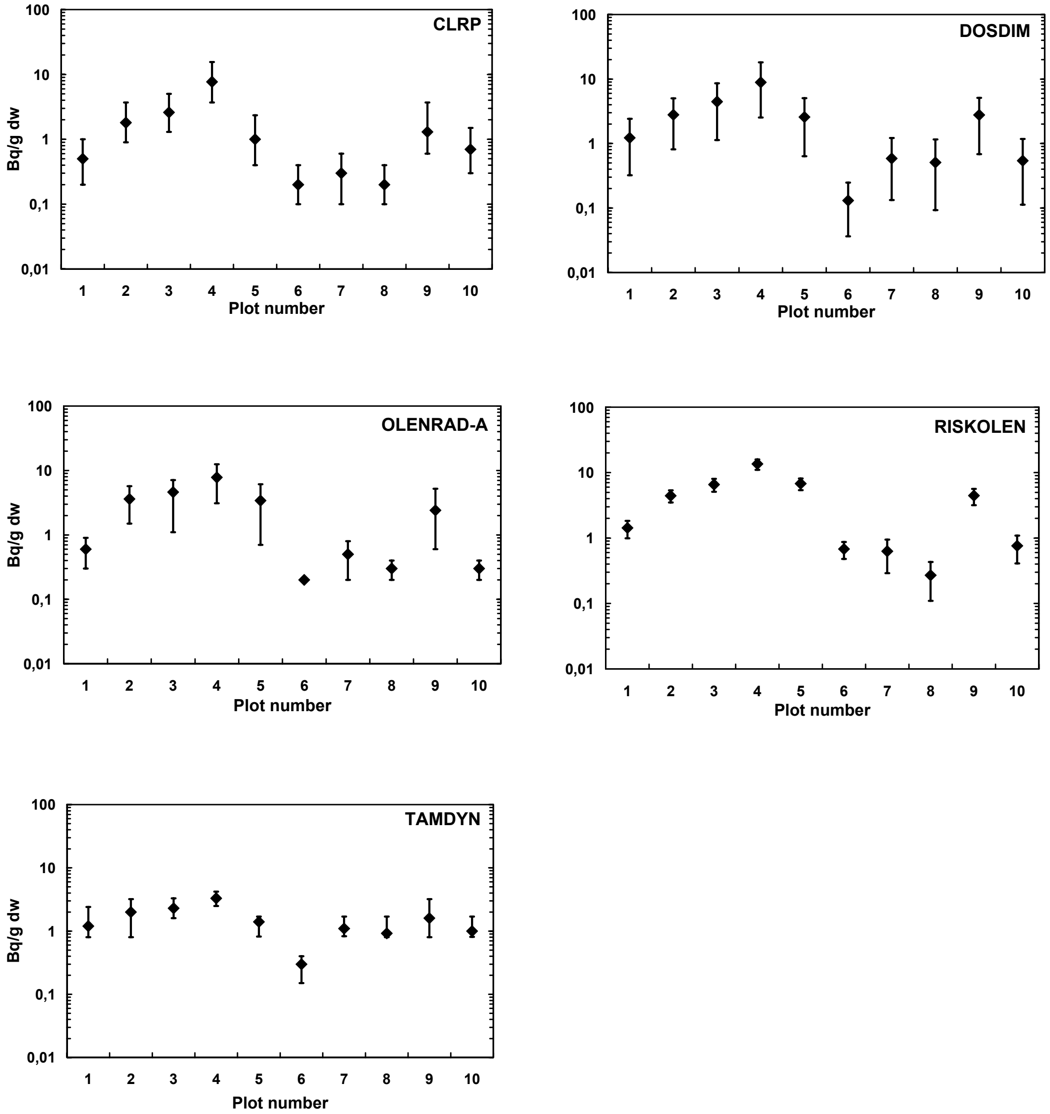


FIG. 3. Radium concentration in root zone before deep ploughing. The symbols refer to the best-estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

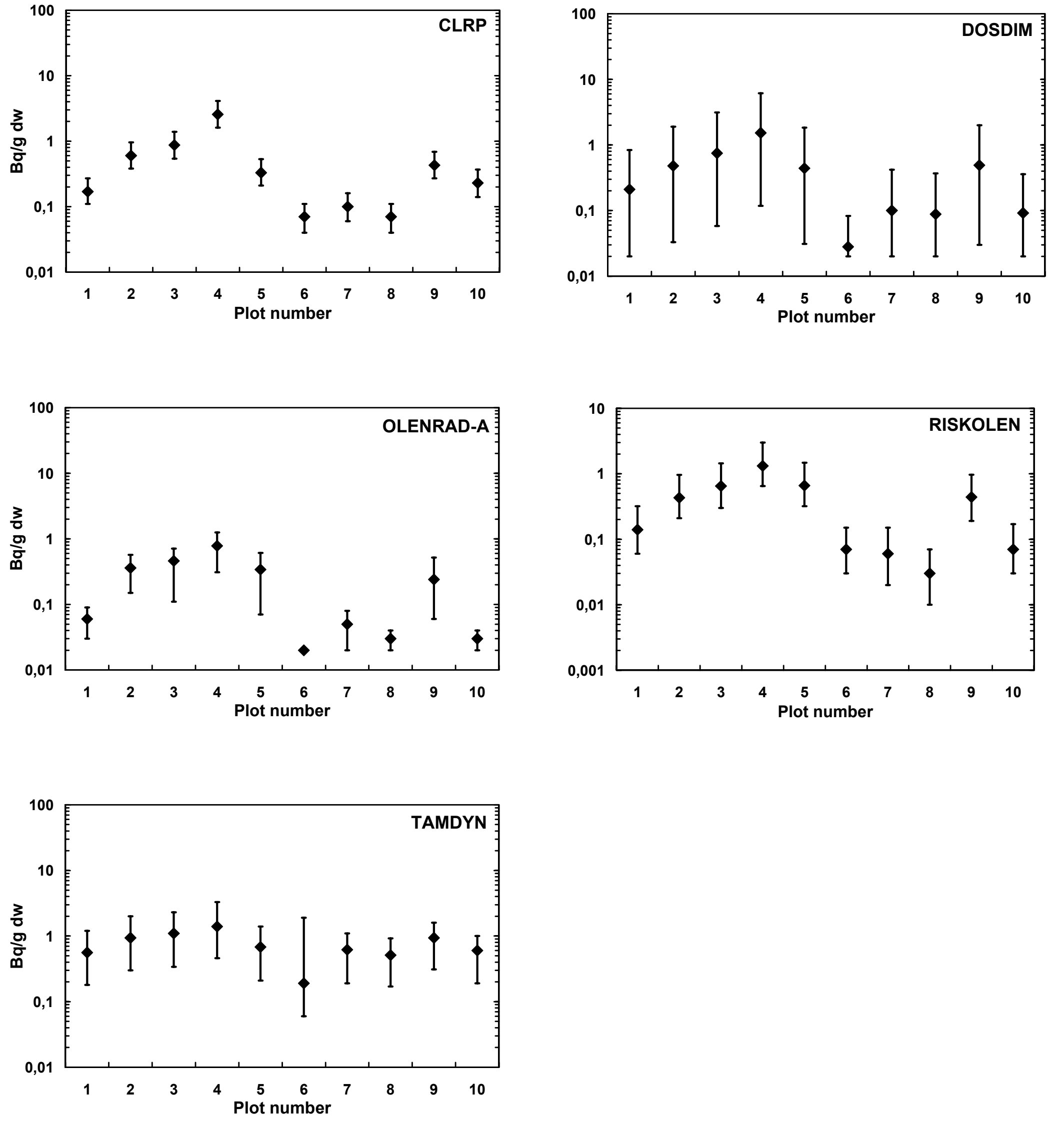


FIG. 4. Radium concentration in root zone after deep ploughing. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

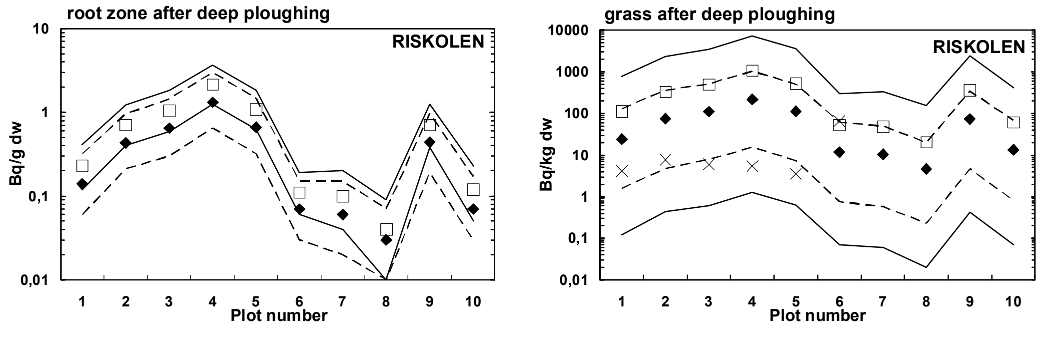


FIG. 5. Initial and revised radium estimates in root zone after deep ploughing and in grass after deep ploughing as produced by RISKOLEN. The symbols (◆) and symbols (□) refer to the revised, respectively initial best estimate values. The symbols (×) refer to the observed data. The dotted lines and full lines indicate the 95% confidence interval of the revised, respectively initial model predictions.

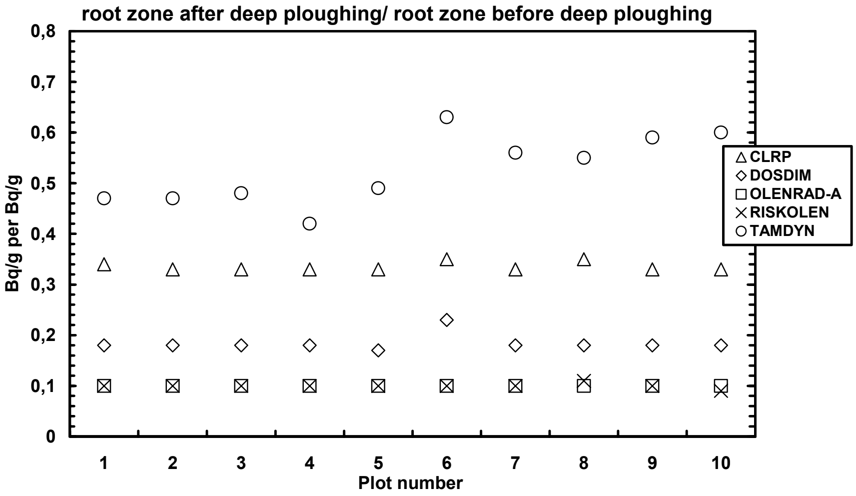


FIG. 6. The predicted mean radium concentration in root zone after deep ploughing, normalised for the predicted mean radium concentration in root zone before deep ploughing.

These different approaches for calculating the dilution factor, involving more or less personal judgement, have resulted in a dilution factor varying from 0.1 to about 0.5 among the models (Table IV and Figure 6). Compared to the situation before deep ploughing, this has led to a wider range of best estimate values; the radium concentration in the root zone may vary over one order of magnitude for the same pasture plot (Figure 4). In contradiction to the predictions before deep ploughing, the lowest soil concentrations for each plot were produced by OLENRAD-A as result of combining a high dilution factor for deep ploughing and rather low radium concentrations in root zone before deep ploughing.

The small uncertainty ranges presented by CLRP are due to the assumption that deep ploughing reduces the spatial heterogeneity of the radium contamination in each plot. All the other models that considered the uncertainty associated with deep ploughing, assumed that it led to larger uncertainty ranges.

5.1.1.3. Radium concentration in grass after deep ploughing

The predicted radium concentrations in grass after deep ploughing are shown in Figure 7. All models used the equilibrium approach and calculated the radium concentration in grass by multiplying the radium concentration in root zone after deep ploughing by the soil-to-plant transfer factor. The soil-to-plant transfer factors are summarised in Table IV. There were two measurements of the radium concentration in grass and soil given in the scenario description that could give an idea of the soil-to-plant transfer factor. Most modellers used these experimental values to determine the best estimate value of the transfer factor and derived the uncertainty ranges from literature or by personal judgement. The variability in the soil-to-plant transfer factor as given in Table IV and Figure 8 (ratios grass-soil after deep ploughing) clearly demonstrates that, particularly in case of limited site-specific information, the choice of parameter values is largely based on subjective judgement.

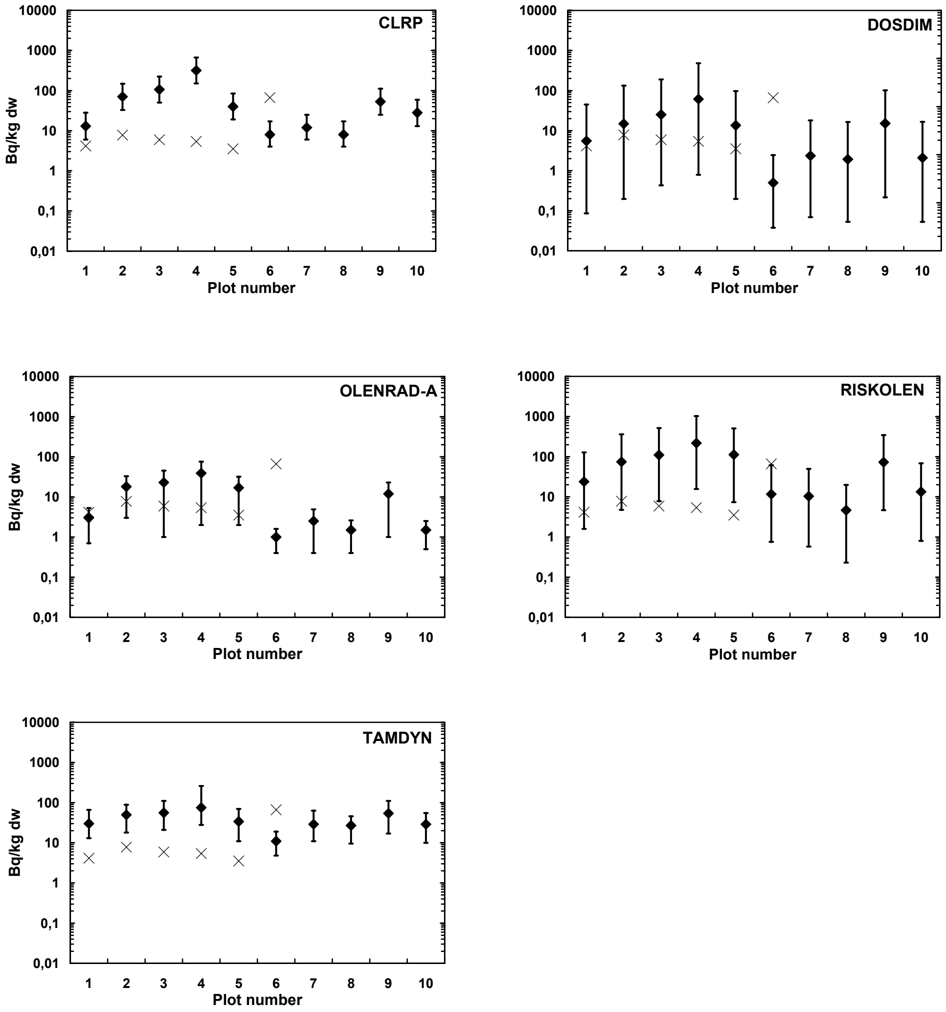


FIG. 7. Radium concentration in grass after deep ploughing. The symbols (◆) and symbols (×) refer to the best estimate values, respectively observed data. The vertical lines indicate the 95% confidence interval of the model predictions.

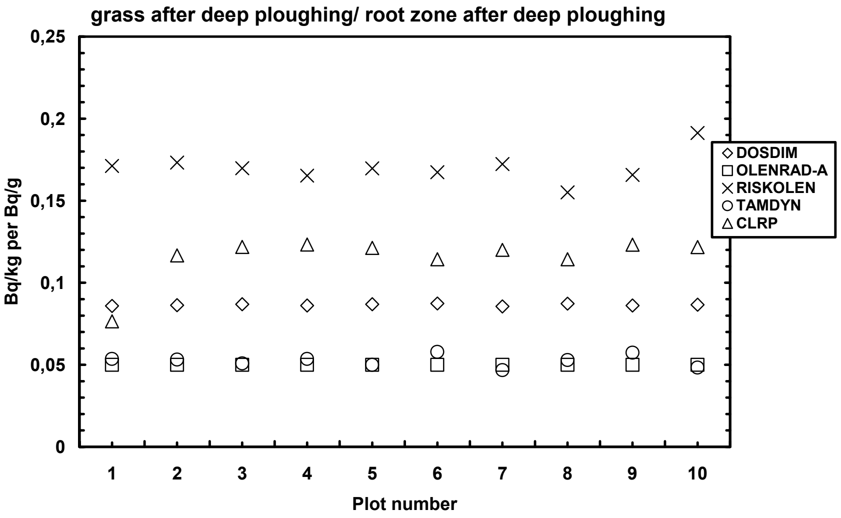


FIG. 8. The predicted mean radium concentration in grass after deep ploughing, normalised for the predicted mean radium concentration in root zone after deep ploughing.

Two modellers, CLRP and RISKOLEN, used a higher soil-to-grass transfer factor than the one that could be derived from experimental data for soil and grass given in the scenario description.

Initially, RISKOLEN used only the experimental data and a lower best estimate value was obtained. The initial uncertainty ranges of the radium concentration in grass varied over more than 3 orders of magnitude. Later, the soil-to-plant transfer factor and its uncertainty ranges were adjusted by taking into account additional data from an IAEA Handbook (TR-364). By correcting the soil-to-plant transfer factor, the uncertainty range of the radium concentration in grass has decreased by more than one order of magnitude (Figure 5). In Table IV and Figure 7, the revised data, respectively the revised predictions in grass are shown.

Prior to deep ploughing, sand was added to enhance the ground level and CLRP assumed that this amendment has led to an increase of soil-to-plant transfer factor. However, addition of sand will not only have an effect at the level of plant uptake but will also have an effect at the soil chemical level and it is not clear whether the result will be a decrease or increase of the radium concentration in grass. In any case, its net effect will be small and ignoring the application of sand can only to a minor extent contribute to the observed mispredictions.

Intercomparison of the model predictions shows that the differences in predictions for grass are comparable with the differences in predictions in root zone after deep ploughing. This is not because the differences in soil-to plant transfer factor are negligible but because of compensating effects. The models that used the highest soil-to-plant transfer factors are not the models that predicted the highest radium concentration in the root zone after deep ploughing. For the first 6 plots, also experimental radium concentrations in grass are available (Figure 7). It is observed that generally the predicted (best estimate) data are higher than the experimental ones, except for plot 6. For this plot, the measured radium concentrations in grass were very high; at average a factor of 10 higher than for other plots. It is possible that this high value represents a local maximum and the average value will likely be more comparable with the values measured for the other plots or that the plot was not deep ploughed, which means no dilution of the radium activity in the root zone.

CLRP and TAMDYN predicted the smallest confidence intervals that fail to overlap the observed data, illustrating overconfidence in some of the parameter values.

5.1.1.4. Radium concentration in milk after deep ploughing

Most modellers used the experimental data from the scenario description to calculate the equilibrium grass-to-milk transfer factor and derived the uncertainty ranges from literature or by personal judgement. As mentioned earlier, CLRP, DOSDIM and TAMDYN considered the transfer parameters to be time-dependent (Table V), others did not. The predicted and observed results are shown in Figure 9. In agreement with the observations made for grass, all models generally overestimated the radium concentrations during the grazing period. Up to two orders of magnitude difference have been observed. The model predictions produced by OLENRAD-A are the lowest, primarily because the predictions of the radium concentration in root zone after deep ploughing are the lowest. The figure shows revised predictions for RISKOLEN. RISKOLEN generally predicted the highest radium concentration in milk, due to the use of high radium concentrations in the root zone before deep ploughing and the highest soil-to-plant transfer factor. These predictions are slightly lower than the initial ones and reflect the lower revised estimates obtained for the root zone after deep ploughing (Figure 10).

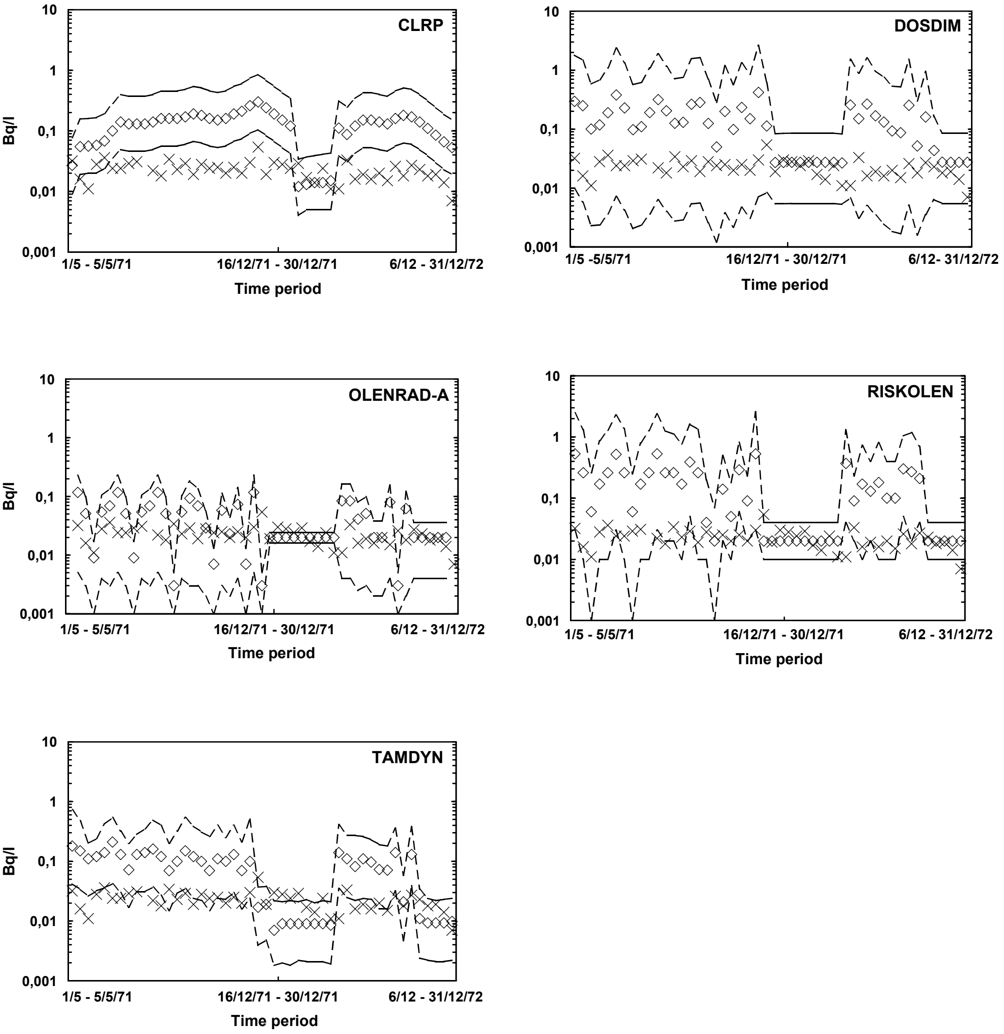


FIG. 9. Radium concentration in cow's milk after deep ploughing. The symbols (◇) and symbols (×) refer to the best estimate values, respectively observed data. The dotted lines indicate the 95% confidence interval of the model predictions.

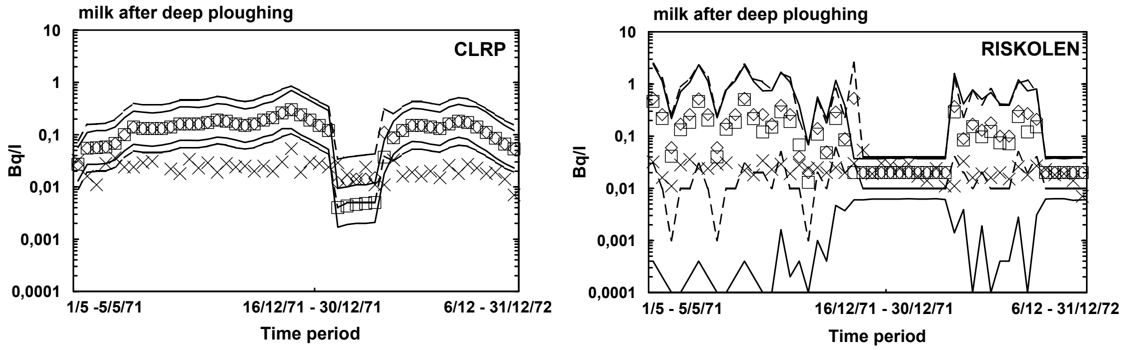


FIG. 10. Initial and revised radium estimates in milk after deep ploughing produced by CLRP and RISKOLEN. The symbols (◇) and symbols (□) refer to the revised, respectively initial best estimate values. The symbols (×) refer to the observed data. The dotted lines and full lines indicate the 95% confidence interval of the revised, respectively initial model predictions.

A decrease of the radium concentration in milk when the cows were stabled as produced by the modellers could not be observed in the field data. In fact, the experimental data showed no trend at all, indicating that probably a mixture of the grass coming from all plots was used to feed the cattle during the stabling period. As could be expected based on this “no trend” observation, comparison with the model predictions showed that the dynamic models did not perform better than the equilibrium models. The overpredictions during the grazing period are possibly due to the fact that the concentrations in grass during the grazing period have been overestimated, since for the grazing period as well as for the stabling period the same grass to milk transport parameters are used. Intercomparison of model predictions has shown the best estimate values vary at average over one order of magnitude.

Although CLRP and DOSDIM used the same equations to calculate the radium transfer from grass to milk, their model predictions have a quite different trend. The predictions produced by CLRP fluctuate barely for the different time periods compared to the predictions produced by DOSDIM. These differences in predictions can be explained by the magnitude of the biological decay coefficient (Table V). CLRP used a biological decay coefficient which is about 20 times lower than the one used by DOSDIM, resulting in higher accumulation of radium from previous plots and hence reflecting less dependency on the spatial radium contamination each time the cows change plots. The predictions by CLRP as shown in Figure 9 are revised predictions. CLRP corrected the predictions for the stabling period (Figure 10). The initial large underestimation was due to an error in the daily radium intake value by cows during the stabling period. Also the uncertainty ranges have slightly been changed. Initially, the compensatory effect of deep ploughing on the uncertainty ranges of the radium concentration in the root zone after deep ploughing was not carried through to subsequent calculations.

The milk to grass concentration ratios shown in Figure 11 demonstrate that the differences in transfer from grass to milk is due to the use of different approaches to model the grass to milk transfer process. For the equilibrium models OLENRAD-A and RISKOLEN, the ratio is approximately 0.003 for all the time periods, the value that is obtained by multiplying the daily grass intake and the equilibrium grass to milk transfer factor. The predictions of the models CLRP, DOSDIM and TAMDYN fluctuate around this value, because they also take into account the time-dependency of the radium transfer to milk. The deviations reflect the radium accumulation in milk from previous plots and the higher the differences in the radium contamination level of the grass between subsequent time periods, the more pronounced the deviations will be.

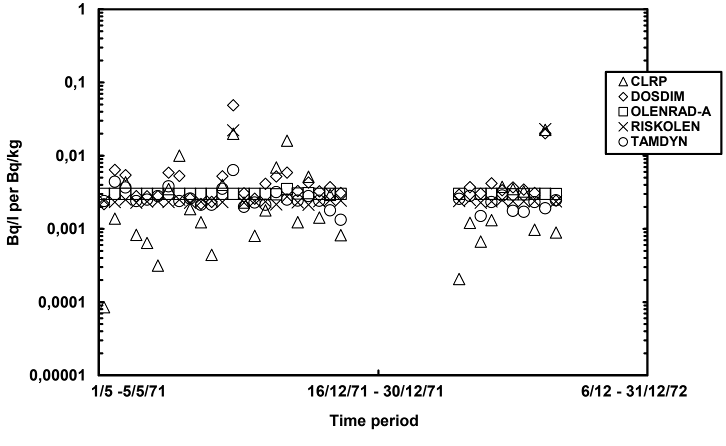


FIG. 11. The predicted mean radium concentration in cow’s milk after deep ploughing, normalised for the predicted mean radium concentration in grass after deep ploughing.

5.1.1.5. Comparison with additional soil profile data

A few soil profiles of 1m depth were taken on the highest contaminated part of the Olen site in the beginning of 1998, nearly 30 years after the deep ploughing action has been carried out. The aim was to get some idea of the effectiveness of deep ploughing.

Somewhere in the middle between the Bankloop and drainage canal at regular distances, samples of 1 m depth were taken and cut into 5 slices (0–15 cm; 15–30 cm; 30–50 cm; 50–75 cm; 75–100 cm). Measurements of the slices have shown that the radium is not distributed homogeneously over 1 m depth. It was impossible to find a consistent trend (increase or decrease) with depth. The radium concentration seems to change randomly with depth; for some samples, the highest radium concentrations were found in the root zone (upper 15 cm) while for others these were found much lower. From these soil profile data, a deep ploughing dilution factor for the root zone that varies between 3 and 20 can be derived. These data were made available after most participants had performed the assessment tasks. Nevertheless, all participants, except TAMDYN, have chosen as best estimate, a value within that range, which also seems to indicate that the overestimation of the radium concentration in milk cannot be explained by underestimating the effectiveness of deep ploughing.

The soil profile data are given in Table X and the location of the sampling points is given in Figure 12. The first sample was taken in the less contaminated area and gives an indication of the background level.

TABLE X. RADIUM CONCENTRATIONS OF SOIL PROFILES (SAMPLING DATE: JANUARY 1998)

Sample number	Depth (cm)	Water content (%)	[Ra] (Bq/kg dw)	Ra distribution over 1 m depth (%)
A	0–15	27	65	
	15–30	25	23	
	30–50	18	16	
B	0–15	35	734	13
	15–30	38	1285	23
	30–50	51	3549	63
	50–75	49	33	0.7
	75–100	19	17	0.3
C	0–15	32	1827	38
	15–30	32	1710	35
	30–50	46	1243	26
	50–75	51	35	0.5
	75–100	76	40	0.5
D	0–15	33	2356	30
	15–30	28	1399	18
	30–50	54	4069	51
	50–75	76	60	0.8
	75–100	69	26	0.2
E	0–15	29	590	4.5
	15–30	29	590	4.5
	30–50	73	11800	90
	50–75	45	25	0.5
	75–100	48	27	0.5
F	0–15	27	267	7
	15–30	21	141	4
	30–50	23	35	1
	50–75	35	68	2
	75–100	69	3223	86

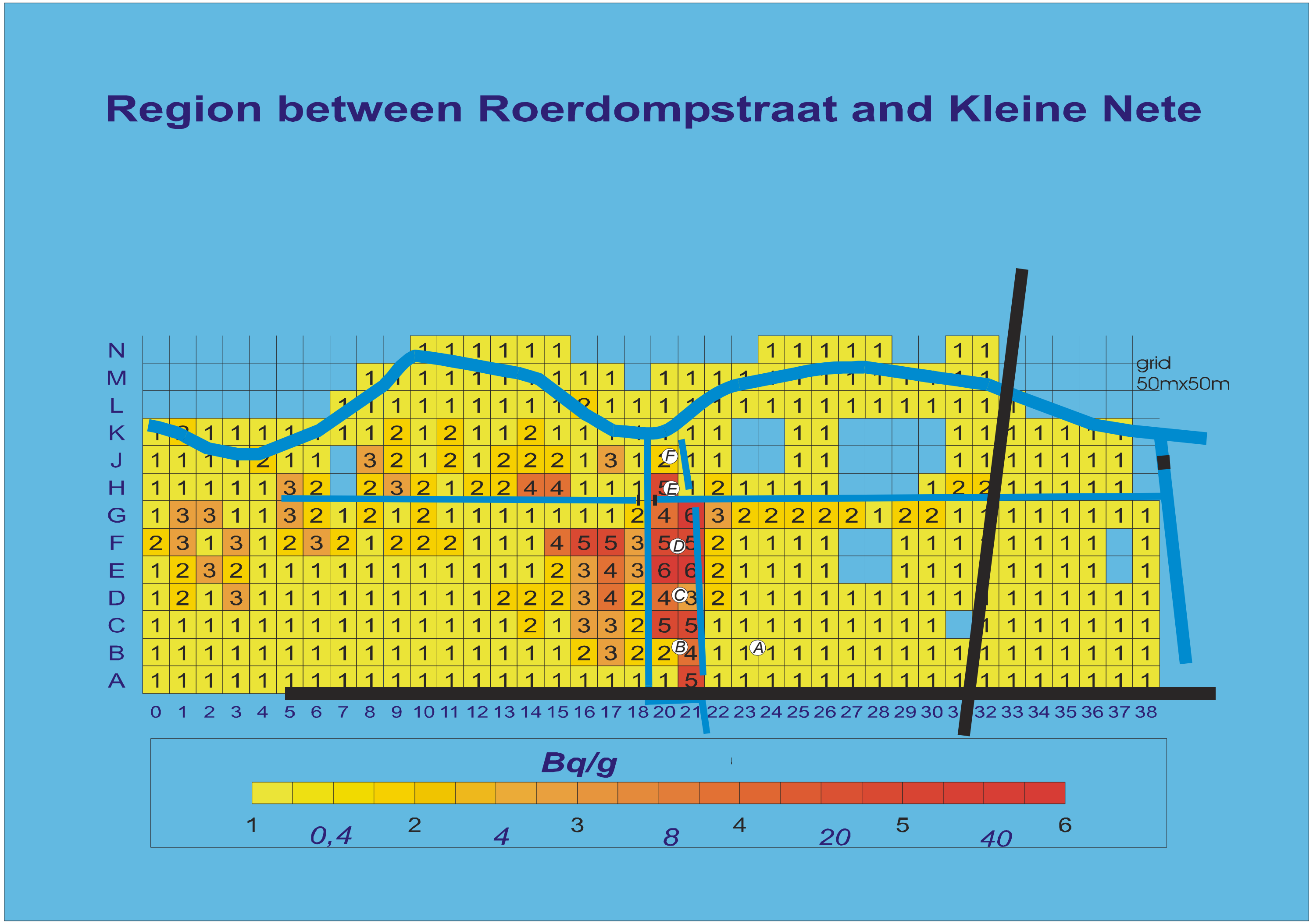


FIG. 12. Localisation of sampling points A, B, C, D, E.

TABLE XI. RADIUM CONCENTRATIONS IN GRASS (SAMPLING DATE: JANUARY 1998)

Sample number[a]	[Ra] (Bq/kg dw)	B_v(dw/dw)
B	104.7	0.14
C	254	0.14
D	110.7	0.05
E	89	0.15

[a] The sample numbers correspond with the places where soil profiles were taken.

The results observed for the root zone are comparable with the predictions made by the modellers. However, by interpreting these results, it should be kept in mind that:

- the samples were taken in the highest contaminated area, for which, according to the scenario description, the radium concentration in the root zone is a factor 1 to 5 higher than the average value obtained for the most contaminated pasture plot. This means, assuming the radium concentration in the root zone did not change very much over the last 25 years, that overestimates of the radium concentration in milk by a factor of 5 can be explained by an overestimation of the radium concentration in root zone;
- during the period 1960 to 1990 the upper 40 cm were ploughed several times;
- migration of radium may have occurred although no increase with depth was noticeable.

Also grass samples were taken and an average in-situ soil-to-plant transfer factor of 0.12 was obtained (Table XI), higher than the value derived from the scenario description. The grass samples were taken not only on the place were the soil profiles (surface area about 0.01 m^2) were taken but also within a radius of 10 cm around the soil sampling place. The problem however is that, due to the spatial heterogeneity of the radium contamination in root zone, the radium concentration in grass is not really related to the radium concentration measured in the soil profiles. This might explain the large range in the soil-to-plant transfer factors.

5.1.2. Uncertainty and sensitivity analysis

5.1.2.1. Uncertainty estimates

All modellers performed uncertainty analyses. Two techniques were used to obtain the uncertainty estimates (Table I). TAMDYN, RISKOLEN and DOSDIM used the Monte Carlo method with either random or Latin Hypercube sampling, CLRP and OLENRAD-A used the error propagation method. There are important sources of uncertainty contributing to the size of the estimated confidence intervals, like:

- the parameters considered in the uncertainty analysis. OLENRAD-A does not consider the uncertainty in the deep ploughing effect, resulting in smaller uncertainty ranges for the soil concentration after deep ploughing than predicted by the other models. In contrast to the other models, OLENRAD-A also assumes no uncertainty associated with the radium concentration in the root zone of plot number 6 before deep ploughing.

  Because of difference in the level of detail and approach, the parameter requirements of the models also differed. To calculate the transport of radium in the cow dynamically, TAMDYN consider more input parameters in the uncertainty analysis than the other models (Table V). None of these input parameters were given in the scenario description and as result, the choice of the parameter values and associated uncertainty ranges are mainly based on personal judgement. Also the type of correlation (positive or negative) between the parameters has an important effect on the size of uncertainty ranges of the predictions. For CLRP, the uncertainty ranges associated with radium concentrations in the root zone after deep ploughing are reduced with respect to those before deep ploughing, due to the assumption that radium is more uniformly distributed over 1 m depth after deep ploughing (negative correlation between the variability of the spatial radium distribution in each plot and the deep ploughing effect).

- The 95% intervals associated with the input parameters. The differences in the uncertainty of the input parameters, in particular the deep ploughing dilution factor, are largely due to the confidence one has in the information given in the scenario description. With exception for OLENRAD-A and CLRP that considered no, respectively a compensatory effect of deep ploughing on the variability of the radium distribution in the root zone, the soil concentrations after deep ploughing vary by a factor of at least 2 more than the soil concentrations before deep ploughing.

  Different assumptions were made concerning the uncertainty estimates of the deep ploughing effect. For example, TAMDYN considered the given soil profile data representative values for the radium distribution over soil depth and used them directly to derive uncertainty estimates for the deep ploughing effect. DOSDIM on the other hand considered the set of data and indirect information about the deep ploughing technology too limited to be useful and assumed a large uncertainty for the deep ploughing dilution factor (between no effect and a dilution factor of 100, with homogeneous mixing over 1 m as best-estimate). CLRP also used personal judgement to estimate the uncertainty ranges of the deep ploughing effect. In contrast to other modellers, the uncertainties associated with the radium concentrations in the root zone after deep ploughing were reduced compared to those before deep ploughing, because CLRP assumed that deep ploughing led to a more uniform distribution of radium in the root zone.

5.1.2.2. Sensitivity analysis

In the equilibrium models presented in this report all input parameters are proportional related to the outcome of the model calculations. This means that for the radium concentration in milk all input parameters are potentially significant and their contribution to the uncertainty of the predictions will depend on the range over which the parameters may vary. On the other hand, for models like DOSDIM and TAMDYN that also use exponential terms to calculate the grass-to-milk transfer of radium, the identification of sensitive parameters may not be so straightforward and a sensitivity analysis may be necessary to determine which parameters have the greatest effect on the radium concentration in milk. However, a sensitivity analysis of the DOSDIM predictions is unnecessary because the model only uses one exponential grass-to-milk transfer coefficient for which no uncertainty ranges were provided. As for the equilibrium models, the sensitivity of the DOSDIM output for milk will only depend on the range over which the other input parameters operate.

TAMDYN is the only model that considers seven additional transfer coefficients in the uncertainty analysis which are not linear correlated with the output (Table V). The most important parameter is the blood plasma-to-milk coefficient, the second one is the GIT-to-plasma coefficient and the third one is the soil-to-grass uptake coefficient. The deep ploughing dilution factor contributes less to the radium concentration in milk because its uncertainty range was unrealistically small chosen. As a result, the uncertainty in the radium concentration in milk by TAMDYN reflects mainly the uncertainties in the radium transfer from grass to milk, whereas the uncertainty in the DOSDIM predictions is primarily due to the uncertainty associated with the deep ploughing effect.

5.1.2.3. Importance of the probability density function type in the uncertainty analysis

In many cases, like the Olen scenario, insufficient data are available to assign appropriate statistical distributions to the parameter values and model users are enforced to use personal judgment to select parameter distributions.

The RISKOLEN user examined the influence of the type of the probability density function (pfd) of the input parameters on his predictions in grass and milk. Two parameters were considered; the deep ploughing dilution factor and the radium concentration in the root zone before deep ploughing, for which three types of pfds (uniform, triangular and lognormal distribution) were examined. It was found that the choice of the pfd type may affect the predictions. Further details of this study are given in Appendix II, par. II-1.4.3.

5.2. SCENARIO TYPE B

5.2.1. Deterministic calculations

The first step in the modelling exercise was to derive the radium and lead concentrations for the areas used as pasture, garden and building site for the farm. All models except OLENRAD-B made predictions for lead and although in order to simplify the calculations, it was given in the scenario description that radium and lead were in equilibrium at year 1, only DOSDIM used this assumption.

In Table XII, the radium and lead concentrations are summarised for the different remedial actions. With exception of CLRP-RAD and TAMDYN-UV, these values represent the concentrations in the upper 1 m soil layer for no remediation and upper 0.5 m soil layer for remediation 1 and 2 whereby homogeneous distribution of radium and lead with depth was assumed. As mentioned earlier, CLRP-RAD and TAMDYN-UV considered the heterogeneity of radium and lead with depth. They break the soil profile down into several soil compartments and calculate the contribution of each soil layer to the different exposure pathways. Their average concentrations over root depth and over, if available, the upper 0.5 or 1 m soil layer are given in Table XII. For the remedial actions, they assumed in agreement with the scenario description that radium and lead were initially homogeneously distributed over the upper 0.5 m soil layer. In the scenario description, it was given that the surface soil layer was ploughed over a depth of 30 cm two-yearly if used as kitchen garden and seven-yearly, if used as pasture. All modellers, except CLRP, took the effect of ploughing into account by averaging the radionuclide concentration over the cultivated soil layer. RESRAD (ONSITE) assumed that remediation 1 involved the covering of the whole site, not only the remediated areas, by a 0.5 m less contaminated soil.

It is observed that for the current situation (‘no remediation’), all models derived comparable concentrations for garden and farm. On the other hand, for the field that covers a much larger area, quite different soil concentrations have been used, probably because there were not enough data available to derive an average representative soil concentration for the whole area. The spread in results reflects mainly the different degrees of conservatism adopted for calculating the soil concentrations. Some modellers (CLRP-RAD, OLENRAD-B, RESRAD-OFFSITE) considered only the highest measured soil data, while the others took an area averaged radium concentration. To calculate the lead concentration in the different soil layers, TAMDYN-UV also took the upward radon flux into account, while the other modellers did not. This explains the higher lead concentrations in the cover for garden and farm compared to the radium concentrations.

TABLE XII. RADIUM AND LEAD CONCENTRATIONS FOR PASTURE, KITCHEN GARDEN AND AROUND THE FARM AFTER THE DIFFERENT REMEDIAL ACTIONS AT YEAR 1 (THE VALUES PRESENT THE AVERAGE CONCENTRATIONS IN THE UPPER 1 M SOIL LAYER FOR NO REMEDIATION AND UPPER 0.5 M SOIL LAYER FOR REMEDIATION 1 AND 2, UNLESS OTHERWISE INDICATED)

	CLRP-RAD	DOSDIM	OLENRAD-B	RESRAD (ONSITE)	RESRAD-OFFSITE	TAMDYN-UV
^{226}Ra concentration (Bq/kg)						
No remediation:						
Pasture	1586 (2459[a])	300	1880	766	2400	128 (250[a,c])
Garden	1586 (1639[b])	2000	1880	1880	1900	1322 (2590[b])
Farm	1586	2000	2356	1880	2800	1322 (2590[b])
Remediation 1: Removal of most contaminated soil						
Pasture	60 (200[d])	150	60	60 (316[d])	60	150
Garden	60 (200[d])	60	60	60 (316[d])	60	60
Farm	60 (200[d])	60	60	60 (316[d])	60	60
Remediation 2: Covering with a 0.5 m clean soil layer						
Pasture	20	21	20	20	0	150
Garden	20	21	20	20	0	20
Farm	20	21	20	20	0	20
^{210}Pb concentration (Bq/kg)						
No remediation:						
Pasture	1370 (2123[a])	300	not done	23	72	102 (200[a,c])
Garden	1370 (1416[b])	1997	not done	57	57	1043 (1980[b])
Farm	1370	1997	not done	57	84	1043 (1980[b])
Remediation 1: Removal of most contaminated soil						
Pasture	52 (170[d])	150	not done	1.8	1.8	110
Garden	52 (170[d])	60	not done	0.9	1.8	46
Farm	52 (170[d])	60	not done	0.9	1.8	46
Remediation 2: Covering with a 0.5 m clean soil layer						
Pasture	17	21	not done	0.6	0	110
Garden	17	21	not done	0.6	0	65
Farm	17	21	not done	0.6	0	65

[a] Average concentration in upper 15 cm soil layer.
[b] Average concentration in upper 30 cm soil layer.
[c] Average concentration in upper 50 cm soil layer.
[d] Average concentration in upper 1 m soil layer.

For the remedial actions, it was assumed in the scenario description that the farm was built after the remediation was carried out. In the table, the concentrations of the farm soil refer to the soil around the farm. Three modellers (CLRP-RAD, OLENRAD-B and TAMDYN-UV) did not consider a cellar. It may however be expected that the foundation of the house, even if no cellar is considered, is deep enough to reach the contaminated soil layer. The differences between the estimated soil concentrations mainly reflect variations in scenario interpretation (misinterpretation). Some modellers assumed that the remedial actions were applied to the whole site, while others assumed that only the most contaminated areas of the site were remediated. For example, in contrast with the other modellers, the TAMDYN-UV user assumed that the covering with a clean soil (remediation 2) was not intended for the whole pasture soil but only for the most contaminated parts of the pasture land (identical to the situation considered for pasture after remediation 1).

5.2.1.1. No remediation

5.2.1.1.1. Radium

The total dose ranges from 5 mSv/y for DOSDIM to 11 mSv/y for TAMDYN-UV at year 1 (Figure 13). The radon inhalation indoors is mainly responsible for these differences (Figures 14 and 15). Its contribution to the total dose of radium varies between 52% (RESRAD-OFFSITE) and 84% (RESRAD (ONSITE)) (Figure 15). The radon concentrations indoors are usually much higher than the radon concentrations outdoors, especially when the building is not well-ventilated.

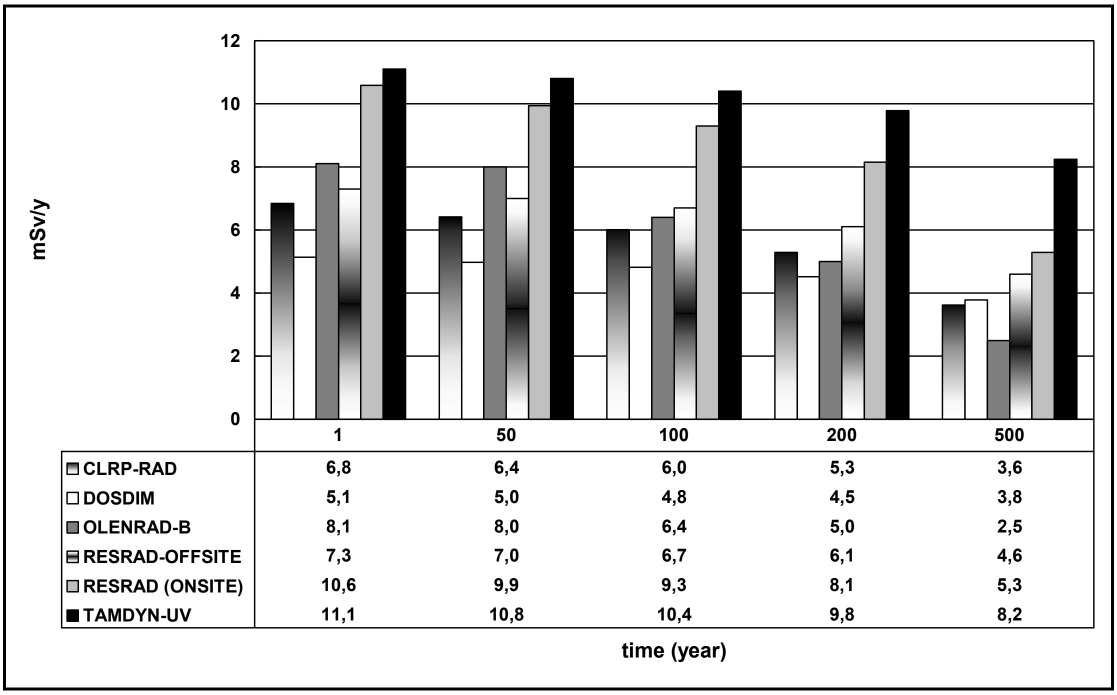
Second most important pathway is the external irradiation. The contribution of the external irradiation in- and outdoors sums up from about 12% (RESRAD (ONSITE) to 42% (RESRAD-OFFSITE) of the total dose at year 1 (Figure 15). According to some models (CLRP-RAD, DOSDIM, RESRAD (ONSITE)) the external irradiation outdoors is less important than indoors, while other models predicted similar (TAMDYN-UV, RESRAD-OFFSITE) or higher doses for the outdoors pathway (OLENRAD-B, RESRAD (ONSITE)). OLENRAD-B calculated the external irradiation based on the measured dose rates that were given in the scenario description.

Except for CLRP-RAD, the third most important pathway is the ingestion of leafy vegetables (via root uptake). Its contribution varies between 2.8% (RESRAD (ONSITE)) and 6% (DOSDIM) of the total dose.

With time, the total dose of radium decreases, due to changes in radium fixation in the soil and radioactive decay. The doses via the various pathways decrease more or less to a same extent, leading to nearly no changes in their relative contribution to the total dose with time (Figures 15 and 16).

Intercomparison of the radium concentrations in soil shows the losses of radium from the root zone of the soil in time are modelled differently (Figure 17). CLRP-RAD and DOSDIM considered leaching as the most important downward transport process in the soil, but CLRP-RAD used other parameter values than given in the scenario description to calculate the leaching rate. OLENRAD-B and RESRAD (ONSITE) considered also the losses of radium by wind erosion, leading to a much higher decrease of the radium concentration in the root zone. TAMDYN-UV previously only considered diffusion of radium and no leaching, leading to small losses of radium from the root zone soil (only 20% after 500 years). The model predictions given in Figure 17 are the revised ones which take into account leaching, leading to losses up to 40% after 500 years. It is obvious that the different assumptions made concerning the importance of the various soil processes are reflected in the time evolution of the dose impact of most exposure pathways. An exception is the radon indoor inhalation dose for which also the modelling approach seems to have a great effect on the time evolution of the dose.

Differences up to two orders of magnitude at the most are observed among the models for all exposure pathways contaminated by radium via the soil. For the exposure pathways contaminated via water through drinking or irrigation, for example potatoes contaminated via foliar absorption, the differences are more pronounced (Figure 14).



	1	50	100	200	500
▤ CLRP-RAD	6,8	6,4	6,0	5,3	3,6
□ DOSDIM	5,1	5,0	4,8	4,5	3,8
▩ OLENRAD-B	8,1	8,0	6,4	5,0	2,5
▤ RESRAD-OFFSITE	7,3	7,0	6,7	6,1	4,6
▨ RESRAD (ONSITE)	10,6	9,9	9,3	8,1	5,3
■ TAMDYN-UV	11,1	10,8	10,4	9,8	8,2

FIG. 13. Predictions of the total radium dose for the current situation 'no remediation'.

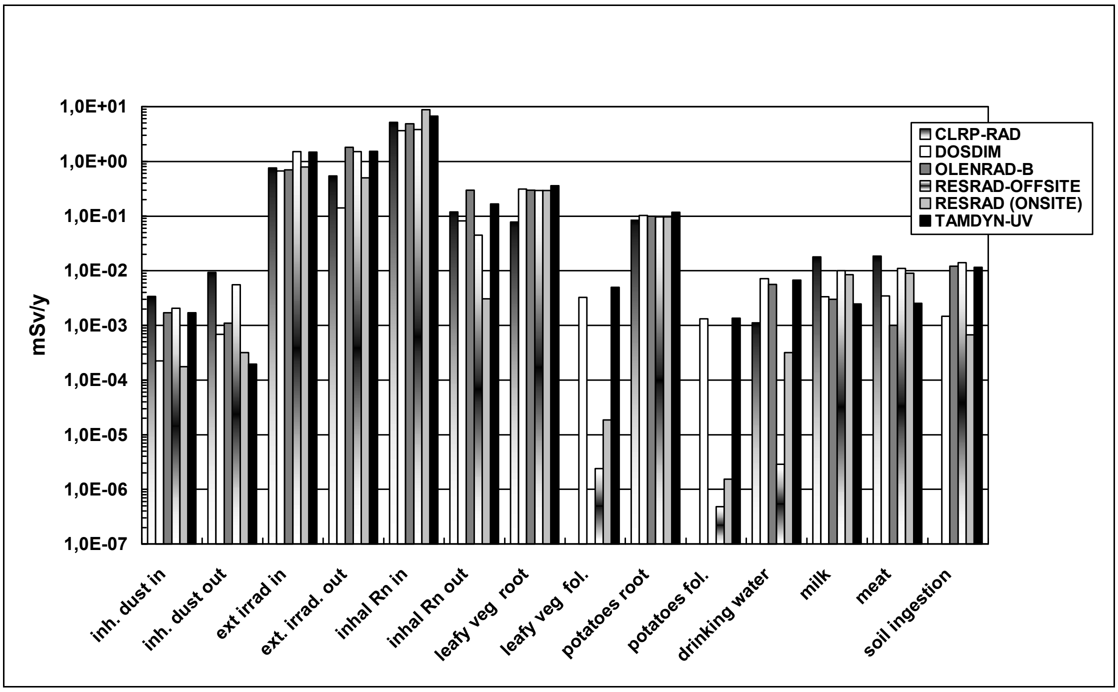


FIG. 14. Predictions of the radium dose via different pathways for the current situation 'no remediation' at year 1.

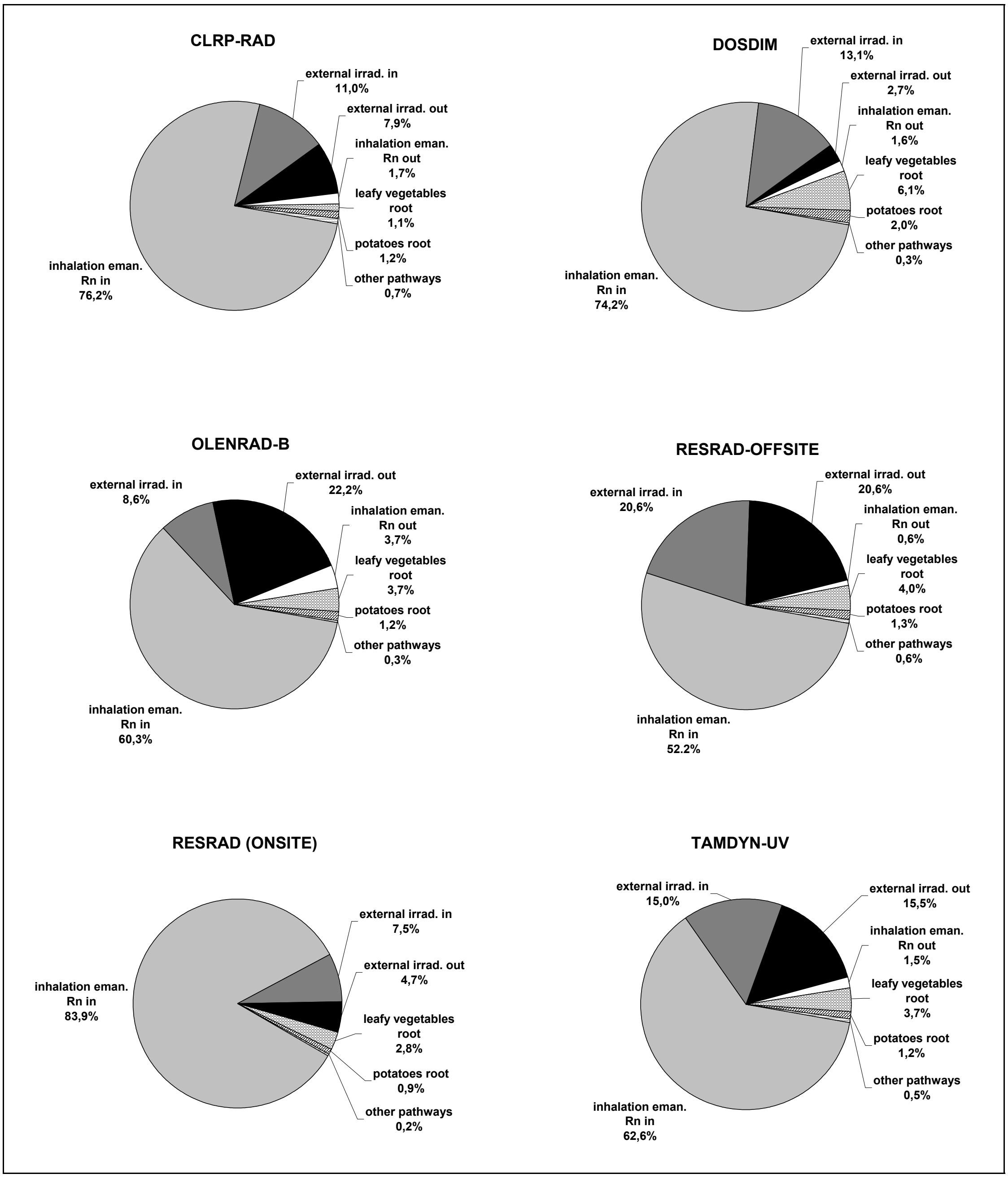


FIG. 15. Contribution of the different pathways (%) to the total predicted radium dose for the current situation 'no remediation' at year 1.

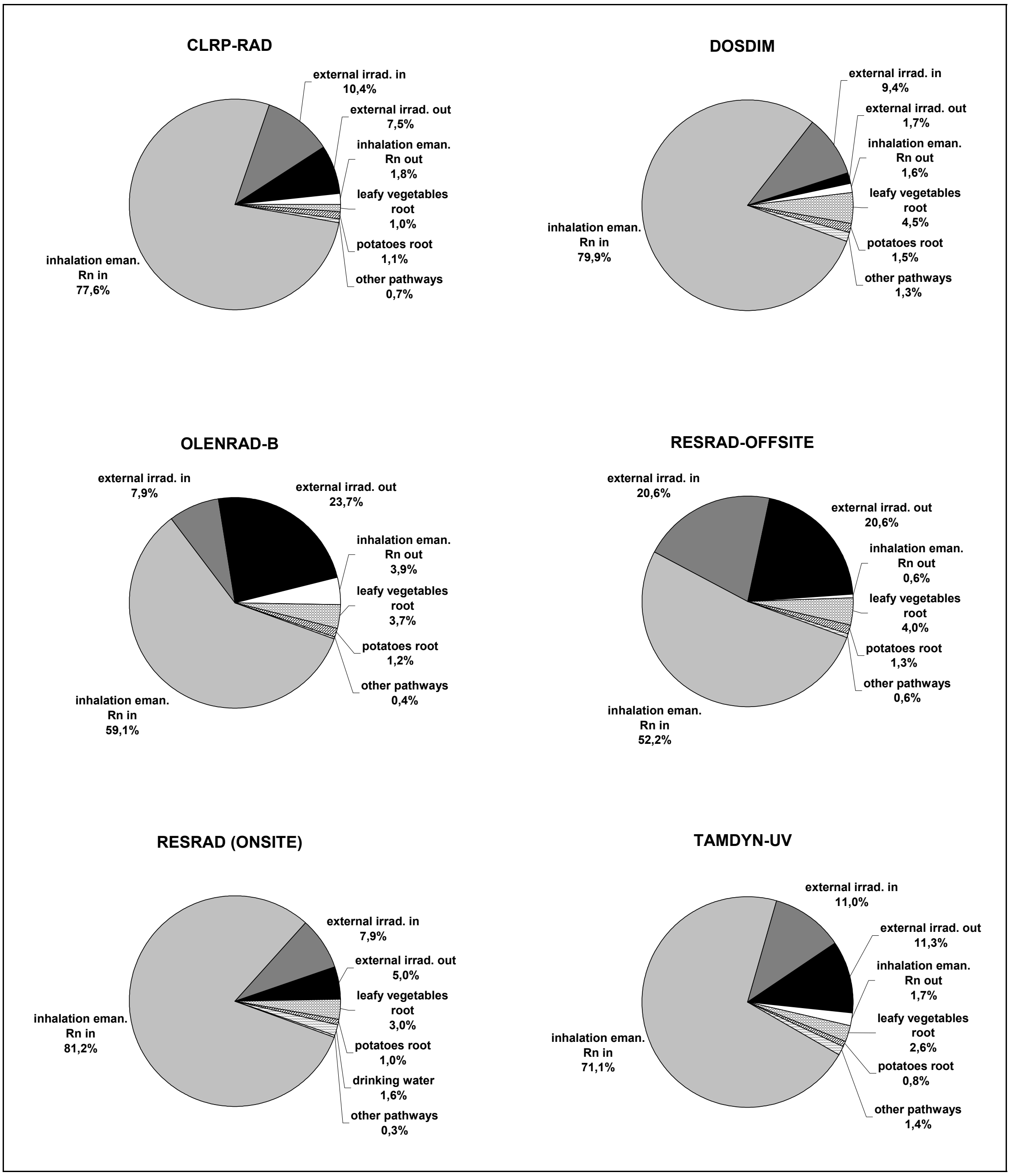


FIG. 16. Contribution of the different pathways (%) to the total predicted radium dose for the current situation 'no remediation' at year 500.

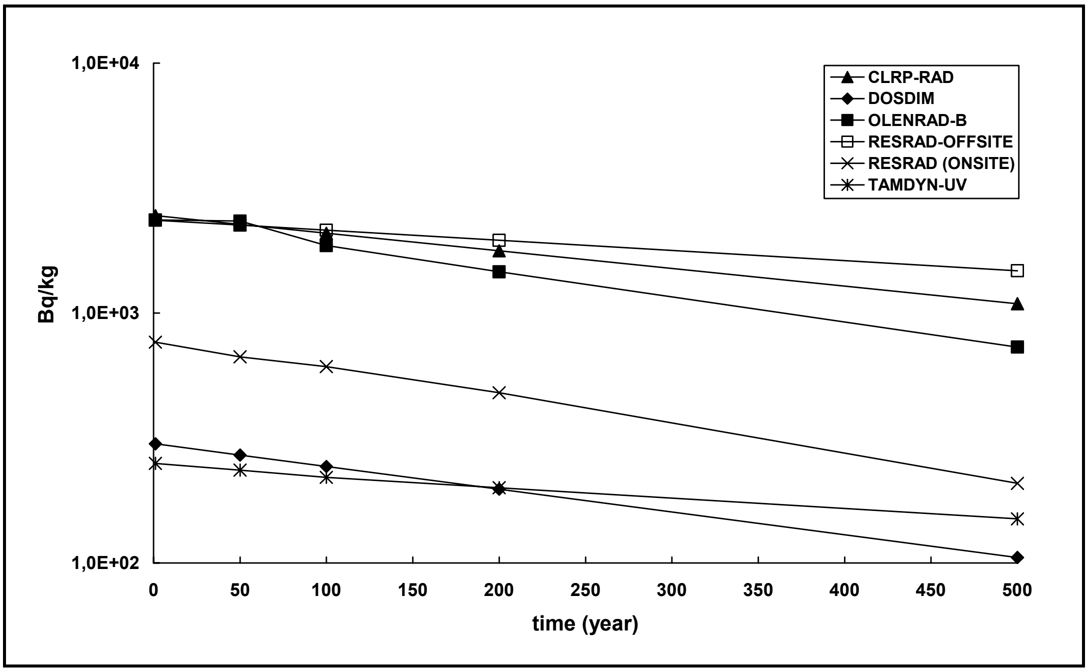


FIG. 17. Time-dependence of the predicted concentration of radium in the upper 15 cm of pasture land for the current situation 'no remediation'.

The differences observed reflect mainly that the scenario was interpreted differently by the modellers. For the dust inhalation pathway the differences are mainly due to the different assumptions made concerning the areas (pasture/garden/farm) the dust is coming from, the inhalable dust concentration in air in- and outdoors and the breathing rate during the different activities (Table VIII). Normalisation for the soil concentration decreases the differences to one order of magnitude (Figure 19). As expected, the dose due to inhalation of dust is very low. Only up to 0.1% of the total radium dose is caused by inhalation of contaminated dust.

For the external irradiation and radon inhalation pathways similar conclusions can be drawn. Especially how to take into account the time spent outdoors (on the field, in the garden or near the house) was not very clear and led together with the differences in soil concentration for pasture (Table XII) to differences up to two orders of magnitude for the outdoors pathways, while for the indoors pathways less than one order of magnitude was observed. OLENRAD-B did not estimate the dose rates but used the measured ones given in the scenario description. The uncertainty associated with the scenario may also explain the observation that some models obtain higher doses for the inhalation of dust and external irradiation indoors while other models get the highest doses outdoors.

Although the radon concentration in indoor air originates mainly from the radium in the soil surrounding the house, it is difficult to relate the observed radon concentrations indoors to the measured radium concentrations in soil. The situation arises because radon concentrations indoors depend upon a large number of factors including the number and size of cracks in the foundation of the house, the air exchange rate, diffusion coefficients in soil and building materials and the lifestyle of the house's occupants [4, 5]. The model predictions for the radon inhalation dose indoors however agree rather well (factor of 4), despite the large modelling uncertainty. This can be explained by the fact that most models used a similar approach taking, due to the lack of data, into account the parameter values for properties of the house and soil, the ventilation rate, measured exhalation factors, etc as given in the scenario description. Most modellers also used the measured transfer coefficients of the radium concentration in soil to the radon concentration indoors and to the radon concentration outdoors to derive values for input parameters that were not given in the scenario description or to adjust given values. An exception is DOSDIM that used the measured transfer coefficients directly in the radon inhalation calculations.

CLRP-RAD and OLENRAD-B assumed that the contamination of food crops (leafy vegetables, potatoes) via foliar absorption is negligible. The other models also showed that the foliar contamination of leafy vegetables and potatoes is less important (Figures 24 to 27). It is seen that the foliar absorption is one to two orders of magnitude lower than the contamination of the food crops via root uptake. Because CLRP-RAD used a lower consumption rate than given in the scenario description (e.g. 17 kg/y instead of 56 kg/y, Table VIII), the ingestion dose of leafy vegetables (via root uptake) as obtained by CLRP-RAD is the lowest. With exception of CLRP-RAD for leafy vegetables, the model predictions for leafy vegetables and potatoes via root uptake are quite consistent. Differences of less than a factor of two are observed. For the ingestion via foliar uptake, the differences are much larger, due to the uncertainty associated with the ground water predictions. The differences obtained for the ingestion dose of leafy vegetables/potatoes (foliar)-to-ground water ratio are mainly due to differences in the considered subpathways (Figure 25). The RESRAD codes calculate the contamination of the food crops via a water independent pathway (e.g. root uptake and foliar dust deposition) and water dependent pathway (e.g. overhead irrigation pathway). But although the contamination of plants via root uptake and via foliar uptake are not standard outputs of the RESRAD codes, they can be extracted by running the code several times. RESRAD (ONSITE) submitted results for the water dependent and water independent pathways. In the Figures 23 to 26, it was however assumed that the water independent pathway represented the root uptake and the water dependent pathway represented the foliar uptake. The RESRAD-OFFSITE user performed separate runs to produce the subpathway doses. Thus, like for other models, the results reported by RESRAD-OFFSITE for root uptake include uptake from the contaminated soil and root uptake from the contaminants accumulated in soil following irrigation. The results reported for foliar uptake include dust deposition and irrigation sprinkled on the foliage.

In contrast with the RESRAD codes and TAMDYN-UV, DOSDIM did not consider the contamination of the foliage via dust deposition. DOSDIM assumed that the contribution of dust deposition to the dose is negligible compared to the contamination via irrigation.

It is furthermore seen that the dose via foliar absorption gets more important with time, while the dose via root uptake decreases slowly. The reason is the leaching of radium from the soil into the aquifer.

The dose via ingestion of drinking water is very low (less than 0.1% of the total dose). It varies between 3E-06 mSv/y (RESRAD-OFFSITE) and 0.007 mSv/y (DOSDIM, TAMDYN-UV) at the first year (Figure 29). The time dependency of the doses is consistent with the time dependency of the radium concentrations in ground water (Figure 28).

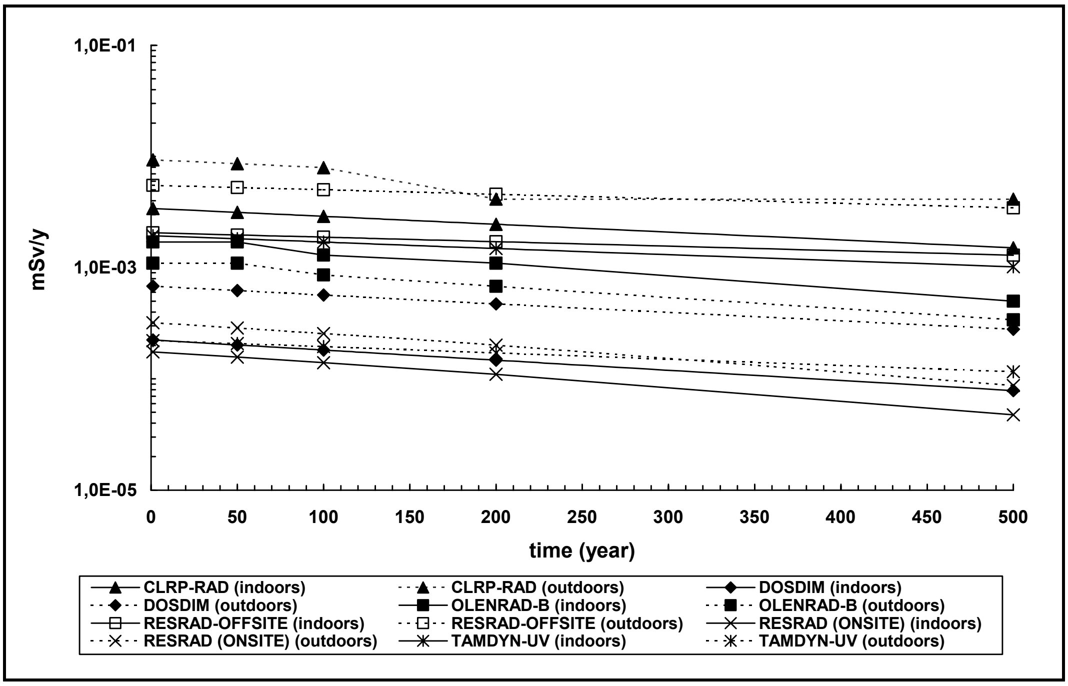


FIG. 18. Predicted inhalation dose of ^{226}Ra contaminated dust for the current situation 'no remediation'.

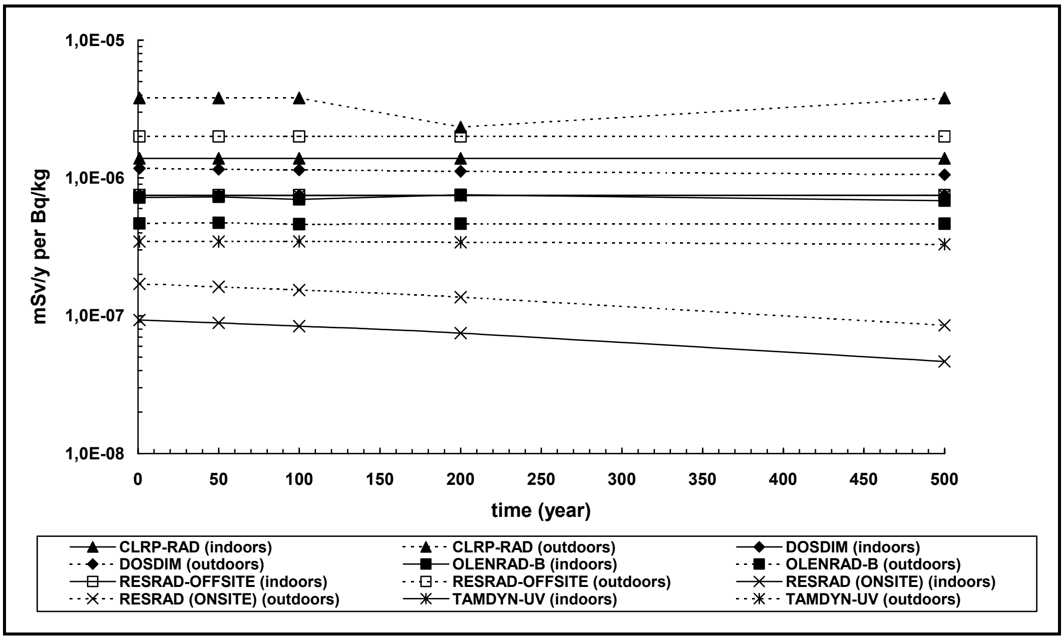


FIG. 19. Predicted dust inhalation dose of radium normalised against the predicted concentration in soil for the current situation 'no remediation'.

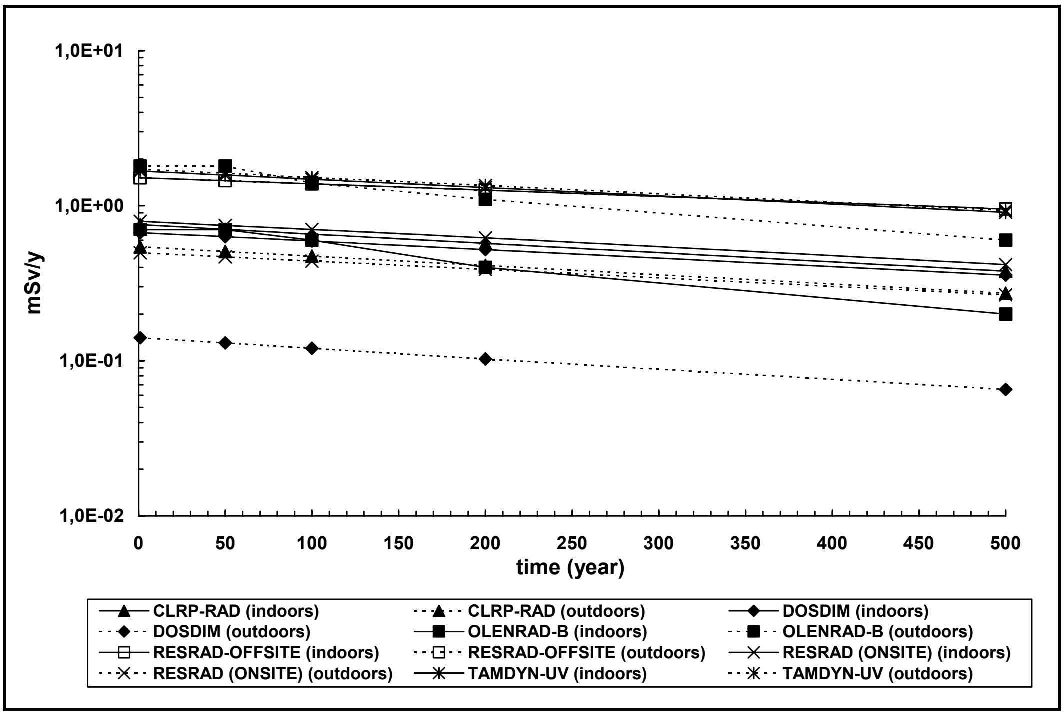


FIG. 20. Predicted external irradiation dose of ^{226}Ra for the current situation 'no remediation'.

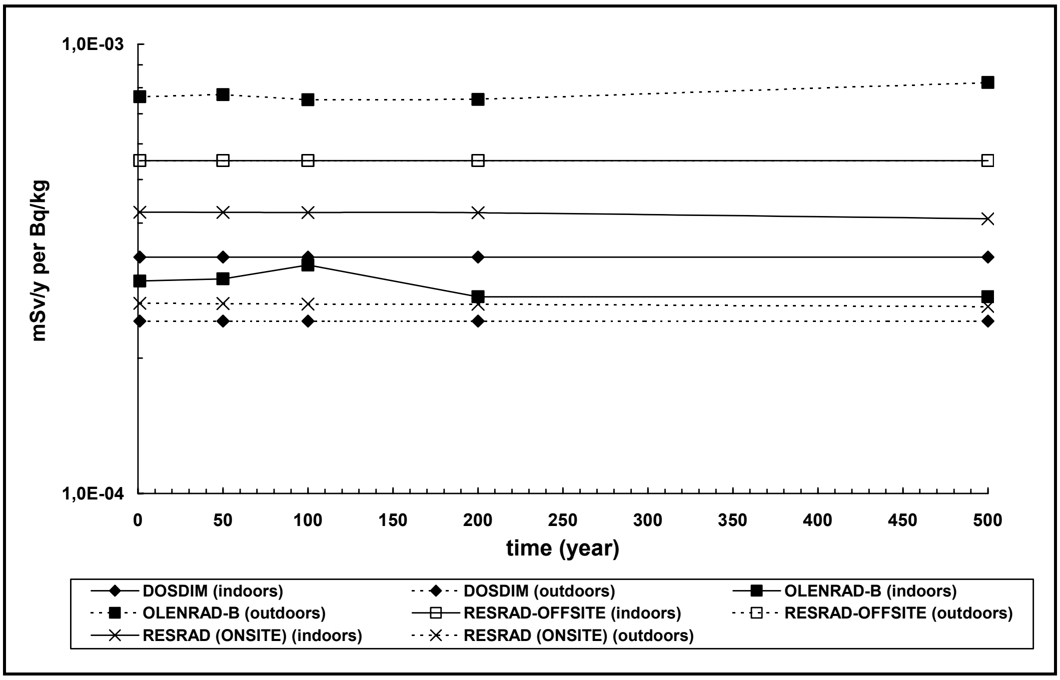


FIG. 21. Predicted external irradiation dose of ^{226}Ra normalised against the predicted concentration in soil for the current situation 'no remediation'.

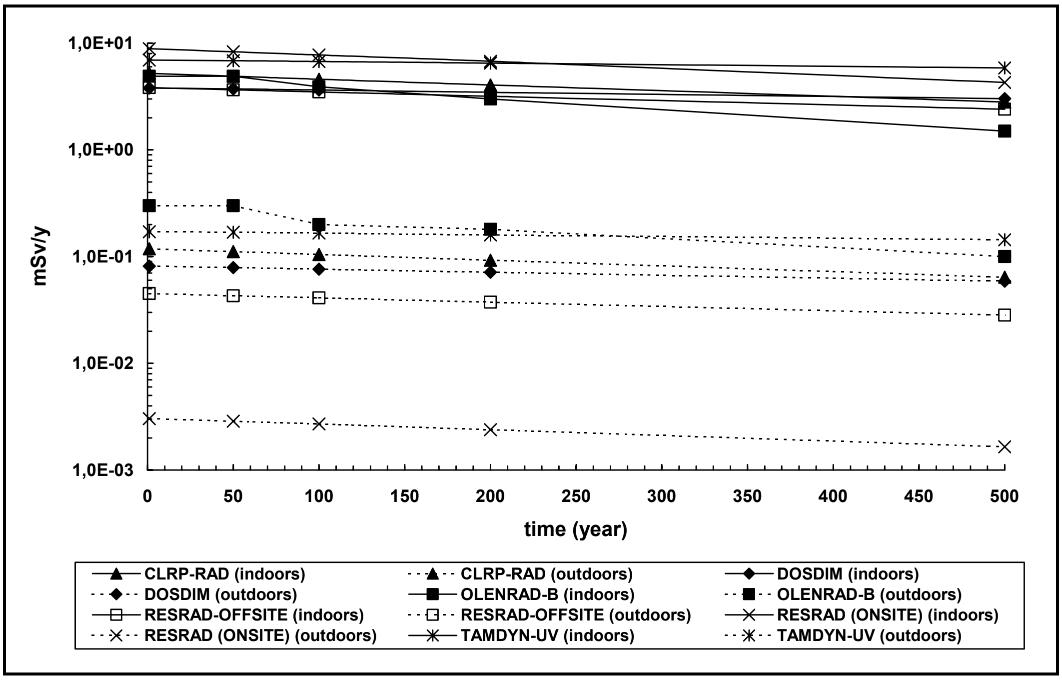


FIG. 22. Predicted inhalation dose of radon for the current situation 'no remediation'.

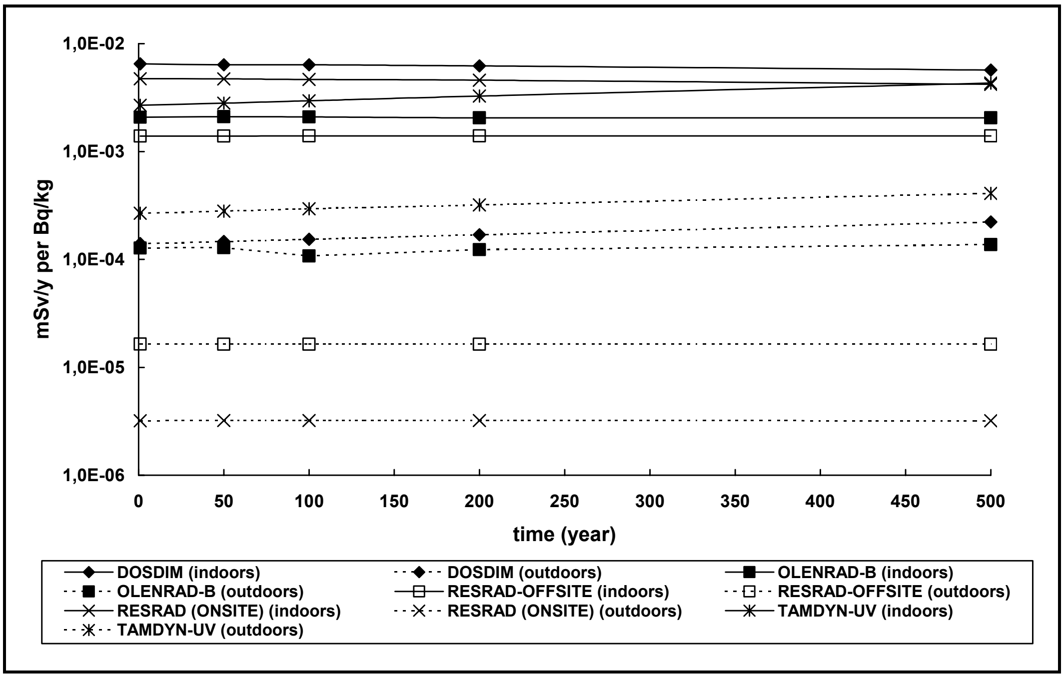


FIG. 23. Predicted inhalation dose of radon normalised against the predicted concentration in soil for the current situation 'no remediation'.

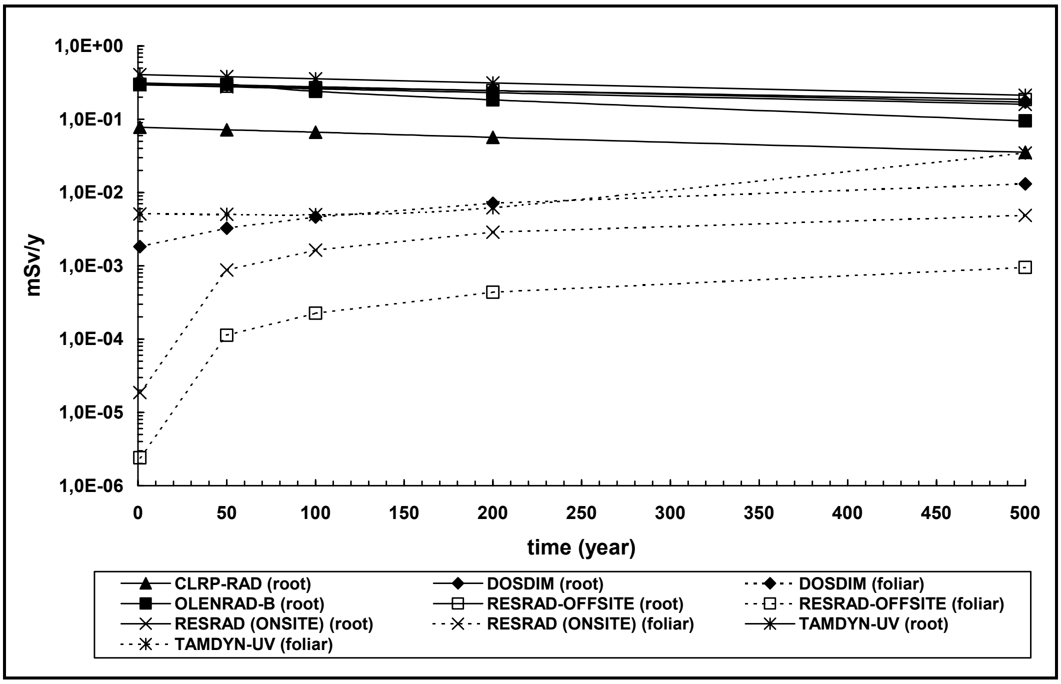


FIG. 24. Predicted ingestion dose of ^{226}Ra contaminated leafy vegetables for the current situation 'no remediation'.

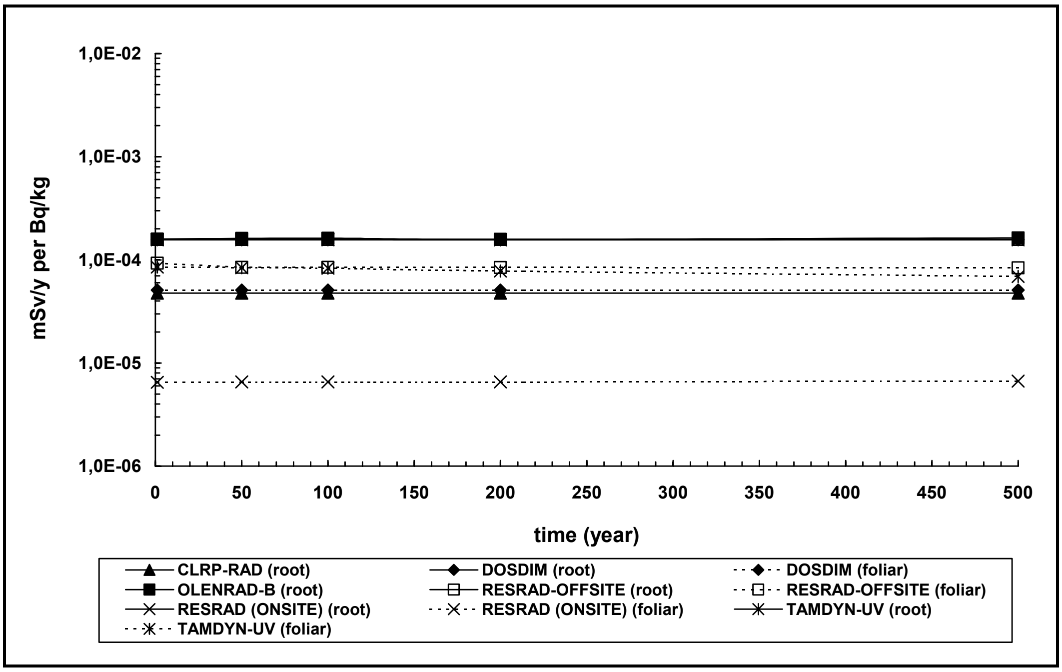


FIG. 25. Predicted ingestion dose of leafy vegetables ^{226}Ra contaminated via root uptake, respectively via foliar uptake normalised against the concentration in garden, respectively ground water for the current situation 'no remediation'.

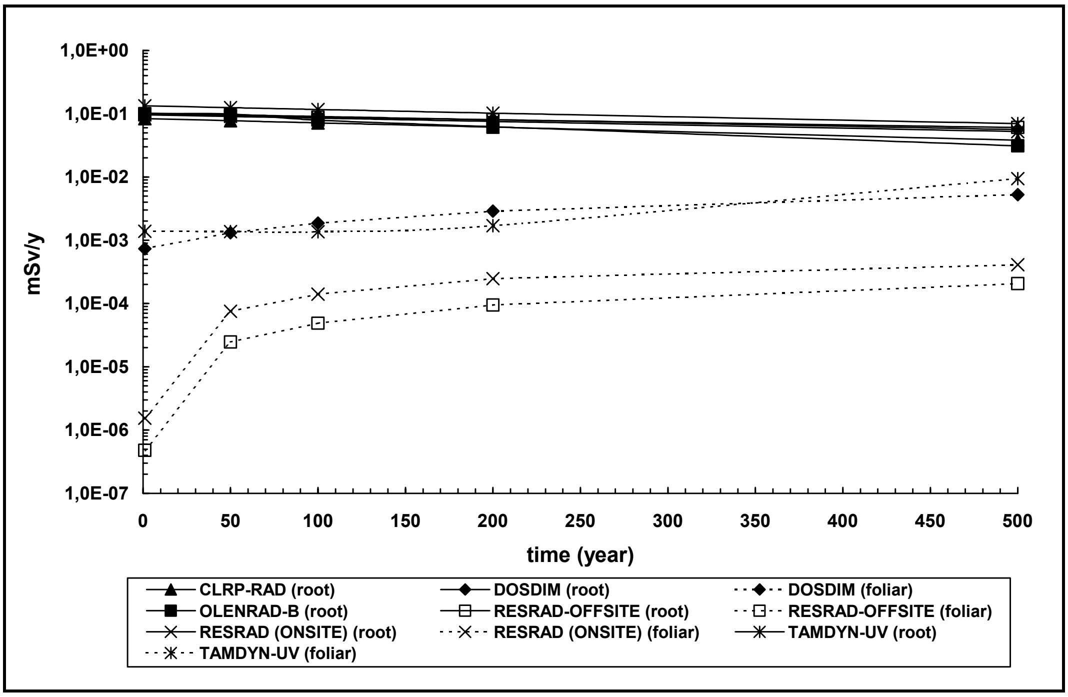


FIG. 26. Predicted ingestion dose of ^{226}Ra contaminated potatoes for the current situation 'no remediation'.

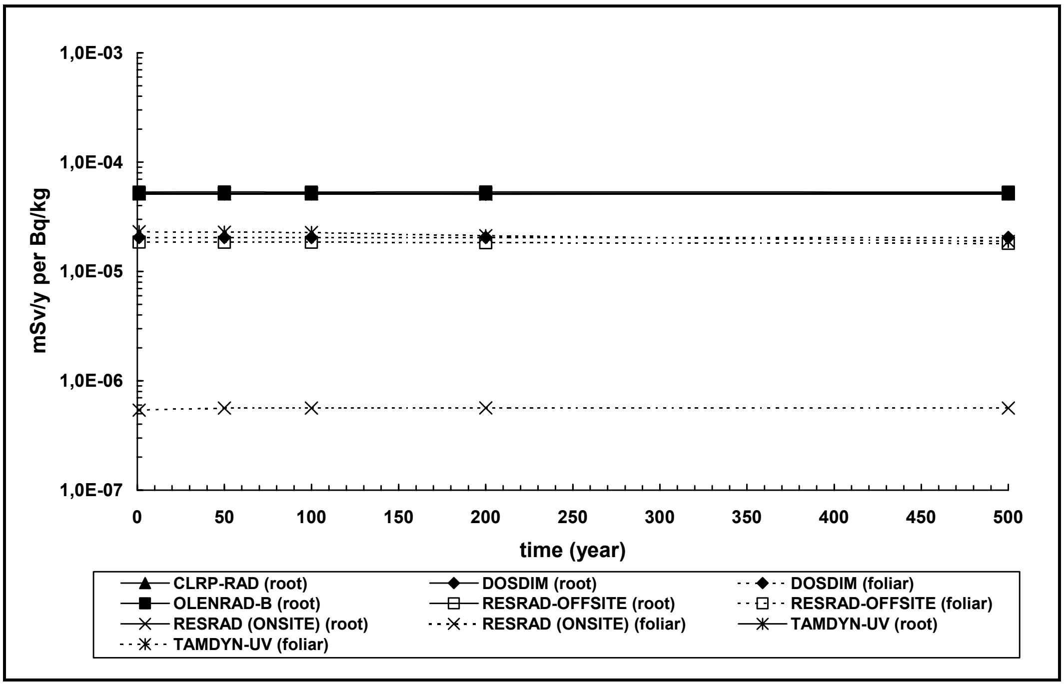


FIG. 27. Predicted ingestion dose of potatoes ^{226}Ra contaminated via root uptake, respectively via foliar uptake normalised against the concentration in garden, respectively ground water for the current situation 'no remediation'.

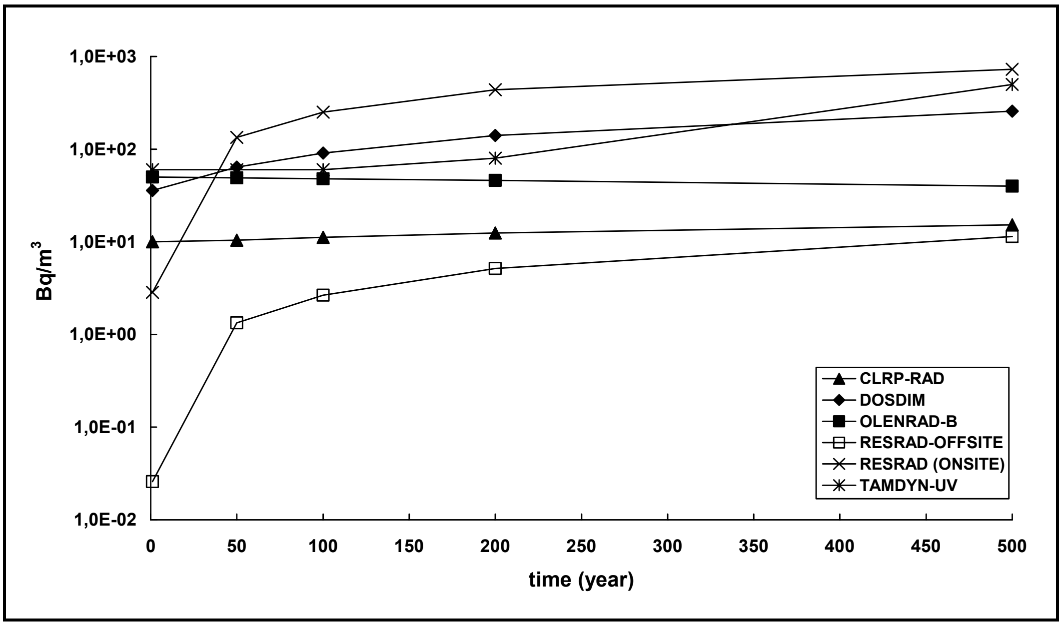


FIG. 28. Time-dependence of the predicted concentration of radium in ground water for the current situation 'no remediation'.

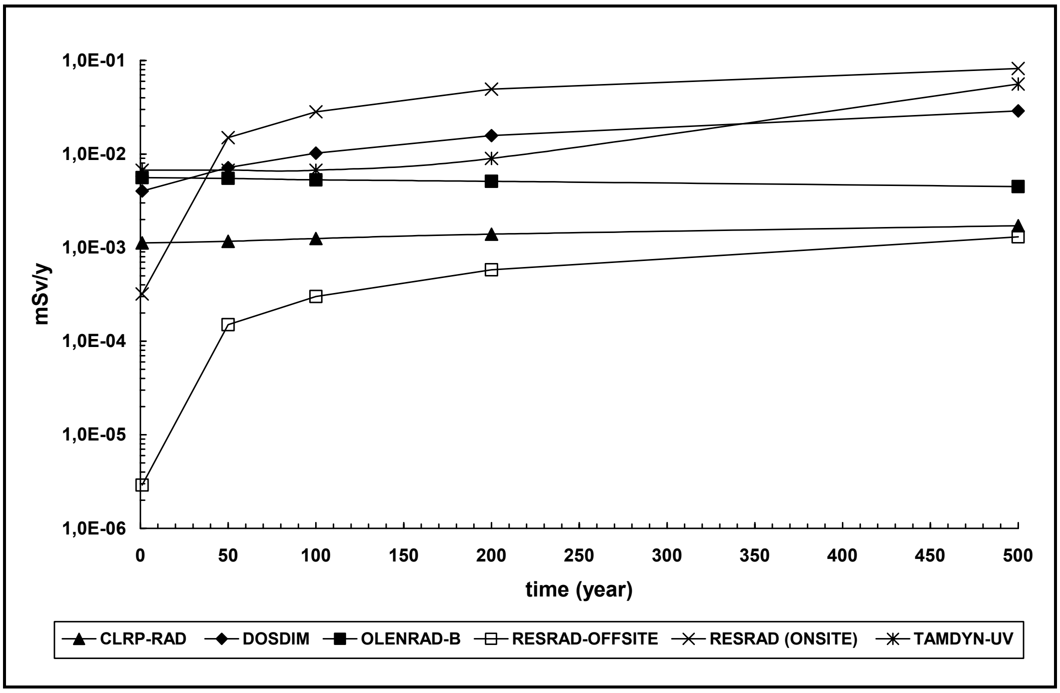


FIG. 29. Predicted ingestion dose of ^{226}Ra contaminated drinking water for the current situation 'no remediation'.

It is seen that with time different trends are observed. RESRAD-OFFSITE and RESRAD (ONSITE) show an initial rapid increase of the radium concentration, followed by a slower increase, while CLRP-RAD, DOSDIM and TAMDYN-UV give only a small increase of radium in drinking water with time. OLENRAD-B on the other hand even gives a small decrease of the radium concentration in drinking water with time. The differences observed for the initial drinking water concentration are more pronounced than the long-term differences and reflect mainly the different assumptions that were made. Since the contamination of the site occurred in the past (between 1922 and 1960), some modellers took into account the leaching of radium during that time. RESRAD (ONSITE) and RESRAD-OFFSITE however did not consider the historical contamination of the ground water. They assumed that the downward migration of radium to the ground water started recently. RESRAD-OFFSITE also assumed that the thickness of the aquifer was 10 m instead of 1 m that was given in the scenario description, leading to the lowest drinking water doses as seen in Figure 29. Two different approaches were used to derive the radium concentration in drinking water. Five modellers calculated the migration of radium from soil into ground water, using the distribution coefficient and the radium concentration of the soil. The other two modellers CLRP-RAD and OLENRAD-B estimated the initial dose based on the measured radium concentration data for ground water given in the scenario description. In contrast with CLRP-RAD, OLENRAD-B also assumed no accumulation of the radium in the aquifer by leaching processes. Only the radioactive decay was considered, leading to the decrease of the drinking water dose with time. CLRP-RAD used the measured ground water data also to derive a distribution coefficient for radium in the aquifer, while the other modellers used the same distribution coefficient as given for the soil in the scenario description. The fairly slow long-term increase as observed for CLRP-RAD and the other models reflects the accumulation of radium in ground water. DOSDIM, RESRAD (ONSITE), RESRAD-OFFSITE used the radium concentration of the most contaminated area (averaged over 1 m depth) to calculate the radium leaching out, because in the scenario description it was given that the well was located there. Compared to TAMDYN-UV who also used a soil model with several soil layers the radium concentrations in ground water predicted by CLRP-RAD are 6 times lower. This can be explained by the use of soil layers at different depths to calculate the radium concentration in the ground water since the radium contamination decreases with depth. CLRP only considered the radium concentration of the ground water at 2 m depth, while TAMDYN-UV used the mean value of the radium concentration in ground water at 1 m and 2 m depth. The normalised figure (Figure 30) gives the same picture as the non-normalised figures of the radium concentration (Figure 28) and the ingestion dose of ground water (Figure 29), indicating that differences in scenario interpretation and differences in calculation methods obscure differences in soil concentrations.

Less than 0.5% of the total dose is caused by the ingestion of radium contaminated milk or meat. The milk and meat ingestion doses vary by about one order of magnitude among the models and decrease with time (Figures 31 and 35), following a similar trend as the radium concentration in the root zone (Figure 17). The differences among the models are mainly due to the different radium concentrations used for pasture. CLRP-RAD and RESRAD-OFFSITE used the highest radium concentration for the root zone (about ten times higher than the concentration used by DOSDIM and TAMDYN-UV), leading to the highest milk and meat ingestion doses. All modellers, except CLRP-RAD, assumed that the cows take up soil while eating grass. The importance of this pathway to the total dose varies between the modellers due to differences in different grass and soil ingestion rates. OLENRAD-B and RESRAD-OFFSITE assumed lower intake rates of grass by the cattle than the other modellers. Instead of 12.5 kg dry grass per day as given in the scenario description, RESRAD-OFFSITE assumed that 12.5 kg fresh grass (with a moisture content of 90%) per day was eaten by the cows. OLENRAD-B even considered differences in the pasture consumption rate and assumed 12.5 kg fresh grass per day was eaten by beef cows and 40 kg fresh grass per day was eaten by dairy cows (Table VIII). Although both modellers used the same grass consumption rates for dairy cows and produced similar results for the radium concentrations in the root zone soil (Figure 17), it is shown in Figure 31 that the OLENRAD-B predictions for meat are about one order of magnitude lower than those of RESRAD-OFFSITE. This difference mainly reflects the difference in the amount of contaminated soil ingested by cattle per day. RESRAD-OFFSITE assumed that 0.04 kg soil is ingested per kg pasture *fresh* weight while OLENRAD-B used the fractional uptake rate of 0.04 kg soil per kg pasture *dry* weight as given in the scenario description. This results in differences in importance of the soil ingestion pathway; from about 83% (for the RESRAD-OFFSITE) to about 33% (for the other models) of the dose via ingestion of milk and meat. The RESRAD codes and TAMDYN-UV also assumed contamination of the grass via foliar uptake (dust deposition due to resuspension), while the others did not and CLRP-RAD and OLENRAD-B assumed no contaminated water intake by the cattle. However, because the soil-to-grass and soil ingestion pathways contribute the most to the contamination of milk and meat, these different assumptions are less important. In time, the ingestion dose mainly reflects the decrease of the radium concentration in the root zone, due to downward transport processes, obscuring the increase of the contamination via more contaminated water intake. The small differences in milk ingestion dose-to-grass ratio and milk ingestion dose-to-soil ratio among the models CLRP-RAD, DOSDIM, RESRAD (ONSITE) and TAMDYN-UV are due to differences in the radium concentration of pasture and differences in the contribution of soil ingestion and uptake of contaminated drinking water from the water well. The same conclusions can be drawn for meat (Figures 34, 35 and 36).

The contribution of the soil ingestion to the total dose is negligible (only up to 0.2%) and was not calculated by CLRP-RAD. The soil ingestion dose varies by one order of magnitude between the models (Figure 37). All models show a decrease with time, reflecting the decrease of radium concentration in the root zone. The soil ingestion dose-to-soil ratio indicates mainly that different consumption rates were used to calculate the soil ingestion dose (Figure 38).

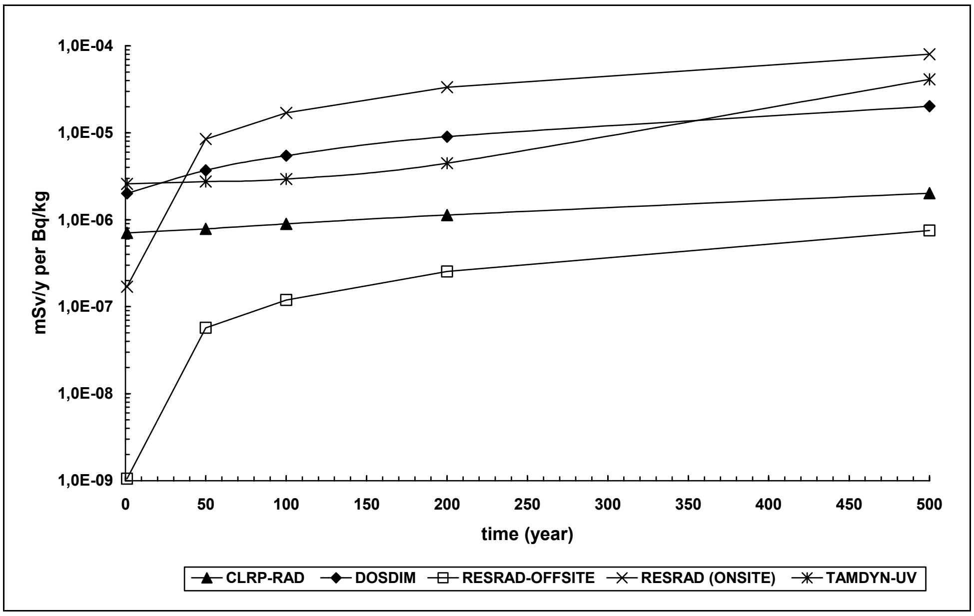


FIG. 30. Predicted ingestion dose of ^{226}Ra contaminated drinking water normalised against the concentration in soil for the current situation 'no remediation'.

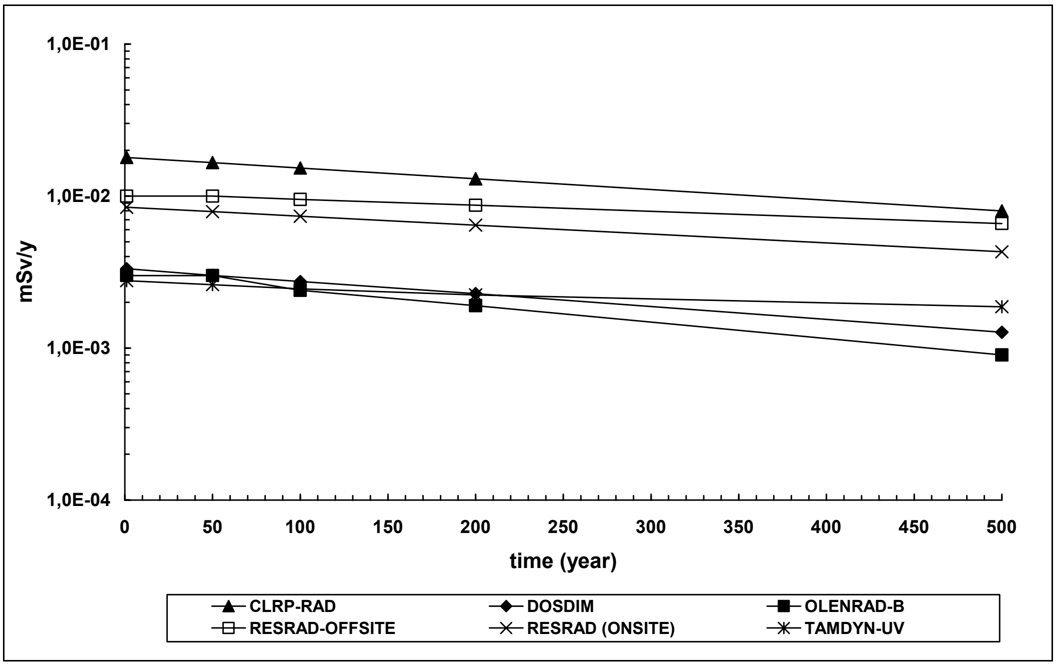


FIG. 31. Predicted ingestion dose of ^{226}Ra contaminated milk for the current situation 'no remediation'.

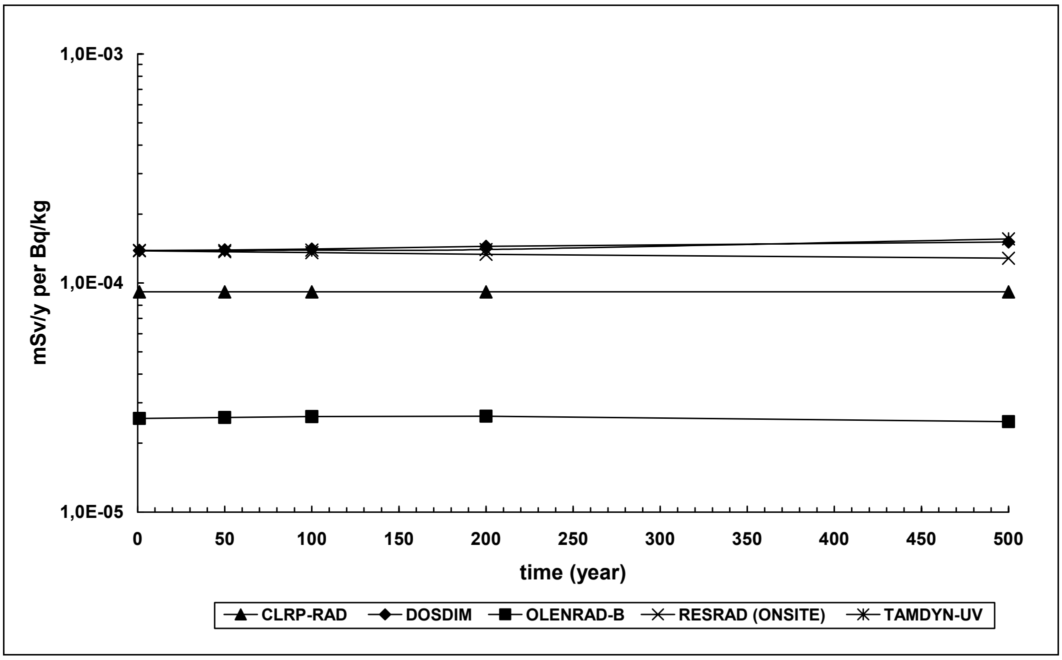


FIG. 32. Predicted ingestion dose of ^{226}Ra contaminated milk normalised against the concentration in grass for the current situation 'no remediation'.

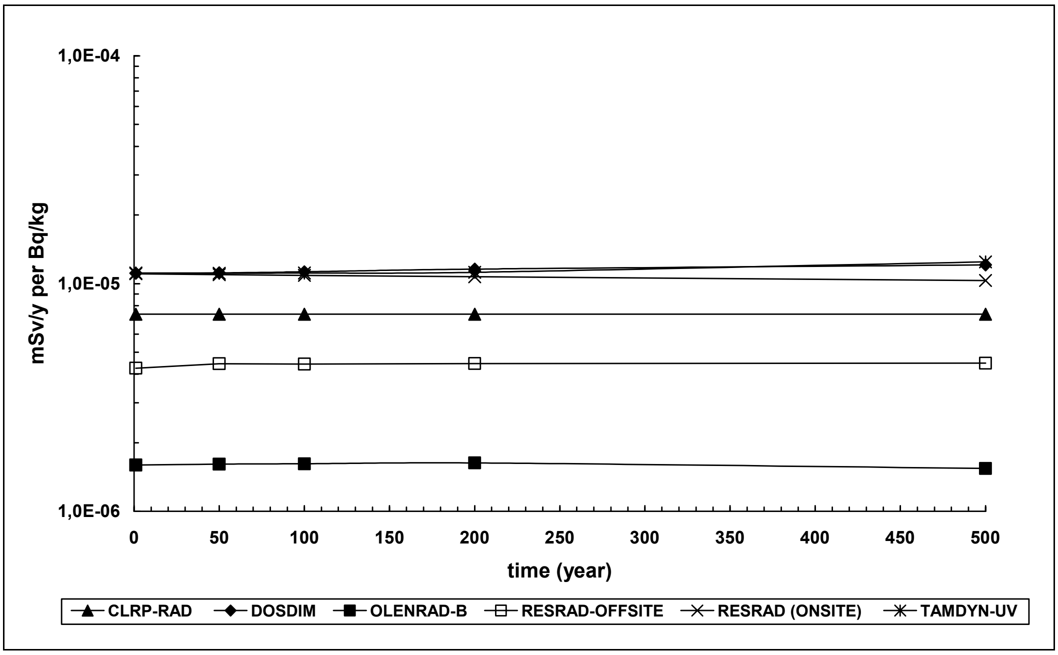


FIG. 33. Predicted ingestion dose of ^{226}Ra contaminated milk normalised against the concentration in soil for the current situation 'no remediation'.

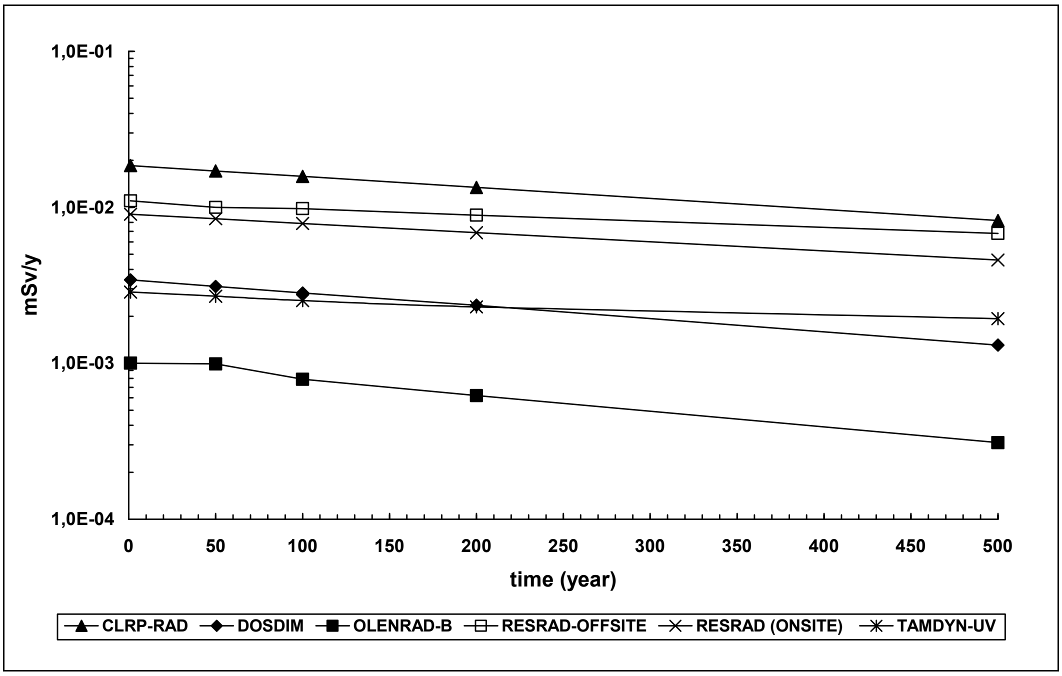


FIG. 34. Predicted ingestion dose of ^{226}Ra contaminated meat for the current situation 'no remediation'.

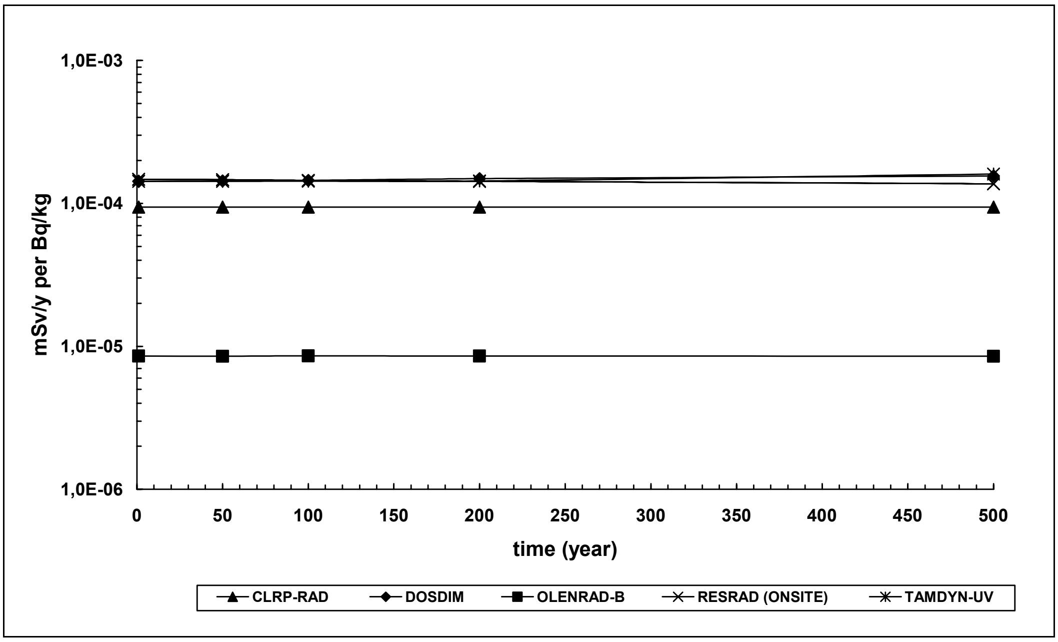


FIG. 35. Predicted ingestion dose of ^{226}Ra contaminated meat normalised against the concentration in grass for the current situation 'no remediation'.

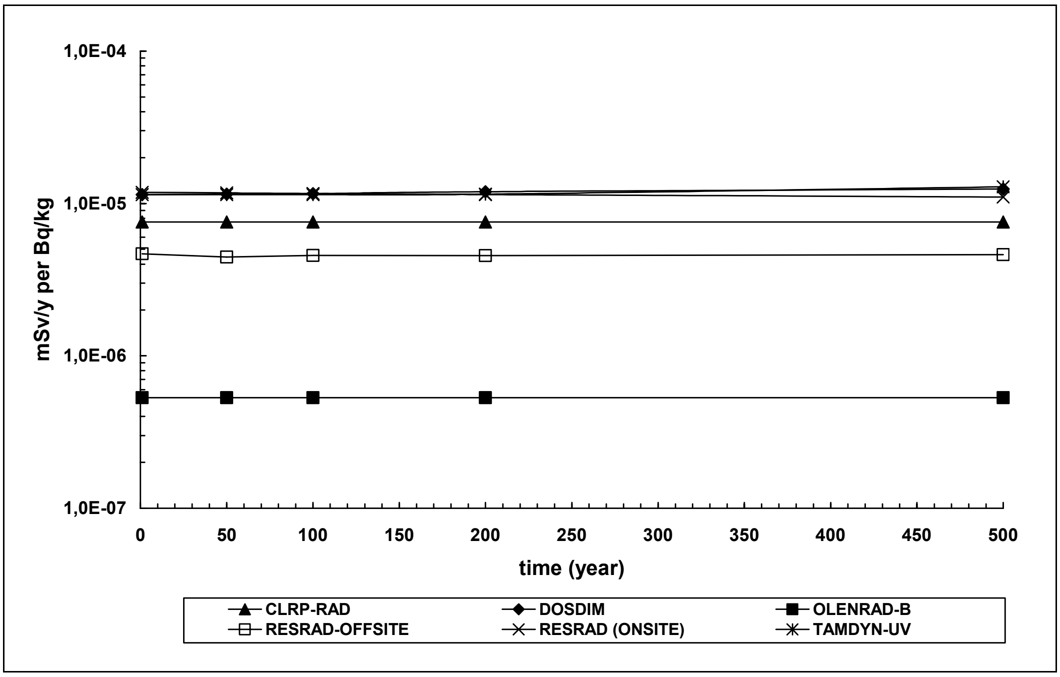


FIG. 36. Predicted ingestion dose of ^{226}Ra contaminated meat normalised against the concentration in soil for the current situation 'no remediation'.

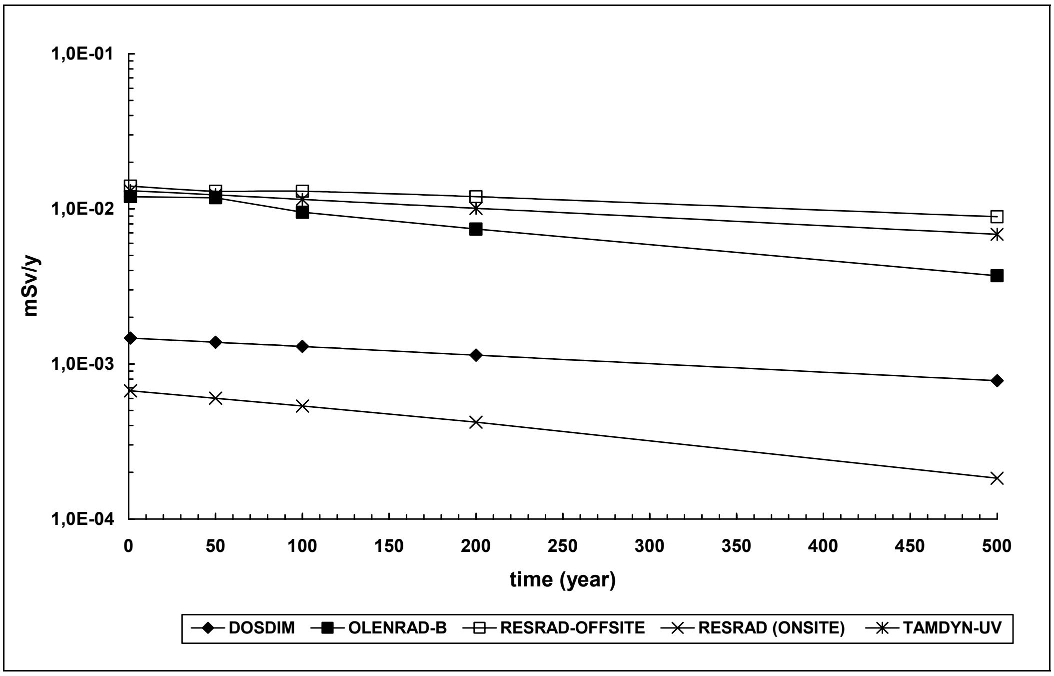


FIG. 37. Predicted ingestion dose of ^{226}Ra contaminated soil for the current situation 'no remediation.

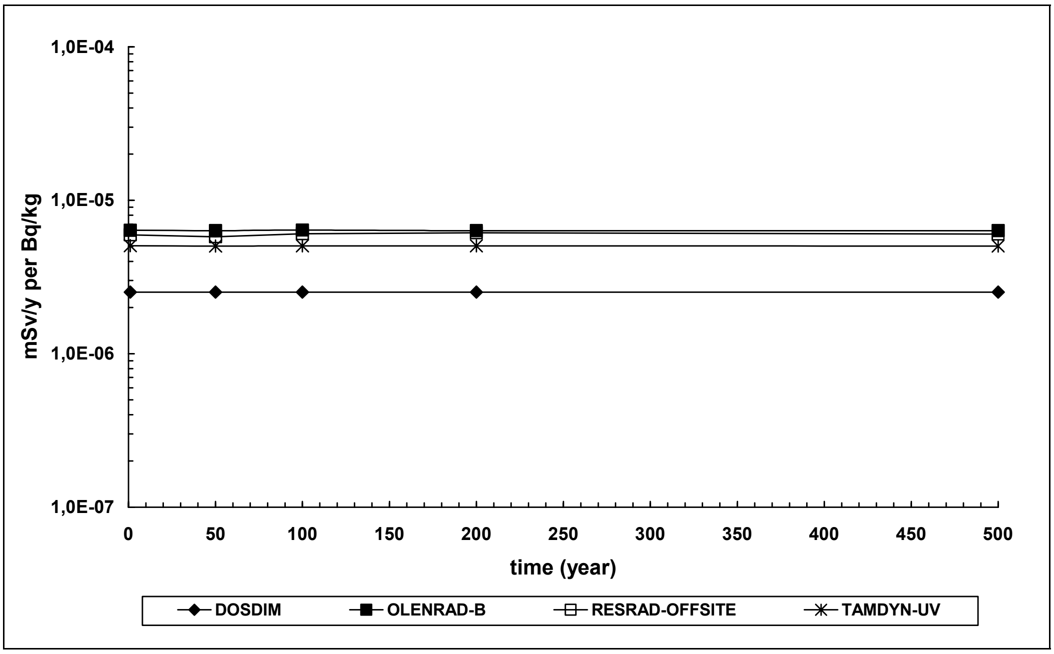


FIG. 38. Predicted ingestion dose of ^{226}Ra contaminated soil normalised against the concentration in soil for the current situation 'no remediation'.

5.2.1.1.2. Lead

In general, the model predictions show that the dose impact of lead, although it is at least 5 times lower than the dose impact of radium, is not negligible. Doses up to 1 mSv/y have been calculated (Figure 39). No predictions for lead were given by OLENRAD-B.

One of the main problems encountered by the dose calculation of lead is the calculation of its concentration in soil. For one, there is the ingrowth of lead from radium and radon and the radioactive decay of lead, for another there is also the different behaviour of radium and its daughters in the soil that makes the calculation of the lead concentration in soil difficult. For the simplicity, it was therefore assumed in the scenario description that radium and lead are already in equilibrium at year 1. This is likely to be a conservative approach. However, only DOSDIM assumed that there was an equilibrium at year 1. CLRP and both users of RESRAD codes took into account the ingrowth of lead. TAMDYN-UV also took, at least partly, the differences in behaviour in soil into account by incorporating the upward flux of radon to calculate the lead concentration in the soil profile.

In Figures 40, 41 and 42 the time dependency of lead in the root zone of garden, pasture and ground water is given. It is clearly seen that compared to the long-term predictions, the differences in lead concentration on the short term are more pronounced. As already mentioned for radium, this can mainly be explained by the fact that some models consider the historical lead contamination, while others did not.

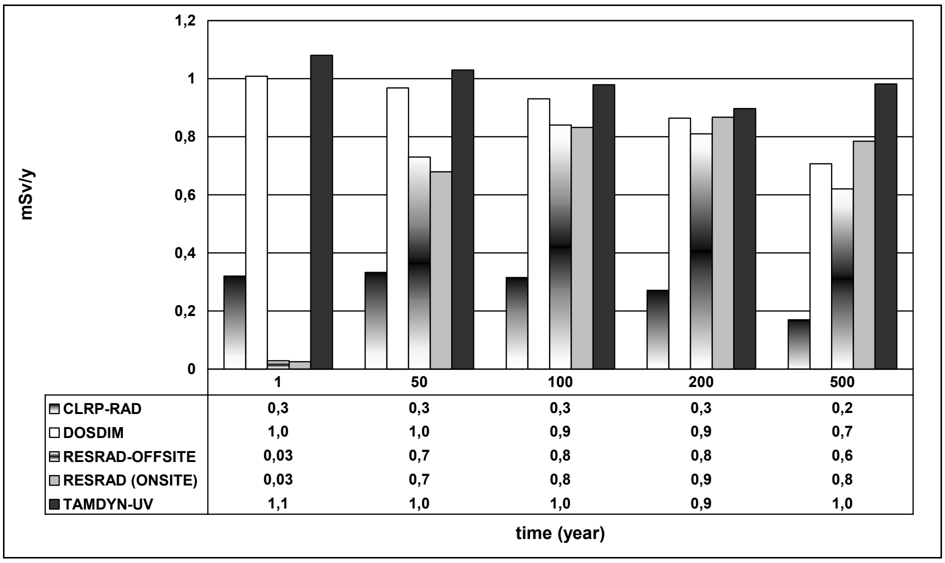
Figure 43 shows that the short-term dose predictions via the different exposure pathways may range by five orders of magnitude between the models. While the short-term differences are mainly due to differences in scenario interpretation (e.g. past contamination, lead in equilibrium with radium) and calculation methods, the long-term differences are more consistent. With time, the effect of the past contamination on the calculations diminishes due to continuous ingrowth of lead from radium, leading on the long term (100 years or more) to a decrease of the differences by two orders of magnitude for the various exposure pathways (Figures 46 to 55).

All models predicted that the ingestion of leafy vegetables (via root uptake) is the most important pathway (Figures 43, 44 and 45). Its contribution to the total lead dose varies between 47% (CLRP-RAD) and 77% (DOSDIM) at year 1 (Figure 44) and decreases with time for most models due to an increase of the lead contamination of drinking water (Figures 44 and 45). Second most important pathway is the ingestion of potatoes contaminated via root uptake. The total dose contribution varies between 16% (TAMDYN-UV) and 37% (CLRP-RAD) at year 1 (Figure 44). The contamination via foliar uptake is less important than via root uptake, but increases with time due to the accumulation of lead in ground water. It is clearly seen that the time dependency observed for the ingestion of food crops contaminated via root uptake (Figures 46 and 48) reflects more or less the trend observed for the soil concentration (Figure 40), i.e. an initial increase of the lead concentration, if no equilibrium with radium at year 1 was assumed, followed by a slow decrease. The occurrence of the initial rapid increase depends on whether or not the past lead contamination of the site was taken into consideration. The RESRAD codes (RESRAD-OFFSITE and RESRAD (ONSITE)) give initially very low doses for leafy vegetables, because it is assumed that there was no prior lead concentration in soil. CLRP-RAD gives one of the lowest doses for leafy vegetables (via root uptake), because, as mentioned earlier, a much lower consumption rate was used (17 kg/y instead of 56 kg/y (Figure 46)). Based on the assumption that the contamination via root uptake would obscure the contamination via foliar uptake, CLRP-RAD did not consider the foliar contamination of the leafy vegetables and potatoes. The predictions of the other models are very consistent for root uptake (Figures 46 and 47). For foliar uptake, the differences in model predictions are caused by the differences in ground water predictions and are initially large due to the different assumptions concerning the past contamination of the site. The differences obtained for the ingestion dose of leafy vegetables/potatoes (foliar)-to-ground water ratio are mainly due to differences in the considered subpathways as discussed earlier. The same conclusions can be made for potatoes (Figures 48 and 49).

Due to the higher mobility of lead compared to radium, the ingestion dose of lead contaminated water becomes with time more important than the dose via ingestion of radium contaminated water (up to 10 times higher after 500 years). Also its contribution to the total lead dose increases with time. Initially the contribution to the total dose is quite small for all models. It varies between 3E-3% (RESRAD-OFFSITE) and 6% (TAMDYN-UV) at year 1, but gets more important due to lead accumulation (Figures 44 and 45). At year 500, the drinking water pathway contributes up to 37% (RESRAD (ONSITE)) to the total dose. Predictions for drinking water are shown in Figure 50. Initially, the predictions vary by five orders of magnitude between the models. As for radium, CLRP-RAD did not calculate the lead concentration in ground water, but estimated the concentration based on the scenario description. RESRAD-OFFSITE gives one of the lowest lead concentration in drinking water because as mentioned earlier it was assumed that the thickness of the aquifer is 10 m instead of 1 m and that at year 0 there is no lead. The ingestion dose of drinking water normalised for the lead concentration in soil (Figure 51) give the same trend as the non-normalised figure (Figure 50), indicating that the differences in soil contamination have only a minor effect on the results. These observations are consistent with those for radium and were already elaborated more in detail for radium (see above).

Like observed for the food crops, the milk and meat ingestion pathways follow the same time dependency as the soil concentration in pasture (Figures 49, 51). It is also seen that the order of ranking was the same as found for the lead concentration in pasture; the models that derived the highest/lowest lead concentrations in pasture predict the highest/lowest lead concentrations in milk. In contrast, the order of ranking of the models for ground water is almost the opposite. This indicates the milk and meat contamination via the soil pathways (grass and soil ingestion) is more important than the contamination via water intake.

For the inhalation of dust, ingestion of soil and the external irradiation pathways, the results are not that much different from those obtained for radium and similar conclusions can be drawn (see above).



	1	50	100	200	500
▨ CLRP-RAD	0,3	0,3	0,3	0,3	0,2
☐ DOSDIM	1,0	1,0	0,9	0,9	0,7
▤ RESRAD-OFFSITE	0,03	0,7	0,8	0,8	0,6
▨ RESRAD (ONSITE)	0,03	0,7	0,8	0,9	0,8
■ TAMDYN-UV	1,1	1,0	1,0	0,9	1,0

FIG. 39. Predictions of the total lead dose for the current situation 'no remediation'.

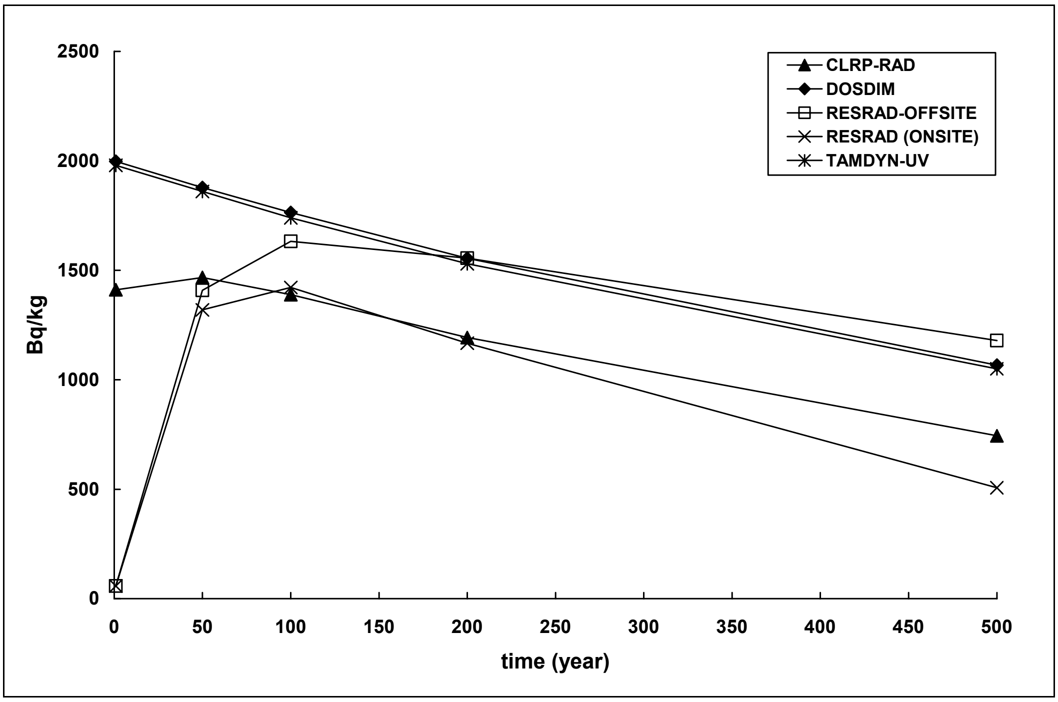


FIG. 40. Time-dependency of the predicted concentration of lead in the root zone of the garden for the current situation 'no remediation'.

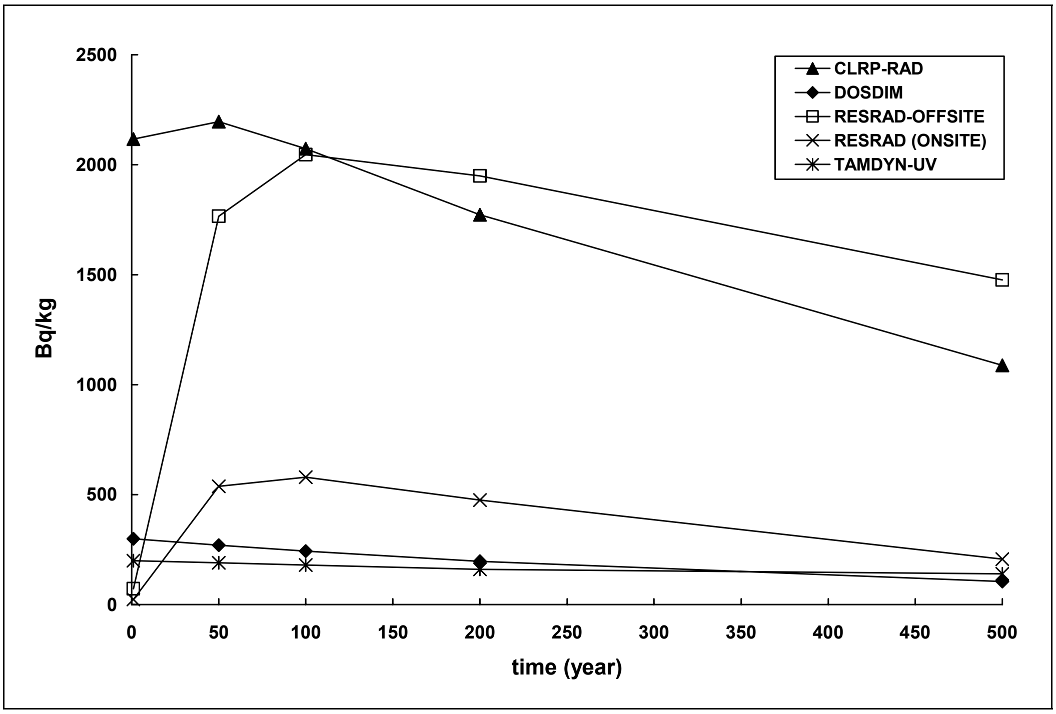


FIG. 41. Time-dependency of the predicted concentration of lead in the upper 15 cm of pasture land for the current situation 'no remediation'.

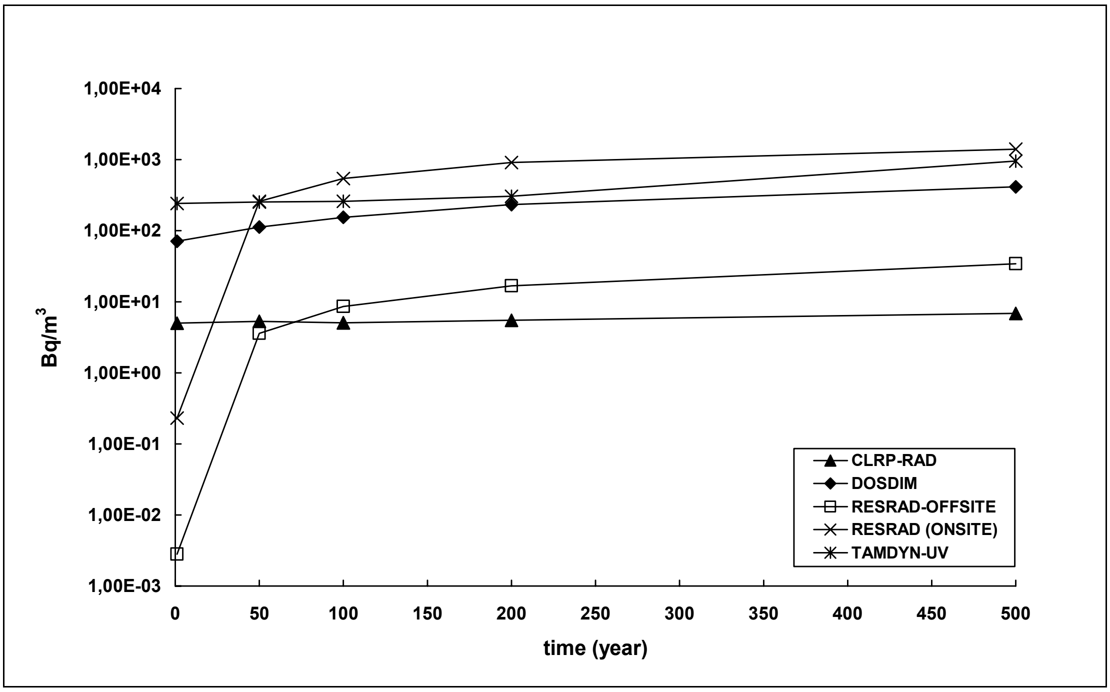


FIG. 42. Time-dependency of the predicted concentration of lead in ground water for the current situation 'no remediation'.

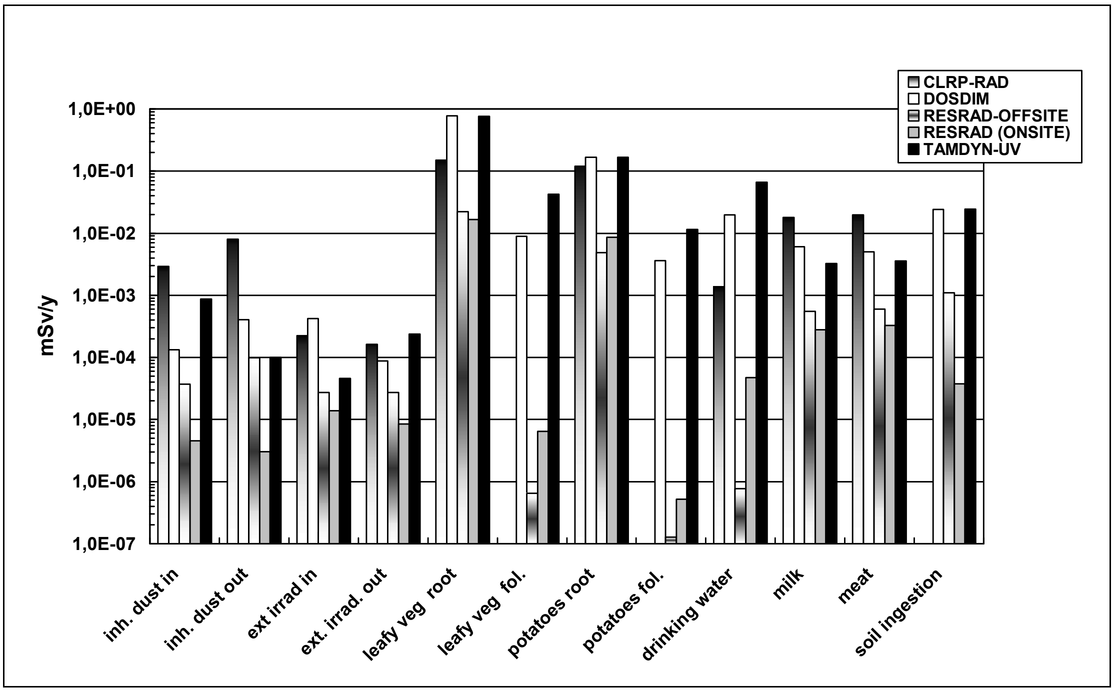


FIG. 43. Predictions of the lead dose via different pathways for the current situation 'no remediation' at year 1.

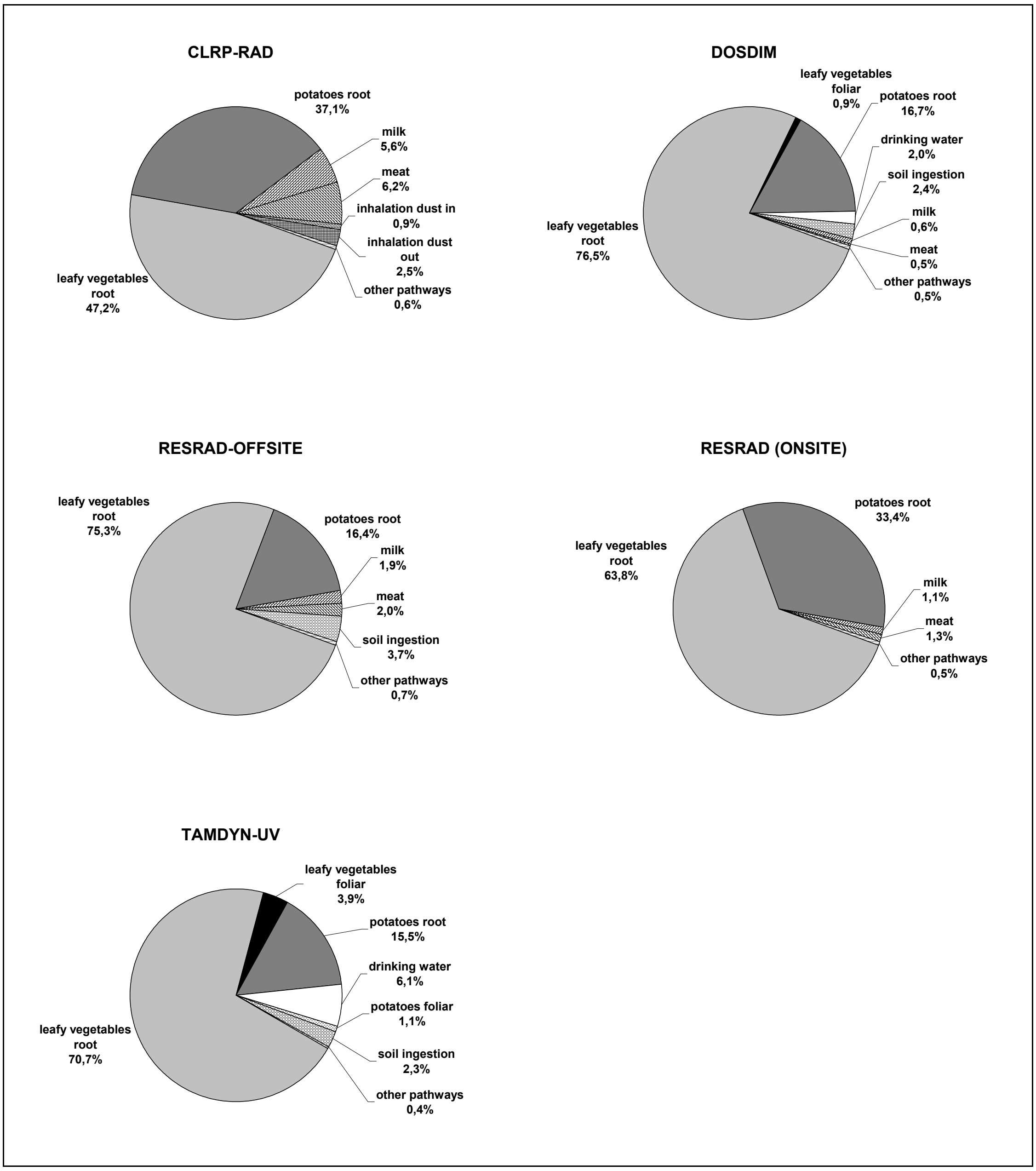


FIG. 44. Contribution of the predictions via different pathways (%) to the total predicted lead dose for the current situation ‘no remediation’ at year 1.

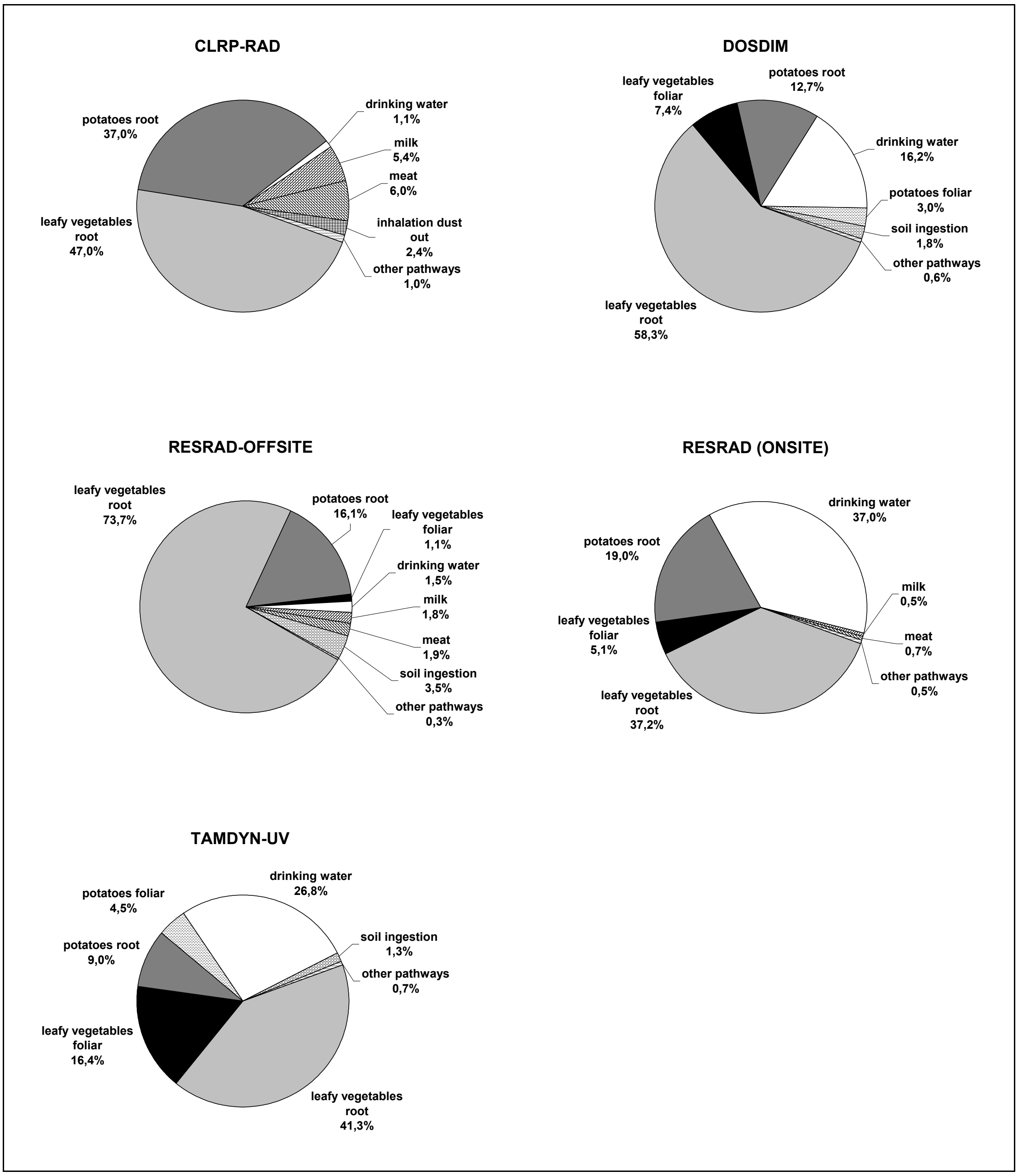


FIG. 45. Contribution of the predictions via different pathways (%) to the total predicted lead dose for the current situation 'no remediation' at year 500.

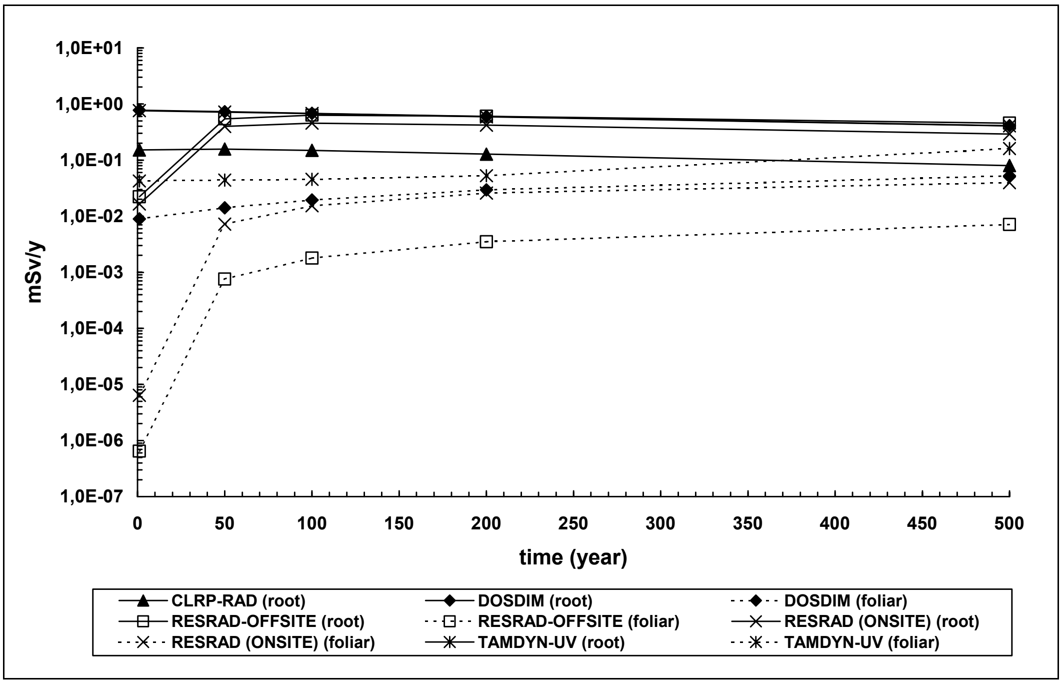


FIG. 46. Predicted ingestion dose of ^{210}Pb contaminated leafy vegetables for the current situation 'no remediation'.

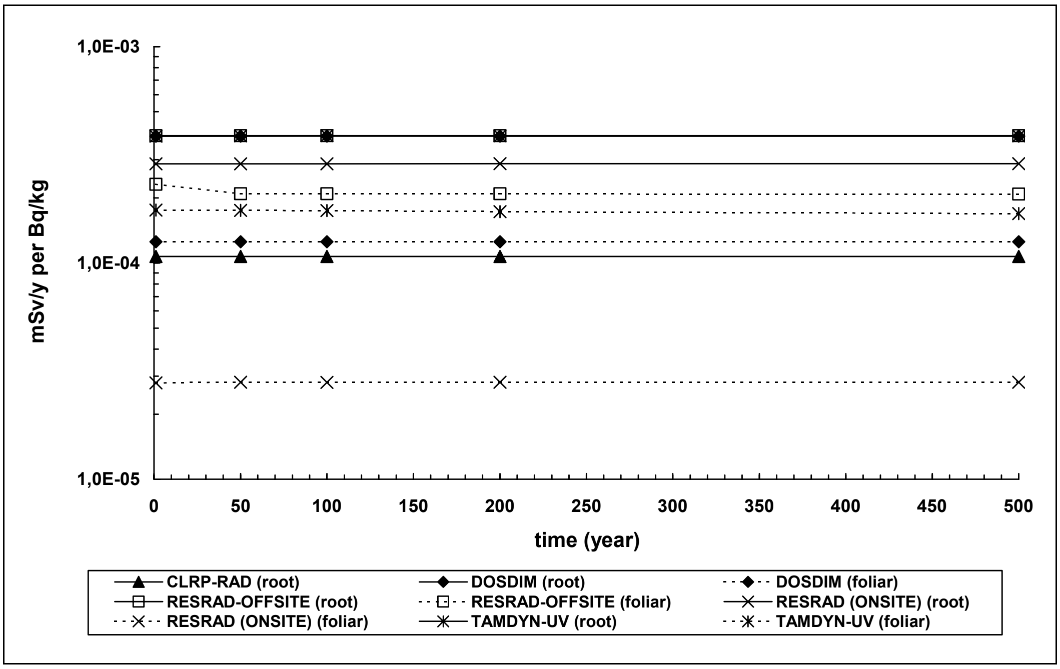


FIG. 47. Predicted Ingestion dose of leafy vegetables ^{210}Pb contaminated via root uptake, respectively via foliar uptake normalised against the concentration in garden, respectively in ground water for the current situation 'no remediation'.

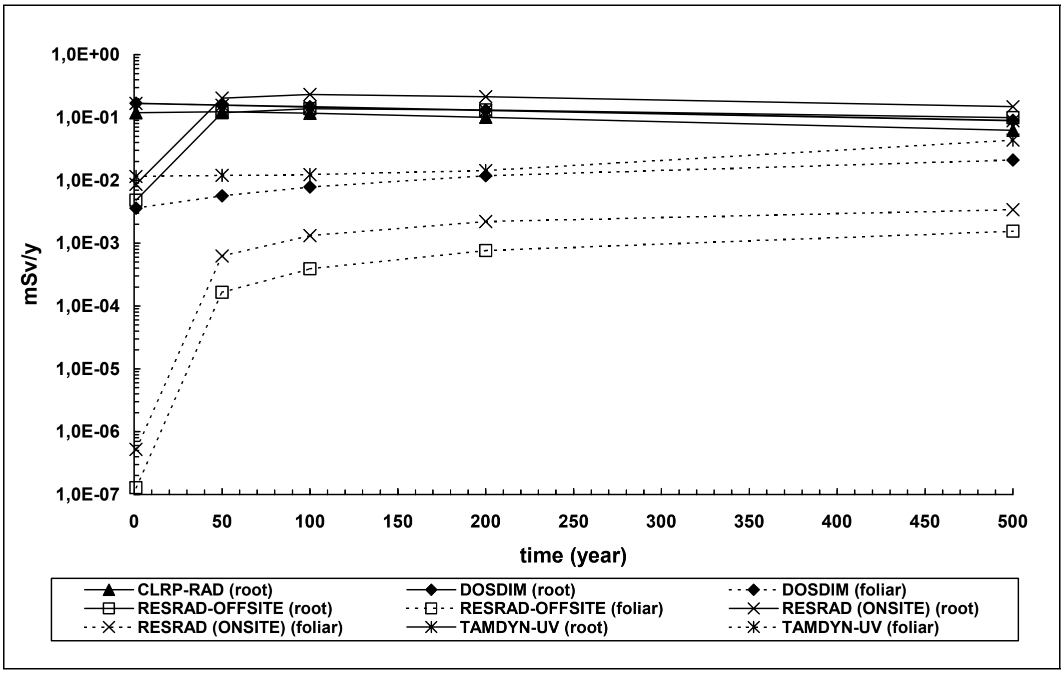


FIG. 48. Predicted ingestion dose of ^{210}Pb contaminated potatoes for the current situation 'no remediation'.

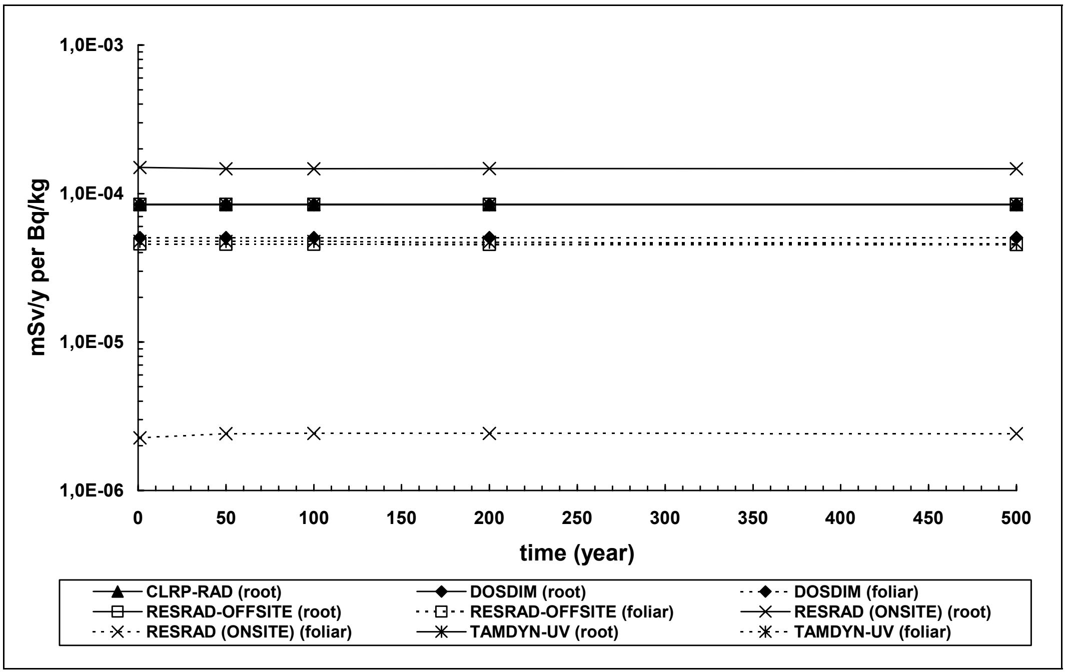


FIG. 49. Predicted ingestion dose of potatoes ^{210}Pb contaminated via root uptake, respectively via foliar uptake normalised against the concentration in garden, respectively in ground water for the current situation 'no remediation'.

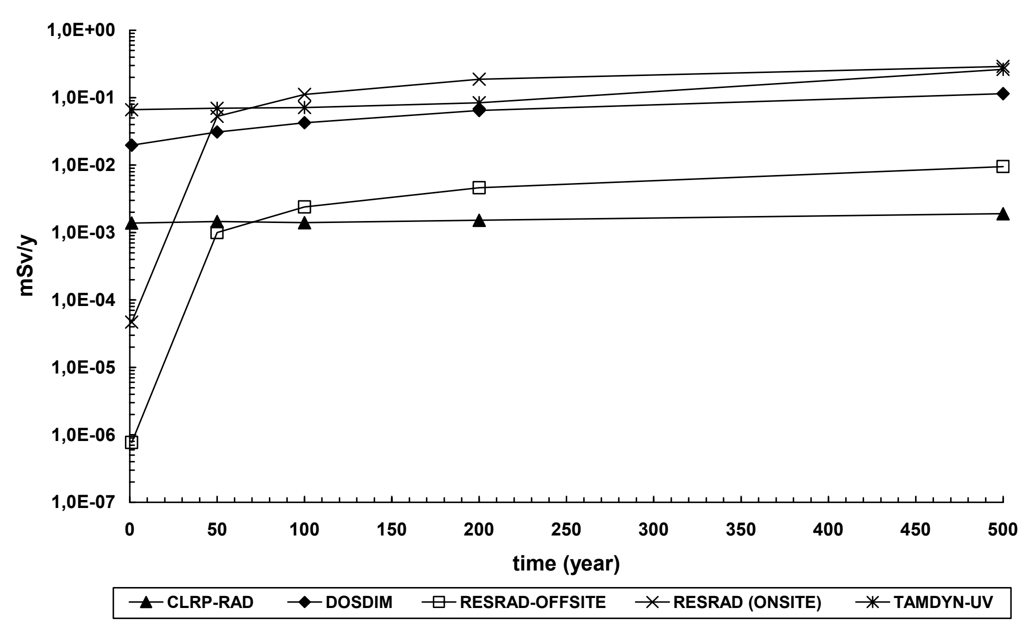


FIG. 50. Predicted ingestion dose of ^{210}Pb contaminated drinking water for the current situation 'no remediation'.

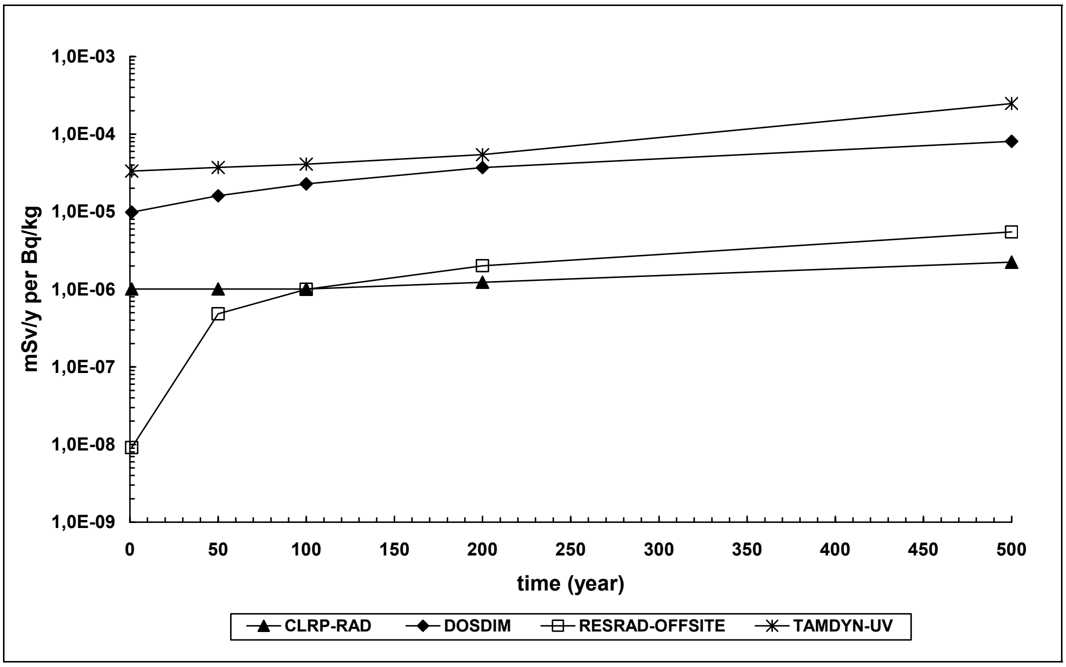


FIG. 51. Predicted ingestion dose of ^{210}Pb contaminated drinking water normalised against the concentration in soil for the current situation 'no remediation'.

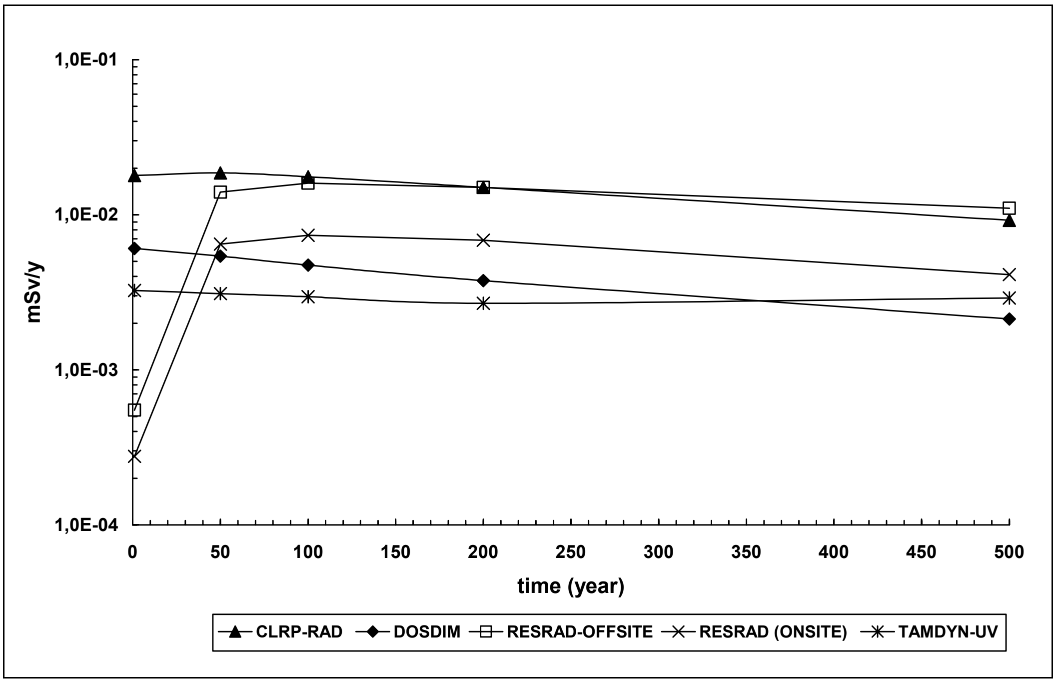


FIG. 52. Predicted ingestion dose of ^{210}Pb contaminated milk for the current situation 'no remediation'.

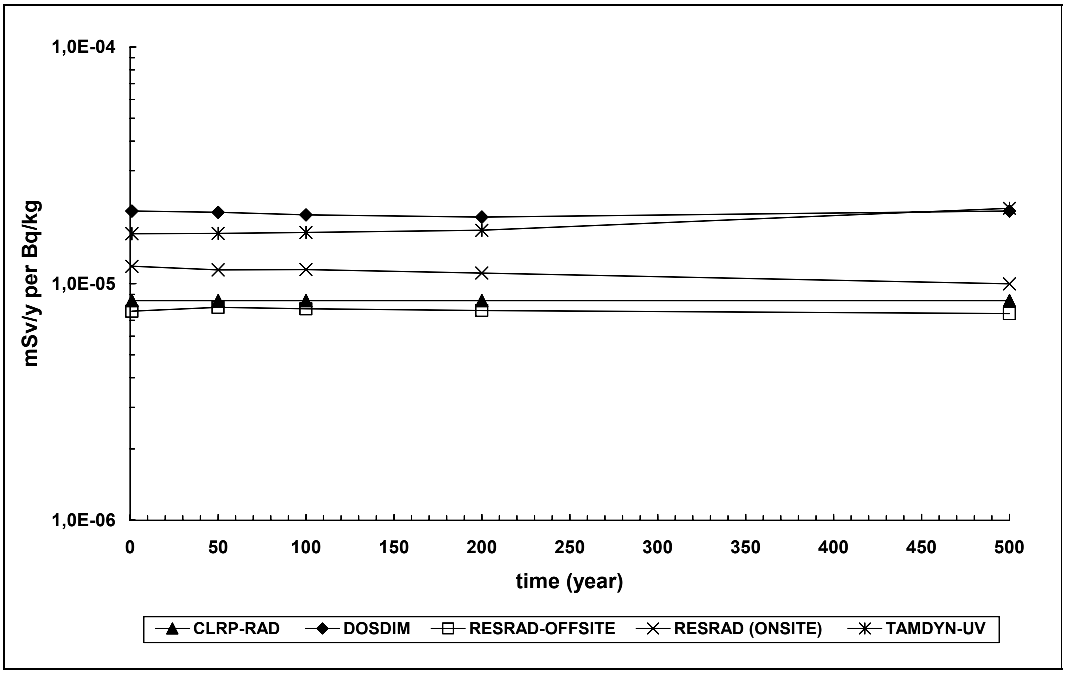


FIG. 53. Predicted ingestion dose of ^{210}Pb contaminated milk normalised against the concentration in soil for the current situation 'no remediation'.

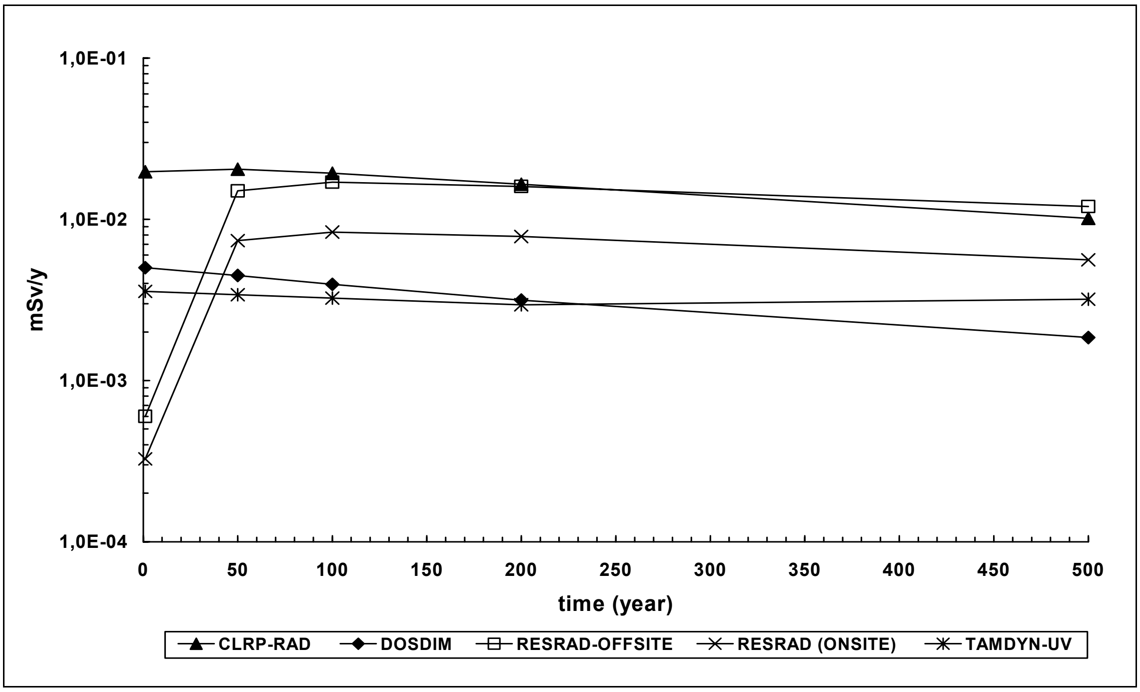


FIG. 54. Predicted ingestion dose of ^{210}Pb contaminated meat for the current situation 'no remediation'.

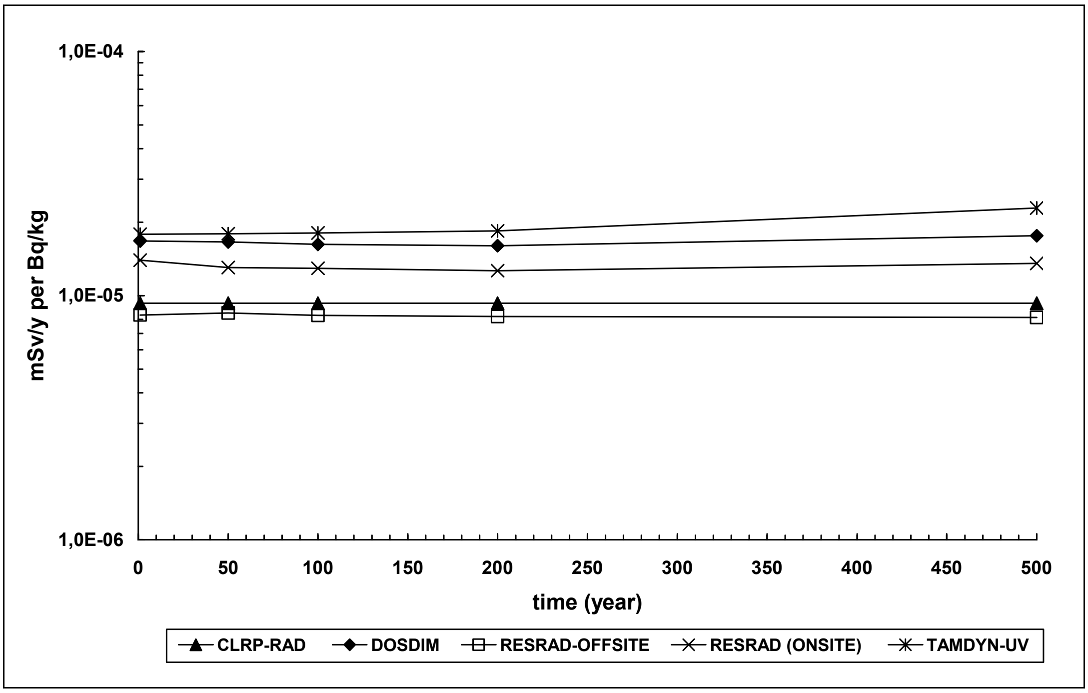


FIG. 55. Predicted ingestion dose of ^{210}Pb contaminated meat normalised against the concentration in soil for the current situation 'no remediation'.

5.2.1.1.3. ICRP recommendations for remediation of contaminated sites

ICRP states that:

> *"A system of radiological protection should aim to do more good than harm, should call for protection arrangements to maximise the net benefit, and should aim to limit the inequity that may arise from a conflict of interest between individuals and the society as a whole."*
>
> (ICRP 60, paragraph S14 [1]).

"Do more good than harm" implies that the cleanup should be justified. If the cleanup action is justified, then optimisation (radiological risks as low as reasonable achievable) should be used to determine an appropriate cleanup strategy. Beside the radiological risks, justification and optimisation decisions on cleanup will usually involve other equally important non-radiological factors like non-radiological environmental effects, economic and social factors. Consideration of the non-radiological factors is however beyond the scope of this report.

The total dose predictions for radium and lead are summarised in Table XIII. It is seen that the dose predictions for year 1 are much higher than the dose limit of 1 mSv/y for members of the public. They vary between 6 and 11 mSv/y. However, the dose limit of 1 mSv/y is not directly applicable to cleanup decisions, because its use could, in some cases, invoke the use of action that causes more harm than good, i.e. the action is not justified. ICRP recommends the use of generic reference levels for cleanup, expressed in terms of existing annual dose (ICRP 82) [2].

Since the average annual individual doses worldwide from natural sources vary from 2.4 to 10 mSv/y [5], an existing annual dose approaching about 10 mSv/y is chosen as generic reference level below which intervention is unlikely to be justifiable. However, ICRP also stated that the generic reference levels give merely guidance and should be used with caution. Beneath the level of 10 mSv/y for which cleanup is not likely justifiable, action may possible be necessary and its justification needs to be addressed on a case-by-case basis.

As written in ICRP-82 [2]:

> *"If some exposure pathways are dominant, the use of generic reference levels should not prevent that protective actions are taken to reduce these dominant components. In such cases, action levels specific to particular components can be established on the basis of appropriate fractions of the recommended generic reference level."*

Looking at the total dose predictions (Table XIII), this means that based on the generic criterion, cleanup actions are not likely needed. However, as shown earlier, the radon indoors is the main exposure pathway. The inhalation dose of radon indoors is at least 52% of the total dose (Ra&Pb) and varies between 3.8 (DOSDIM) and 7 mSv/y (TAMDYN-UV). This implies according to the above ICRP statement that actions to reduce the radon indoors might still be justifiable. ICRP issued specific recommendations for radon indoors [3] whereby an action level for radon in dwellings should be selected from the range of 3 to 10 mSv/y for simple remedial measures. This means that in the case of the Olen B scenario at least remedial measures to reduce the radon indoors should be taken.

TABLE XIII. PREDICTED TOTAL DOSE FOR THE CURRENT SITUATION

	Total (Ra&Pb) dose (mSv/y)		
	Year 1	Year 100	Year 500
CLRP-RAD	7.2	6.3	3.8
DOSDIM	6.1	5.8	4.5
OLENRAD-B	8.1	6.4	2.5
RESRAD-OFFSITE	7.3	7.5	5.2
RESRAD (ONSITE)	10.6	10.1	6.1
TAMDYN-UV	11.1	10.4	8.2

5.2.1.2. Remediation 1: Removal of the most contaminated soil

This remedial action consisted of the removal of the surface soil down to 1 m in the most contaminated areas (areas with dose rate > 200 nSv/h) and replacement with 0.5 m of less contaminated soil. The radium concentration of the less contaminated soil was 60 Bq/kg.

The spread in soil concentrations reflects the differences in interpretation of the scenario description. OLENRAD-B and RESRAD-OFFSITE adopted a conservative approach for calculating the effect of the remedial action. They assumed that this remedial action would lead to an average radium concentration of 60 Bq/kg for the upper 1 m of pasture, farm and garden soil (Table XII). They considered the highest reduction of the radium concentration that could possibly be obtained, i.e. the remedial measure leads to an average radium concentration for the site as low as the radium concentration of the replacement soil. Whether this efficiency can be obtained is however highly questionable. CLRP-RAD and RESRAD (ONSITE) misinterpreted the scenario. CLRP-RAD assumed that only the upper 0.5 m of soil of the most contaminated areas was removed and replaced by 0.5 m of less contaminated soil, resulting in higher average radium concentrations over 1 m depth (Table XII). RESRAD (ONSITE) assumed that not only the remediated areas of the site (as given in scenario description) but also the non remediated areas were covered by a clean soil and that this cover remained intact during at least 500 years. RESRAD (ONSITE) considered the contribution of the deeper contaminated soil layer to some exposure pathways (external irradiation, radon inhalation) by using an average radium concentration for cover and contaminated soil layer.

DOSDIM and TAMDYN-UV assumed that after the remediation the radium concentration of pasture will be a few times higher than the radium concentration of the clean soil. A justification for this is that, in contrast with the remediation of farm and garden, the removal of contaminated soil and replacement by clean soil would be limited because whole areas of pasture already have a dose rate < 200 nSv/h. Based on the dose rate measurements, it can be assumed that the background dose rate varies between 50 and 80 nSv/h. Therefore, the average concentration of the pasture will probably be a few times higher than the concentration of the clean soil. How much higher was difficult to derive due to the lack of detailed information about the heterogeneity of the radiocontamination of the site and consequently the choice of the radium concentration in pasture after remediation was highly subjective.

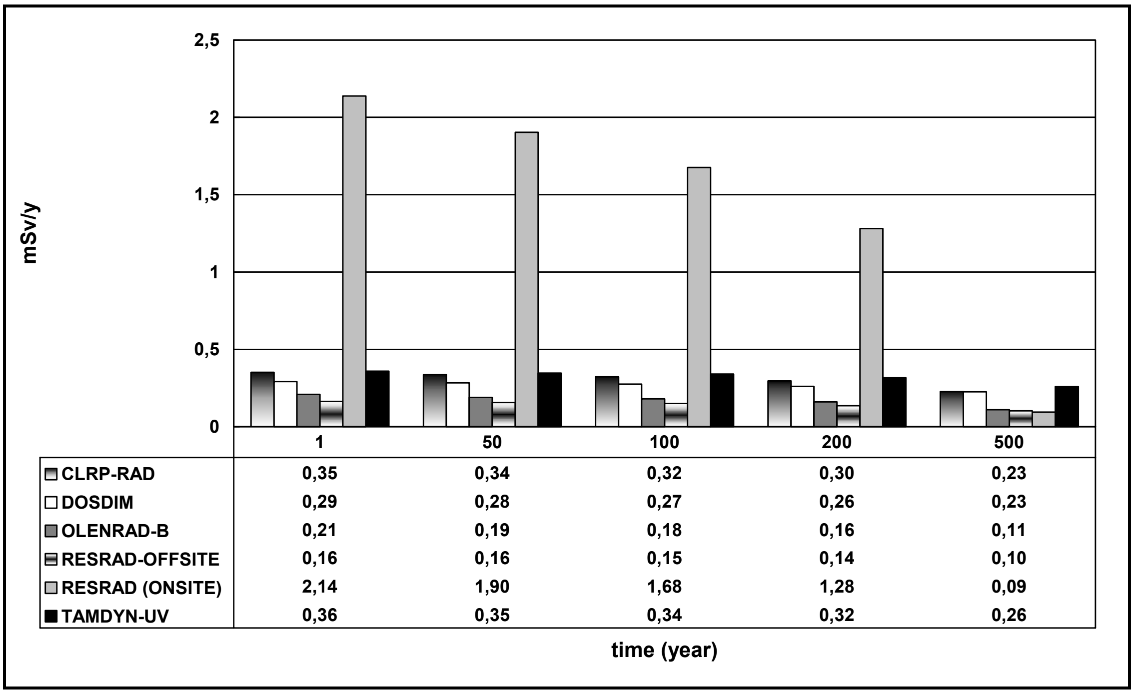
TABLE XIV. EFFICIENCY (%) OF REMEDIAL ACTION 1 ON THE TOTAL DOSE

	^{226}Ra			^{210}Pb		
	Year 1	Year 100	Year 500	Year 1	Year 100	Year 500
CLRP-RAD	95	95	94	96	96	95
DOSDIM	94	94	94	93	96	96
OLENRAD-B	97	97	96	n.c.	n.c.	n.c.
RESRAD (ONSITE)	80	82	n.c.	97	97	98
RESRAD-OFFSITE	98	98	98	97	97	97
TAMDYN-UV	97	97	97	89	89	90

n.c. = not calculated.

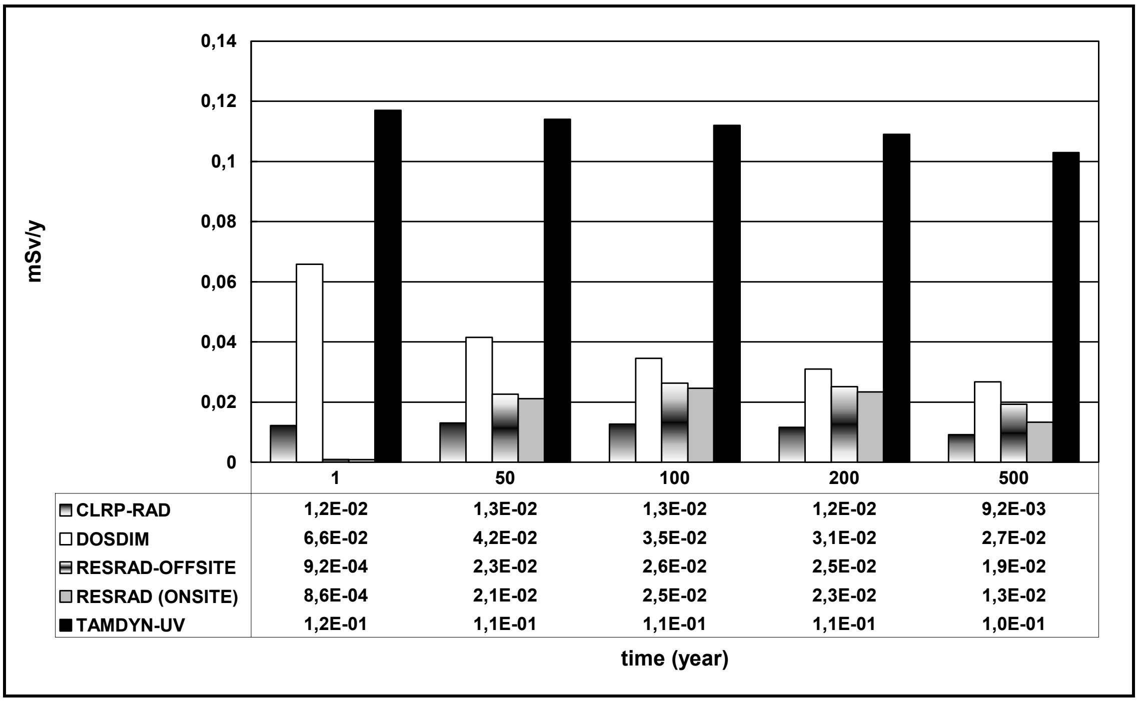
By reducing the radium concentration in the upper 1 m soil layer, the total radium dose will decrease by a factor of 5 (RESRAD (ONSITE)) to 45 (RESRAD-OFFSITE) and the lead dose will decrease by a factor of 10 (TAMDYN-UV) to 30 (RESRAD (ONSITE)) at year 1. The doses vary between 0.2 (RESRAD-OFFSITE) and 2.1 mSv/y (RESRAD (ONSITE)) for radium and between 1E-03 (RESRAD-OFFSITE, RESRAD (ONSITE)) and 0.1 mSv/y (TAMDYN-UV) for lead at year 1 as shown in Figures 56 and 57. The differences in reduction factor can mainly be explained by the differences in radium concentration derived for farm, garden and pasture soil before and after remediation (Table XII) and the different assumptions made concerning the past contamination and the origin of radon in air indoors. The efficiency of the remedial action is summarised in Table XIV. It is seen that the modellers obtained comparable efficiencies. In Figure 56, it is shown that the RESRAD codes give the highest and lowest radium dose after remedial action 1. The differences can mainly be explained by the differences in soil radium concentration used to calculate the radon inhalation indoors (Table XII). Most modellers (OLENRAD-B, DOSDIM, RESRAD-OFFSITE, TAMDYN-UV) assumed that remedial action 1 would reduce the radium concentration of the upper 1 m soil surrounding the farm to the level of the less contaminated soil, resulting in a large reduction of the radon concentration indoors. RESRAD (ONSITE) on the other hand considered a higher average radium concentration for the upper 1 m soil layer, taking into account the non remediated areas of the site. As mentioned above, the RESRAD (ONSITE) user assumed that the whole site was covered by 0.5 m less contaminated soil and that this cover remained intact during the considered time period. This implies that for exposure pathways (like dust inhalation, ingestion of food crops, milk, meat and soil) which only involve the upper few tens of cm of the soil the remedial action will have a greater beneficial effect than for exposure pathways like the external irradiation, inhalation of radon. Since the inhalation of radon indoors is the dominant component of the total radium dose, this means that the efficiency of the remedial action on the radium dose as calculated by RESRAD (ONSITE) will be lower compared to the results of the others (Table XIV). The CLRP-RAD user also produced a higher average radium concentration for the upper 1 m soil layer of the farm soil after remediation. Nevertheless, the predictions of CLRP-RAD for the inhalation of radon indoors are comparable with those of the other four modellers, probably because of the assumptions made concerning the construction of the house. Unlike RESRAD (ONSITE), CLRP-RAD did not consider a cellar.

Figures 58 and 60 show that after remediation the inhalation of radon is still the dominant component of the total radium dose, followed by external irradiation. In Figures 59 and 61 the contribution of the different exposure pathways to the total lead dose is given. For those modellers who considered the historical contamination, the remedial action has initially a rather small beneficial effect on the exposure pathways via water compared to the exposure pathways via soil, because the remedial action has no influence on the radium and lead that is already migrated to the aquifer. This explains, compared to the no remediation case, the increase of the relative contribution of the drinking water pathway to the total dose at year 1 (Figures 60 and 62 versus Figures 15 and 16). According to the TAMDYN-UV predictions, it is even the most important exposure pathway for lead (Figures 59 and 61). However, the beneficial effect of remedial action grows in time since due to the removal of contaminated soil, the accumulation of radium and lead in the aquifer during the following 500 years will be lower than compared to the situation for “no remediation”. DOSDIM produced the largest dose reduction for ingestion of drinking water and calculated that, compared to the no remediation case, remediation 1 will reduce the ingestion dose by a factor of 6 for radium and by a factor of 22 for lead after 500 years. For models that did not consider the historical contamination (e.g. RESRAD (ONSITE) and RESRAD-OFFSITE) the beneficial effect of the remedial action is already significant at year 1 and remains unchanged in time. Consequently, as seen in Figures 62 and 63, their dose predictions for drinking water after remediation 1, although lower values are obtained due to the radium and lead reduction in soil, will behave the same in time as the dose predictions obtained for the no remediation case (Figures 29 and 50). OLENRAD-B produced the same dose predictions for ingestion of drinking water after remediation 1 as for no remediation. The modeller assumed that the radium concentration in the drinking water was coming from a contaminated area much larger than the remediated site, leading to nearly no beneficial effect of the remedial action on the drinking water contamination. It is clear that the exposure pathways contaminated via water through drinking or irrigation show the same trend in time as the drinking water pathway. For the exposure pathways contaminated via soil, the differences in dose predictions between the remediation 1 case and the no remediation case mainly reflect the degree of radium and lead reduction in the soil. The dose predictions normalised for the soil concentration will give the same results for both cases.



	1	50	100	200	500
▥ CLRP-RAD	0,35	0,34	0,32	0,30	0,23
□ DOSDIM	0,29	0,28	0,27	0,26	0,23
▩ OLENRAD-B	0,21	0,19	0,18	0,16	0,11
▤ RESRAD-OFFSITE	0,16	0,16	0,15	0,14	0,10
▨ RESRAD (ONSITE)	2,14	1,90	1,68	1,28	0,09
■ TAMDYN-UV	0,36	0,35	0,34	0,32	0,26

FIG. 56. Predictions of the total radium dose after remediation 1.



	1	50	100	200	500
▨ CLRP-RAD	1,2E-02	1,3E-02	1,3E-02	1,2E-02	9,2E-03
□ DOSDIM	6,6E-02	4,2E-02	3,5E-02	3,1E-02	2,7E-02
▤ RESRAD-OFFSITE	9,2E-04	2,3E-02	2,6E-02	2,5E-02	1,9E-02
▩ RESRAD (ONSITE)	8,6E-04	2,1E-02	2,5E-02	2,3E-02	1,3E-02
■ TAMDYN-UV	1,2E-01	1,1E-01	1,1E-01	1,1E-01	1,0E-01

FIG. 57. *Predictions of the total lead dose after remediation 1.*

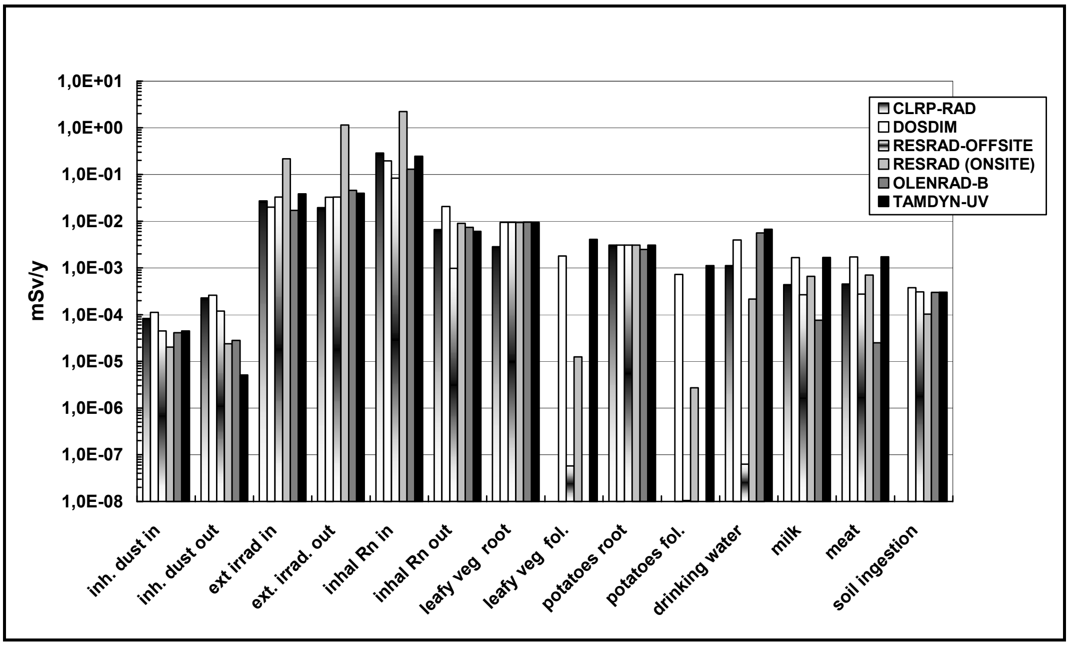


FIG. 58. *Predictions of the radium dose via different pathways for remediation 1 at year 1.*

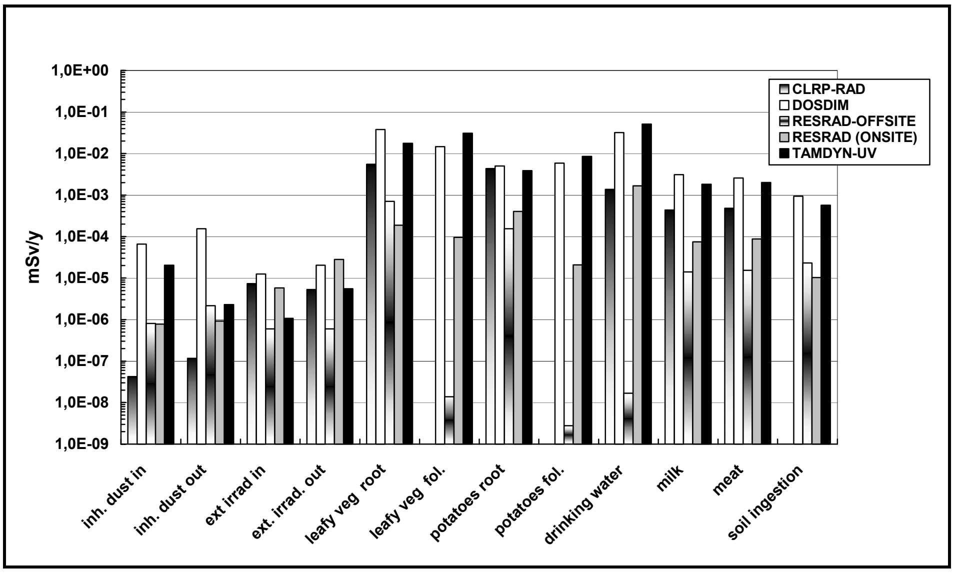


FIG. 59. *Predictions of the lead dose via different pathways for remediation 1 at year 1.*

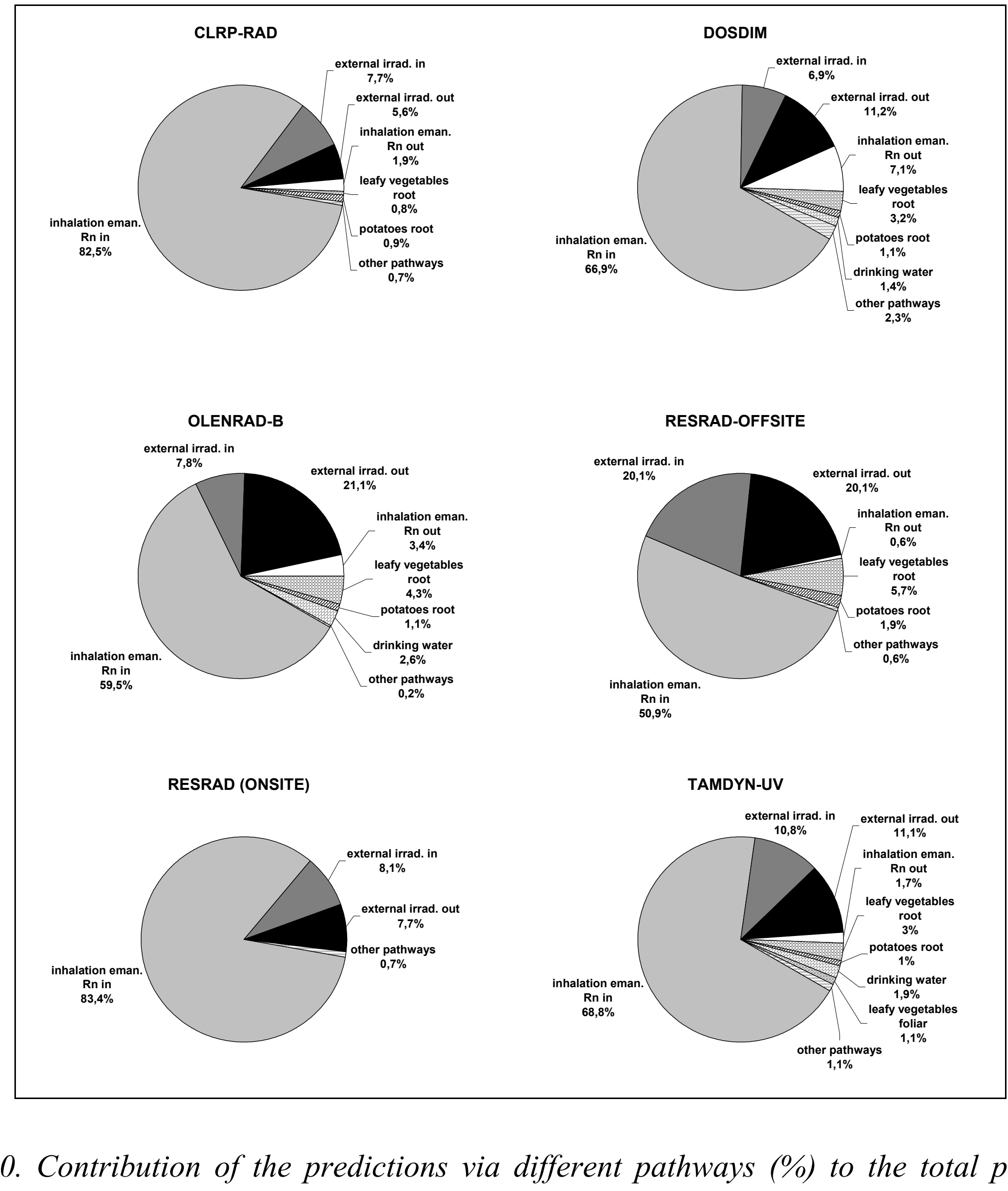


FIG. 60. *Contribution of the predictions via different pathways (%) to the total predicted radium dose for remediation 1 at year 1.*

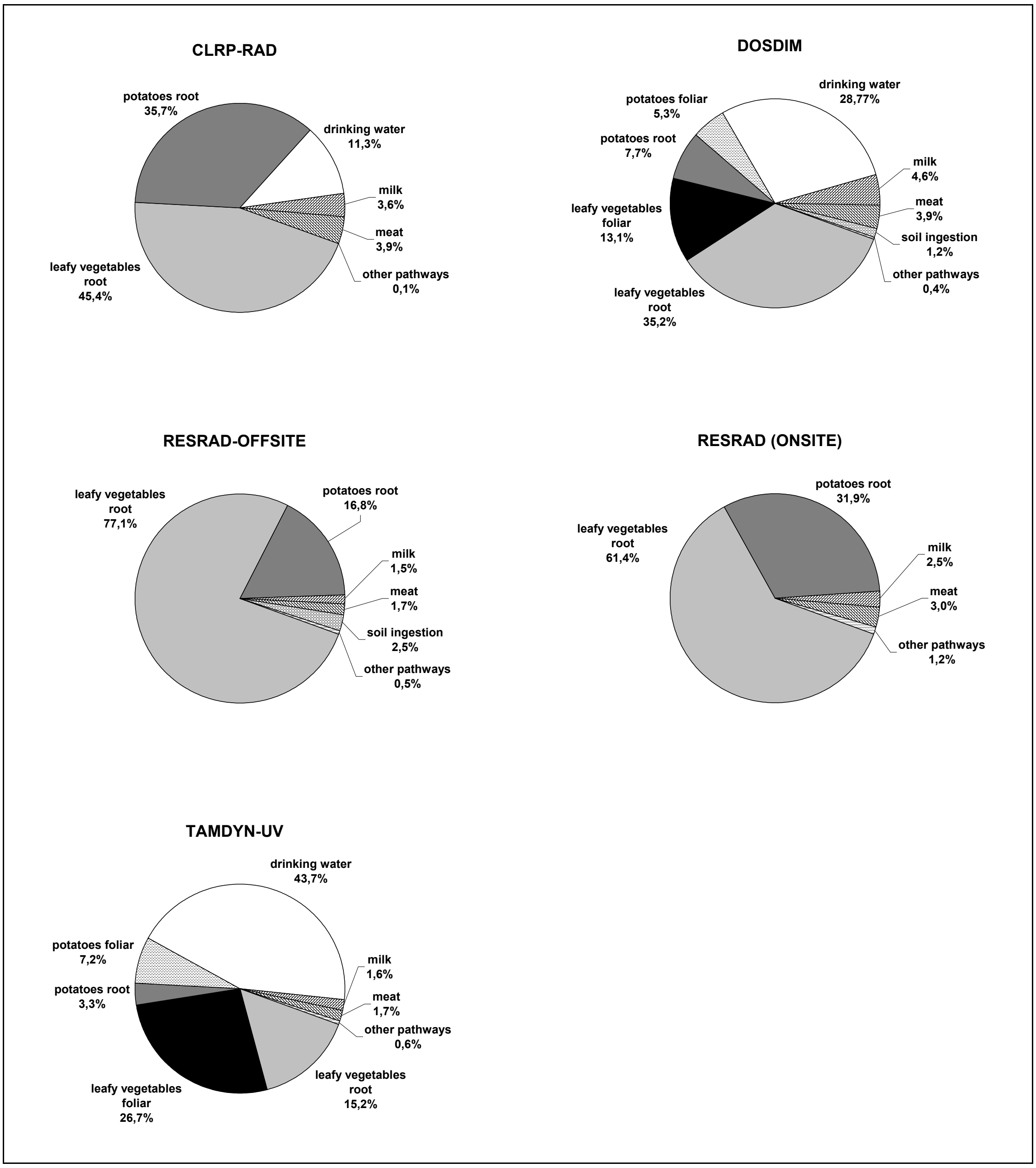


FIG. 61. Contribution of the predictions via different pathways (%) to the total predicted lead dose for remediation 1 at year 1.

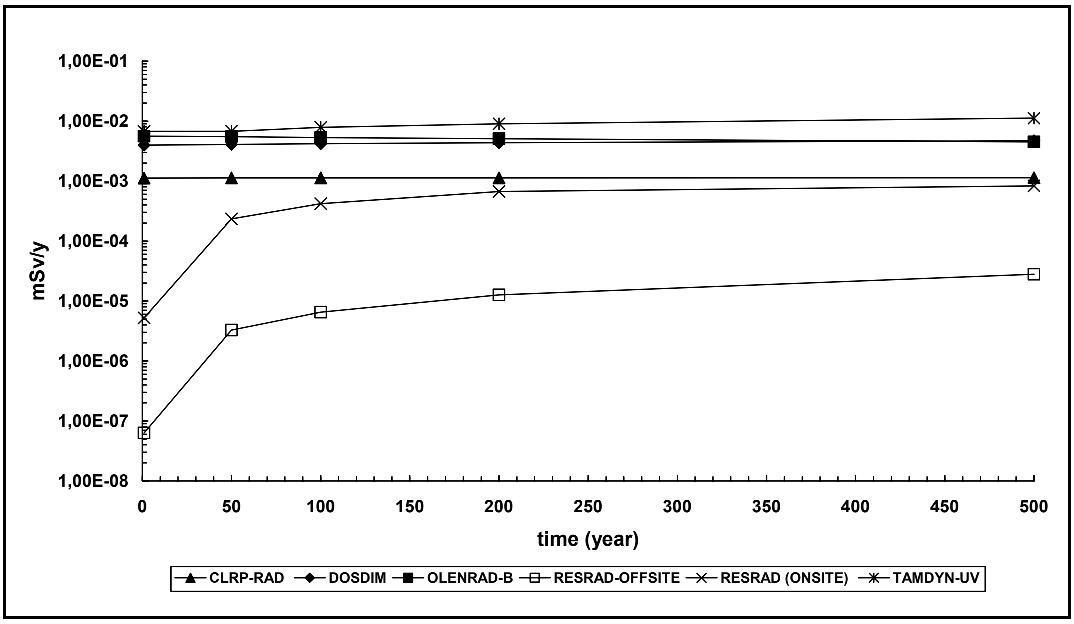


FIG. 62. Predicted ingestion dose of ^{226}Ra contaminated drinking water after remediation 1.

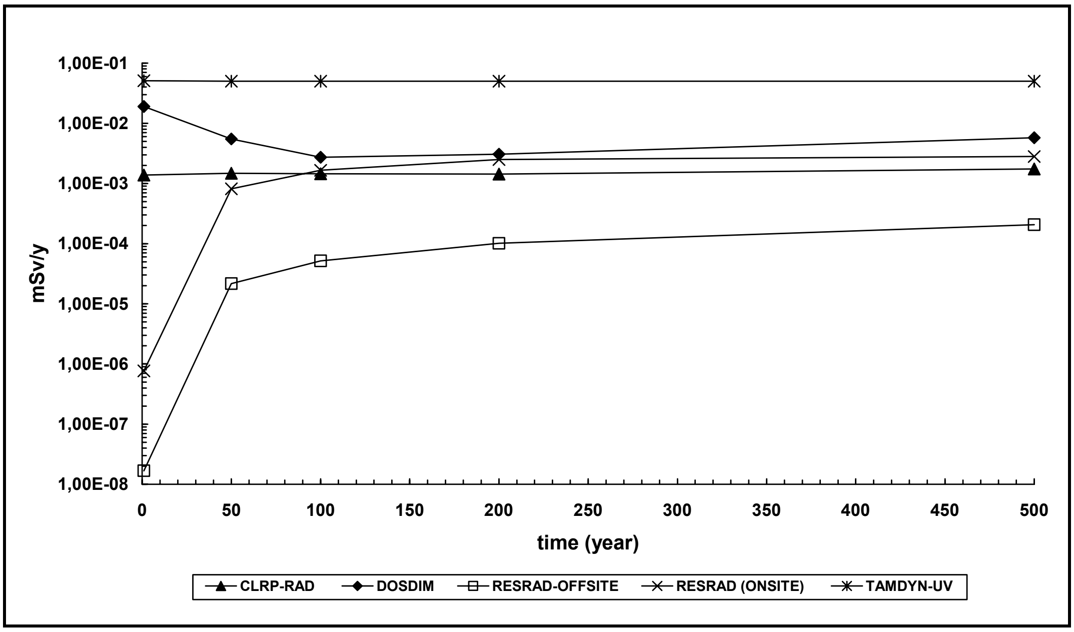


FIG. 63. Predicted ingestion dose of ^{210}Pb contaminated drinking water after remediation 1.

5.2.1.3. Remediation 2: Covering the contaminated area with a clean soil layer of 0.5 m

The covering of the whole site with a 0.5 m soil layer (with a background radium concentration of 20 Bq/kg) has the greatest effect on the dust inhalation pathways, the external irradiation pathways and the ingestion pathways, with exception of the drinking water pathway. This beneficial effect however may decrease with time due to soil processes like diffusion, erosion and bioturbation, changes in the water table level which subsequently may lead to a contamination of the cover by the deeper soil layer and also due to irrigation with contaminated water.

All modellers except RESRAD-OFFSITE and RESRAD (ONSITE) considered mixing processes between the root zone and deeper soil layers which led to a contamination of the root zone. RESRAD-OFFSITE assumed there was no radium (and lead) in the cover and found that the doses for the inhalation of dust are zero during the 500 years because the ploughing depth assumed (0.3 m) is less than the thickness of the cover of 0.5 m. The fact that the inhaled dust does not become contaminated with radium (and lead) during the 500 years also indicates that RESRAD-OFFSITE assumed that the inhaled dust originates only from the not irrigated pasture. The assumption that the cover remains more or less intact also implies that the contamination of the ingestion pathways (food crops, milk, meat and drinking water) can only be caused by contaminated well water via irrigation and drinking. Figure 64 represents the radium concentration in the root zone of the garden. The radium (and lead) concentration in root zone as predicted by RESRAD-OFFSITE increases in time due to accumulation of radium (and lead) in the root zone by irrigation. The other modellers assumed that at least a part of the inhaled dust outdoors was resuspended soil from the garden. RESRAD (ONSITE) considered the losses of soil by wind erosion, but assumed that it is a very slow soil transport process, leaving the cover nearly intact during the 500 years. Upwards acting transfer processes that lead to a higher contamination of the cover were not considered, only irrigation with contaminated water and losses of radium (and lead) by leaching and radioactive decay were assumed. The contamination of the cover due to irrigation is however overcompensated by the losses. This explains the decrease in time of the dose predictions for the inhalation of dust and ingestion pathways which only involve the upper few tens of cm of the soil. Exceptions are the estimated milk and meat ingestion doses which increase in time due to the intake of contaminated water by the cattle. For exposure pathways whose impact was also influenced by the soil layers beneath the root zone (external irradiation, inhalation of radon, drinking water), RESRAD (ONSITE) made a simplification by assuming an average radium (and lead) concentration for cover and the underlying contaminated soil layer as if immediate mixing of the two layers would occur. Also for the calculation of the dust inhalation indoors, RESRAD (ONSITE) did not use the radium (and lead) concentration of the upper soil layer as done for the dust inhalation outdoors but considered an average value for cover and contaminated soil layer below. This results in higher dose predictions via inhalation of dust for remediation 2 compared to those for remediation 1. The use of an average radionuclide concentration however is highly questionable since one can expect that most dust in the air in- and outdoors is coming from the upper soil layer.

For pasture, TAMDYN-UV assumed that only the most contaminated areas are covered and used an average radium (and lead) concentration for the upper 0.5 m soil layer to calculate the dose impact of the various exposure pathways. In contrast with the modellers who assumed covering of the whole pasture land, this led to a higher concentration in the root zone and hence resulted in higher doses via ingestion of milk and meat. Since TAMDYN-UV assumed the same initial radium (and lead) concentration in root zone of pasture after remediation 1, the dose predictions for milk and meat will be nearly the same as those predicted for remediation 1.

The small differences are probably due to the differences in contamination via water intake by the cattle.

The other modellers assumed that there were different mixing processes that could lead to a contamination of the cover. OLENRAD-B assumed that several processes like bioturbation, diffusion, fluctuations in ground water level led to a complete mixing of the cover with the deeper contaminated soil layer within 100 years and simply used an average mixing rate for all these processes. DOSDIM considered bioturbation to be an important mixing process and predicted, using data from literature, that the highest contamination of the cover would occur after 200 years. Afterwards a decrease in the contamination will occur because the losses of radium by radioactive decay and leaching become more important as also observed for OLENRAD-B after 100 years. This trend is reflected in the inhalation of dust and ingestion of food crops contaminated via root uptake. CLRP-RAD and TAMDYN-UV assumed that diffusion is responsible for the upward migration of radium (and lead). However only CLRP-RAD estimated that diffusion would lead to a small increase of the radium (and lead) concentration of the cover and predicted that the highest contamination of the cover would be reached between 200 and 500 years. TAMDYN-UV predicted, in contrast with CLRP-RAD, that leaching is always more important than diffusion resulting in a net downward transport of radium (and lead) and hence a decrease of radium (and lead) concentration in the cover during the considered 500 years (Figure 64).

All modellers, except OLENRAD-B, predicted that the radium (and lead) concentration in drinking water increases during the 500 years due to leaching from the contaminated soil layer. The dose predictions of most modellers (Figure 65) are comparable with the dose predictions for no remediation. This can be expected since the cover, being a local sandy loam soil, can only cause some delay in the migration of radium (and lead) to the aquifer. Exceptions are RESRAD (ONSITE) and TAMDYN-UV who predicted that the radium concentration in drinking water after capping is generally at least two times lower than those obtained for no remediation.

Also for this pathway, RESRAD (ONSITE) assumed one soil layer instead of the two different soil layers (e.g. cover and underlying contaminated soil layer) and used the weighted average of the radium concentrations in these soil layers to calculate the radium concentration in ground water. This simplification of the scenario has led to the observed reduction of the radium concentration in drinking water. The large reduction in the drinking water pathway as estimated by TAMDYN-UV after the remedial action is probably due to a misinterpretation of the scenario. In contrast to the other modellers, TAMDYN-UV assumed that the ground water table reaches the cover and that there is radionuclide exchange between the clean soil and ground water, leading to more radium and lead adsorbed to the clean soil and less radium and lead in the ground water. As mentioned earlier, OLENRAD-B did not consider accumulation of radionuclides in the aquifer by leaching. OLENRAD-B and RESRAD-OFFSITE assumed that remediation 2 did not affect the water pathway at all and produced the same dose predictions for drinking water as for no remediation.

For the external irradiation pathway, differences with time are observed and also the efficiency of the remedial action varies between 36% (OLENRAD-B) and 100% (RESRAD-OFFSITE) at year 1. These differences can be explained by differences in assumptions regarding the contamination of the cover and the degree of mixing with the underlying layers initially and with time and differences in calculation methods. The modellers considered different transport processes (e.g. leaching, diffusion, bioturbation, erosion) to calculate the contamination in cover and underlying soil. DOSDIM predicted an increase of the external irradiation dose, reflecting an increase in the contamination of the surface soil. The others predicted a decrease with time because they did not consider the contamination of the cover by upwards acting processes (RESRAD codes) or calculated that the losses of radium and lead from the cover (TAMDYN-UV) and/or deeper soil layers (CLRP-RAD) obscured any small effect of the upward acting soil processes. OLENRAD-B did not calculate the dose rates but derived them from the measured dose rates for the current situation (no remediation) taking into account the radium and lead concentration of the clean cover and the effect of leaching and radioactive decay in time.

Because only a few exposure pathways determine the dose impact in case of no remediation (Figures 15 and 44), the efficiency of the remedial action will mainly depend on its capacity to reduce the dose via these dominant components. The efficiency of the remedial action is higher for lead than for radium (Table XV), because covering with a clean soil layer that is thicker than the root zone will significantly affect the dominant components of the lead dose, i.e. the ingestion dose of leafy vegetables and potatoes via root. The main contributor to the radium dose, i.e. the inhalation of radon indoors, is also affected by deeper contaminated soil layers and hence will be less reduced. While for the no remediation, the contribution of radon indoors to the total radium dose is high (53 to 84% as predicted by the modellers), its contribution to the total radium dose after remediation 2 is even higher. All modellers predicted that this pathway is less affected by the remedial action than the other pathways. In fact, all model predictions show that more than 85% of the total radium dose is due to the inhalation of radon (Figure 68). Compared to no remediation, the total radium dose will only decrease by a factor of 1.4 (DOSDIM) to 3.4 (CLRP-RAD) while the lead dose will decrease by a factor of 9 (TAMDYN-UV) to 20000 (RESRAD-OFFSITE) at year 1. The doses vary between 2 (CLRP-RAD) and 5 mSv/y (TAMDYN-UV) for radium and between 1.5E-06 (RESRAD-OFFSITE) and 0.1 mSv/y (TAMDYN-UV) for lead at year 1 as shown in Table XVI and Figures 66 and 69. The differences in efficiency between the models are mainly due to the assumptions made regarding the calculation of the radon concentration indoors. It is furthermore seen that the efficiency may change in time. This is mainly due to transport processes in the soil (like bioturbation, diffusion, erosion) and irrigation with contaminated well water which lead to a contamination of cover and partly offset the beneficial effect of the remedial action. The importance of the different pathways is represented in Figures 67 and 68. In agreement with the predictions for the ‘no remediation’ scenario and remedial action 1, the radon inhalation indoor remains the critical pathway. For lead, the ingestion of food crops and drinking water are the dominant pathways, except for RESRAD (ONSITE) (Figure 70 and 71). RESRAD-OFFSITE calculated that the dose via ingestion of drinking water after year 1 contributes only 3.5% to the total lead dose (fifth pathway in ranking of importance), while according to the other models, the contribution of the drinking water is more than 25% (Figure 71). However with time, the importance of the drinking water pathway increases for most models (except DOSDIM). RESRAD-OFFSITE, RESRAD (ONSITE) and TAMDYN-UV calculated that the drinking water pathway is most important contributor to the total lead dose after 500 years (50% (RESRAD-OFFSITE) to 84% (RESRAD(ONSITE) of the total lead dose). DOSDIM calculated that the contribution of drinking water pathway to the total lead dose decreases with time (from 40% to 19%), while the contribution of ingestion of leafy vegetables (contaminated via root uptake) increases with time (from 27% to 56%). These changes in importance with time are due to assumed significant transfer from radium to the cover by upwards acting bioturbation. For remediation 2, the differences in importance of the pathways between models are mainly due to the differences in scenario interpretation (such as taking the historical contamination of the ground water into account or not, considering initially background levels of radium and lead in cover or not, considering mixing of cover with underlying contaminated soil layer and types of mixing processes).

TABLE XV. EFFICIENCY (%) OF REMEDIATION 2 ON TOTAL DOSE

	^{226}Ra			^{210}Pb		
	Year 1	Year 100	Year 500	Year 1	Year 100	Year 500
CLRP-RAD	71	70	68	98	98	96
DOSDIM	28	18	7	95	58	17
OLENRAD-B	68	66	68	n.c.	n.c.	n.c.
RESRAD (ONSITE)	35	33	21	99	95	87
RESRAD-OFFSITE	62	62	62	100	99	97
TAMDYN-UV	55	57	67	89	88	69

TABLE XVI. TOTAL RADIUM AND TOTAL LEAD DOSE FOR THE DIFFERENT REMEDIAL OPTIONS

		No remediation		Remediation 1		Remediation 2	
		Year 1	Year 500	Year 1	Year 500	Year 1	Year 500
Radium:	CLRP-RAD	6.8	3.6	0.35	0.23	2.0	1.2
	DOSDIM	5.2	3.8	0.29	0.23	3.7	3.5
	OLENRAD-B	8.1	2.5	0.21	0.11	2.6	0.8
	RESRAD (ONSITE)	10.6	5.3	2.1	1.3	6.9	4.2
	RESRAD-OFFSITE	7.3	4.6	0.16	0.1	2.8	1.8
	TAMDYN-UV	11	8.2	0.4	0.3	5	2.7
Lead:	CLRP-RAD	0.32	0.17	0.012	0.009	0.005	0.0064
	DOSDIM	1.0	0.7	0.07	0.03	0.04	0.59
	OLENRAD-B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	RESRAD (ONSITE)	0.026	0.78	8.6E-4	0.013	3.4E-4	0.1
	RESRAD-OFFSITE	0.03	0.6	0.001	0.02	1.5E-6	0.02
	TAMDYN-UV	1.1	1.0	0.1	0.1	0.1	0.3

n.c. = not calculated.

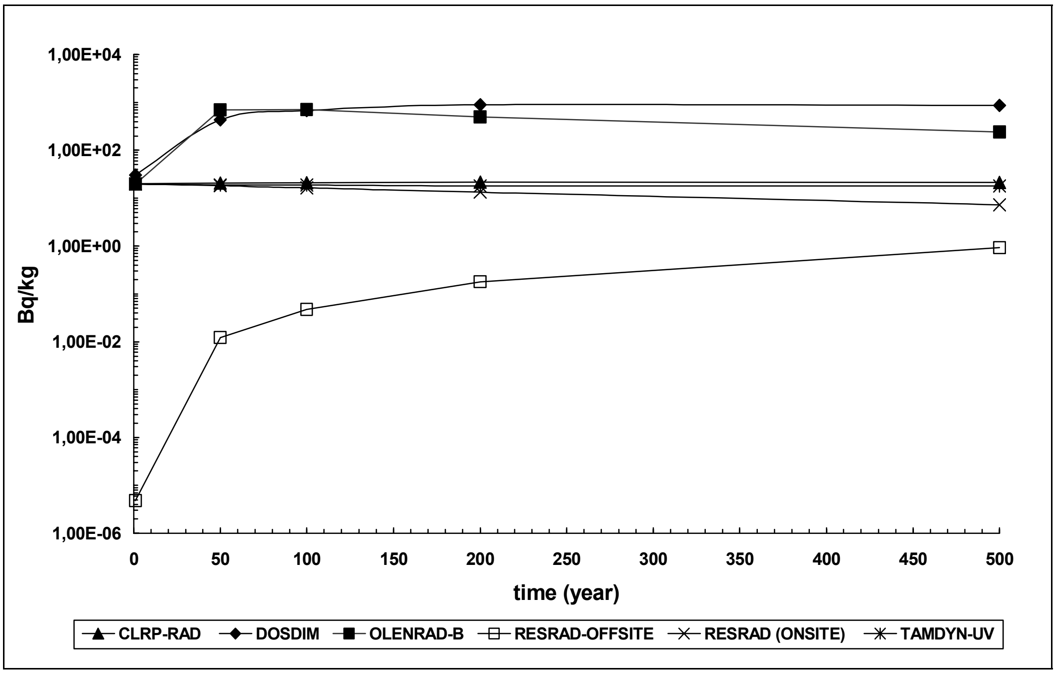


FIG. 64. Time-dependency of the predicted concentration of radium in the root zone of the garden after remediation 2.

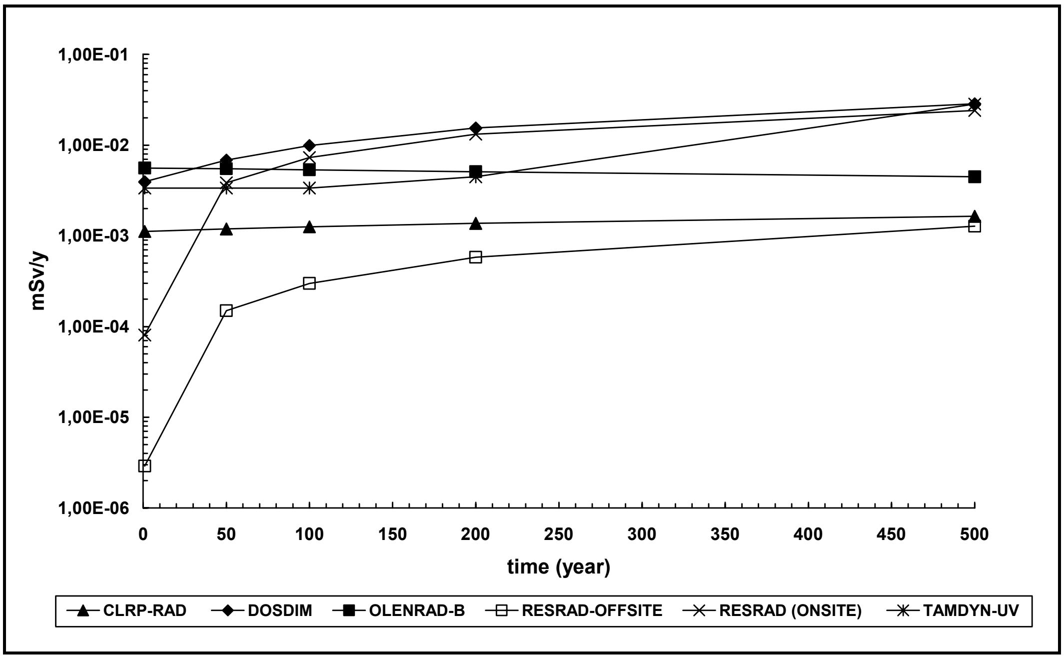
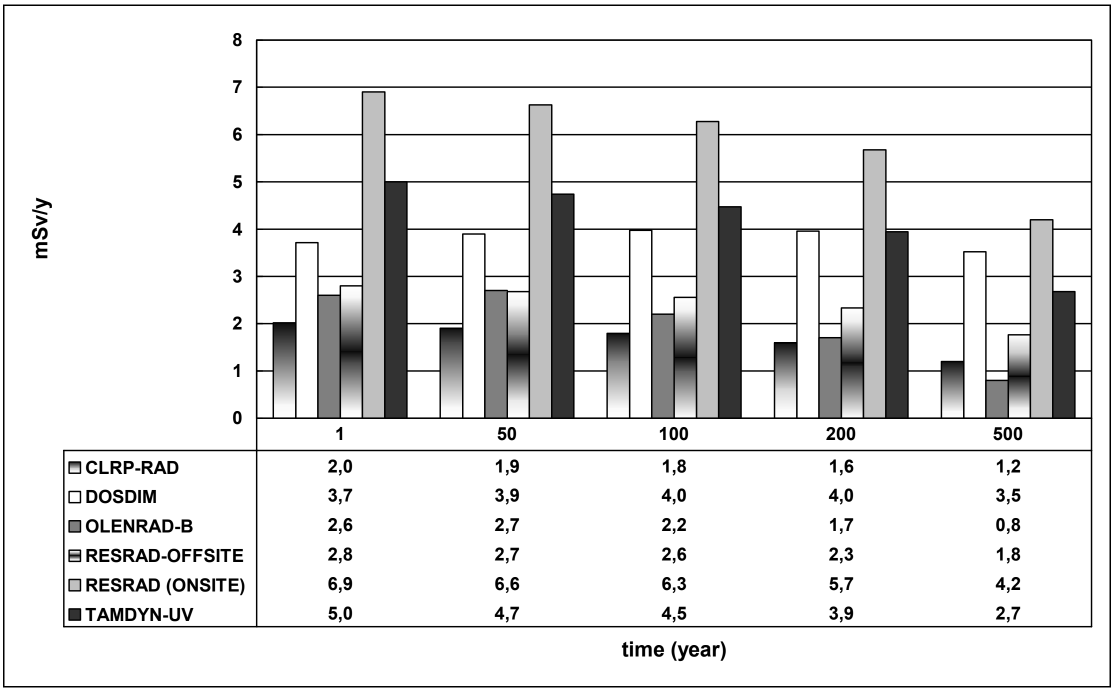


FIG. 65. Predicted ingestion dose of ^{226}Ra contaminated drinking water for remediation 2.



	1	50	100	200	500
▤ CLRP-RAD	2,0	1,9	1,8	1,6	1,2
□ DOSDIM	3,7	3,9	4,0	4,0	3,5
■ OLENRAD-B	2,6	2,7	2,2	1,7	0,8
⊟ RESRAD-OFFSITE	2,8	2,7	2,6	2,3	1,8
▨ RESRAD (ONSITE)	6,9	6,6	6,3	5,7	4,2
■ TAMDYN-UV	5,0	4,7	4,5	3,9	2,7

FIG. 66. *Predictions of the total radium dose after remediation 2.*

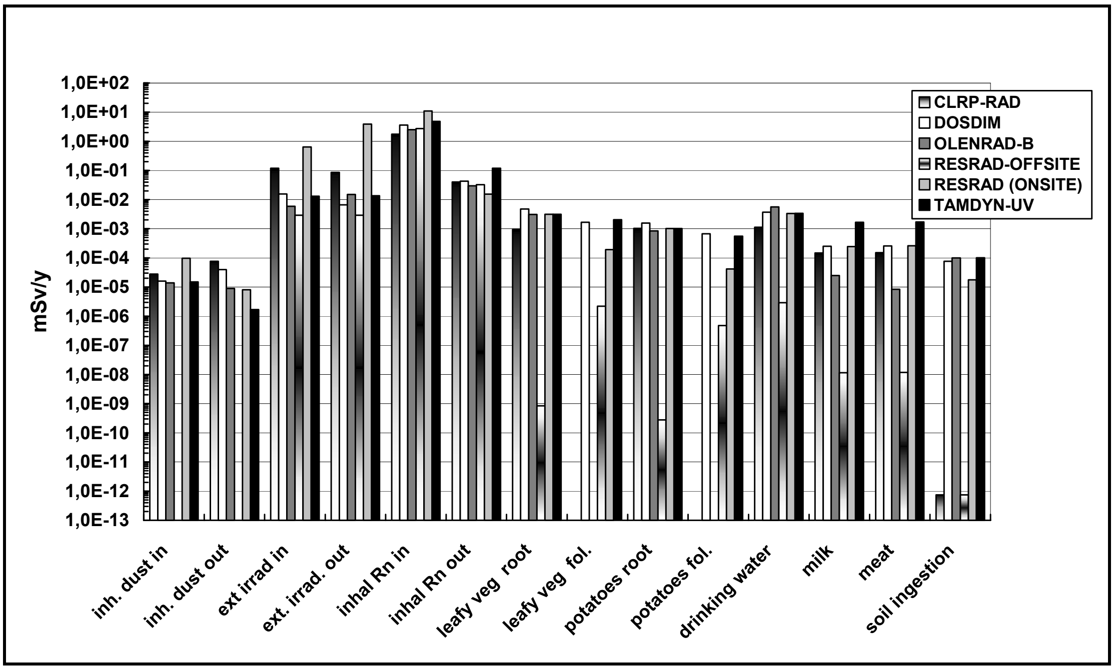


FIG. 67. *Predictions of the radium dose via the different pathways for remediation 2 at year 1.*

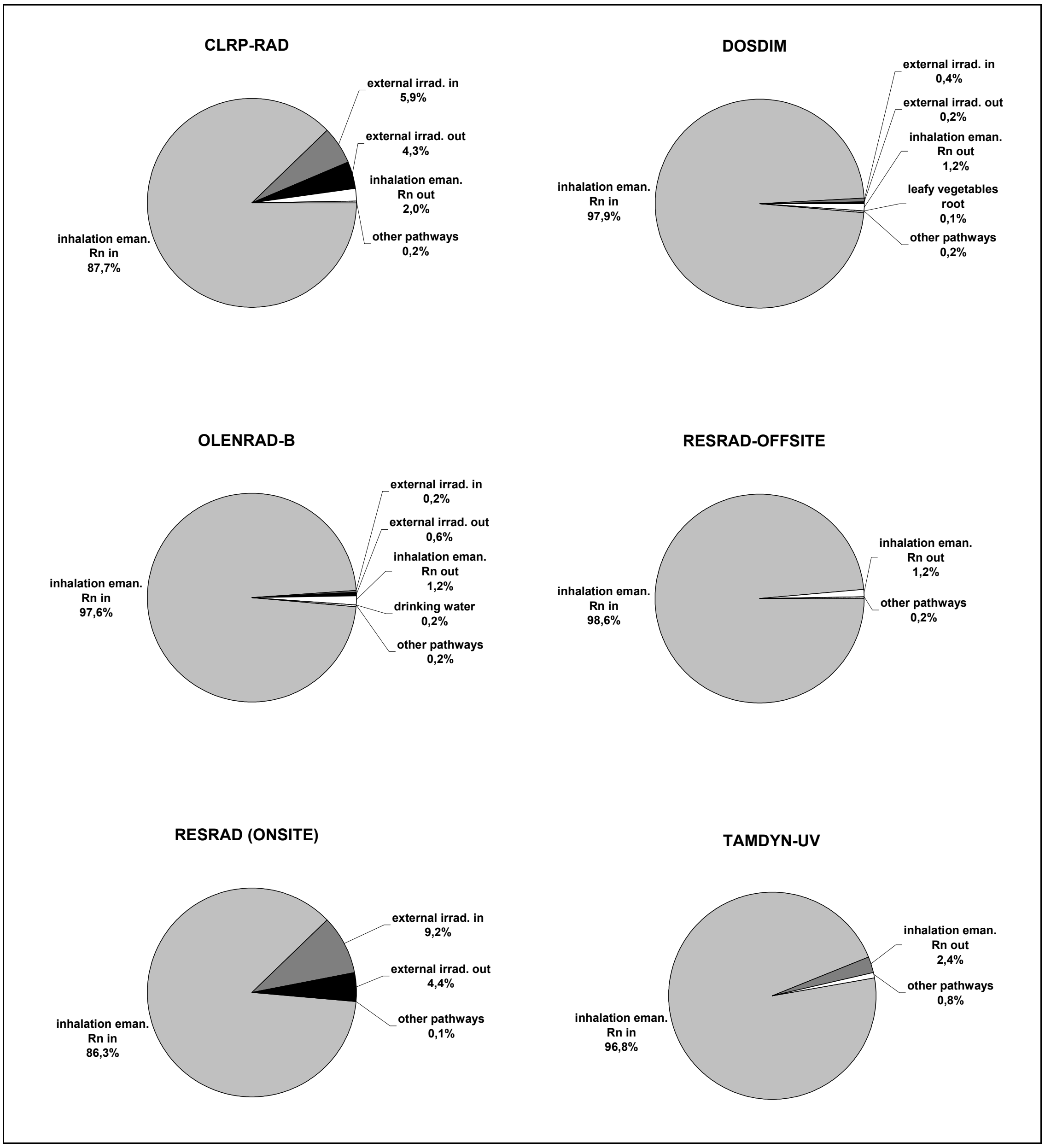
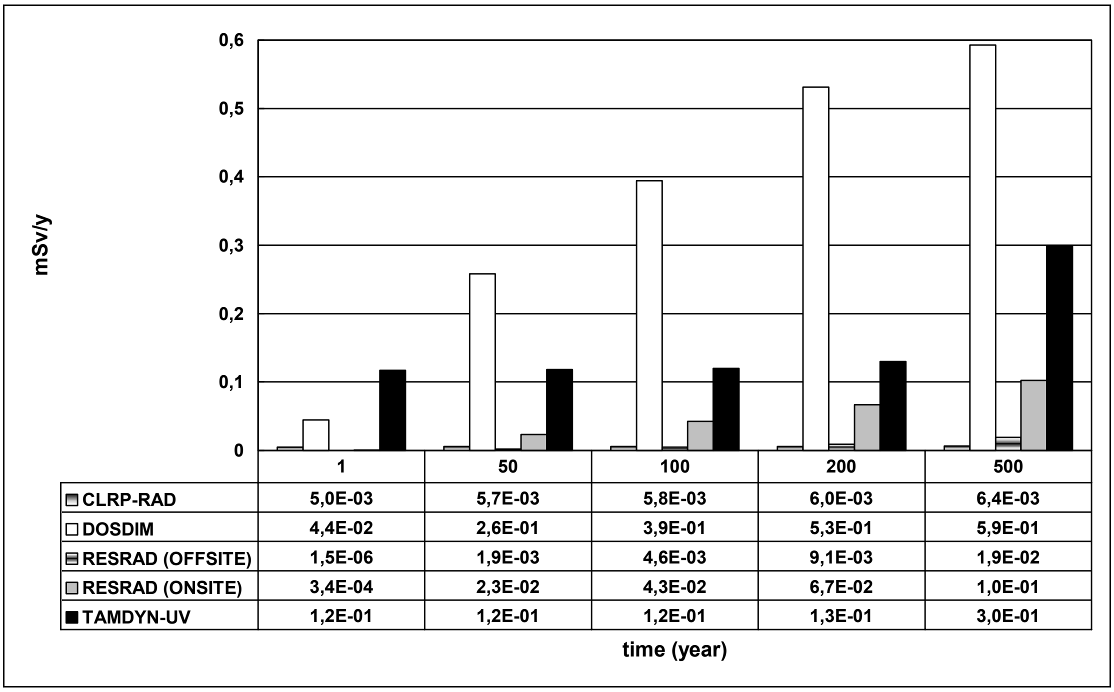


FIG. 68. Contribution of the predictions via different pathways (%) to the total predicted radium dose for remediation 2 at year 1.



	1	50	100	200	500
▤ CLRP-RAD	5,0E-03	5,7E-03	5,8E-03	6,0E-03	6,4E-03
☐ DOSDIM	4,4E-02	2,6E-01	3,9E-01	5,3E-01	5,9E-01
▤ RESRAD (OFFSITE)	1,5E-06	1,9E-03	4,6E-03	9,1E-03	1,9E-02
▨ RESRAD (ONSITE)	3,4E-04	2,3E-02	4,3E-02	6,7E-02	1,0E-01
■ TAMDYN-UV	1,2E-01	1,2E-01	1,2E-01	1,3E-01	3,0E-01

FIG. 69. Predictions of the total lead dose after remediation 2.

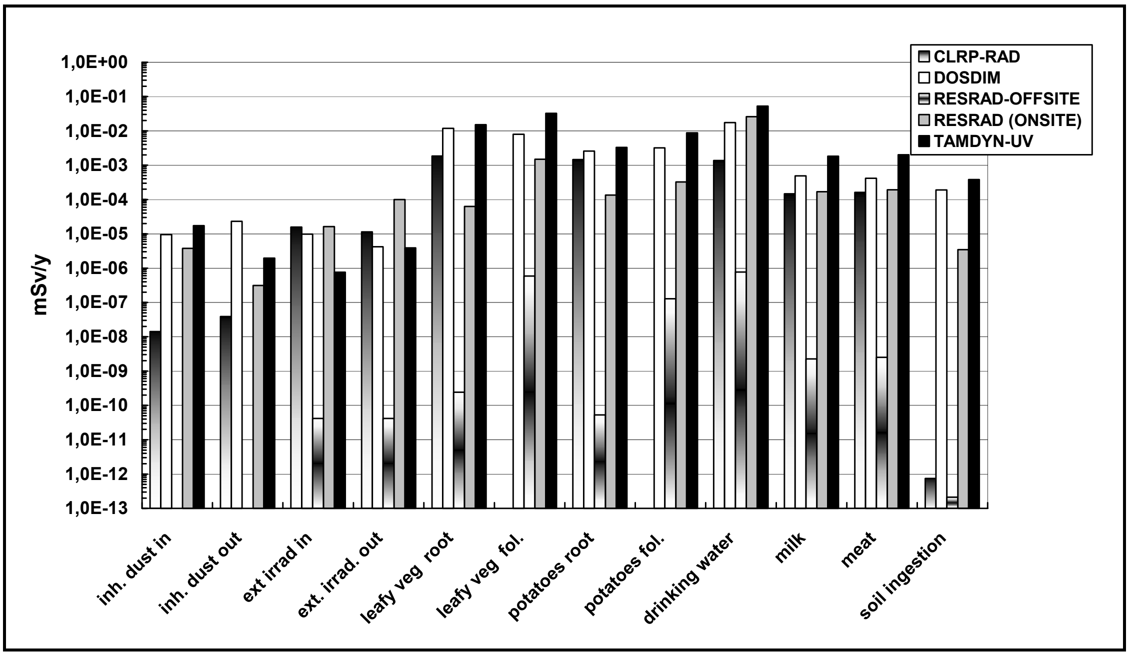


FIG. 70. Predictions of the lead dose via different pathways for remediation 2 at year 1.

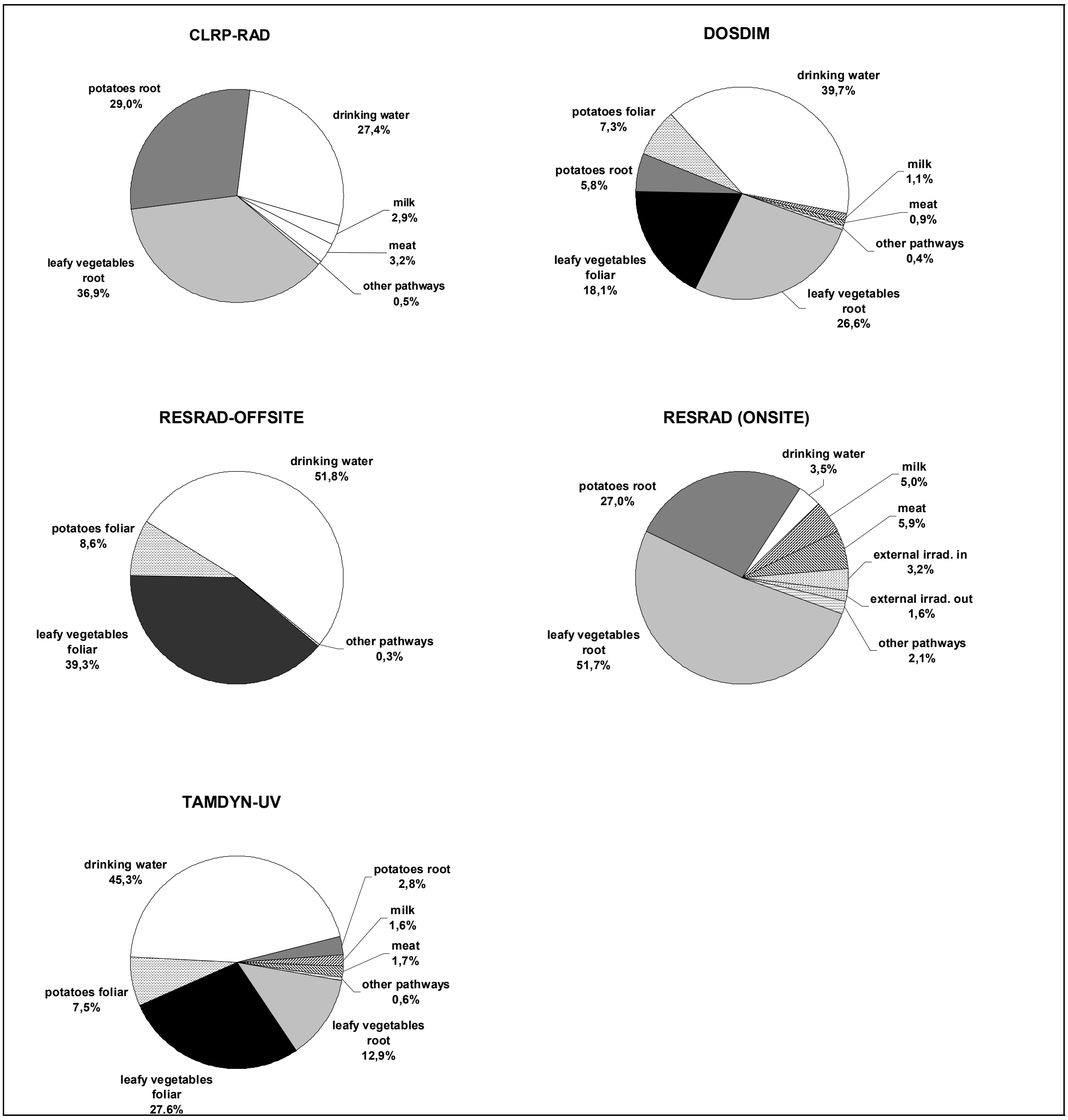


FIG. 71. Contribution of the predictions via different pathways (%) to the total predicted lead dose for remediation 2 at year 1.

5.2.2. Uncertainty analysis

All modellers, except RESRAD (ONSITE), carried out stochastic calculations. The uncertainty technique used and the uncertainty ranges of the input parameters that have been considered in the uncertainty analysis are listed in Table II, respectively Tables VII and VIII. For most input parameters, the uncertainty ranges (and probability density functions (pdfs)) were given in the scenario description. However, for some input parameters some modellers like CLRP-RAD defined other uncertainty ranges and/or pdfs based on their own expert judgement and also the data requirements of the different models varied, leading to differences in the input parameters included in the uncertainty analysis. Some models also required more input parameters than given in the scenario description. For these parameters, if considered at all in the uncertainty analysis, the uncertainty ranges were highly dependent on personal judgement. None of the modellers considered scenario evolution, i.e. variations in parameter values with time.

It should be noticed that RESRAD-OFFSITE did not calculate the stochastic doses for radium and lead individually, only combined results for radium and lead are reported. Furthermore RESRAD-OFFSITE did not give uncertainty estimates for radon inhalation in- and outdoors separately. Also leafy vegetables and potatoes were not considered separately in the uncertainty analysis.

5.2.2.1. No remediation

5.2.2.1.1. Radium

The modellers were asked to produce uncertainty estimates for different periods of time. For no remediation, two models (CLRP-RAD, RESRAD-OFFSITE) calculated that the uncertainty ranges of the dose predictions broaden by a factor of 2 to 4 in time for almost all the exposure pathways. In the case of the RESRAD-OFFSITE model, there is one exception, namely the drinking water pathway for which uncertainty ranges were produced that decrease by a factor of 3 in size during the considered 500 years. This can be explained by the decrease in sensitivity of the drinking water ingestion dose to the input parameters (e.g. distribution coefficient, soil density) which influence the migration of radium to the aquifer. Unlike the other modellers who carried out uncertainty analysis, the RESRAD-OFFSITE modeller did not consider the historical contamination of the ground water, making the input parameters responsible for the downward movement of radium in soil initially the main contributors to the uncertainty of the drinking water ingestion dose. However, due to the accumulation of radium in ground water, their contribution to the contamination of drinking water becomes less important in time. The sizes of the predicted uncertainty ranges for the no remediation case produced by the other models (DOSDIM, OLENRAD-A and TAMDYN-UV) are generally less time dependent. With exception of some pathways, their calculated uncertainty ranges for the different pathways show no change in size during the considered time period. DOSDIM found that the uncertainty in dust inhalation dose, external irradiation dose and soil ingestion dose increase with time. These changes are due to changes in importance of the input parameters contributing to the uncertainty of the dose predictions. DOSDIM calculated that initially only the radium concentration in root zone and the soil density contribute to the uncertainty. With time however, DOSDIM found that also the distribution coefficient becomes an important contributor because of its effect on the radium concentration in the root zone soil.

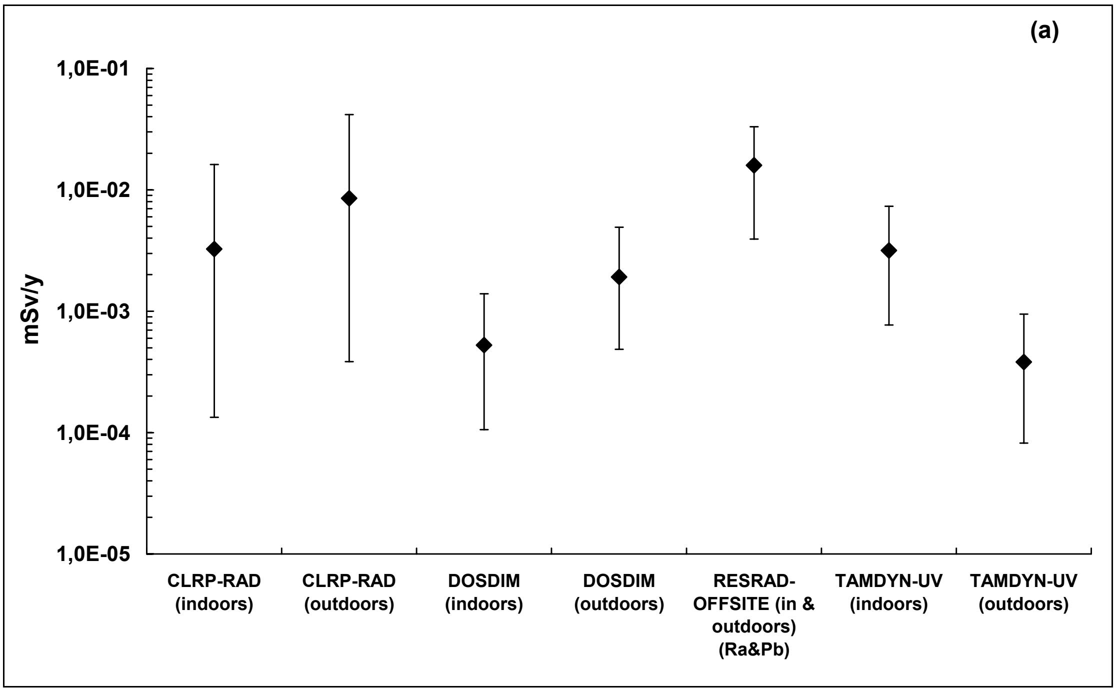
In general, the differences in sizes of the predicted uncertainty ranges for each pathway as well as the differences in sizes with time observed between the models can be explained by the differences in input parameters considered in the uncertainty analysis, differences in uncertainty ranges associated with the input parameters and differences in the influence of parameters and their interactions on the model output.

— **Inhalation of dust**

The uncertainty estimates for dust inhalation dose at year 1 are shown in Figure 72. OLENRAD-B did not provide results for this pathway. It is seen that the uncertainty ranges may differ by more than 1 order of magnitude between the models. Two parameters are responsible for these differences, namely the soil concentration in the surface soil layer and the inhalable dust concentration in air. Comparison of the results shows that the uncertainty ranges calculated by DOSDIM, RESRAD-OFFSITE and TAMDYN-UV are comparable. Nevertheless, the input parameters that were considered in the uncertainty analysis differ. DOSDIM and RESRAD-OFFSITE considered the uncertainty of the parameters used to calculate the leaching rate, while TAMDYN-UV also considered the uncertainty of the diffusion coefficient. DOSDIM and TAMDYN-UV also included uncertainty associated with the initial radium concentration in soil, while RESRAD-OFFSITE did not. The uncertainty ranges obtained by CLRP-RAD are more than one order of magnitude broader. A possible explanation is that the CLRP-RAD user, in disagreement with the other modellers, also considered uncertainty ranges for the time spent in- and outdoors. The effect of this time occupation on the uncertainty range is however limited and cannot explain the one order of magnitude difference, since CLRP-RAD varied the time periods only by a factor of 2 (using a triangular probability density function). Another more important explanation is that CLRP-RAD used a lognormal probability density function for the radium concentration in the surface soil layer instead of a triangular probability density function like DOSDIM did, leading to larger uncertainty ranges. The uncertainty ranges are expected to increase with time for pathways that are affected by the uncertainty of input parameters (e.g. the leaching rate, bioturbation rate, diffusion coefficient) whose influence on the radium inventory in soil becomes greater with time. This explains the larger uncertainty ranges of the dust inhalation dose obtained after 500 years by some models (CLRP-RAD, DOSDIM, RESRAD-OFFSITE).

— **External irradiation**

A similar explanation for the observed differences in uncertainty estimates can be given for external irradiation (Figure 73). For this pathway, the uncertainty range of the radium concentration in soil is for most models an important contributor to the uncertainty of the external irradiation dose. Other important parameters that contribute to the uncertainty are the soil density and with time the distribution coefficient in soil. The effect of the uncertainty associated with the radium concentration in soil is reflected in the differences between the uncertainty ranges obtained by DOSDIM, OLENRAD-B and TAMDYN-UV on the one hand and RESRAD-OFFSITE on the other hand. In contrast with RESRAD-OFFSITE that predicted the smallest ranges of uncertainty, CLRP-RAD, DOSDIM and TAMDYN-UV included the uncertainty ranges of the initial soil radium concentration in the uncertainty analysis. All three models (CLRP-RAD, DOSDIM and TAMDYN-UV) derived the best estimate values and uncertainty ranges of the radium concentration in soil from observed data and the differences in these values and ranges are due to differences in the interpretation of the imperfect data set. For the larger uncertainty ranges calculated by CLRP-RAD the same explanation can be given as for the inhalation of dust. OLENRAD-B used the measured external dose rates to calculate the external doses and derived the uncertainty ranges of the external doses from the variability in measured external dose rate values.



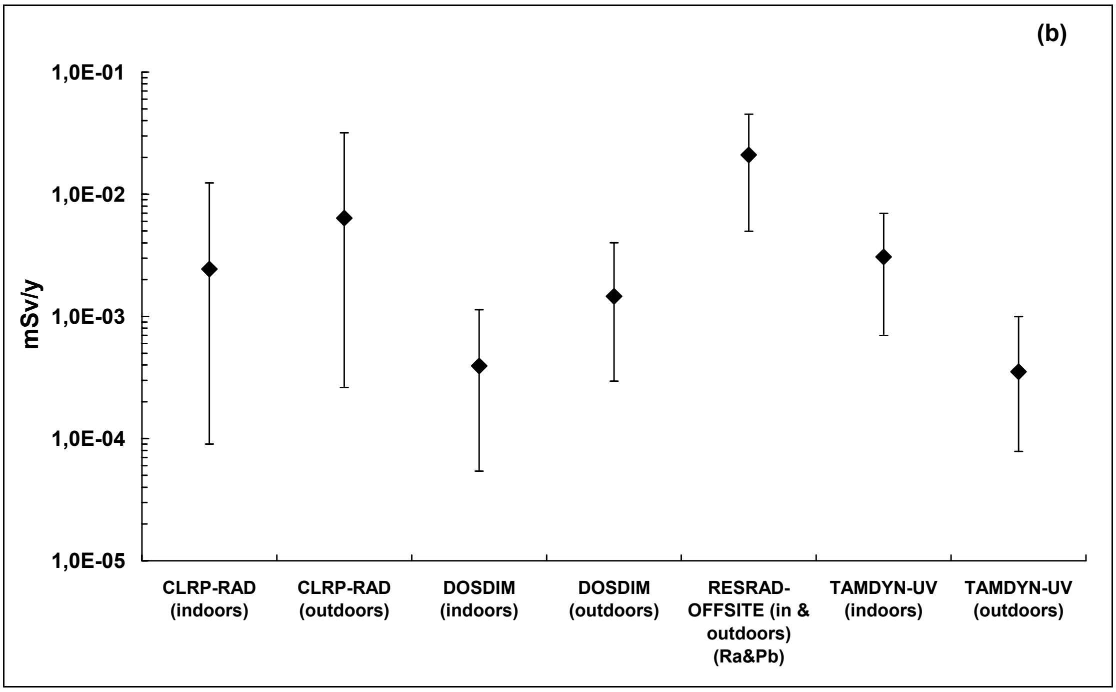


FIG. 72. Inhalation dose of ^{226}Ra contaminated dust for no remediation at year 1 (a) and year 100 (b). The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

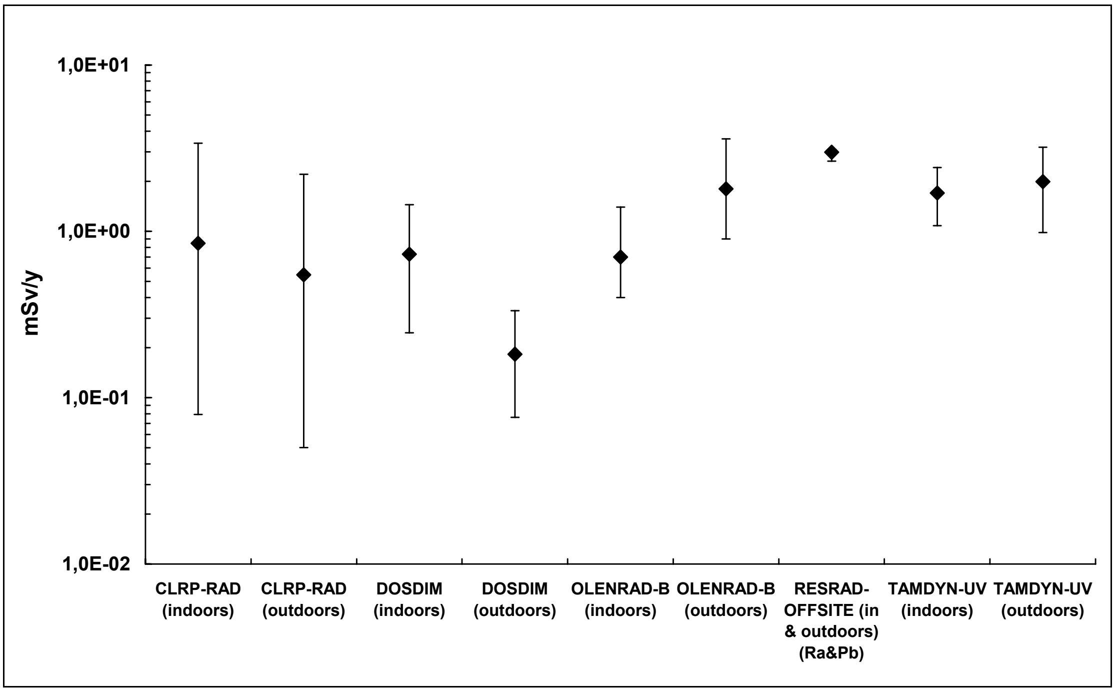


FIG. 73. External irradiation dose of ^{226}*Ra for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.*

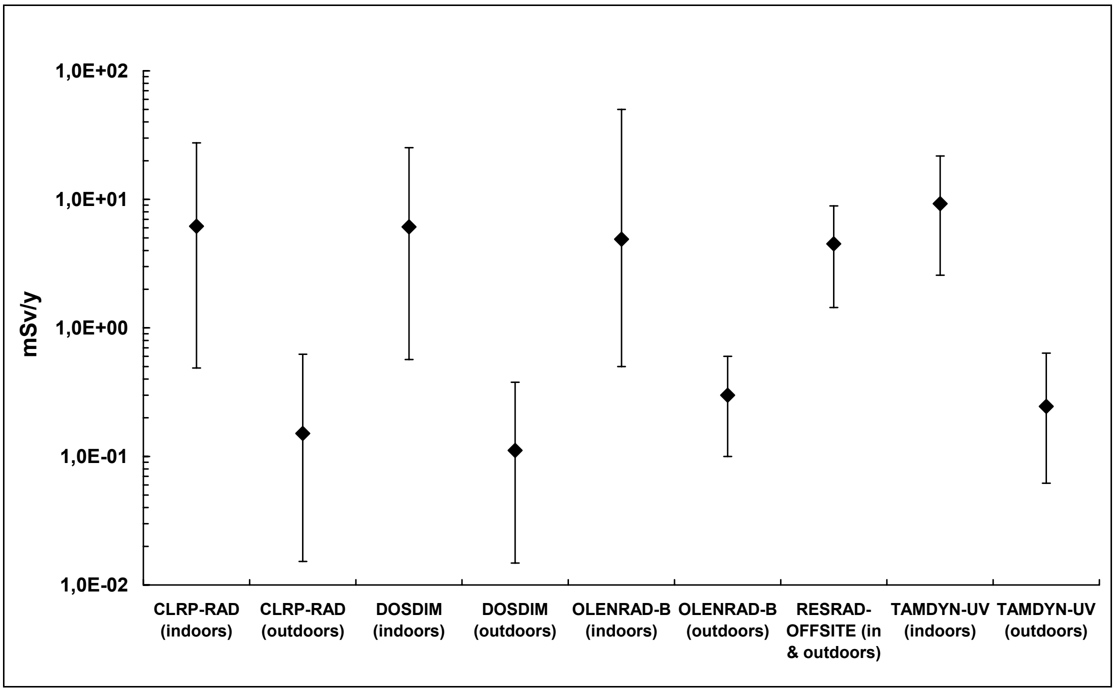


FIG. 74. Inhalation of radon for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

- **Inhalation of radon**

In general, the uncertainty ranges obtained for the indoor inhalation dose of radon are higher than the uncertainty ranges obtained for the outdoors dose (Figure 74). This was to expect since there are also various factors involved in the transfer from outdoors to indoors (e.g. the thickness of the basement, ventilation rate of the house diffusion coefficient in building materials etc.) which contribute to the uncertainty of the dose predictions. Most of these factors are very site-specific. This implies that even for sites with little spatial variability in soil radium concentrations, the indoor radon concentration can range over several orders of magnitude.

In contrast with the other modellers that used diffusion equations, DOSDIM calculated the indoor radon concentration from the surrounding soil by considering a simple site-specific 'radium in soil'-to-'radon in air' transfer coefficient. This approach was used because due to the lack of knowledge not all the important processes contributing to the radon concentration indoors can be modelled. Most models neglected the fact that radon does not only enter the house via diffusion but also via advection (e.g. through cracks in the foundation of the house). More research and high quality data are needed to increase the understanding and to allow better modelling of the processes involved, reducing the model and parameter uncertainty.

In the scenario description, measured transfer coefficients of radium concentration in soil to radon concentration indoor and outdoor are given. DOSDIM assumed an uncertainty range of 100 for the transfer coefficient of radium concentration soil to radon concentration indoor and an uncertainty range of 50 for the transfer coefficient of radium concentration soil to radon concentration outdoor. These large ranges were chosen to represent uncertainty due to the limited knowledge about the pathway and the site. Compared to radon outdoors, a larger uncertainty range for radon indoors was adopted to include additional sources of uncertainty associated with the transfer of radon in air outdoors to air indoors (like the ventilation rate, thickness of basement, number and size of cracks in the foundation, volume of the rooms, etc). OLENRAD-B did not consider the uncertainty of input parameters separately. Only the uncertainty ranges of radium concentration in soil was considered separately. For the other input parameters, it was assumed that due to their uncertainties, the uncertainty ranges of the radon dose outdoors and indoors would increase by a factor of 2, respectively a factor of 10. Due to these assumptions, the uncertainty ranges of the inhalation doses produced by OLENRAD-B barely change in size with time. The other modellers that used diffusion equations to model the radon concentration differed in the parameters considered in the uncertainty analysis. CLRP-RAD and RESRAD-OFFSITE needed more input parameters than given in the scenario description. Instead of using the diffusion rate of radon in soil as input parameter, they calculated it using a number of other input parameters (like soil porosity, saturation rate) for which neither values nor uncertainty ranges were given in the scenario description. In disagreement with RESRAD-OFFSITE, the CLRP-RAD modeller chose not only best estimate values for these parameters but also considered the contribution of these parameters to the overall uncertainty. This explains the larger ranges of uncertainty as predicted by CLRP-RAD. The size of the uncertainty ranges as predicted by RESRAD-OFFSITE are comparable with those predicted by TAMDYN-UV because in the uncertainty analysis both modellers only considered the input parameters for which uncertainty ranges were given in the scenario description.

— **Ingestion of leafy vegetables, potatoes**

The uncertainty ranges obtained for the ingestion of leafy vegetables (potatoes) via root uptake vary from less than one order of magnitude (OLENRAD-B) to 3 orders of magnitude (CLRP-RAD) (Figures 75, 76). It should be noticed that the results of RESRAD-OFFSITE given in Figure 75 represent the results for leafy vegetables and potatoes together. For most models, the radium concentration in the root zone soil, the soil-to-plant transfer factor and with time the distribution coefficient are the main contributors to the uncertainty. OLENRAD-B considered uncertainty ranges for the radium concentration in soil, but did not consider uncertainty ranges for the other parameters separately. To take into account the uncertainty of other factors involved in the uptake of radium by plants and its subsequent ingestion by man, the OLENRAD-B modeller assumed an overall uncertainty factor of 2, which explains the small uncertainty ranges obtained for these ingestion pathways. The same assumption was made for the other ingestion pathways (milk, meat). Due to the use of this overall uncertainty factor, the sizes of the uncertainty ranges of the ingestion doses are hardly time dependent. CLRP-RAD gives the highest uncertainty estimates for leafy vegetables and potatoes, not only because for the soil concentration a lognormal distribution is used, but also because for the soil-to-plant transfer coefficient a lognormal distribution instead of logtriangular distribution as given in the scenario description was used. The CLRP-RAD modeller felt that a lognormal distribution is more representative for the variations in the soil-to-plant transfer data. This resulted in larger ranges of uncertainty.

The large uncertainty ranges calculated by DOSDIM for the ingestion dose of leafy vegetables and potatoes contaminated via foliar uptake are mainly reflecting the uncertainty ranges obtained for the ground water pathway.

— **Ingestion of drinking water**

CLRP-RAD obtained very small uncertainty ranges for drinking water (Figure 77). As mentioned earlier, the CLRP-RAD modeller derived the initial drinking water concentration and also the ranges of uncertainty from measured ground water data. For the following years, the diffusion and leaching of radium was taken into account and the uncertainty ranges mainly reflect the uncertainty of the input parameters (e.g. diffusion coefficient, distribution coefficient, the infiltration rate, the volumetric water content and the soil porosity and soil density of the contaminated zone) needed to calculate the diffusion and leaching rate. As a result, the initial uncertainty ranges expand by a factor of 10 after 500 years. For the very small uncertainty ranges obtained by the OLENRAD-B for the drinking water dose the same remarks as for the ingestion of leafy vegetables and potatoes can be made.

TAMDYN-UV is the only model that assumes uncertainty for the consumption rate of water (variations within a factor of 4). Compared to the results of DOSDIM and RESRAD-OFFSITE, the uncertainty estimates of TAMDYN-UV are rather small because it mainly reflects the uncertainty in the distribution coefficient of the soil.

The uncertainty ranges calculated by DOSDIM and RESRAD-OFFSITE are larger because they also reflect the uncertainty range of the distribution coefficient in aquifer. For the distribution coefficient in aquifer, the same values and uncertainty ranges as for the soil were taken. Their uncertainty ranges however decrease in size with time, because the drinking water pathway becomes less sensitive to the parameters (e.g. distribution coefficient) responsible for the downwards migration of radium due to accumulation of radium in the aquifer.

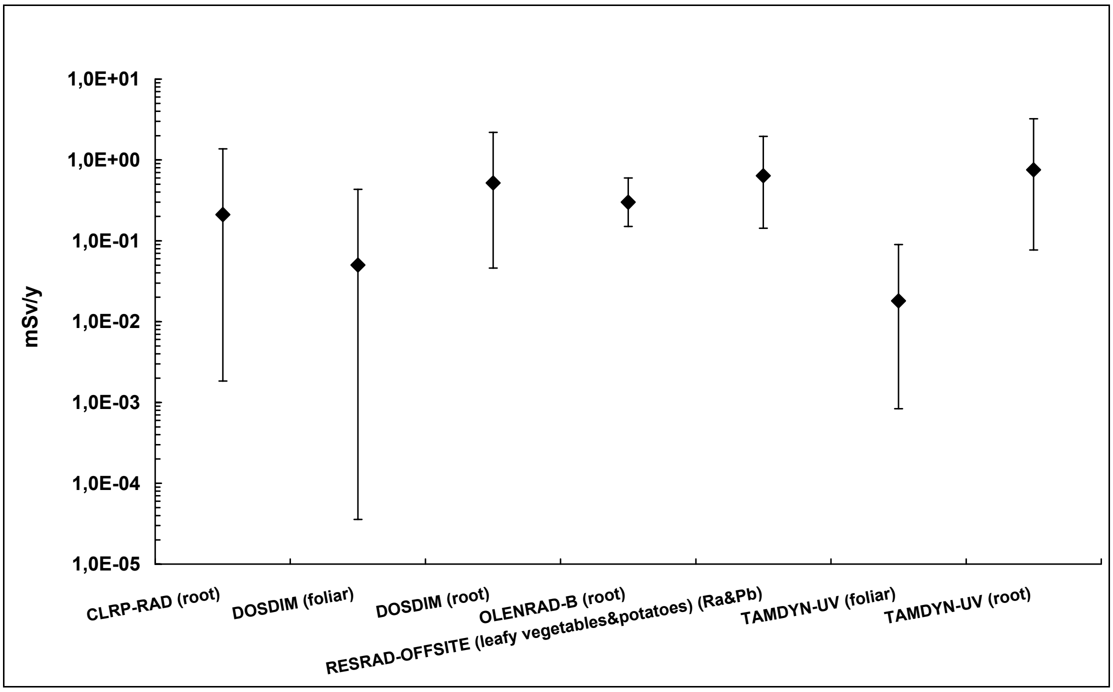


FIG. 75. Ingestion dose of ^{226}Ra contaminated leafy vegetables for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

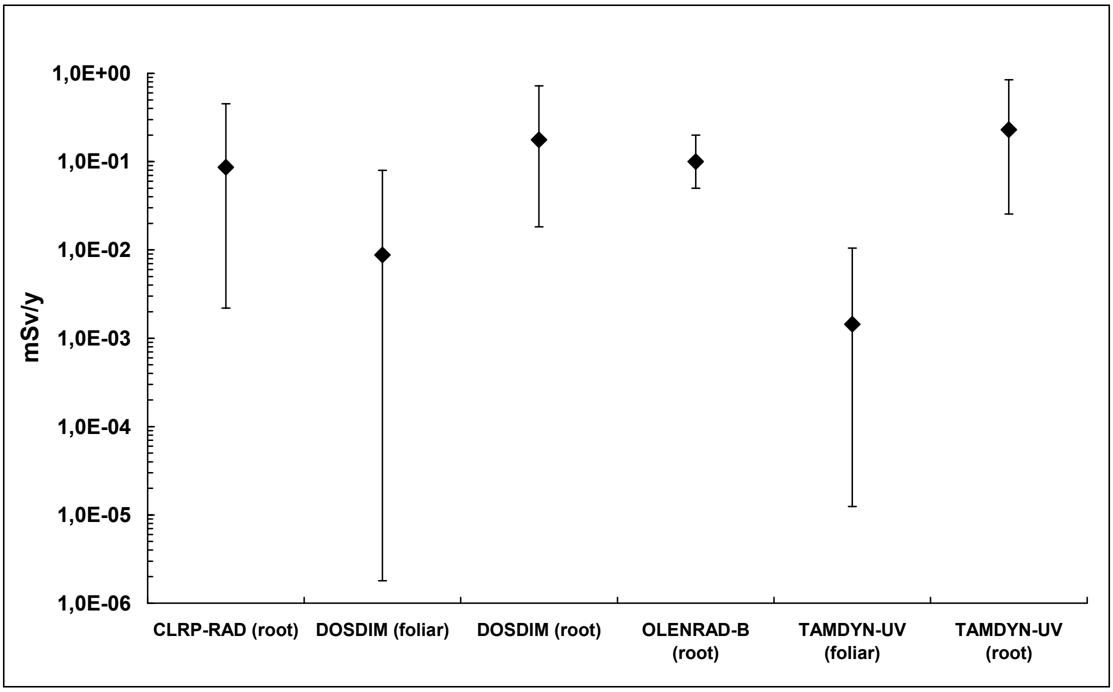


FIG. 76. Ingestion dose of ^{226}Ra contaminated potatoes for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

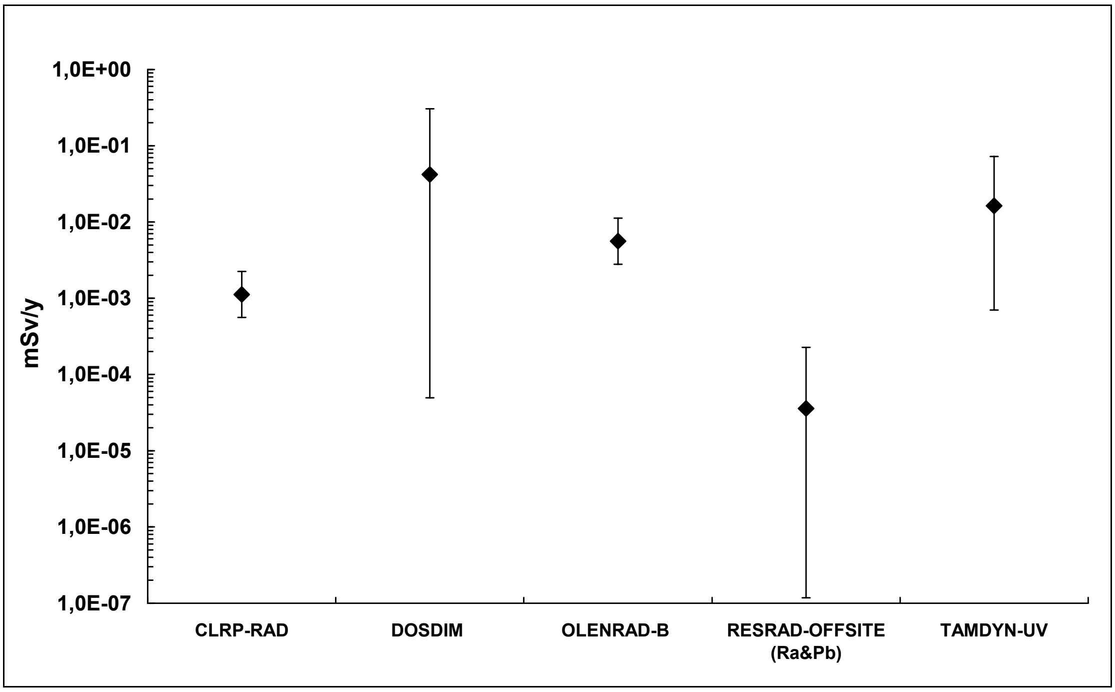


FIG. 77. Ingestion dose of ^{226}Ra drinking water for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

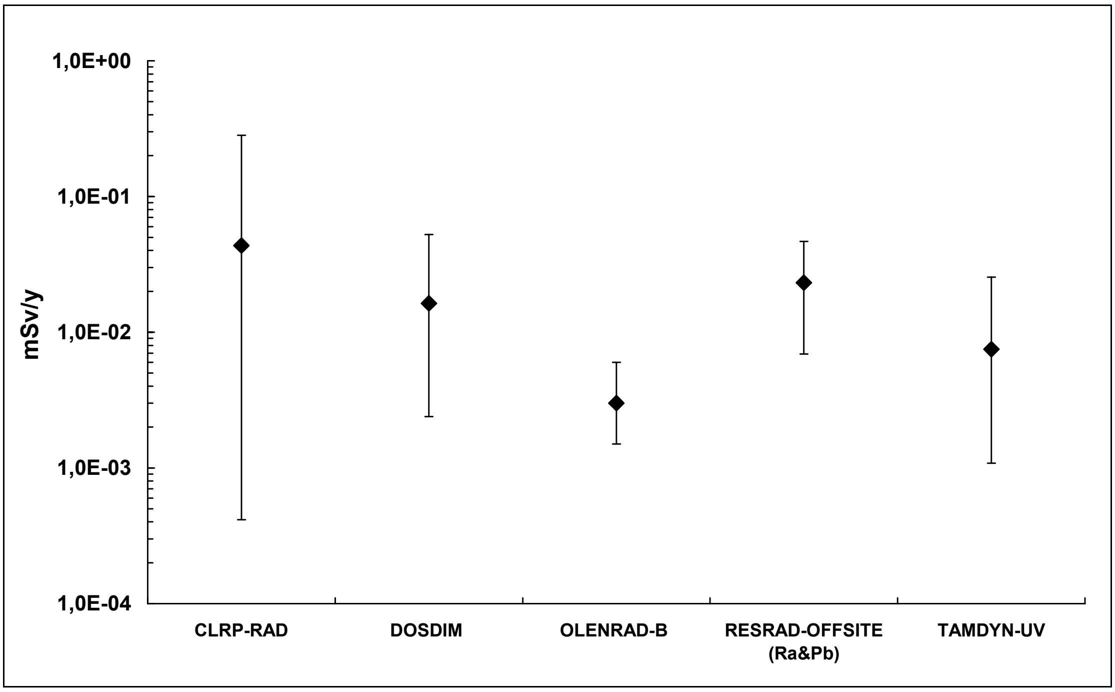


FIG. 78. Ingestion dose of ^{226}Ra contaminated milk for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

— Ingestion of milk and meat

OLENRAD-B calculated the smallest uncertainty ranges because as mentioned earlier, an overall uncertainty factor of 2, beside the uncertainty of the initial soil concentration, was considered for the transfer of radium to man via the ingestion pathways (Figures 78, 79). The uncertainty ranges of the DOSDIM and TAMDYN-UV results are comparable and reflect mainly the uncertainty associated with the distribution coefficient in soil, the soil-to-grass and grass-to-milk transfer factors. CLRP-RAD obtained the largest ranges of uncertainty (3 orders of magnitude) associated with the predicted values via root uptake because of the same reason as mentioned earlier, namely the use of a lognormal distribution function instead of a triangular distribution function for the soil concentration and the soil-to-grass transfer coefficient. The intake of contaminated water by cattle is a less important pathway than the uptake via pasture (roots) as shown by the smaller uncertainty ranges obtained for milk by DOSDIM and RESRAD-OFFSITE compared to those obtained for drinking water. OLENRAD-B and CLRP-RAD did not consider the drinking of the cattle.

— Ingestion of soil

The parameters contributing to the uncertainty of the soil ingestion dose may be the uncertainty of the initial soil concentration, the uncertainty of parameters determining the leaching rate (e.g. distribution coefficient) and the consumption rate of soil (Figure 80). DOSDIM did not consider the consumption rate of soil in the uncertainty analysis because no uncertainty ranges were given in the scenario description. The uncertainty estimates of DOSDIM are mainly influenced by the uncertainty of the radium concentration in soil and in the long term the uncertainty associated with the distribution coefficient in soil. TAMDYN-UV however did not consider the initial soil concentration in the uncertainty analysis but assumed that the intake of soil vary by a factor of 5. RESRAD-OFFSITE did not assume uncertainty for the initial soil concentration nor for the consumption rate. No uncertainty ranges were given for year 1. The uncertainty range obtained for year 100 indicates that RESRAD-OFFSITE considered the uncertainty of parameters associated with the leaching rate whose contribution to the uncertainty of the dose predictions becomes more important in time. This also explains the slow enlargement of the uncertainty ranges for the soil ingestion doses with time as obtained by DOSDIM and TAMDYN-UV.

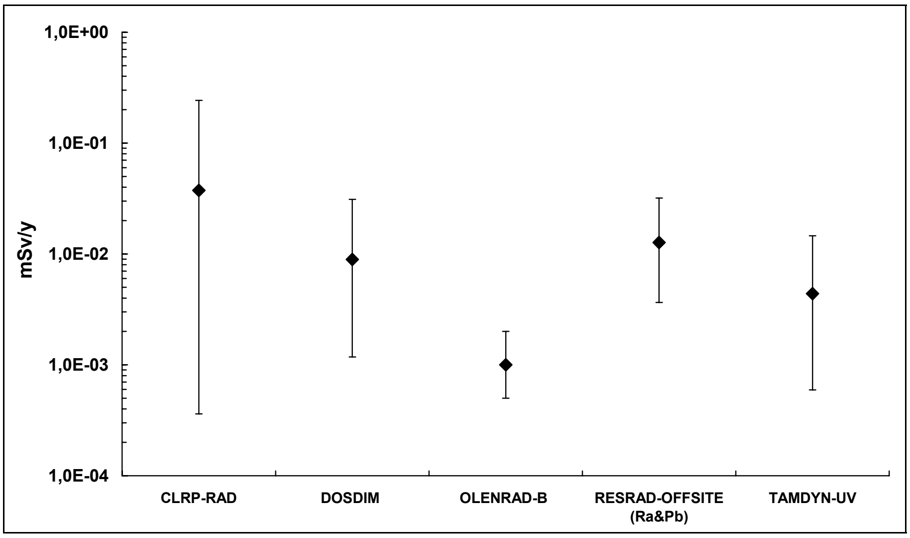
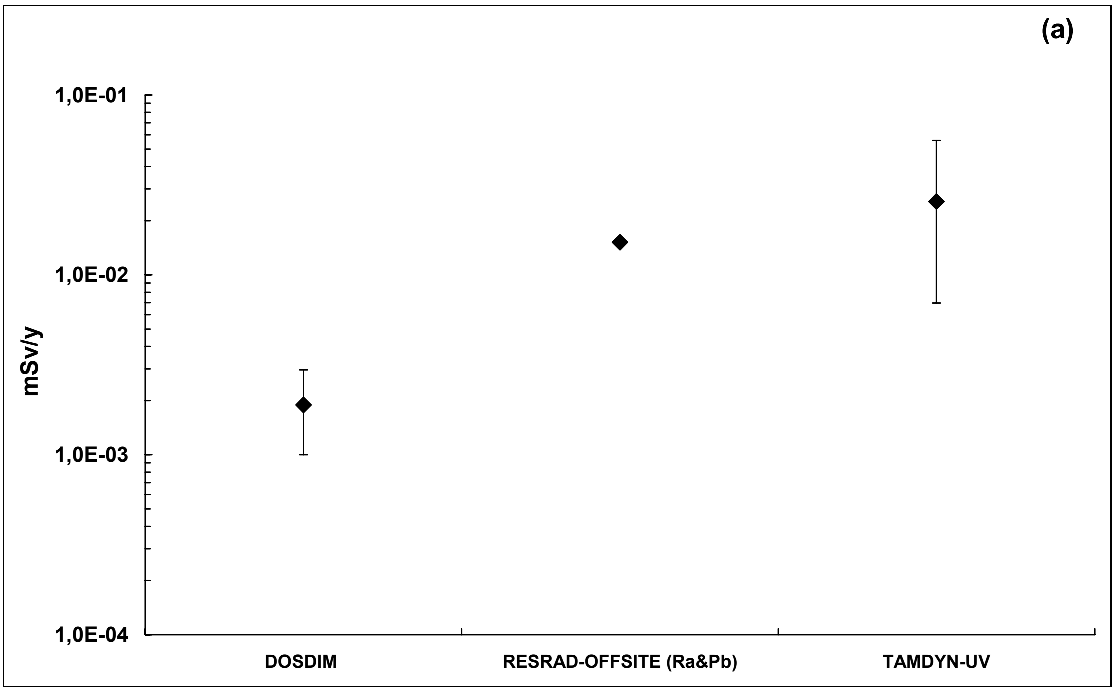


FIG. 79. Ingestion dose of ^{226}Ra contaminated meat for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.



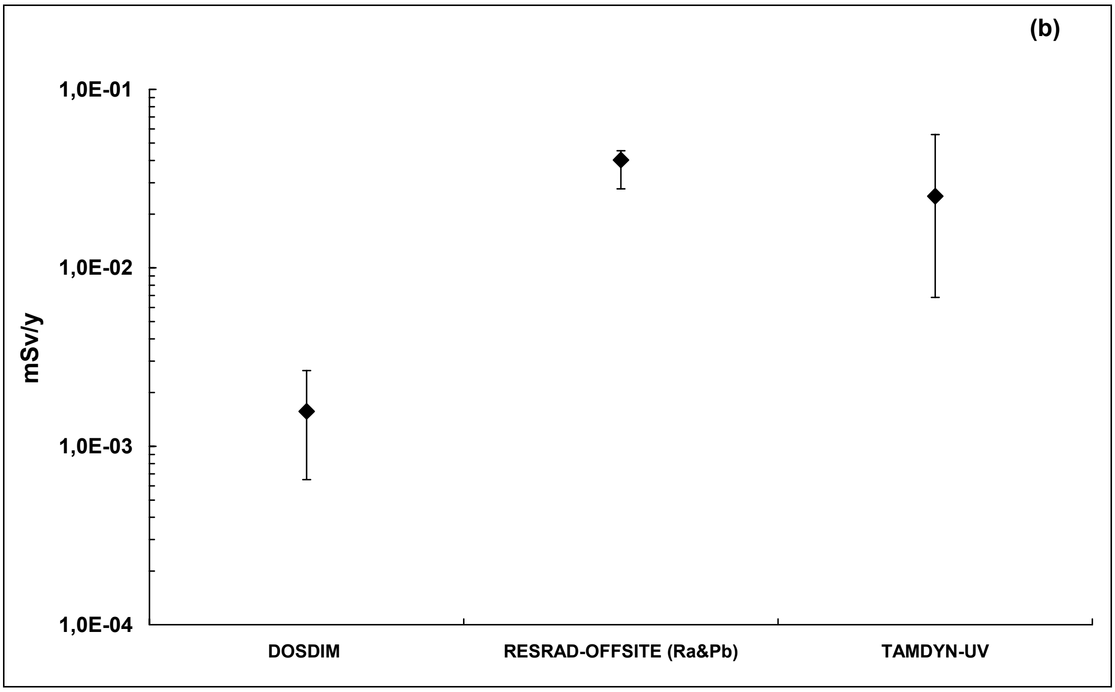


FIG. 80. Ingestion dose of ^{226}*Ra contaminated soil for no remediation at year 1 (a) and at year 100 (b). The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.*

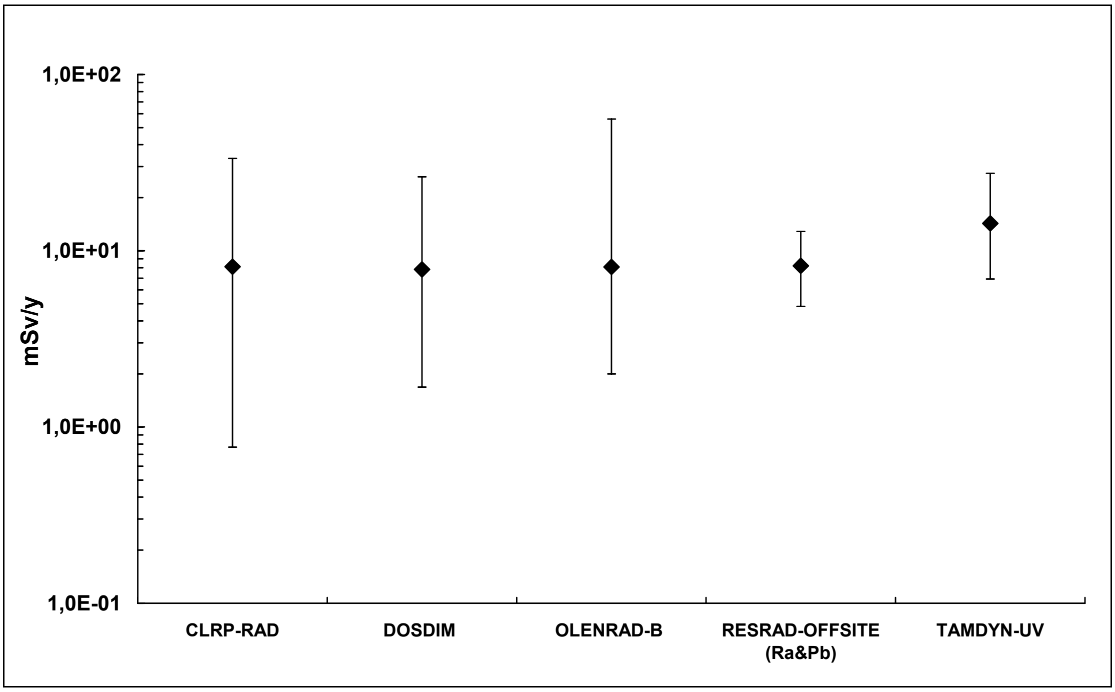


FIG. 81. Total radium dose for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

— **Total dose**

Since the inhalation of radon indoors is the main contributor to the total dose, its uncertainty will be mainly determined by the uncertainty of the radon inhalation indoors dose as clearly seen in Figure 81 (similar ranges as obtained in Figure 74). With exception of CLRP-RAD and RESRAD-OFFSITE, the uncertainty ranges of the dose predictions remain more or less constant in time indicating that the input parameters that dominate the uncertainty of the radon inhalation dose indoors do not become more important with time. For example, the uncertainty of the leaching rate which influence on the radium concentration in soil increases with time contributes very little to the overall uncertainty due to the low mobility of radium.

5.2.2.1.2. Lead

Only the predictions of CLRP-RAD, DOSDIM and TAMDYN-UV can be discussed because RESRAD (ONSITE) and OLENRAD-B did not give uncertainty estimates for lead and RESRAD-OFFSITE only submitted stochastic results for radium and lead combined which were discussed in the previous section.

Intercomparison of the predictions of the models shows that for lead very similar observations as those already discussed for radium can be made. The models that give the largest (respectively smallest) uncertainty ranges for radium give similar results for lead. Compared to the calculations made for radium, the input parameters considered in the uncertainty analysis for all appropriate exposure pathways do not change. Only the best estimate values and uncertainty ranges of the radionuclide-specific parameters have changed and resulted in uncertainty ranges for each pathway that vary by no more than one order of magnitude in size from those obtained for radium.

The uncertainty of the total lead dose (Figure 85) at year 1 is mainly determined by the uncertainty associated with the ingestion of leafy vegetables and potatoes via root uptake (Figures 82, 83) which are the dominant exposure pathways (Figures 44). For CLRP-RAD, and RESRAD-OFFSITE the relative significance of these pathways do not change in time. For DOSDIM and TAMDYN-UV however, the drinking water pathway becomes the second most important pathway after 500 years (Figure 45). As a result, their predicted uncertainty ranges for the total lead dose increase in size with time, reflecting the large uncertainty estimates of the drinking water pathway (Figure 84). It is furthermore observed that the best estimate values of the total lead dose predicted by DOSDIM slightly increase with time, while for the deterministic results a slow decrease has been observed. The large uncertainty of the drinking water pathway and the importance of this pathway and the ingestion pathways via foliar uptake in the total lead dose which increase with time may also give an explanation for these discrepancies.

5.2.2.1.3. Total dose

The total dose (Ra&Pb) is, as could be expected, mainly determined by the uncertainty estimates of the total radium dose (Figure 86 versus Figure 81).

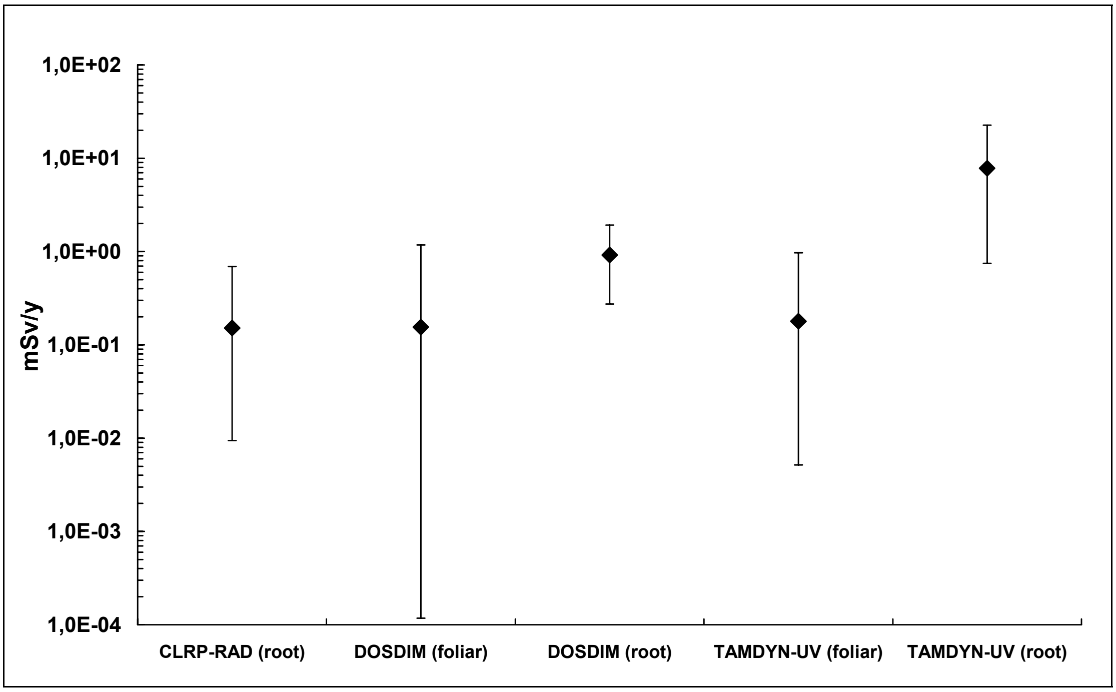


FIG. 82. The ingestion dose of ^{210}Pb contaminated leafy vegetables for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

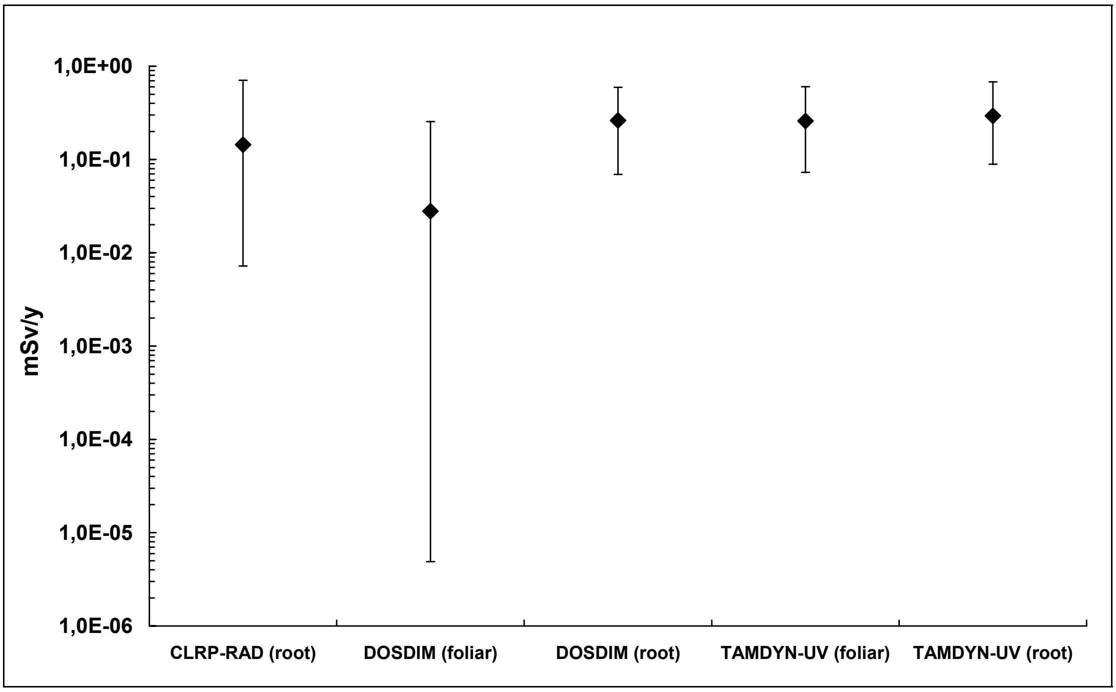


FIG. 83. The ingestion dose of ^{210}Pb contaminated potatoes for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

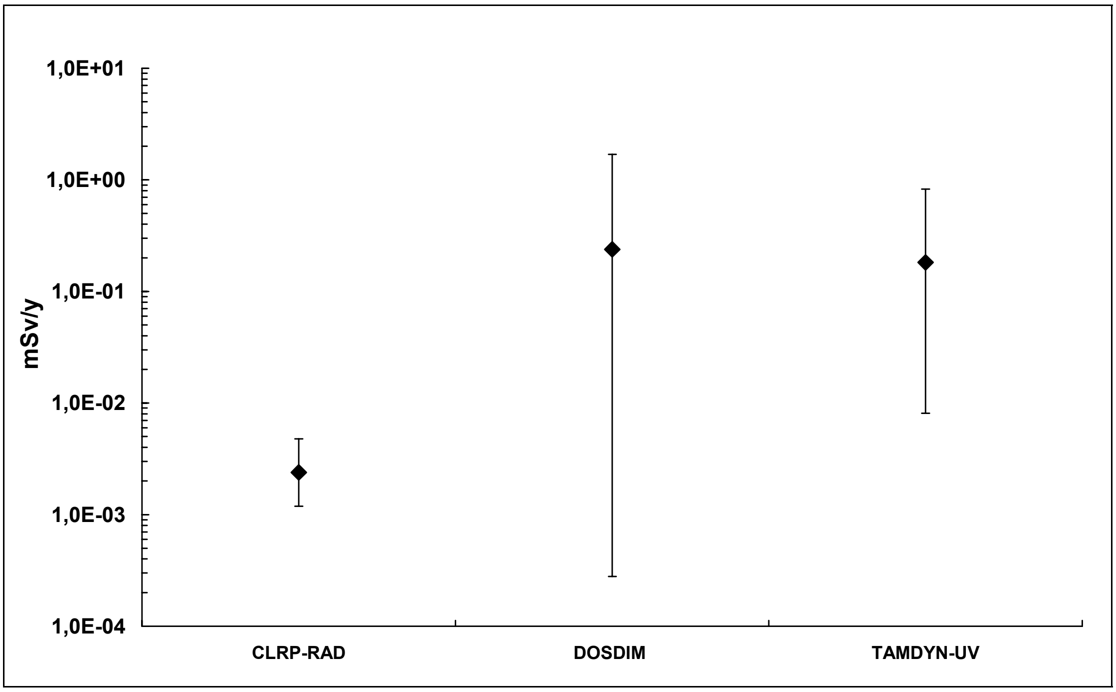


FIG. 84. Ingestion dose of ^{210}Pb contaminated drinking water for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

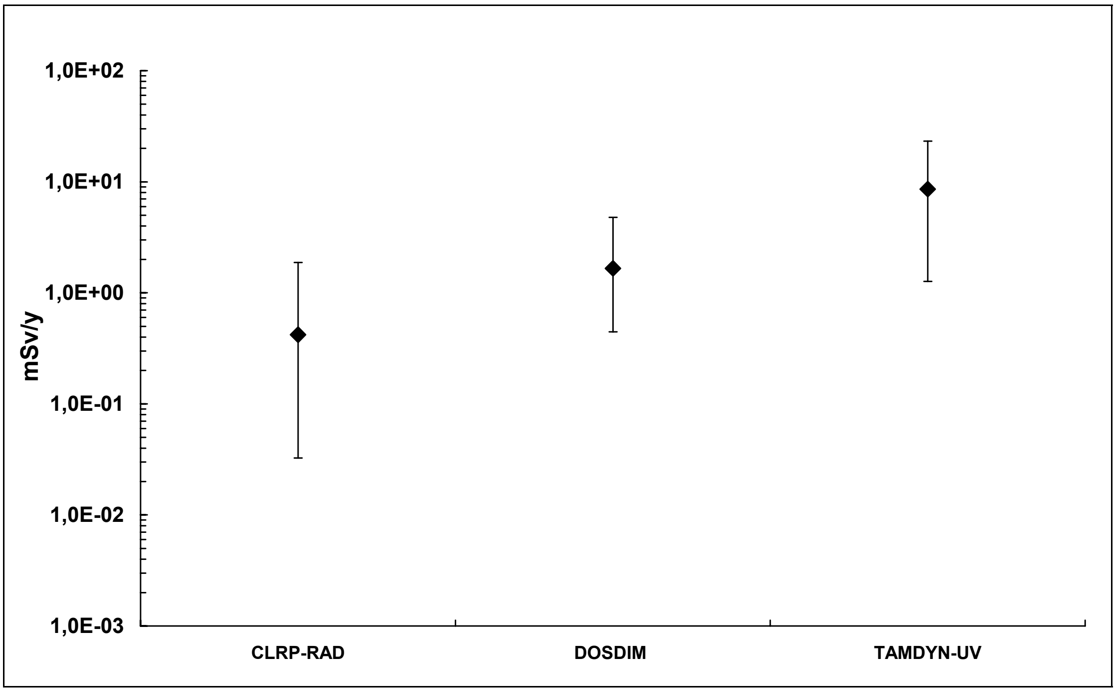


FIG. 85. Total Pb dose for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

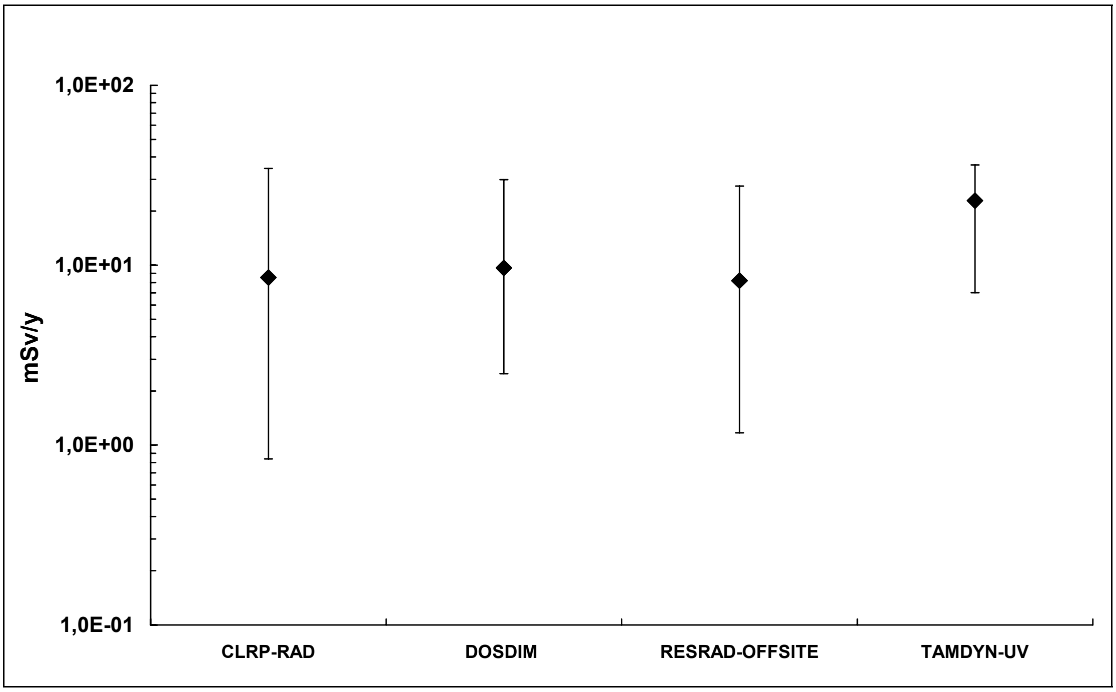


FIG. 86. Total Ra&Pb dose for no remediation at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

5.2.2.2. Remediation 2

Also for the remediation 2 case, the modellers were asked to produce uncertainty estimates for different periods of time. CLRP-RAD, DOSDIM, OLENRAD-B and TAMDYN-UV calculated that the uncertainty ranges of the dose predictions barely change for most exposure pathways. RESRAD-OFFSITE however, produced for the ingestion pathways uncertainty ranges which narrow in time, reflecting changes in uncertainty ranges of the main contributor to these uncertainties, namely the drinking water pathway. The water pathway is the sole contributor to the uncertainty of the ingestion dose because the RESRAD-OFFSITE modeller assumed that the contamination of the ingestion pathways after remediation (covering the site) was mainly caused by irrigation with contaminated groundwater. Unlike the other modellers that carried out an uncertainty analysis, the RESRAD-OFFSITE modeller did not consider the contamination of the cover in time due to upwards movement of radionuclides by natural soil processes (like bioturbation, diffusion, water table fluctuations, etc).

5.2.2.2.1. Radium

- **Inhalation of dust**

Although, compared to the no remediation case, the uncertainty ranges associated with the initial radium concentration in the surface soil are smaller (by a factor of 2), the size of uncertainty ranges of the DOSDIM dose due to inhalation of dust remains more or less the same (Figure 87). This is because additionally the uncertainty associated with the bioturbation process (via bioturbation rate, radium concentration of underlying soil layer) contributes to the overall uncertainty. As mentioned earlier, CLRP-RAD and TAMDYN-UV are the only models that took the heterogeneity of the soil profile before remediation into account and considered different soil layers, varying in radium concentration. In contrast with the other models, this also means that the parameters (e.g. diffusion coefficient) responsible for the mixing of the upper soil layer will contribute to the overall uncertainty before and after remediation in a similar way. Since TAMDYN-UV model also considered the same values (with the same uncertainty ranges and pdfs) for the other input parameters before and after remediation, it produced uncertainty ranges of the dust inhalation dose after remediation that do not differ from those before the remediation. CLRP-RAD on the other hand obtained smaller uncertainty ranges compared to those predicted for the no remediation case, because a uniform distribution instead of a lognormal distribution was assumed for the radium concentration in the cover, whereby the radium concentration could only vary by a factor of 3. As mentioned earlier, RESRAD-OFFSITE did not calculate dose due to inhalation of dust because it was assumed that the cover contains no radium and remains intact during the considered time period.

- **External irradiation**

The sizes of the uncertainty estimates of the external irradiation dose are for most models comparable with those obtained for no remediation. The small differences in size compared to the no remediation indicates that the uncertainty associated with the soil processes responsible for the contamination of the cover has a rather small impact on the uncertainty of the external doses and/or is compensated by assuming smaller uncertainty ranges for the radium concentration in the root zone soil (Figure 88). CLRP-RAD and DOSDIM produced smaller uncertainty ranges after remediation (by a factor of 2) than before remediation because smaller uncertainty ranges were associated with the radium concentration in the upper 50 cm soil layer (cover). As for no remediation the largest uncertainty ranges were obtained by CLRP-RAD and the smallest ranges were obtained by RESRAD-OFFSITE.

— **Radon inhalation**

The cover does not have a great effect on the size of the uncertainty ranges of the radon inhalation dose (Figure 89). No distinct differences with the no remediation case are observed indicating that the uncertainty of the soil concentration and parameters responsible for the transfer from the soil (emanation factor) and into the house are the main contributors to the uncertainty in the radon inhalation dose estimates.

— **Ingestion of leafy vegetables, potatoes, drinking water, milk, meat and soil**

For most models, the size of uncertainty estimates obtained for the ingestion pathways are comparable with those for no remediation. In figure 90, the uncertainty estimates of the dose due to ingestion of leafy vegetables are given. CLRP-RAD and OLENRAD-B did not consider the contamination of food crops via foliar uptake. RESRAD-OFFSITE only produced uncertainty estimates for leafy vegetables and potatoes together. For most models, the relative contribution of foliar uptake to the ingestion dose of food crops is more important after remediation than before remediation. However, the importance of the foliar uptake decreases with time because the contamination via root uptake increases due to mixing of the cover with the underlying contaminated soil as well as irrigation with contaminated water. Hence, compared to the no remediation case, the uncertainty of the overall ingestion dose of food crops will initially be more influenced by the parameters contributing to the uncertainty associated with the foliar uptake. Similar remarks can be made for milk and meat (Figure 92). Two models (CLRP-RAD and RESRAD-OFFSITE) produced uncertainty ranges for the ingestion pathways that have noticeable differences in size compared to those obtained for the no remediation case. Figure 92 shows that RESRAD-OFFSITE estimates much larger uncertainty ranges for remediation 2, at least two orders of magnitude larger for milk than for the no remediation case (Figure 78). The same observation can be made for the other ingestion pathways, except for drinking water (Figure 91 versus Figure 76). The enlargements of the uncertainty ranges of the ingestion pathways after remediation are caused by changes in importance of the drinking water pathway in determining the ingestion doses. Because, unlike the other modellers, RESRAD-OFFSITE assumed no transfer or mixing processes that could lead to a contamination of the 0.5 m cover by the underlying contaminated soil, the ingestion doses via contributions directly from the soil are zero. Since pasture is not irrigated, the milk and meat ingestion doses produced by RESRAD-OFFSITE are only caused by drinking of contaminated water by cattle. For food crops, irrigation with contaminated water was assumed, leading to accumulation of radium in the soil and subsequently contamination of pasture and food crops via root uptake that becomes more important with time. Thus the uncertainty in the food products after remediation 2 reflects the high uncertainty in the drinking water. Compared to the no remediation option, the results for drinking water remain nearly the same because the cover will have only a small retardation effect on the infiltration of water into the contaminated soil layer and hence on the leaching of radium and lead into the aquifer. OLENRAD-B and RESRAD-OFFSITE assumed that the cover has no effect. Their best-estimates and uncertainty ranges for the drinking water ingestion dose before and after remediation are the same. Compared to the situation before remediation, CLRP-RAD estimates lower uncertainty ranges for leafy vegetables, potatoes, milk and meat after remediation, probably because a uniform distribution instead of a lognormal distribution as for the no remediation case was used for the radium concentration in the upper 50 cm soil layer. For the drinking water pathway however, CLRP-RAD produced larger uncertainty ranges after remediation, while the other models did not. This can be explained by the differences in parameters included in the uncertainty analysis. Compared to other models, CLRP-RAD included in the uncertainty analysis additional parameters that determine the infiltration rate of water through the cover.

5.2.2.2.2. Lead

Similar observation and conclusions as for radium can be drawn for lead. For most models, the sizes of the uncertainty ranges of the various pathways after covering with a clean soil layer are comparable with those for the no remediation case.

5.2.2.2.3. Total dose

Although for the individual pathways hardly any differences exist between the size of the uncertainty ranges for no remediation and remediation 2, it is seen that for most models the uncertainty ranges of the total radium dose (Figure 93) tend to expand after remediation (up to a factor of 2). This small contribution to the uncertainty seems mainly to reflect the changes in the relative contribution of the different pathways (and hence different input parameters) to the total dose. For the total dose of lead, the trend is not so clear (Figure 94 versus Figure 85). The DOSDIM uncertainty ranges enlarge after remediation by a factor of 25 that however seems to diminish in time, while for CLRP they narrow by a factor of 2 to 3. The enlargement can be explained by the relative high importance of the drinking water ingestion pathway and the leafy vegetables and potatoes ingestion pathways (via foliar uptake), all characterised by large uncertainty ranges. The ingestion pathways being the main contributors to the lead total dose are also responsible for the smaller uncertainty ranges of CLRP, because for these pathways CLRP estimated lower uncertainty ranges after remediation compared to the situation before remediation.

The uncertainty ranges of the total radium and lead dose, on the other hand represent mainly the trend observed for the total radium dose and, compared to the no remediation case, tend to increase by a factor of 2 to 3 in size (Figure 95).

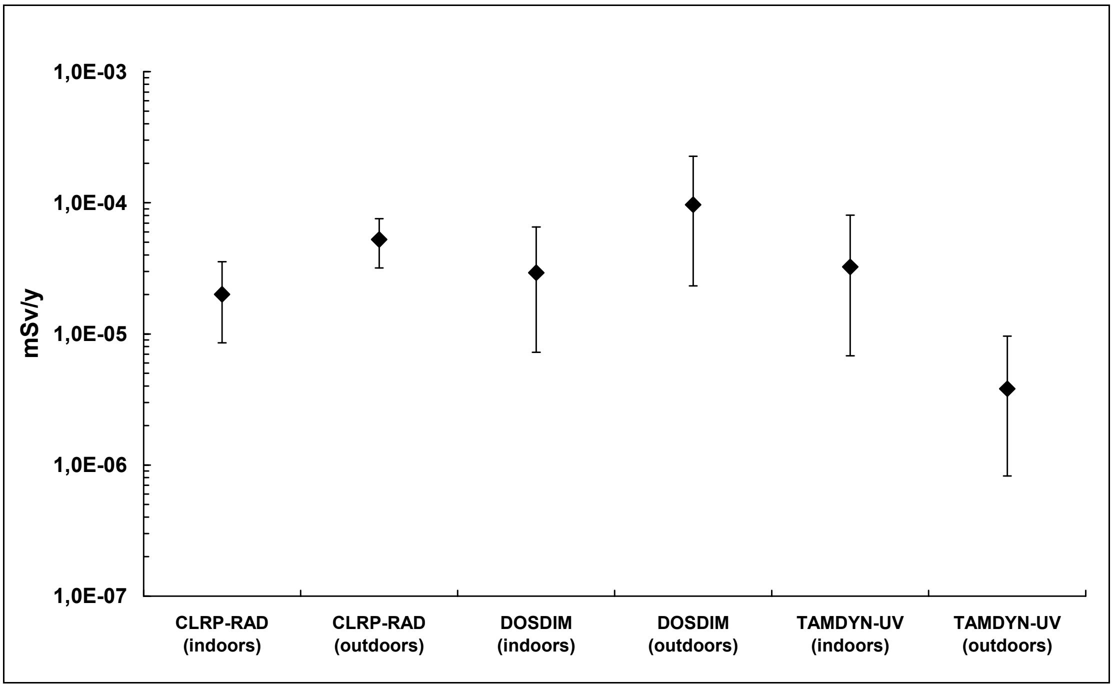


FIG. 87. Inhalation dose of ^{226}Ra contaminated dust for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

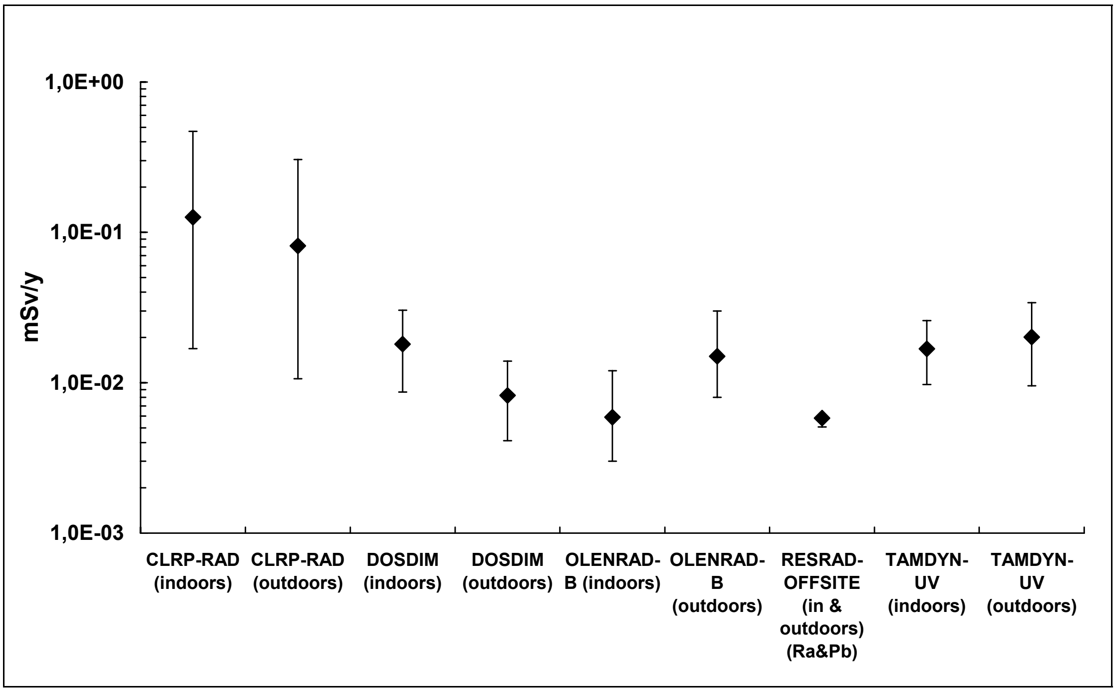


FIG. 88. External irradiation dose of ^{226}Ra for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

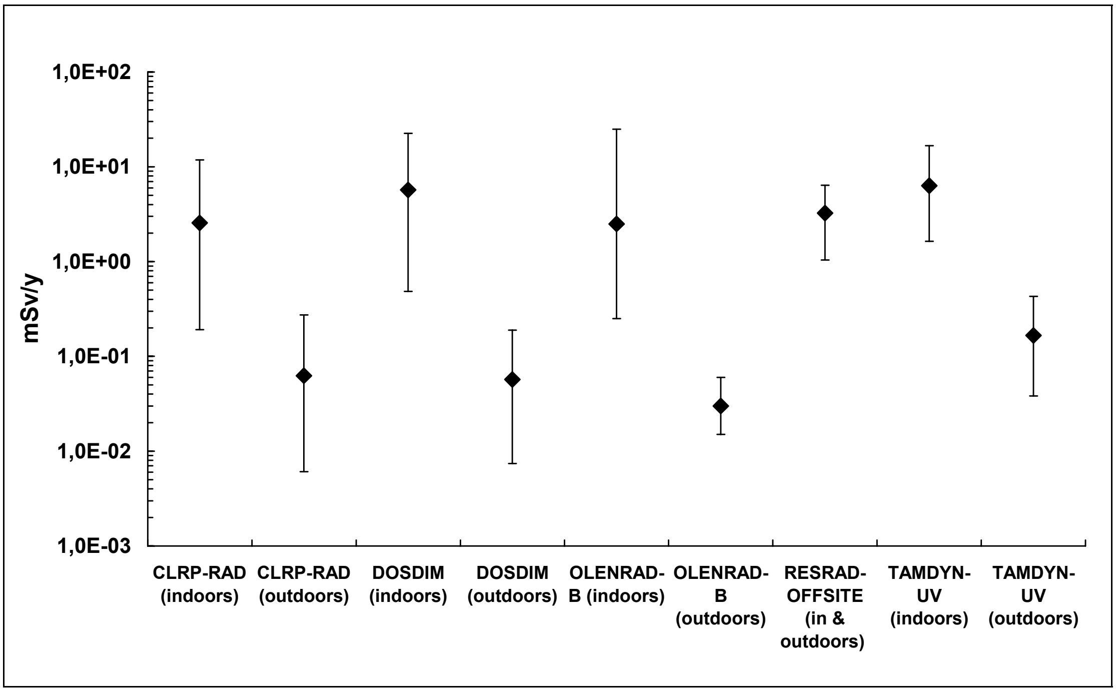


FIG. 89. Inhalation of radon for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

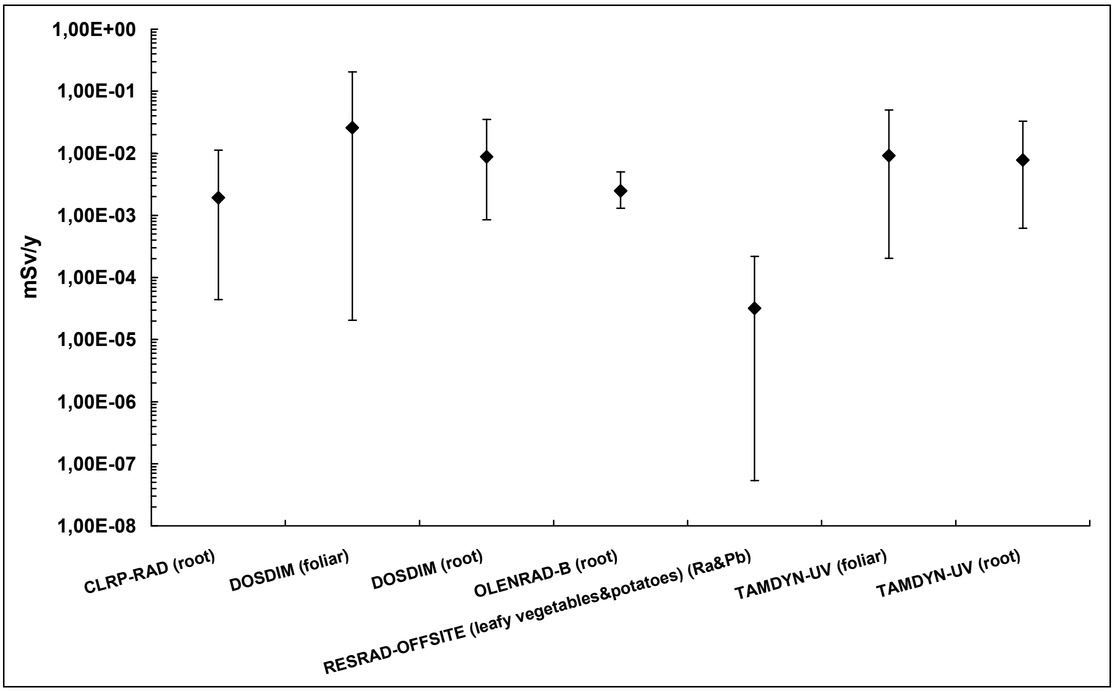


FIG. 90. Ingestion dose of ^{226}Ra contaminated leafy vegetables for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

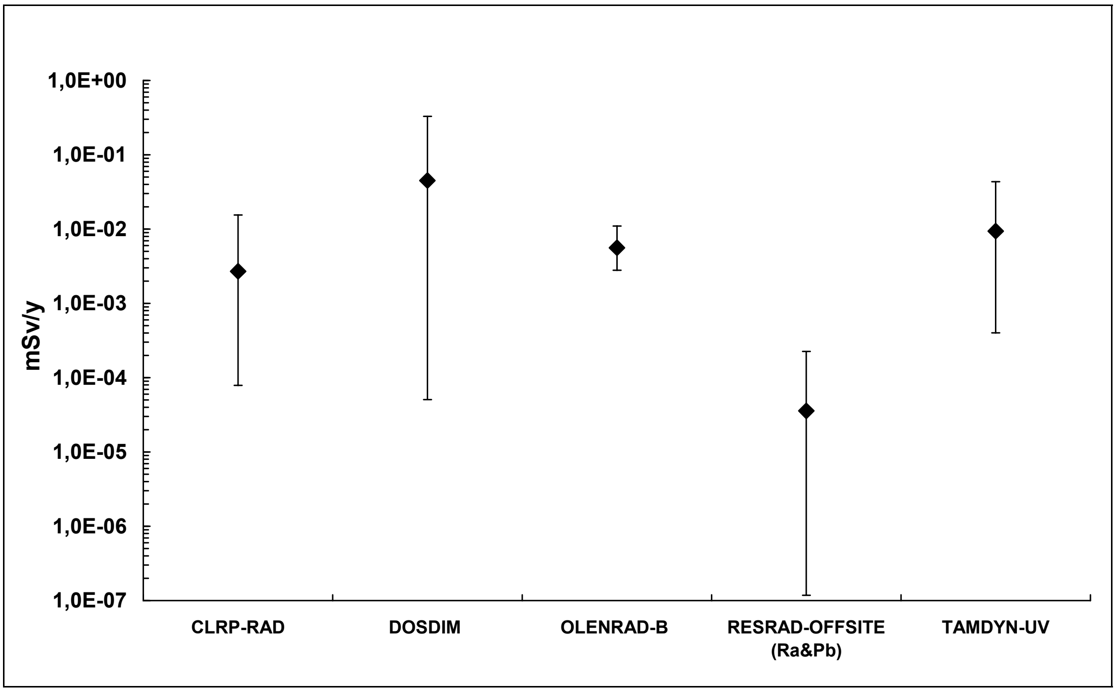


FIG. 91. Ingestion dose of ^{226}Ra contaminated drinking water for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

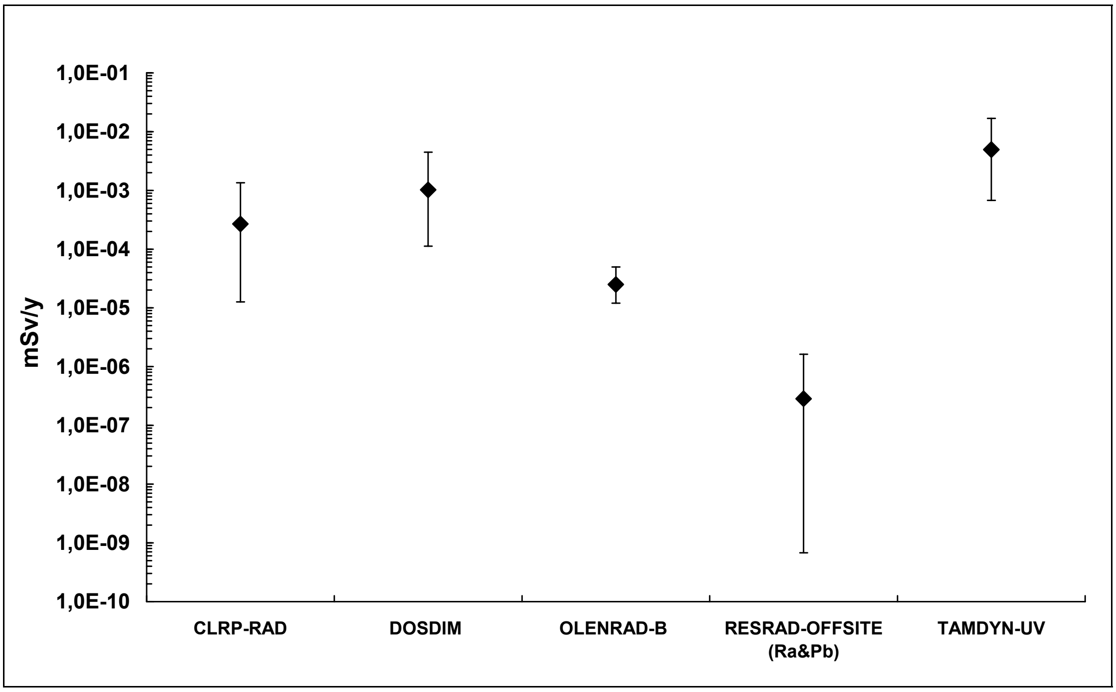


FIG. 92. Ingestion dose of ^{226}Ra contaminated milk for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

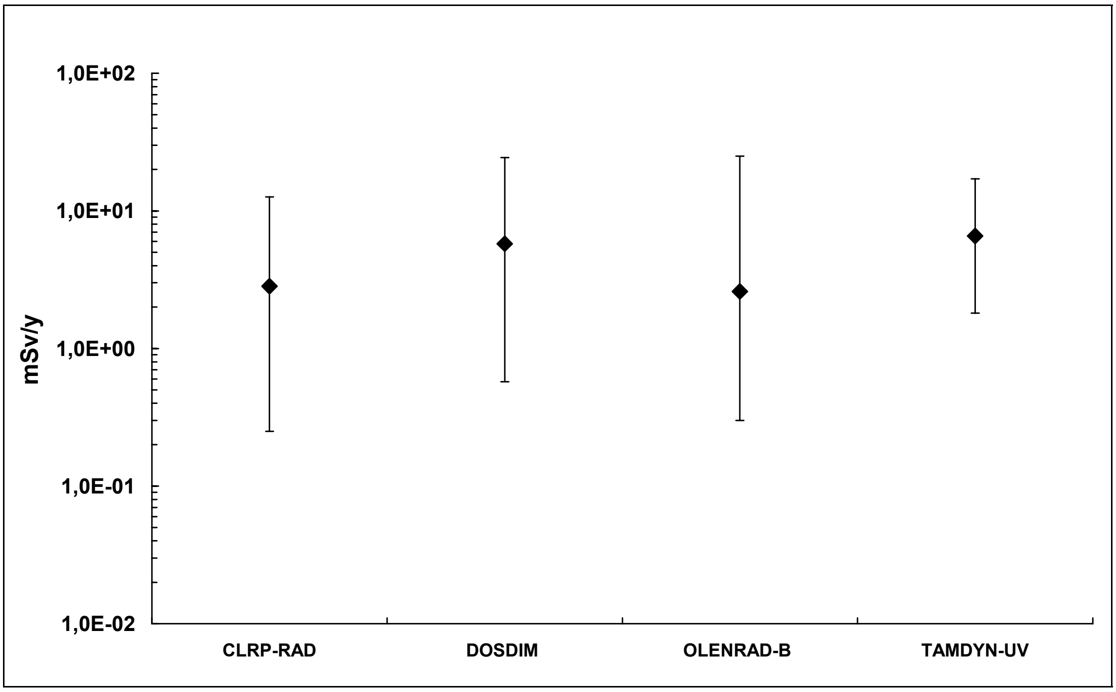


FIG. 93. Total Ra dose for remediation 2 at year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

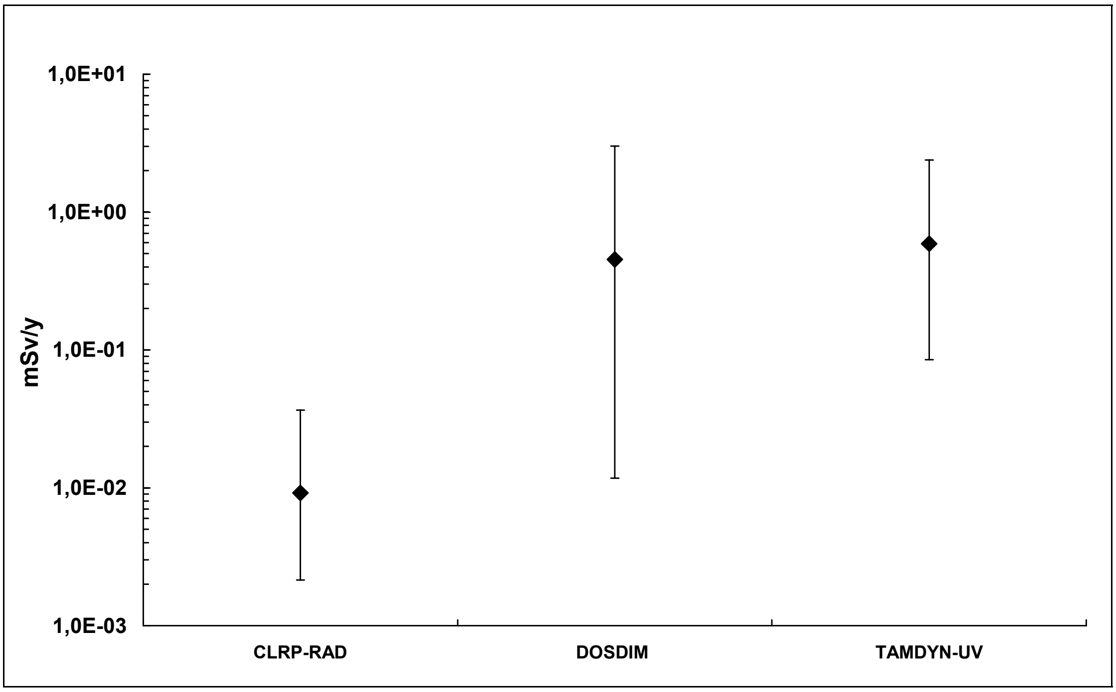


FIG. 94. Total Pb dose for remediation 2 after year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

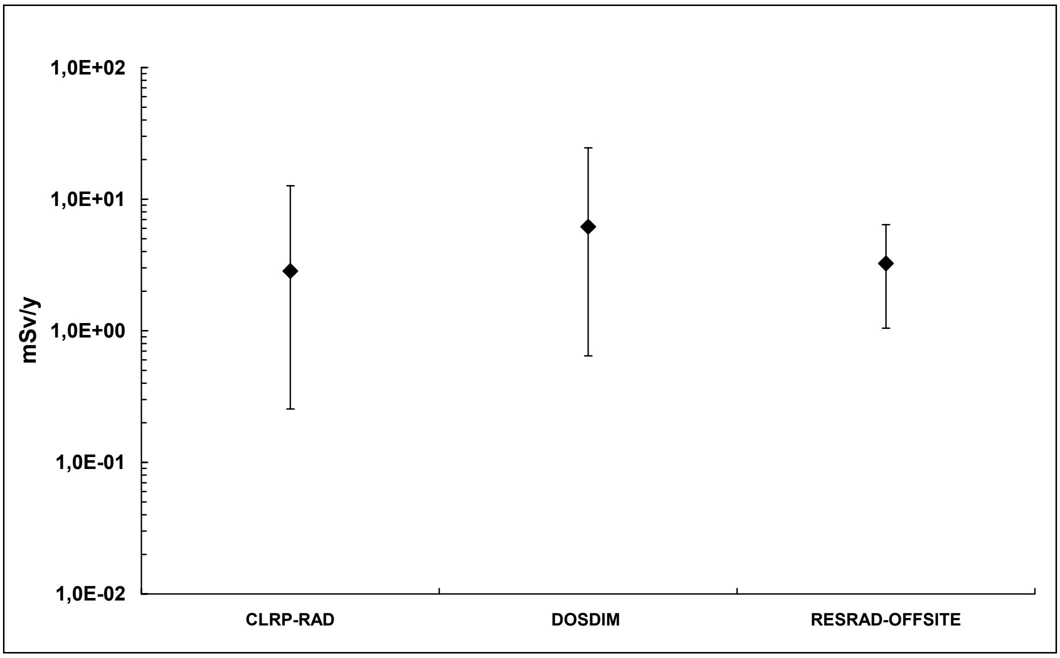


FIG. 95. Total Ra&Pb dose for remediation 2 after year 1. The symbols refer to the best estimate values, the vertical lines indicate the 95% confidence interval of the model predictions.

5.2.3. Sensitivity analysis

Five modellers (CLRP-RAD; DOSDIM; OLENRAD-B; RESRAD-OFFSITE and TAMDYN-UV) also performed a sensitivity analysis. In Table XVII, the three most sensitive parameters of the total (Ra & Pb) dose are ranked.

It is clear that the significance of the pathways in the total dose will determine the sensitivity of its parameters. OLENRAD-B does not give the three most sensitive parameters, but the three most important pathways. These pathways are also the main contributors of the (Ra & Pb) dose estimated by the other models. It indicates that input parameters involved in these pathways will be to the most sensitive ones. The ranking of the parameters will of course depend on the parameters considered in the uncertainty analysis, their uncertainty ranges and modelling approach. In Table XVII, it is shown that the most sensitive parameters are parameters related with the radon concentration indoors. The fourth most sensitive parameter of CLRP-RAD is the ventilation rate in the house. These results also show that for the ingestion pathways, the soil-to-plant transfer factors of lead are the most important contributors to the overall uncertainty.

It should however be noticed that it is not possible to really compare the results of the sensitivity analysis between the models. This is because the input parameters considered in the uncertainty analysis do not only differ due to differences in model structure. Some modellers did not include all the uncertainties of the input parameters given in the scenario description. Some modellers chose uncertainty ranges for input parameters for which only best estimate values were given, while others showed an unwillingness to specify any range due to the lack of information about the parameter. For example, RESRAD-OFFSITE did not consider the uncertainties associated with the radium concentrations in soil, while according to DOSDIM and CLRP-RAD that did consider uncertainty ranges for the initial soil concentration, this parameter plays also a significant role in the uncertainty ranges of the dose. An observation that could also be derived from the uncertainty analysis.

TABLE XVII. THE THREE MOST SENSITIVE PARAMETERS OF THE TOTAL (Ra&Pb) DOSE FOR 'NO REMEDIATION' AND 'REMEDIATION 2'

	Most sensitive parameters		
	First	Second	Third
No remediation:			
CLRP-RAD	Ra conc [0–15 cm]	Ra conc [30–50 cm]	Ra conc [15–30 cm]
DOSDIM	TF (Ra soil to Rn in-doors)	Ra conc in contaminated soil layer farm	TF(Pb) soil to leafy vegetables
OLENRAD-B	Inhalation Rn indoors	External irradiation outdoors	Leafy vegetables , root uptake
RESRAD-OFFSITE	Emanation factor	Soil density	TF(Ra&Pb) soil to leafy vegetables
TAMDYN-UV	Rn diffusion coefficient (soil to indoors)	Soil density	Emanation factor
Remediation 2: Covering with clean soil layer			
CLRP-RAD	Ra conc [80–100 cm]	Ra conc [50–65 cm]	Porosity of the cover
DOSDIM	TF (Ra soil to Rn in-doors)	Ra conc in contaminated soil layer farm	TF(Pb) soil to leafy vegetables/potatoes
OLENRAD-B	Inhalation Rn indoors	External irradiation outdoors	Leafy vegetables , root uptake
RESRAD-OFFSITE	Emanation factor	Soil density	House ventilation rate
TAMDYN-UV	Rn diffusion coefficient (soil to indoors)	Emanation factor	Soil density

6. CONCLUSIONS

6.1. SCENARIO TYPE A

The test scenario Type A reflects a real situation and gave the modellers the opportunity to compare their model predictions with measured values. As usually is the case for real situations, the amount of data available was rather limited and the modellers used their own experiences to interpret the data. A more comprehensive site characterisation might have improved the model development.

All modellers assessed the influence of deep ploughing in a simple way, just by considering a dilution factor for the radium concentration in soil. Perhaps, other ways would have been possible, if more information on the radium distribution as a function of depth or more technical details of the deep ploughing had been available.

In addition, the model may provide feedback to the site characterisation. For instance, all modellers underestimated the radium concentration in grass coming from plot number 6. This has led to the conclusion that plot number 6 might not have been deep ploughed.

6.1.1. Intercomparison of the model predictions

The differences in radium concentrations in root zone before and after deep ploughing and in grass can mainly be explained by the lack of detailed information. Modellers had to interpret the scenario description, the radium distribution in the root zone before deep ploughing and the deep ploughing effect being the main sources of variability in the model predictions. The differences observed for the transfer to milk can partly be explained by differences in the parameter values. Part of the differences is also caused by a different approach of calculation. Some modellers considered dynamic transfer coefficients to model the radium transfer in cow's milk, others assumed equilibrium conditions. There was also a difference in level of detail. Most models considered 3 compartments (soil, grass, milk), only TAMDYN considered the bioassimilation in the cow's body more in detail and used an extra cow compartment divided in 4 subcompartments. The aim of the detailed modelling was the simulation of the evolution of the milk contamination with time taking into account the changes due to the stepwise and rapid rotation of the cows on the different contaminated grazing areas and stables.

6.1.2. Comparison of model predictions against observed data

In general most models overestimate the radium concentration in milk with nearly one order of magnitude. There are four possible explanations for these overestimations:

- the radium measurements in soil represent rather maximum than average values;
- the initial radium contamination of the soil was more superficial than assumed, in other words less than the upper 10 cm of the soil (as assumed in the scenario description) was contaminated before deep ploughing;
- deep ploughing is more effective than predicted, although based on recent soil profile data this explanation seems to be less plausible;
- use of conservatively biased parameters throughout the whole modelling process, due to the absence of data.

A conservative approach can be considered as reasonable for situations, when only limited amount of relevant input data is available. The uncertainty ranges associated with the effect of deep ploughing, the soil-to-plant transfer factor and the initial radium concentration in soil before deep ploughing mainly determine the uncertainty ranges obtained for the radium concentration in milk. Due to the lack of sufficient or relevant information, the choice of their uncertainty ranges is largely based on personal judgement. The confidence intervals of three models cover entirely the available experimental data (DOSDIM, OLENRAD-A, RISKOLEN) and for the remaining two models, the experimental values of radium concentration in milk are very close to the calculated 95% confidence intervals (CLRP, TAMDYN). For the radium concentration in grass, the predicted confidence intervals of CLRP and TAMDYN did not encompass the observed data, illustrating overconfidence in the model predictions.

The differences between the calculated and observed radium concentrations in milk can also partly be explained by the absence of a dynamic trend in these observed data and the more dynamic models did not necessarily perform better than the simple equilibrium models.

The measured levels of radium in the milk vary between 10.7 and 35.9 mBq/l, at most 7 times higher than the average background concentration of radium in milk. These low figures show that radium in cow's milk is not really a problem.

6.2. SCENARIO TYPE B

For this test scenario in which several remedial actions are compared, no measured data sets of the end points are available. It is therefore only possible to compare model predictions and to identify similarities and discrepancies in modelling approaches and results.

The scenario reflected the worst case whereby the farmer family was living on the most contaminated area of the site and part of its food (leafy vegetables, potatoes, milk, meat and drinking water) was coming from this area. Two remedial actions were considered. Remedial action 1 consists of the removal of the surface soil down to 1 m in the most contaminated areas. Remedial action 2 consists of covering with clean soil. All modellers used the same approach to assess the impact of the first remedial action. They considered a lower radium concentration for the upper soil layer, using the information given in the scenario description. Concerning remediation 2, all modellers, except RESRAD-OFFSITE, assumed that in the soil several migration processes will take place leading to an upward movement of radium from the contaminated soil layer to the cover in time. However there was some disagreement on the occurrence and importance of the different transport processes in soil. Some modellers consider diffusion, while others consider other transport processes like erosion, transport by earthworms, fluctuations of the water table, leading to different modelling approaches and differences in results.

RESRAD-OFFSITE assumes that the cover remains intact and neglects the upward movement of radium and lead by diffusion or soil solids movement (bioturbation, erosion). It can however be expected that when considering time-scales of hundred of years as in this exercise the influence of soil processes like soil erosion and bioturbation on the migration of radium in soil cannot be ignored. Comparison of the results of the other models even indicates that because of its high adsorption capacity the movement of radium (adsorbed on soil solids) by bioturbation and erosion is more important than radium movement by diffusion. However, in contrast to the radionuclide movement by diffusion the movement of soil solids by bioturbation and erosion is not well known and more experimental work is needed to increase our understanding of these processes and consequently enhance our ability of modelling them on the long term.

Comparing the benefits of the remedial actions shows that remedial action 1 gives the best results. According to all models, a decrease of dose by at least one order of magnitude was observed. One of its side effects however is that, in contrast to remediation 2, it will also lead to additional exposures at other times and places, because the contaminated soil must be dumped somewhere.

In general, the differences among the model predictions are rather due to differences in the interpretation of the scenario description than due to differences in modelling approach. While the predictions for the main pathways are quite similar, greater variations between the less significant pathways are observed. These differences are mainly caused by different interpretation of the current situation. For example, some modellers considered the historical contamination of the ground water while others did not.

All models neglected scenario evolution. However, when considering time scales of more than hundred years, it is probably necessary to take into account the variation in parameter values over time.

For radium, the radon indoor and the external irradiation in- and outdoors are the main contributors to the total dose of all three cases (no remediation, remediation 1 and 2). For lead, the ingestion of leafy vegetables is the most important pathways. In this exercise Po-210 was not taken into account. It should however be noted that the dose impact of Po-210 is not negligible because dose factors for the ingestion and inhalation of Po-210, which can be assumed in equilibrium with lead after 1 year, are similar to those of Pb-210 [6].

The calculation of the indoor radon concentration was one of the main problems in the calculations. The pathway is poorly understood due to the complexity of the processes involved. There are several parameters that have a great influence on the radon concentration indoors such as the current state of the house (construction quality), the ventilation rate, the type of soil, the homogeneity of the soil, surface vegetation, etc. As a result, indoor radon concentrations can range over several orders of magnitude even in areas where the soil radium concentrations show little spatial variability. Although in many situations advection is the main process by which radon gets indoors, most modellers considered only diffusion to calculate the radon concentration indoors. This is due to the fact that the diffusion of radon into buildings has been extensively studied and as a result fairly sophisticated models of radon transport via diffusion are available. The entry of radon via advection is not well understood because some important parameters such as the size and number of cracks in the foundation of houses, lifestyle of the residents are difficult to quantify. But despite the differences in modelling approach, the predictions among the modellers are quite consistent. The main reason for this close agreement in results is the lack of detailed site-specific information. Most modellers used the measured concentration ratios between the radon in air indoor and the radium in soil given in the scenario description directly to calculate the inhalation dose or indirectly to adjust their parameter values. A similar remark can be made for the radon concentration outdoors. Despite the poor understanding of the processes involved, some modellers predict small confidence intervals for the inhalation dose of radon in- and outdoors. Their uncertainty estimates only reflect the uncertainty associated with a limited set of model parameters. Uncertainties due to the lack of knowledge were not taken into account. This implies that the uncertainty estimates calculated for radon inhalation do not represent the lack of confidence in the model performance.

Another difficulty was the calculation of the behaviour of lead in soil and food chain. On the one hand there is ingrowth from radium but on the other hand radium and lead behave quite differently in the environment which probably means that lead will never be in equilibrium with radium in soil. Due to the lack of data for lead however, most modellers calculated the lead concentration in soil based on the ingrowth from radium and the radioactive decay rates of radium and lead and attained equilibrium between radium and lead after 200 years. The differences in losses from the soil due to the fact that lead is more mobile than radium (i.e. leaching and plant uptake) were not taken into account. These differences in behaviour were only considered when calculating the contamination of the food chain (ground water, foodstuffs). Furthermore, only TAMDYN-UV simulated the effect of radon emanation on the lead concentration profile in soil.

Five of the six modellers performed parameter uncertainty and sensitivity analysis. The parameters included in the uncertainty analysis and their best estimate values and 95% confidence intervals differ among the modellers. One reason is the difference in model structure. Due to differences in model structure, different parameters are used. Another, more important, reason however is “expert judgement”. For some parameters, only best estimate values were given in the scenario description and quantifying the uncertainty ranges may cause some difficulties. According to their experience and level of familiarity with the site, the data and the pathways, modellers defined different uncertainty ranges or did not consider the contribution of such parameters to the overall uncertainty. Also for parameters for which information (i.e. estimate values, uncertainty ranges and/or probability density functions) were given in the scenario description, some modellers used other values because they found them to be more representative.

This exercise demonstrates clearly that the modeller’s experience and familiarity with the code, the site and with the scenario is very important. During the course of the exercise workgroup meetings were organised. The aim of these meetings was to compare and explain discrepancies in the model predictions and to correct mistakes. It was shown that the largest errors were due to misinterpretations of the scenario (e.g. neglecting the effect of the remedial actions on the ground water level) and the inexperience of the user with the code (e.g. omission of the ingrowth of lead from radium).

The Olen-B scenario is a rather complex scenario due to the numerous pathways involved and the fact that the models used were not developed to evaluate the radiological effectiveness of remediation techniques. Most models had to be modified either in structure or/and in formulation of the parameters. These extended modifications have led to several mistakes like inadequate uses of models and parameters, misprints of inputs etc because controlling and testing of the changes is intensive work which takes a lot of time. Most mistakes were corrected during the course of the exercise, errors with less impact on the results were usually only detected after comparisons with the results of other modellers. This observation underlines the relevance of intercomparison studies. If possible, model predictions should always be compared with real data or if not available, with the results of other modellers, especially in the case of scenarios differing from the scenario for which the model was developed.

The assessment of the long-term effect of remedial actions (over hundreds of years) is highly subjective because the modeller has to make assumptions about the changes in site characteristics (e.g. soil processes) that may affect the performance of the remedial action on such a time scale.

6.3. GENERAL CONCLUSIONS

General conclusions drawn from the two test scenarios:

- Differences in model predictions are not only due to the use of different models and parameter values. Modeller's interpretation of the scenario description plays also a very important role in the outcome of the modelling performance. In order to minimise misinterpretation, much effort should be devoted to the scenario description. The information should be as accurate, detailed and representative as possible. Mispredictions can also occur due to the inexperience of the user with the code, errors in the code, errors in unit conversion. Comparison of predicted results with measurements in the field or with the results of other models proves to be a valuable tool in identifying, explaining and if needed correcting discrepancies in model predictions. It helps to improve the modelling and consequently gives more confidence in the model calculations.
- Care is needed in the selection of the values of parameters influencing strongly the final outputs of model predictions. These parameters can be identified by the sensitivity analysis of used computer codes. The information obtained by the sensitivity analysis can be used as a guideline for a monitoring campaign in the sense that sensitive parameters must be measured accurately and is also useful for recommending research priorities.
- There is a lot of qualitative information available about the radon concentrations in- and outdoors. However, the knowledge, in mechanistic terms, about the processes and their interrelationships determining the transfer of radon (especially indoors) is rather limited. Due to the complexity of the various processes involved, the modelling approach is highly empirical or theoretical and often unsatisfactory. More research should be done to understand and quantify the key features of these processes.
- Although radium is a natural radionuclide that is a major source of concern in uranium mining and milling and other industries dealing with the extraction or processing of material containing naturally occurring radionuclides, there is a lack of high quality data. One of the reasons is that it is difficult and costly to measure the radium levels.
- Most of the biosphere models were also not developed for testing the effectiveness of remedial actions and this study demonstrates that it is mostly not easy to use such models without major modifications either in the structure or formulation of the parameters. Especially the Olen B exercise clearly indicates that more work should be done on the reliability of biosphere models as decision-aiding tool in remedial programmes.
- In common with the findings of the VAMP and BIOMOVS programmes [7], the more complex dynamical models did not necessarily perform better than the simple equilibrium models.

Suggestions for future work:

- There is a lack of knowledge or data on the effects of remediation techniques, other than simply removing contaminated soil or coverage (e.g. efficiency of immobilisation techniques, separation techniques). Some additional expertise on this issue would be welcome.
- It would be interesting to expand the assessments to test sites with mixed contamination (radionuclides and non-radioactive contaminants) since many radioactively contaminated sites are also contaminated with other contaminants (such as heavy metals). Radiological and non-radiological health risks (also non-radiological risks of radioactive contaminants such as U) would have to be assessed on a common basis.

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APPENDIX I

DESCRIPTION OF THE OLEN SCENARIO TYPE A AND B

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I-1. CASE HISTORY

This remediation case concerns the radioactive contamination of a site (Olen-Belgium), brought about by a former radium plant, which was shut down more than 30 years ago.

After the discovery of radium by Pierre and Marie Curie, around the beginning of the 20th century, soon a radium production industry developed. At the time radium was used as the only raw material for radiation sources for medical and industrial applications. It has been applied on dials of clocks, where it was mixed with scintillising substances, for luminescent purposes. In the medical sector it has been used for the treatment of cancer (radiotherapy) and, especially in the United States around the 20’s, as a universal miraculous remedy against all kinds of diseases. It was applied orally, by injection or externally on the skin. It has even been added to beauty products, toothpaste, etc.

The discovery of very rich ores with a uranium oxide content of 50 % in Shaba (in former Belgian Congo) in 1915 led to the development of the radium industry in Olen-Belgium [1], [2]. In 1921 the first ore arrived in Belgium and in 1922 the radium production began in a factory in Olen, where also copper and cobalt (not radioactive) were being produced. Within one year, Belgium dominated the world market and this until the mid 1930's when comparable high grade ore was discovered in Canada. In 1938 the Belgians and the Canadians divided the world market to stabilise the price. The production continued in Canada until the mid 1950's and in Belgium until 1960. The total radium production in Olen was above 500 grams. The exact amount is not known because the annual radium production was kept secret from 1937 for military reasons, radium being a by-product in the fabrication of nuclear weapons. The rapid growth of the gamma of artificial radioisotopes led to a rapid decrease of the importance of radium as a radiation source. This is the reason why the radium extraction in Olen was stopped in 1960 and the radium factory was dismantled in 1977.

The radium production of the factory in Olen has led to a non-negligible radium contamination of the site in the neighbourhood, made possible through the absence of adequate regulations and control on the discharge of radioactive effluents. This caused:

- the discharge of radioactively contaminated liquid effluents in the brook Bankloop (since 1922), flowing into the Kleine Nete and finally into the river Nete;
- the creation of dumping grounds (5) in the vicinity of the factory, used for discharging radioactive and other waste;
- the use of waste material as a layer for hardening a few roads.

In the late 1950’s the authorities located the new Belgian Nuclear Research Centre (SCK·CEN) in the same region. The environmental survey that was required in the authorisation for discharging liquid effluents from the laboratories revealed abnormal Ra-226 levels in some of the small rivers. It then became clear that the water and the sediments of the Kleine Nete and of the Bankloop were contaminated through the liquid effluents from the radium plant in Olen.

The banks of the Bankloop brook were also contaminated because the brook was cleaned regularly and the sediments that were removed were placed on the banks. The Bankloop regularly flooded the land located just before its confluence with the Kleine Nete as a result of heavy rain, contaminating this boggy soil. Because an agricultural organisation wanted to make this land ready for farming, it had acquired the land and had taken some measures to change the water management of this piece of land.

Following actions were taken:

- the moving of the last part of the Bankloop (New Bankloop) leaving the Old Bankloop as standing water;
- the construction of a drainage canal to drain the boggy soil;
- the construction of a road (Roerdompstraat) to gain access to the area.

This was the situation in 1960, when a first study on the biological cycle of radium, applied to the Olen site, was undertaken from 1961 to 1967, with a follow-up until 1977. This study included aerial radiological survey, ground measurements, sampling of water, fish, vegetables, agricultural products, etc. The results were reported by Kirchmann [3]. As a result of the study, a number of actions were recommended. Some of these actions were executed, others were not. The actions taken included that the Old Bankloop was filled up and that deep ploughing was applied to make pastures for dairy cows.

In 1989 and 1990, the population of St. Jozef-Olen became anxious as a result of coverage by the media of observations in some places of very high (localised) contamination in the village. The existing data were mostly about the land near the Kleine Nete, and there was not sufficient data in the context of a more stringent radiation protection approach. As a result, the federal ministry of public health and environment (DBIS/SPRI) decided to carry out a more detailed assessment of the scattered contamination by a mobile survey and a survey on foot of the most contaminated parts, including the dumping grounds and the Bankloop. The programme also included an evaluation of the radon exposure in the dwellings of St. Jozef-Olen, the village surrounding the factory, and in open air above the dumping grounds, as well as an evaluation of radium in airborne dust, in surface water, in ground water, in the food chain and in milk teeth of children.

The results of the study were published by DBIS/SPRI, SCK·CEN and the Institute for Hygiene and Epidemiology (IHE) in 1993 [4, in Dutch].

Government, factory, research institute (SCK·CEN), local government, NIRAS (federal nuclear waste agency) and OVAM (non-nuclear waste agency) are working together to define possible remediation strategies taking into account all relevant aspects (radiological evaluation, chemical and toxicological hazards, cost, public acceptance, public concern, ...).

A number of streets with localised contamination were identified. A consensus exists to eliminate the contamination in a controlled way when ground works are done in these streets. The contaminated material will be stored temporarily on the D1 dumping ground. Two streets have been remediated to date.

I-2. SITE DESCRIPTION

The site proposed for this remediation study is the area between Kleine Nete and Kempisch Kanaal that has been contaminated through the liquid effluents of the former radium plant of Olen. Olen is situated in the Campines, a region in the northern part of Belgium, with a flat relief and a predominantly sandy soil. In Figure I-1 the former radium plant (now it is a metallurgical factory) is indicated, on the southern side of the Kempisch Kanaal.

In Figure I-2 the course of the brook Bankloop is indicated. Liquid effluents from the radium plant have been released in the brook Bankloop, which leaves the factory (Metallurgie Hoboken) at point A and receives the water of another brook (Meirenloop) at C. It then flows under the canal (Kempisch Kanaal) and a road and goes round a farm at E before flowing to the Kleine Nete. Before 1960 the Bankloop flowed straight to the Kleine Nete (EH). Regular floodings and dredging of sediments caused important Ra-226 contaminations over some tens of ha, especially at the western side of the last part of the brook.

Around 1960, a road (Roerdompstraat) was constructed to gain access to the area. Where the road intersected the Bankloop (point F) a new course was given to the brook (FMN). This new section was called the New Bankloop; the old part which was left as standing water, was called the Old Bankloop. (The section AN will be called the Bankloop from now on.).

At the same time a canal was constructed to drain the site (especially the wetter western part). This canal passed under the New Bankloop and cut the Old Bankloop into two blind arms (FG and GM). The original east to west flow in the marsh was reversed and the drainage water pumped into the Kleine Nete upstream of the confluence with the Bankloop.

All the adaptations led to a drying of the marsh and a displacement of contamination in the peat from west to east. However in the winter of 1960-1961, because of heavy rain storms, the verges collapsed at the place of the passage of the drainage canal and a new dispersion of the water of the Bankloop took place.

Radiological studies have been undertaken by Kirchmann [3] in the period 1961–1967 in order to evaluate the possibility of using the site for agricultural purposes. As a result, some recommendations were formulated. Consequently in the following years the Old Bankloop has been filled up and deep ploughing has been applied to the site between the new road (Roerdompstraat) and the Kleine Nete where then pastures for dairy cows were arranged.

Meanwhile, in the area between the metallurgical factory and the Kleine Nete, 5 discharges (dumping grounds) were created. They are indicated in Figure I-3:

D1:	large dumping ground (9 ha) of Ra-226 contaminated waste
D2 and D3:	former dumping grounds of Ra-226 contaminated waste, actually being used as municipal discharges. The radioactive-contaminated waste is buried by 15 m household refuse
D4:	discharge of copper (not radioactive-contaminated)
D5:	discharge of charcoal ashes (not radioactive-contaminated).

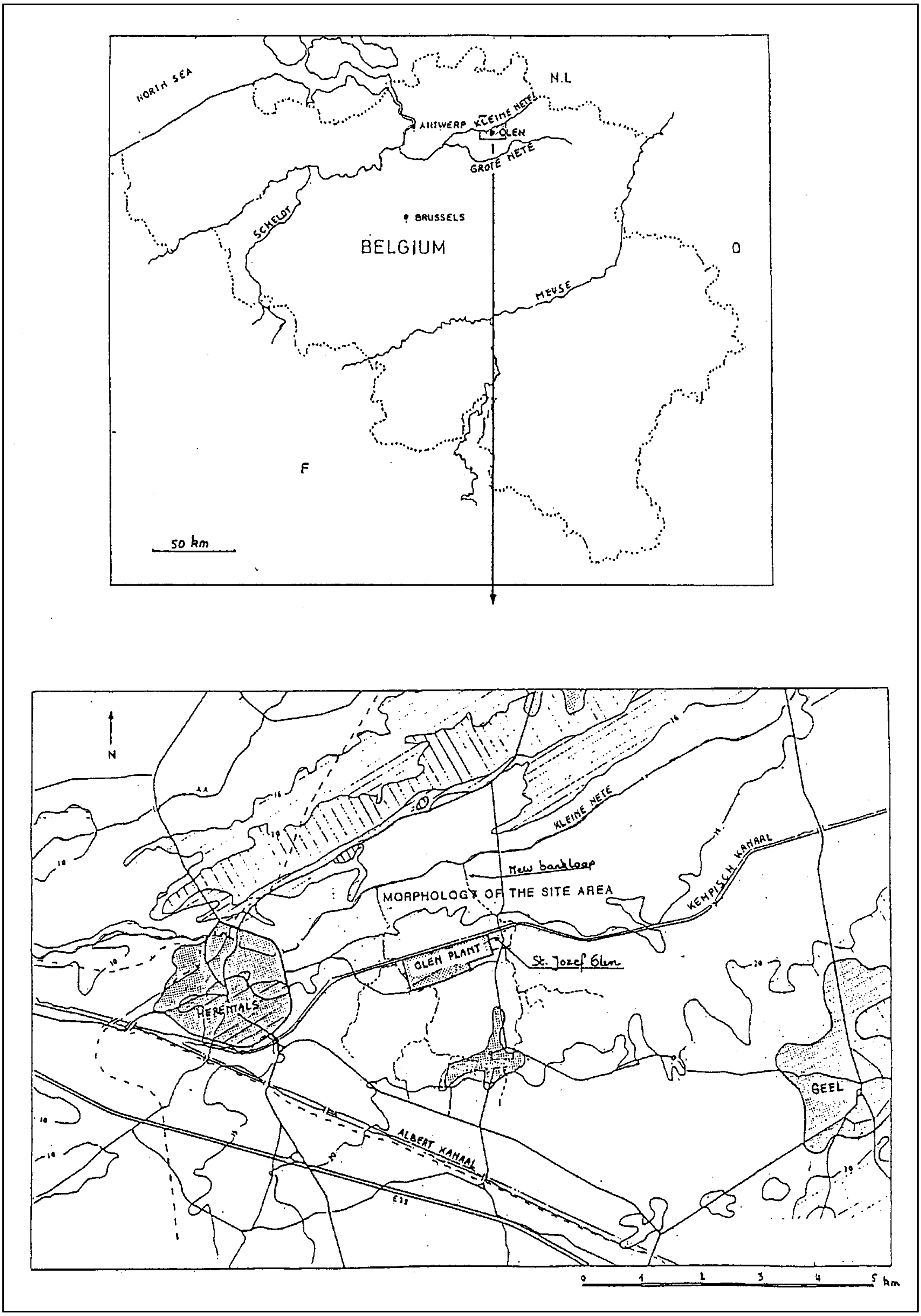


FIG. I-1. Localisation of the site.

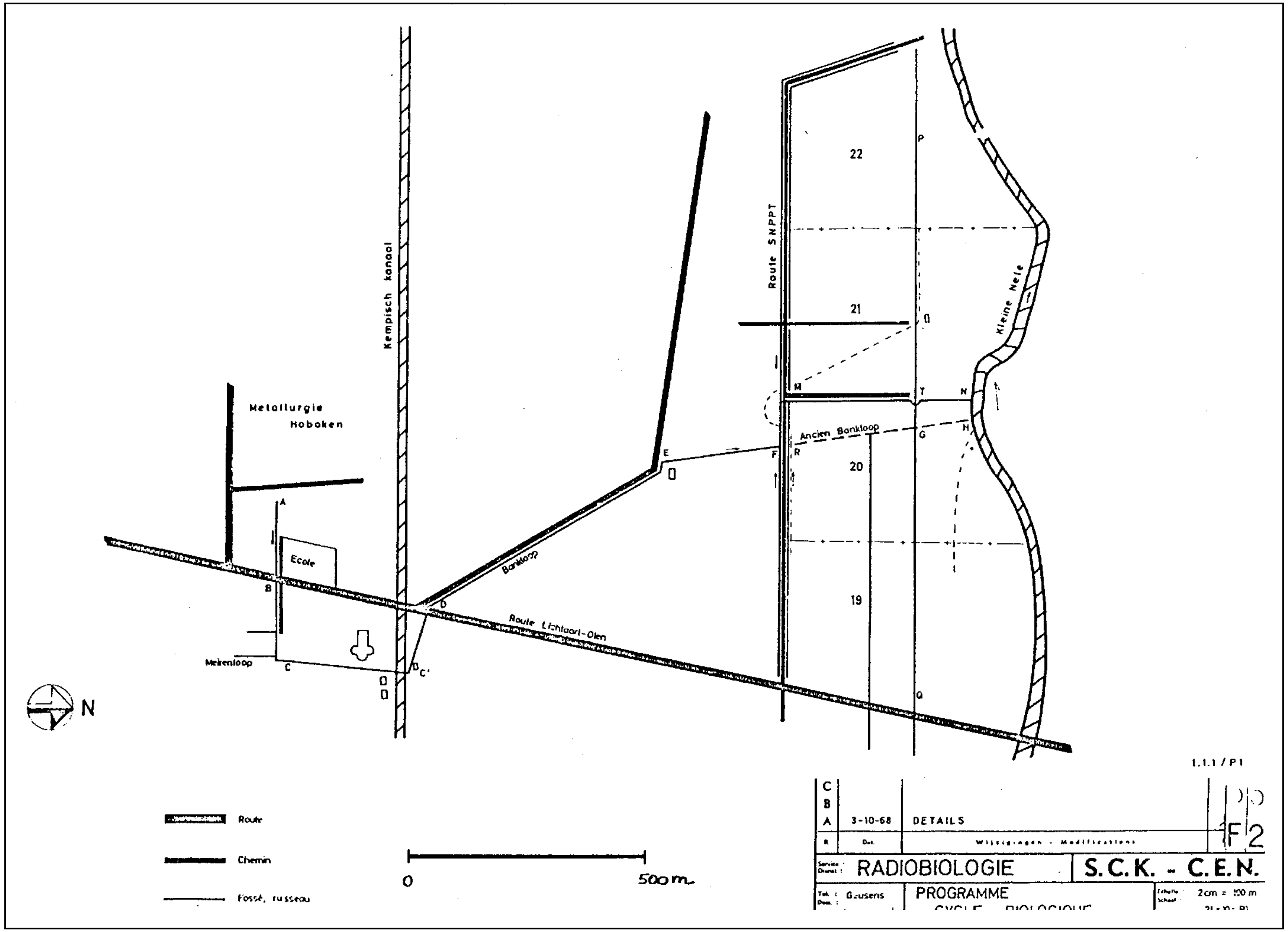


FIG. I-2. Site: St-Jozef-Olen Bankloop.

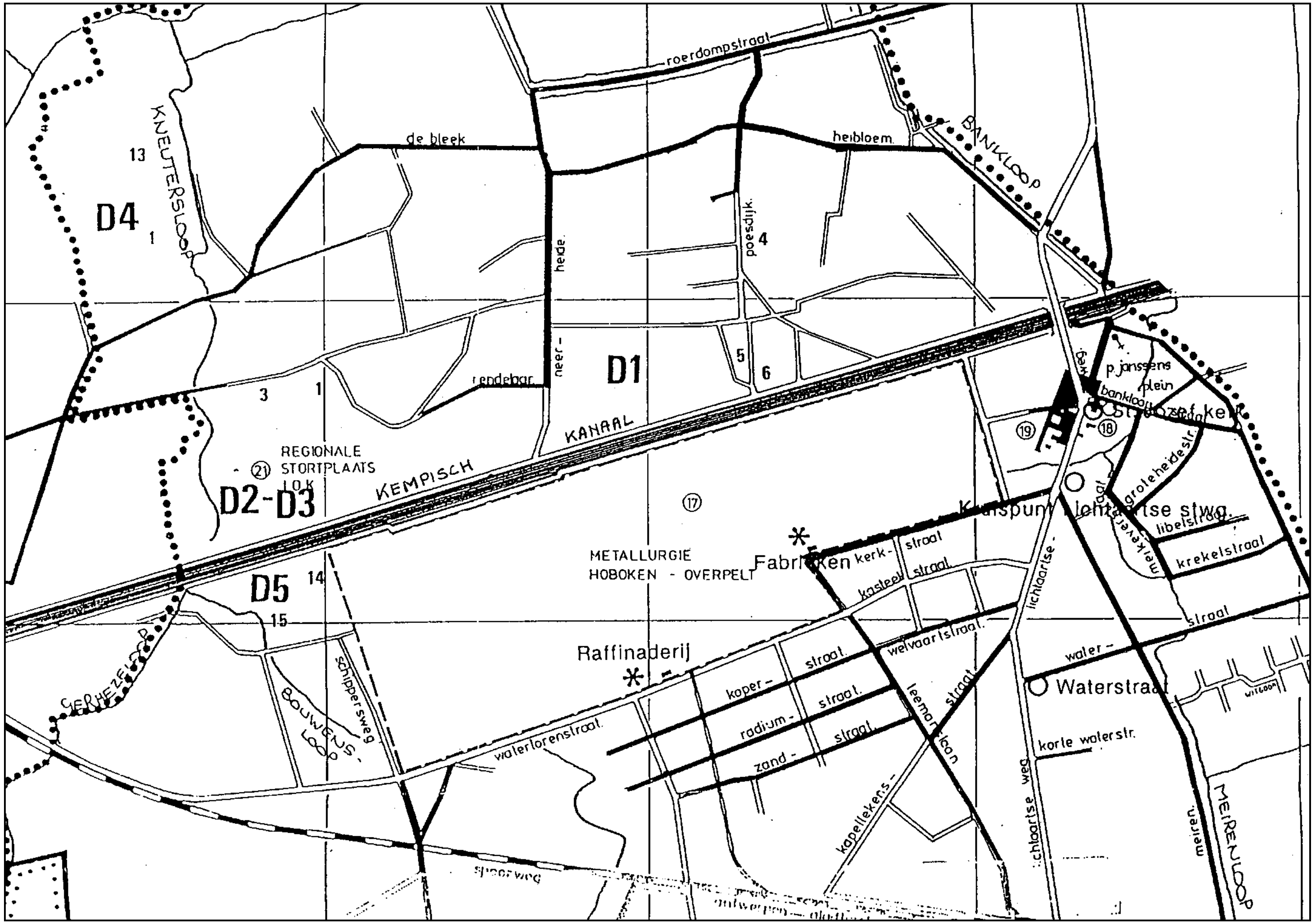


FIG. I-3. Localisation dumping grounds.

I-2.1. Soil

At the site considered, near the Kleine Nete the soil is mostly composed of peat and peaty sands up to a depth of 2-3 m (quaternary deposits – alluvium) (Figure I-4). They have a humic or/and iron B horizon. Sand or clayey sand substrates are situated at small or moderate depths [5]. Before the draining of the terrain it constituted a marshy formation because of the weak slope of the terrain and the frequent inundations of the Old Bankloop and the Kleine Nete (Figure I-7). The peaty layer has an apparent (bulk) density of 320 kg/m^3 and a porosity of 0.5. Its permeability is 1.7 10^{-4} m/s [3].

I-2.2. Surface hydrology

The Olen site is located in the Kleine Nete hydrographic basin. The basin surface area amounts to 600 km^2 and the annual average flow is approximately 3 m^3/s at the site considered. The drainage basin of the Bankloop occupies a surface area of 7.7 km^2. The average and maximum flow rates of the Bankloop are not known. An average flow rate in natural conditions has been calculated to amount to 170 m^3/h, but several 100 m^3/h are added by discharges from the Olen plant.

I-2.3. Geology

The most important geological substrate of the region is constituted by the Kasterlee formation, a tertiary formation (Lower Pliocene) which is approximately 10 m thick at the site considered (Figure I-5). It is constituted by clayey fine sands, micaceous and slightly glauconitic with some purple clay horizons [6]. The lower portion of the formation is enriched in silt and clay minerals.

The Kasterlee formation is lying upon the Diest formation (Upper Miocene), to which it is closely related. The Diest formation has a thickness of approximately 70 m and is constituted by strongly glauconitic and mostly coarse-grained sands. The sands contain layers of limonite and clayey and micaceous horizons.

The Olen site is not located in a seismic area. The regional subsidence in the coastal area does not reach the Olen area.

I-2.4. Hydrogeology

There are three aquifers in the Olen area. The surface aquifer is the Kasterlee aquifer. It is a fine clayey sand layer of approximately 10 m thickness. The water table of the aquifer lies between one and two metres beneath ground level. The lower part of the Kasterlee formation contains a significant clay content which limits the water migration into the underlying Diestiaan aquifer. The latter aquifer has a vertical thickness of nearly 70 m at the Olen site. The permeability of the Kasterlee aquifer varies between 0,09 and 0,9 m/day. In the upper 40 m of the Diestiaan aquifer, the permeability is about 20,4 m/day. Beneath this aquifer, there is a third aquifer consisting of a 20 m layer of fine sand and a 10 to 15 m layer of coarse sand. The average permeability through the second and the third aquifer is about 9,1 m/day. Further downwards movement of water is very low due to the underlying clay formation (Boom clay).

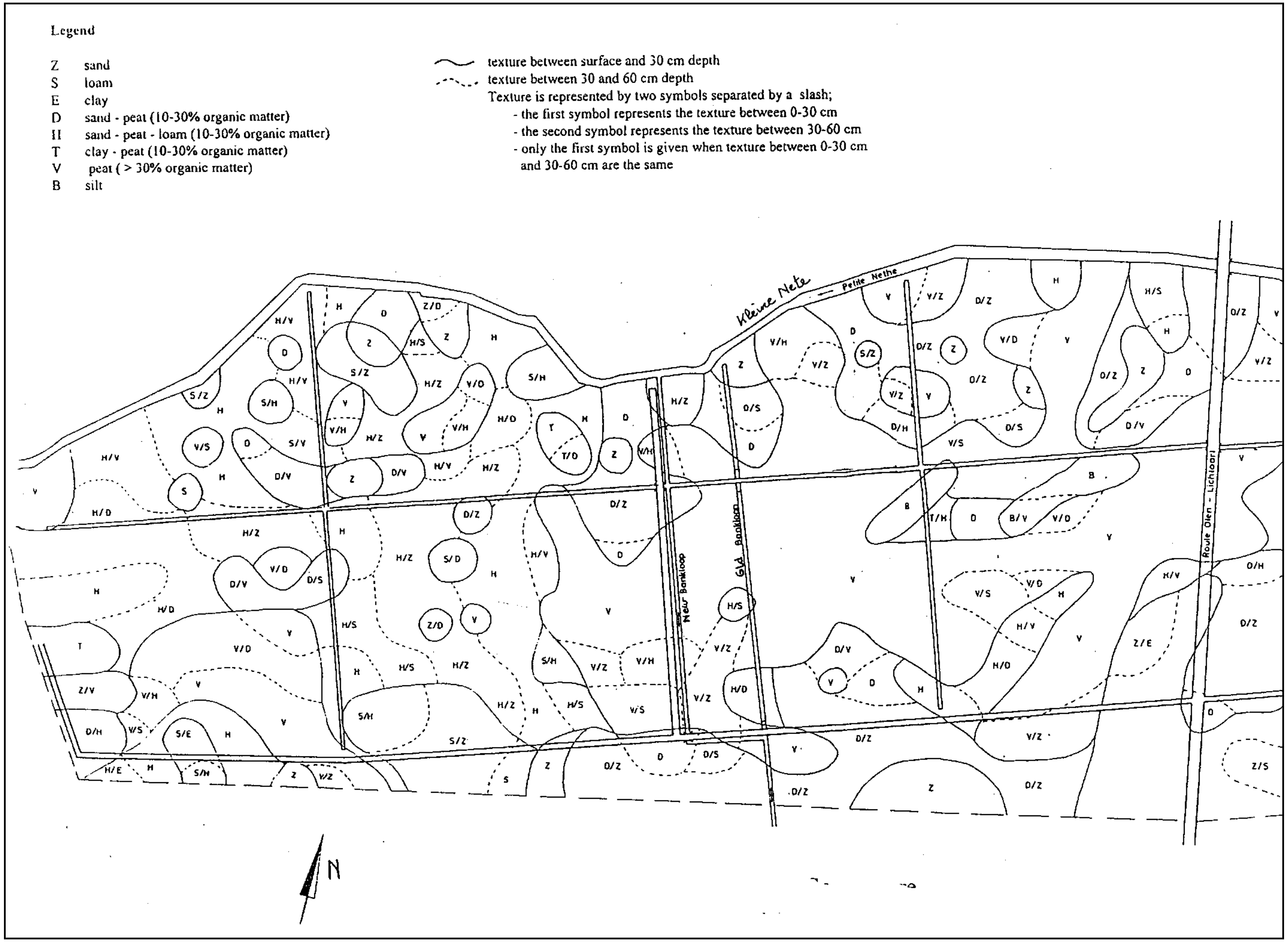


FIG. I-4. Soil texture.

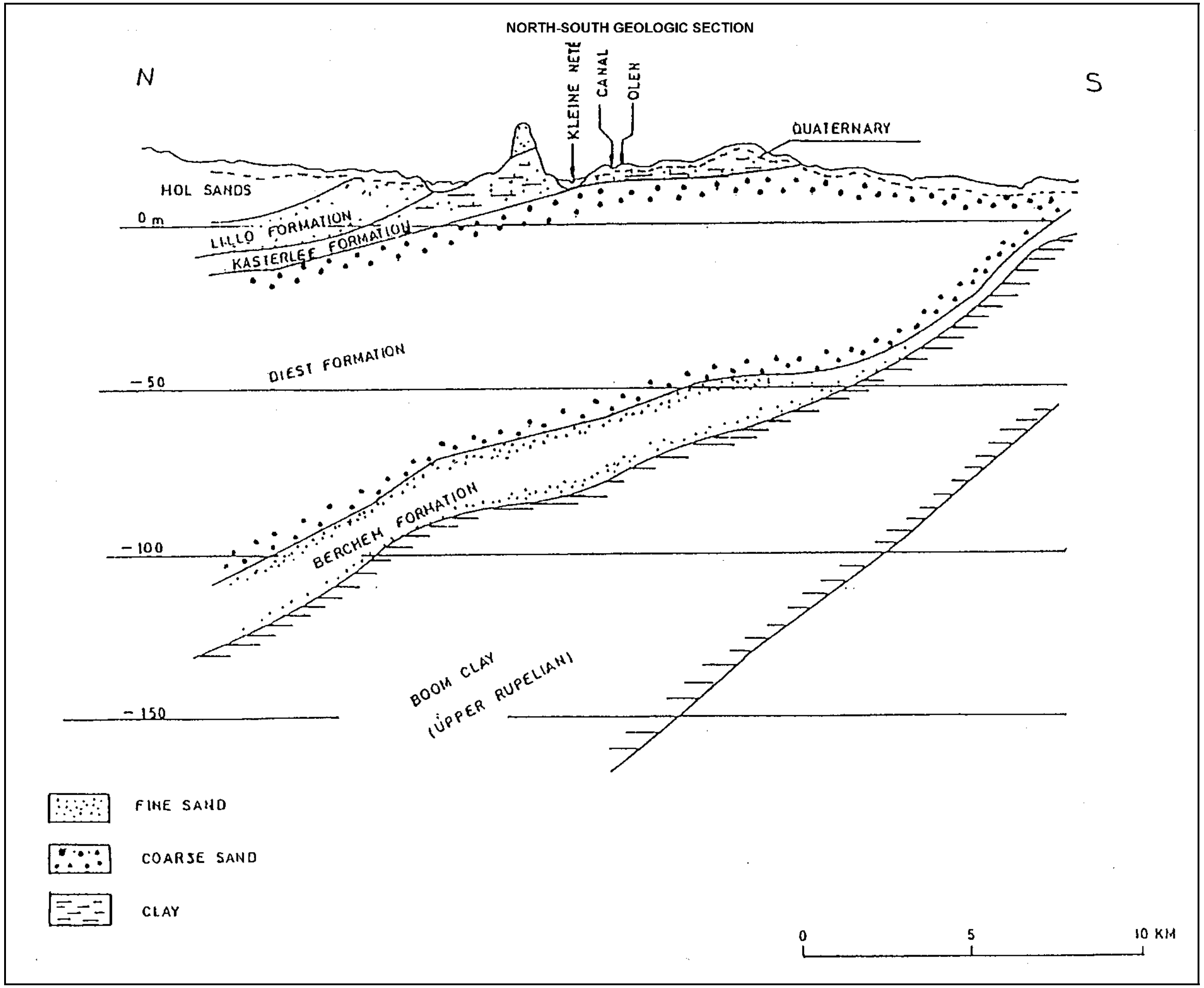


FIG. I-5. Geology-profile.

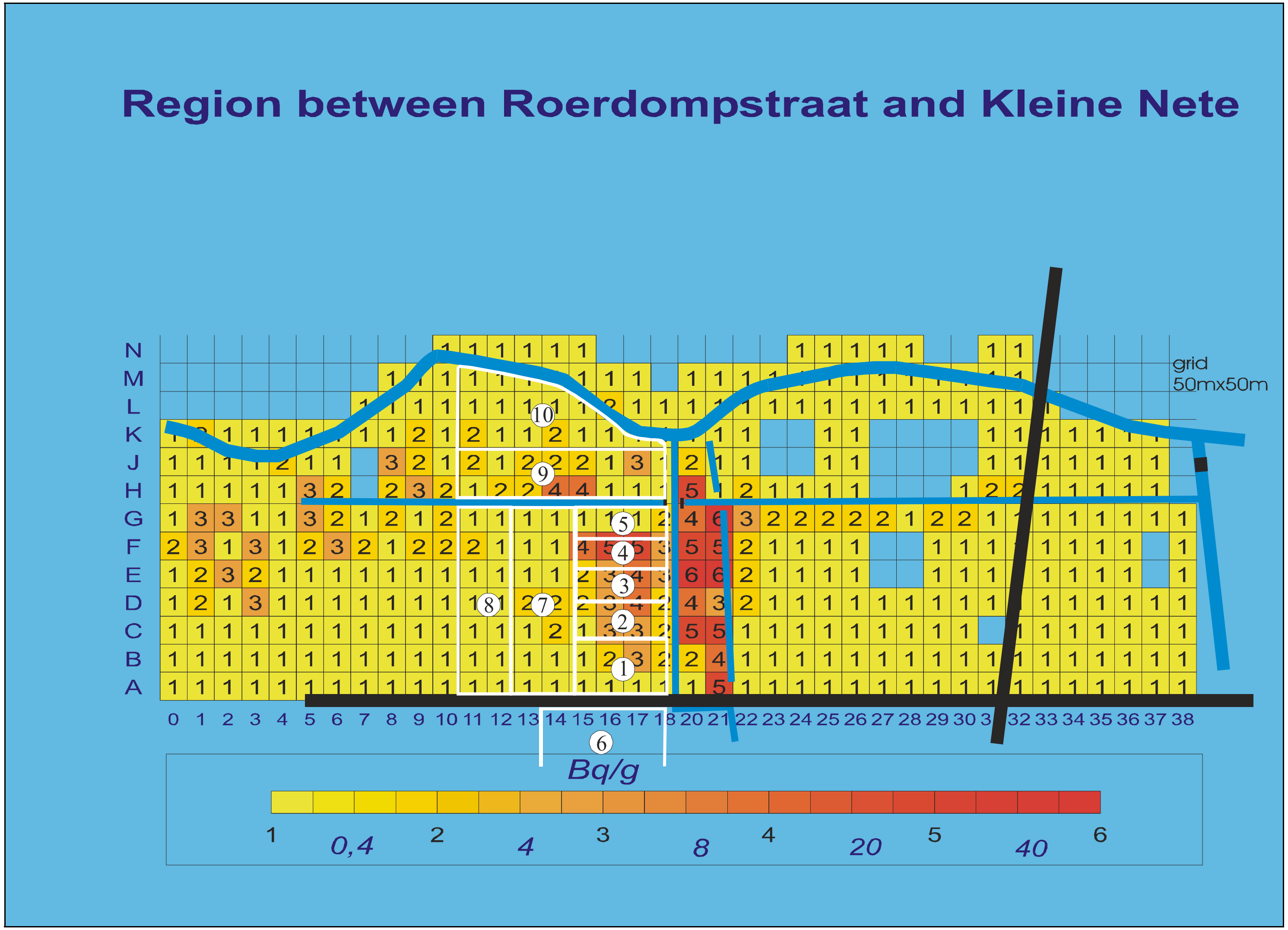


FIG. I-6. ^{226}Ra concentrations in soil and localisation of pasture plots 1 to 10.

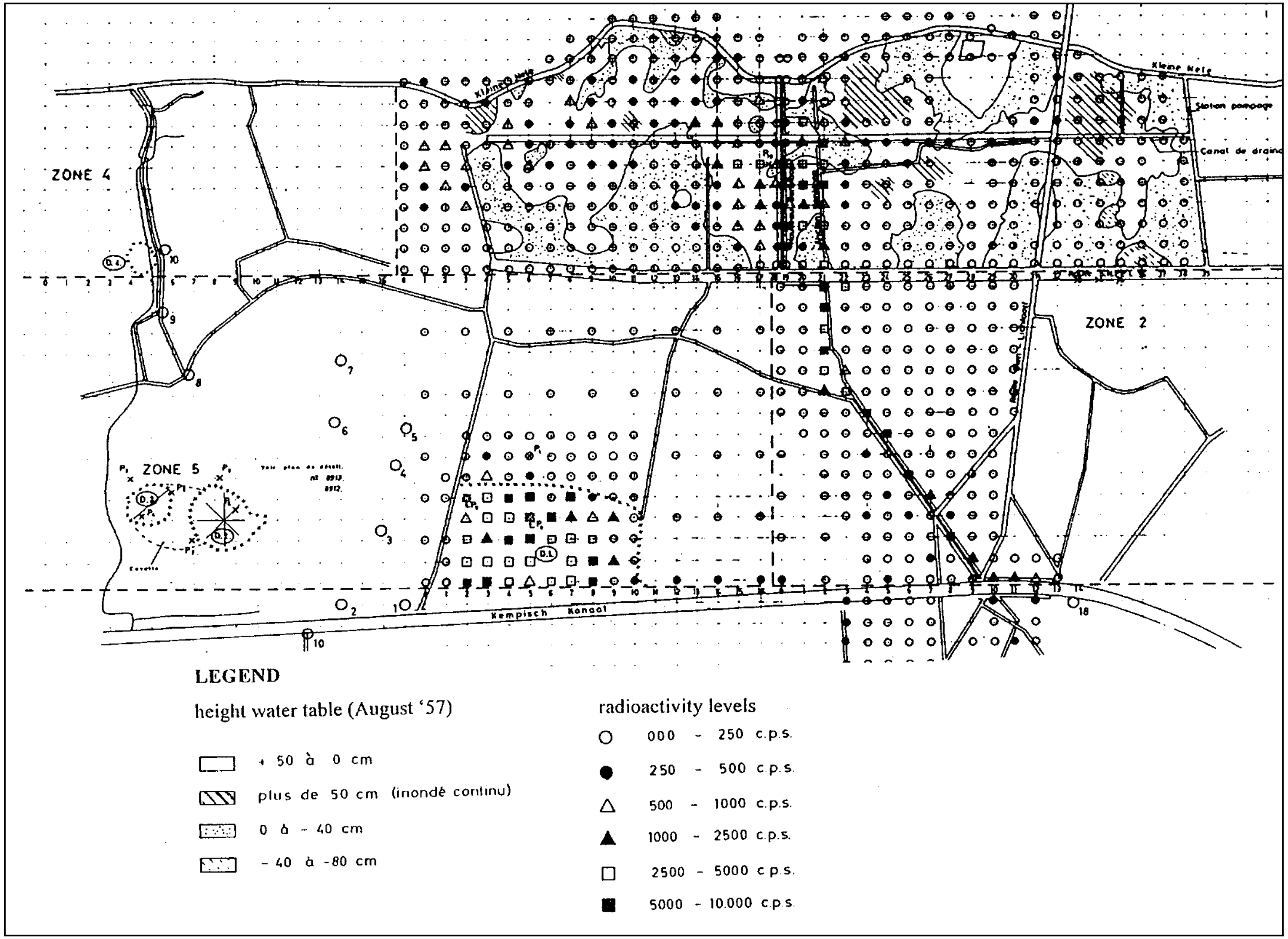


FIG. I-7. Results foot survey and height water table (August '57).

The natural flow direction in the aquifer is from east to west, discharging in the Kleine Nete. Due to drainage, the direction of the water flow in the upper few metres of the soil is reversed and this water is pumped into the Kleine Nete upwards the confluence of the New Bankloop. The water pumping activities at the Olen plant may have a local influence on the flow direction of the underlying aquifer (Diestiaan).

For human consumption, the water of the Diestiaan aquifer is used. The water of the surface aquifer is not suited for this purpose. It is only used for watering cattle.

I-2.5. Climate

The site climate is temperate with a slight maritime influence.

The meteorological characteristics originate from the SCK·CEN which is located at approximately 20 km from the Olen-site (to the east). For temperatures and relative humidity verified data over 28 consecutive years are available, data on precipitation rates and duration over 16 years (Tables I-I to I-III).

Concerning the wind, the distribution of the wind speeds (u) are indicated over several categories (measured over 20 years at 24 m height):

$u < 1.5\ \mathrm{m.s^{-1}}$: 5.5 %
$1.5\ \mathrm{m.s^{-1}} \leq u < 3.5\ \mathrm{m.s^{-1}}$: 53 %
$3.5\ \mathrm{m.s^{-1}} \leq u < 6.5\ \mathrm{m.s^{-1}}$: 37 %
$6.5\ \mathrm{m.s^{-1}} \leq u < 11.5\ \mathrm{m.s^{-1}}$: 3.9 %
$11.5\ \mathrm{m.s^{-1}} \leq u$ 0.02 %

Soil water balance elements have been determined over 6 consecutive years for the Grote Nete basin (very similar to the Kleine Nete basin) by VUB (Prof. Vander Beken). The results are given in Table I-IV.

I-2.6. Demography

The site considered is not densely habitated. At this time, between Kleine Nete and Roerdompstraat, only a few farms are located, utilising the land as pasture for dairy cows or for maize production.

Immediately south of the Kempisch Kanaal, a community of 2000 people (St. Jozef-Olen) is located (Figure I-1). The nearest larger communities are the towns of Herentals (appr. 25.000 inhabitants) and Geel (appr. 30.000 inhabitants), at respectively 4 km (W) and 8 km (SE) distance.

I-2.7. Flora and fauna

The natural ecosystem is only a negligible contributor to the diet of the population. Blackberries are native plants which may occur at the site and may be eaten occasionally. Some small game, mostly rabbits, may be hunted and eaten.

TABLE I-I. MEAN, MAXIMUM AND MINIMUM DAY TEMPERATURES DURING THE PERIOD 1956–1983

Month	Average values of day temperatures (°C)			Highest day	Lowest day
	Mean	Day maximum	Day minimum	maximum	minimum
January	2.3	4.6	-0.1	13.8	-19.0
February	2.6	5.7	-0.5	18.4	-19.0
March	5.6	9.3	2.0	23.0	-15.1
April	8.4	12.8	3.9	28.5	-4.7
May	12.8	17.4	7.7	30.0	-2.2
June	15.8	20.6	10.5	33.5	-0.4
July	17.3	22.0	12.4	36.2	3.1
August	16.7	21.5	12.0	34.6	2.8
September	14.5	19.0	9.9	31.2	-0.3
October	10.4	14.4	6.7	27.0	-2.4
November	6.0	8.7	3.2	19.4	-6.8
December	3.1	5.3	0.7	15.5	-14.9
Year	9.7	13.5	5.8	36.2	-19.0

TABLE I-II. PRECIPITATION DATA DURING THE PERIOD 1968–1983

Month	Precipitation amounts (mm)			Precipitation duration (h)		
	Mean	Mimimum	Maximum	Mean	Mimimum	Maximum
January	60	24	116	32	13	49
February	51	13	113	28	11	58
March	67	23	129	35	11	64
April	47	8	99	21	2	43
May	64	21	129	25	11	68
June	73	17	125	26	5	60
July	71	24	160	21	4	49
August	60	14	136	18	4	40
September	56	8	130	20	2	69
October	62	7	153	26	3	62
November	78	36	171	36	16	63
December	68	16	143	32	5	65
Year	757	527	996	318	206	470

TABLE I-III. RELATIVE HUMIDITY (%) DURING THE PERIOD 1956–1983

Relative humidity	Frequency (%)		
	Mean	Minimum	Maximum
> 90	44.2	26.3	57.0
80-89	21.9	13.3	38.1
70-79	13.6	10.1	18.7
60-69	9.3	7.3	12.8
50-59	6.1	4.3	8.2
40-49	3.3	1.5	5.9
30-39	1.2	0.3	3.4
20-29	0.4	<0.1	2.4
<20	<0.1	<0.1	0.4

TABLE I-IV. WATER BALANCE GROTE NETE 1967–1972

Year	Precipitation (mm)	Evapotranspiration (mm)	Effective precipitation (mm)	Δ storage groundwater (mm)	Discharges (mm)	Losses (mm)
1967	740	384	356	-94.3	376	73.6
1968	761	383	378	-61.4	369	70.4
1969	716	395	321	-20.1	290	50.7
1970	803	386	417	15.5	341	60.5
1971	622	371	252	-35.3	246	41.0
1972	715	368	347	16.0	289	48.9
Average	726	381	345	-29.9	318	57.5

I-3. RADIOLOGICAL DATA

Data concerning the non-radiological characteristics of the Olen-site have been given in the previous section. Radiological characteristics are discussed below.

Several survey and measurement campaigns have been performed. According to the time periods of execution, three important campaigns can be distinguished:

- a large biological study concerning the behaviour of Ra-226 in the environment, carried out during the period 1961-1967, before the first remedial actions [3] (filling up of the Old Bankloop, deep ploughing of the soil between the Kleine Nete and the Roerdompstraat);
- a follow-up survey, primarily focused upon the contamination level in milk in the period 1971–1972, after the first remedial actions [7];
- a large detailed radiological assessment study, carried out on the most contaminated parts in the environment (Bankloop, dumping grounds) and in the village of St. Jozef-Olen in the period 1991–1995 [4], [1].

Of the first study, a summary of the relevant data will be given. The data of the second and third study will not yet been given for the sake of a type A scenario (cf. Scenarios) including the remedial actions indicated.

The site considered in the first two studies is the area between the Kleine Nete and the Kempisch Kanaal, indicated in Figure I-2.

In the following data set we will distinguish between:

- Sector 1: between the Kleine Nete and the Roerdompstraat and
- Sector 2: between the Roerdompstraat and the Kempisch Kanaal.

In the third study also the village of St. Jozef-Olen was included.

I-3.1. Biological study 1961–1967

I-3.1.1. Soil contamination

I-3.1.1.1. Ra-226 concentrations in soil

Only the surface layer (0–10 cm) of the ground, consisting of peat and peaty sands was contaminated. Three contamination levels were distinguished (Figure I-6, only Sector 1 indicated):

- Ra-226 concentrations larger than 37 Bq/g DW: with surface areas of 0.66 ha (Sector 1) and 1.75 ha (Sector 2);
- Ra-226 concentrations between 3.7 and 37 Bq/g DW: with surface areas of 9.12 ha (Sector 1) and 3.75 ha (Sector 2);
- Ra-226 concentrations between 0.37 and 3.7 Bq/g DW: with surface areas of 10 ha (Sector 1) and $150_{=}$ ha (Sector 2)

In Sector 1, covering 94 ha, 22 ha are contaminated. The dumping grounds are outside this sector. Also the radium contamination of the dumping grounds has been shown not to be released outside the dumping grounds. No measured values on localised points are given. The localisations of the contaminated zones have been derived from the foot survey (see Section 3.1.1.2).

The distribution coefficient (K_d) of radium has been measured on several soil samples. For the peat soils (which had a high organic matter content: more than 30 %), measured values ranged from 1.5 to 2.5 m^3/kg. For sand, the values were between 0.15 and 0.20 m^3/kg.

I-3.1.1.2. Foot survey

A survey on foot has been carried out with a NaI crystal (4x5 inch) on a grid of 50 m. A zone of 150 ha (= 600 measuring points) has been explored in that way (Figure I-7). The results are indicated in cps.

I-3.1.1.3. Aerial survey

An aerial survey has been carried out with a helicopter, at a height of 40 m (Figure I-8). The results are indicated in cps. On this map also isopleths are indicated.

I-3.1.2. Aquatic contamination

I-3.1.2.1. Ra-226 concentrations in surface water

A summary of the measured values is given in Table I-V. It is to be kept in mind that the values are based on a limited (mostly unknown) number of measurements.

The activity in the sediment has been shown to be localised in the upper 50 cm layer.

Individual, measured values of relative distributions (in %) between aqueous and solid phases of the water in the Old Bankloop are also available.

TABLE I-V. Ra-226 CONCENTRATIONS IN SURFACE WATERS

	Old Bankloop	New Bankloop	Bankloop[a]	Kleine Nete[b]
Total Ra-226 concentration in river water (Bq/l) (Min-Max)	0.22-7.0	0.23-0.81	0.09-0.41	
Ra-226 concentration in aqueous phase (Bq/l) (Min-Max)	0.022-1.8			
Ra-226 concentration in suspended matter (Bq/g DW) (Min-Max)	11-200			
Ra-226 concentration in bed sediment (Bq/g DW)[c] (Min-Max)	0.1-33	1.8-13	1.5-5.5	0.1-1.5

[c] downstream confluence with Meirenloop.

[b] downstream confluence with New Bankloop.

[c] samples taken with a coring tube, up to 90 cm deep, and measured by (spectrometry (in laboratory).

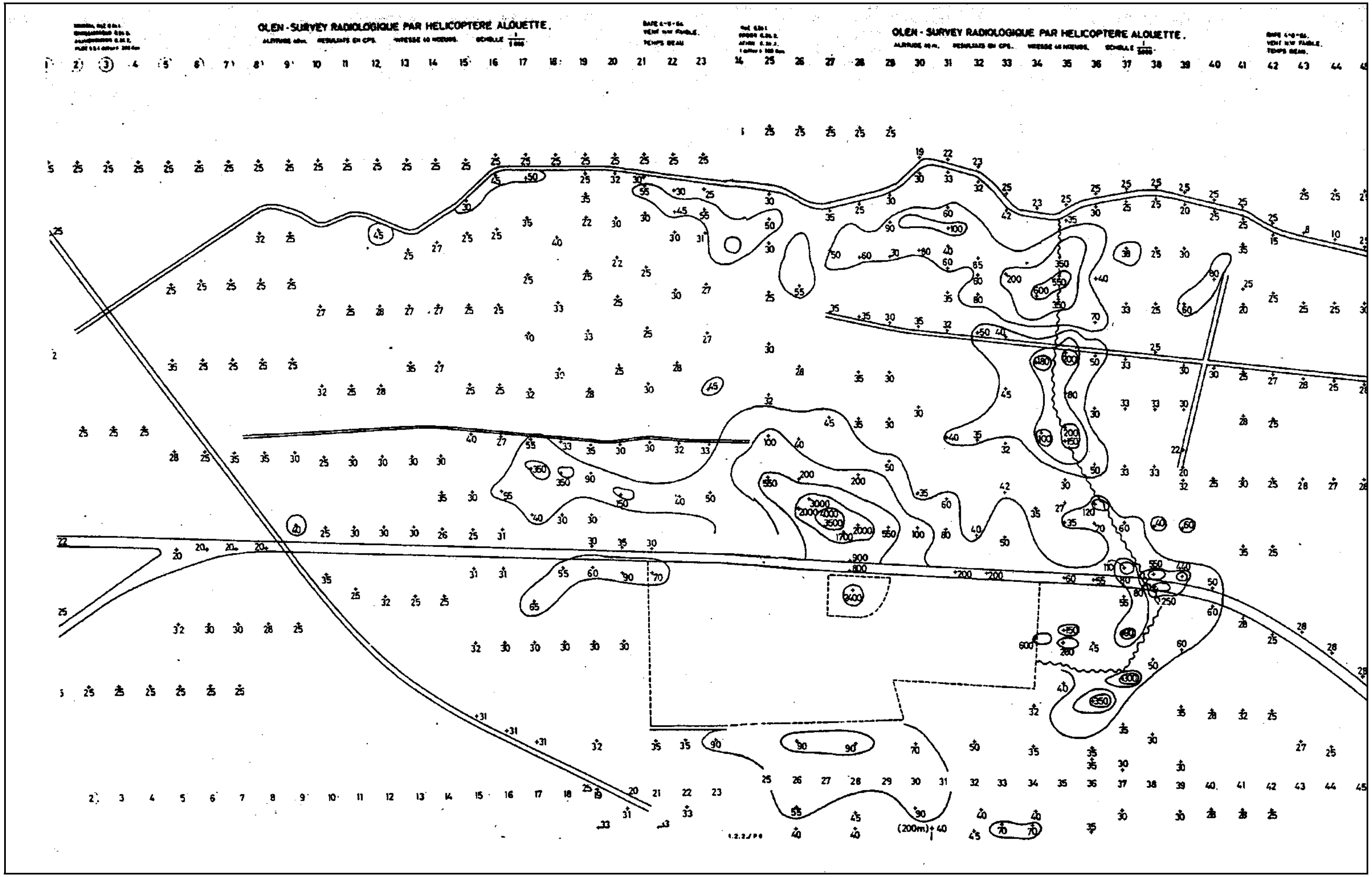


FIG. I-8. Results helicopter survey.

I-3.1.2.2. Survey

A survey of the bed sediment of the surface waters mentioned above has been carried out with a watertight scintillator (NaI), immersed in the water onto the bed. A limited number of measured values (in cps) are available (on request).

I-3.1.2.3. Ra-226 concentrations in groundwater

Groundwater has been sampled through wells and measured for the Ra-226 concentration. The measured values (between 3.7 and 40 mBq/l) were insignificant; tap water containing 7.4 mBq/l.

I-3.1.2.4. Ra-226 concentrations in aquatic animals

Concentrations	in fishes were always less than	1.8 mBq/g FW.
Concentrations	in gastropods (Old Bankloop):	0.36 and 0.64 Bq/g
Concentrations	in amphibians (Old Bankloop):	0.18 and 0.81 Bq/g

I-3.1.3. Agricultural Studies

I-3.1.3.1. Experiments in natural conditions

— **Experimental Fields**

Between the Old and the New Bankloop, 49 plots of 4 m^2 have been cultivated with 7 major food crops and fodder plants.

The aim of the experiments was to determine soil-to-plant concentration factors (B_v). Concentrations measured in various parts of the plants and associated concentration factors were reported (Table I-VI). The minimum and maximum values of concentrations and concentration factors do not necessarily correspond neither to the same plot, nor to the same year. The Ra-226 concentrations in the soil of the plots were not given.

— **Experimental Pastures**

On the western bank of the New Bankloop, 2 plots (4000 and 5000 m^2) have been managed as meadows. Two cows were put on the meadows and the concentration in their milk was measured.

The Ra-226 concentrations measured in soil, pasture and milk are given in Table I-VII. The concentrations in milk may not have been in equilibrium with those in pasture, since they were averages over the 2nd week the cows were on the plot concerned. The Ra-226 intake of the cows through drinking water was negligible.

I-3.1.3.2. Experiments in controlled conditions (greenhouse)

Experiments with crops grown on homogeneous soils and on nutrient solutions have been carried out. The results reported for the experiments on soil are given in Table I-VI. The concentration factors for crops grown on nutrient solution were much higher.

TABLE I-VI. SOIL-PLANT CONCENTRATION FACTORS $\left(\frac{Bq/g\ \mathrm{DW}}{Bq/g\ \mathrm{DW}}\right)^{a}$

		Way of Contamination		
		Experimental Field		Greenhouse
		Concentration Factors (1961–1963)	Concentrations (Bq/g DW) (1963)	Concentration Factors
Ray–grass: overground parts		0.02–0.19	<0.37–13.4	0.41–0.75
Clover: overground parts		0.08–0.44	<0.4–1.3	#0.07–0.50
Barley	– straw	0.01–0.15	0.55–1.2	0.10–0.90
	– ears	0.005–0.03	<0.14–0.50	0.05–0.09
Cabbage	– stem	0.02–0.99	– (0.44)	0.08–0.37
	– leaves	0.03–1.0	<0.15–1.5	0.06–0.81
Carrots	– roots	0.07–0.10	<0.09–2.5	0.26–0.54
	– overground parts	0.08–0.10	<0.54–7.4	0.12–1.15
Beet	– roots	0.04–0.05	<0.07–0.83	0.19–0.74
	– overground parts	0.03–0.16	<0.12–<2.6	0.50–1.51
Peas	– pods			3.1
	– leaves			0.6
Potatoes	– tubers	0.011–0.038	?	0.017–0.06

[a] Before sowing, the soil was ploughed (ploughing depth = 25 cm)

TABLE I-VII. Ra-226 CONCENTRATIONS – EXPERIMENTAL PASTURE (1966)

	Plot 1		Plot 2	
Soil (Bq/g DW)[b]	0.30		0.22	
Pasture (Bq/g DW)	0.025		0.011	
Milk (Bq/l)	Cow 7	Cow 11	Cow 7	Cow 11
	0.033	0.047	0.036	0.047

[b] These results represent the average Ra concentration in the root soil zone (upper 15 cm of the soil). It was not indicated whether the soil was ploughed or not.

I-3.1.3.3. Sampling on site

— **Cultivated plants**

Contamination with Co (not radioactive) prevents or counteracts development of crops in most contaminated places.

Ra-226 concentrations observed in cultivated plants:

Sector 1: only a few cultivated fields
wheat, oats, potatoes sampled
maximum Ra-226 concentration: 0.11 Bq/g DW leaves-potatoes
minimum Ra-226 concentration: 7 mBq/g DW tubers-potatoes
Sector 2: maximum concentrations observed : cabbage: 0.037 Bq/g DW
oats (stem): 0.22 Bq/g DW
beans: 0.44 Bq/g DW
potatoes (tubers): 0.07 Bq/g DW
various leaves in meadows: 0.18 Bq/g DW

TABLE I-VIII: ANNUAL CONSUMPTION - CRITICAL GROUP (kg/y)

Milk	131
Cheese	5.8
Meat	53.7
Poultry	8.2
Fish	5
Vegetables	56
Fruit	56
Potatoes	122
Eggs	18
Flour (wheat)	81
Water (well)	265

— Domestic animals

From the rabbits measured, only two showed a detectable Ra-226 concentration in meat: 0.026 Bq/g FW.

— Animal products (Sector 2)

Milk: Only 1 sample with a detectable concentration of Ra-226: 0.26 Bq/l
other ones: < 0.15 Bq/l
Eggs: Concentrations of 0.55 Bq/egg were observed.

— Dietary habits for critical group

In this study, the critical group has been identified with the cultivator families that would settle on the contaminated site between the Roerdompstraat and the Kleine Nete (Sector 1). The dietary habits have been assumed to be the same as those for the whole country (Belgium). The consumption rates are given in Table I-VIII.

Interrogations with questionnaires of the people living in the farms in the neighbourhood allowed the investigators to determine the food items that were derived from the site. These items included: milk, meat, vegetables and potatoes.

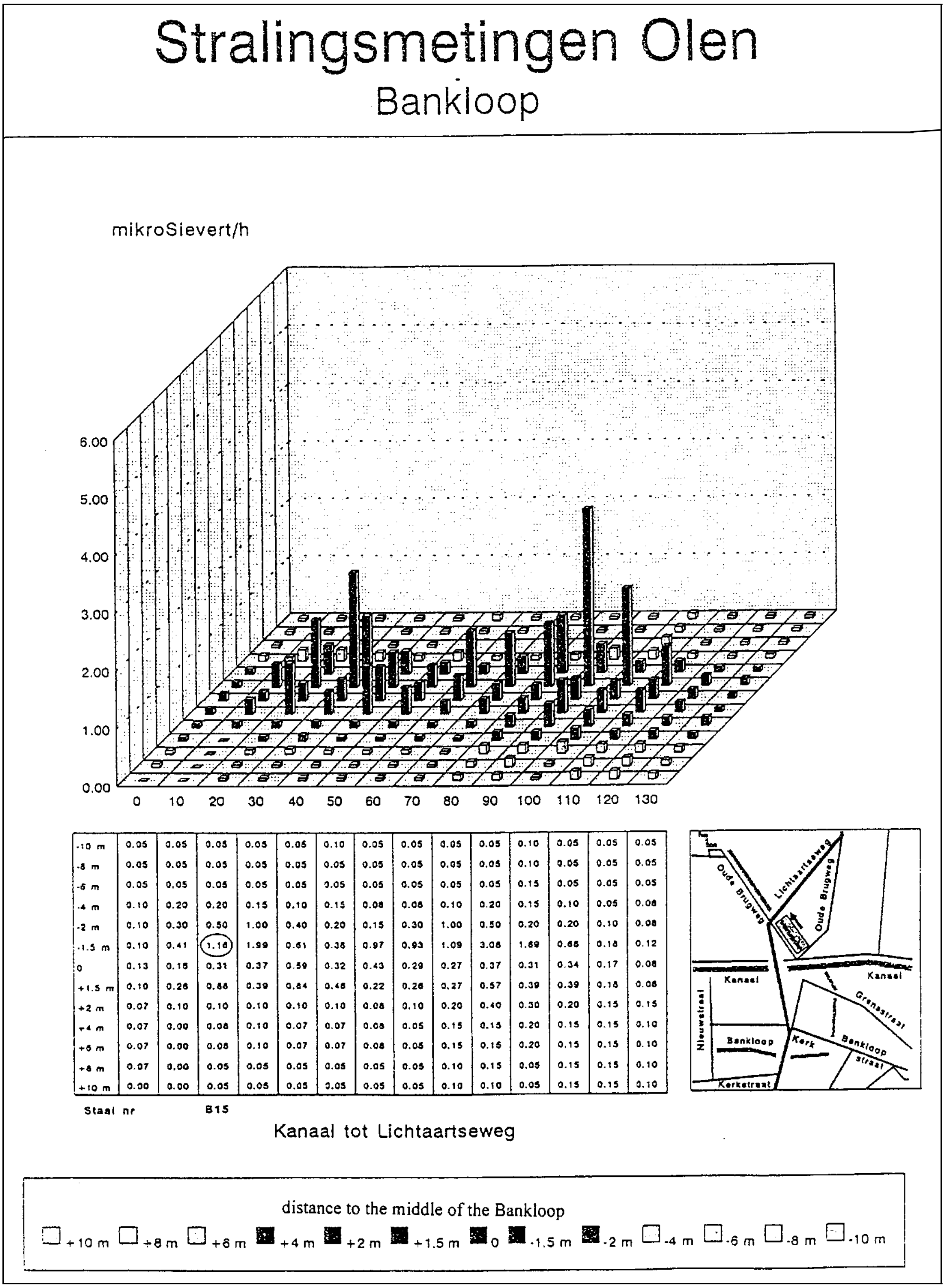
I-3.2. Follow-up survey (1971–1972)

The first remedial actions carried out on the site consisted of filling up the Old Bankloop and of deep ploughing of the soil in sector 1 (between Kleine Nete and Roerdompstraat).

Subsequently survey/measurements have been carried out, focused primarily on the contamination of the milk produced by cows that were put on the remediated soil, where meadows were managed upon [7]. Following measured data were reported:

I-3.2.1 Ra-226 concentrations in milk (Bq/l) of cows put on plots that are specified in Figure I-9.

The measurements were performed on weekly-monthly samples from May ‘71 up to December ‘72. Also from December ‘76 up to April ‘77 measured concentrations were reported.



-10 m	0.05	0.05	0.05	0.05	0.05	0.10	0.05	0.05	0.05	0.05	0.10	0.05	0.05	0.05
-8 m	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.05	0.05	0.05
-6 m	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.15	0.05	0.05	0.05
-4 m	0.10	0.20	0.20	0.15	0.10	0.15	0.08	0.08	0.10	0.20	0.15	0.10	0.05	0.08
-2 m	0.10	0.30	0.50	1.00	0.40	0.20	0.15	0.30	1.00	0.50	0.20	0.20	0.10	0.08
-1.5 m	0.10	0.41	1.16	1.99	0.61	0.38	0.97	0.93	1.09	3.08	1.69	0.68	0.18	0.12
0	0.13	0.16	0.31	0.37	0.59	0.32	0.43	0.29	0.27	0.37	0.31	0.34	0.17	0.08
+1.5 m	0.10	0.26	0.66	0.39	0.64	0.46	0.22	0.26	0.27	0.57	0.39	0.39	0.18	0.08
+2 m	0.07	0.10	0.10	0.10	0.10	0.10	0.08	0.10	0.20	0.40	0.30	0.20	0.15	0.15
+4 m	0.07	0.00	0.08	0.10	0.07	0.07	0.08	0.05	0.15	0.15	0.20	0.15	0.15	0.10
+6 m	0.07	0.00	0.08	0.10	0.07	0.07	0.08	0.05	0.15	0.16	0.20	0.15	0.15	0.10
+8 m	0.07	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.15	0.05	0.15	0.15	0.10
+10 m	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.10	0.05	0.15	0.15	0.10
Staal nr			B15											

Kanaal tot Lichtaartseweg

distance to the middle of the Bankloop

☐ +10 m ☐ +8 m ☐ +6 m ■ +4 m ■ +2 m ■ +1.5 m ■ 0 ■ -1.5 m ■ -2 m ☐ -4 m ☐ -6 m ☐ -8 m ☐ -10 m

FIG. I-9. Example dose rate survey.

I-3.2.2 Ra-226 concentrations in animal feeding stuffs, pasture and ensilage and quantities ingested by dairy cows.

Measurements of concentration in pasture were carried out in August 1970 (3 values) and July 1971 (6 values). The concentrations of July '71 were associated with 6 of the plots specified in previous paragraph.

Measurements of concentration in ensilage were carried out in January, February, April and December 1971 with one result per month.

The quantities of additives to the feeding regime of the cows in winter were also indicated (together with the Ra-226 concentrations in them); they were however not significant.

I-3.2.3 Transfer coefficients from water to milk (2 cows of different breed – measurements on 4 consecutive weeks) and from feeding stuffs to milk (4 cows of same breed – results from 8th to 14th day).

The quantities ingested by the cow and the Ra-226 concentrations in milk, drinking water and feeding stuffs were reported.

I-3.2.4 A new survey by helicopter with only qualitative results.

I-3.3. Detailed radiological assessment study (1991–1995)

An extensive measuring campaign has been carried out over the period 1991–1992, focused on the most contaminated parts in the environment, and in the village of St. Jozef-Olen [1], [4]. Additional measurements have been carried out in 1994 and 1995 with respect to the chemical and radiological characterisation of the bed sediment and banks of the Bankloop. Following surveys were performed.

I-3.3.1. A foot survey with dose rate recordings

The dose rate (in Sv/h) was measured every 10 m from the plant to the confluence with the Kleine Nete, in the middle of the Bankloop, at the borders and at both banks, every 2 m until the background value was attained (e.g. Figure I-9). The dose rate (in Sv/h) was measured in the pastures in the vicinity of the former bed of the Old Bankloop, according to a grid with a nodal point every 10 m. A number of 2938 measurements were carried out. The contamination was shown to be very heterogeneous with large variations over short distances.

Also streets (in St. Jozef-Olen) and the vicinity of dumping grounds have been covered in these surveys.

I-3.3.2. A soil sampling and measuring campaign

Samples have been taken of the soil, at places where important dose rates have been recorded during the foot survey, and measured for the Ra-226 concentration (Bq/g). 31 samples were taken at the banks of the Bankloop and of the New Bankloop, and in meadows in the vicinity of the former bed of the Old Bankloop. 4 samples were taken of the bed sediment (upper mud layer) of the Bankloop near to the plant.

Also soil along and under streets and in the vicinity of the dumping grounds have been sampled and the samples measured for the Ra-226 content.

I-3.3.3. Measurements of the Ra-226 concentrations in aerosols

These measurements have shown the concentrations in aerosols to be radiologically insignificant.

I-3.3.4. Water sampling in the vicinity of the dumping grounds

Samples were taken of surface water in the vicinity of the dumping ground D1 (6 places in brooks, fens) and measured for the Ra-226 content. They have shown the influence of the dumping grounds on the Ra-226 concentrations of those waters to be very minor. Also the groundwater below the dumping grounds was sampled (14 samples) and have shown the migration of Ra-226 to the groundwater to be insignificant.

I-3.3.5. Measurements of the food chain

Samples were taken of the food chain in contaminated areas and measured for Ra-226 content. A number of 32 samples were taken and analysed, including: 12 milk samples, 5 maize samples, 4 samples of chickens' eggs, 4 samples of vegetables (leek, celery and scorzonera), 2 grass samples.

The milk samples were taken at 2 dairy farms with a large milk production (2 x 6 week samples). However only a small fraction of their pastures and fields are located on contaminated terrain. Also 3 maize samples originated from maize fields of one of these farms. 2 maize samples were taken on contaminated terrain. The samples of vegetables were taken from a kitchen-garden next to the banks of the Bankloop.

I-3.3.6. Measurements of milk-teeth of children

In order to examine the internal contamination of children in St. Jozef-Olen, milk teeth of children have been collected in a municipal school, close to the former radium plant (176 teeth from 40 children) and their Ra-226 concentration measured. The influence from the Ra contamination at the site was shown to be very small.

I-3.3.7. Measurements of radon exhalation in houses (dwellings) and above dumping grounds

All dwellings in St. Jozef-Olen (713) and some (133) in the neighbouring community of Geel have been involved. In all these dwellings, radon concentrations have been measured with activated charcoal detectors over 24 h in basements or rarely used places. On the basis of the results of this first campaign, additional measurements have been carried out with activated charcoal, respectively track-edge detectors, in other rooms of the houses, in 67 respectively 14 dwellings. The track-edge detectors were left in place during 80 days.

A number of 18 track-edge detectors were placed above dumping grounds and replaced every 3 months or every month (D1) over 1 year.

I-3.3.8. Measurement of bed sediment and banks of the Bankloop

The additional measurements of bed sediment and banks of the Bankloop, carried out in 1994 and 1995 covered the part of the Bankloop upstream the Roerdompstraat (up to the plant). A number of 13 drillings were executed on the banks, 7 drillings were executed into the bed sediment.

The total depth of the drilling was dependent on the depth of the Ra-226 contamination and amounted up to 1.8 m. The cores were divided into layers of 20 or 30 cm.

The total concentration of Ra-226 and of the -heavy - metals, As, Ba, Cd, Cr, Co, Cu, Hg, Pb, Mo, Ni, Sn and Zn were measured in the samples. The solubility and lixiviability in distilled water of some of those metals were also analysed. In some samples also the carbon and organic matter content were measured.

I-4. TYPE A SCENARIO DESCRIPTION

The major aim of this scenario is to test the accuracy of predictions of environmental assessment models against observed data when remedial actions are involved.

The Olen Scenario Type A is related to the influence of the remedial actions (carried out around 1970) on the Ra-226 concentrations in the food chain. These actions consisted of:

- the filling up of the Old Bankloop
- the deep ploughing of sector 1 (between Roerdompstraat and Kleine Nete).

The modelling task is to assess the Ra-226 concentrations in the milk of dairy cows (a group of 50-60 cows) that were put on pastures arranged on the remediated soil in Sector 1. These cows have been followed and their milk sampled and measured over the periods indicated in Table I-IX (1971–1972). The milk samples measured were averages over the whole group of cows and over the periods indicated in the table. Also in 1977 milk measurements have been carried out, but those only related to stabled cows. Ra-226 measurements of pasture samples were carried out at 6 specified plots in summer 1971.

The input information to this scenario consists of:

- the site description (chapter I-2.);
- the results of the biological study carried out before the remediation (Section I-3.1);
- the specifications of the deep ploughing:
  - technical files concerning this action are missing. According to the memory of people involved, the ploughing consisted in turning soil layers (about 1 m thick) over 90°, in such a way that horizontal layers or surfaces became vertical ones. After this turning the sole of the plough was passed through the soil in order to obtain a better mixing;
  - in order to have an idea about the efficacy of this action, a measurement of the distribution of the Ra-226 concentration with depth, has been made on 1 point in the remediated zone (during the period 1991-1993). The concentrations in the layers from 25 to 55 cm deep and from 55 to 85 cm deep were respectively 4 and 5.5 times lower than the one in the surface layer from 0 to 25 cm deep.
- the plots where the cows have been grazing: Table I-IX (Figure I-6):
  - when stabled during winter (1971 and 1972), the Ra-226 intake of the cows was estimated to be of the order of 100 Bq/day through ensilage. The intake through additives and water was negligible. Furthermore, it can be assumed that the Ra-226 concentration of plot 6 is low (corresponding with a scale value of 1 (max. 0.4 Bq/g));
  - When on pasture, the grass intake by the cows has been indicated to amount to 10-15 kg DW/d.

TABLE I-IX. PASTURE PLOTS WHERE COWS HAVE BEEN GRAZING (SEE FIGURE I-6 FOR LOCALISATION OF PLOTS)

Period	Pasture plot(s)	Period	Pasture plot(s)
1/5–5/5/71	4	30/12/71–14/1/72	stable
6/5–9/5	5	15/1–31/1	stable
11/5–17/5	1	1/2–15/2	stable
18/5–22/5	2	16/2–28/2	stable
23/5–26/5	3	1/3–15/3	stable
27/5–1/6	4	16/3–31/3	stable
2/6–8/6	5	1/4–17/4	stable + 1 h on plots
9/6–14/6	1	18/4–1/5	4+5
15/6–17/6	2	2/5–20/5	several
18/6–22/6	3	21/5–31/5	4+5
23/6–24/6	4	1/6–15/6*	2
26/6–28/6	5	1/6–15/6*	3
28/6–30/6	6	1/6–15/6*	9
1/7–4/7	2	1/6–15/6*	10
4/7–9/7	3+4	16/6–30/6	5
9/7–12/7	3	1/7–19/7	9+10
12/7–23/7	5+7	20/7–10/8	9+10
23/7–30/7	7+8	10/8–31/8	2+3+4
12/8–27/8	4+5+8	1/9–15/9	6
31/8–9/9	2+8+1	16/9–22/9	1+2+3+4
14/9–4/10	2+3+4+5	30/9–15/10	stable
5/10–28/10	1 to 8	16/10–31/10	stable
31/10–15/11	4	1/11–27/11	stable
16/11–27/11	stable	28/11–6/12	stable
29/11–15/12	stable + 1 h on plots	6/12–31/12	stable
16/12–30/12	stable		

* Group of cows split over several plots.

- the rooting depth of the pasture grass: between 10 and 25 cm, best-estimate: 15 cm [8]
- the natural background of Ra-226 in the Campines soil: 0.01–0.02 Bq/g DW.

The calculation results required are:

- Ra-226 concentrations in root zone soil (corresponding to the root-zone depth of pasture) for each of the ten pasture plots (averaged over each plot) expressed in Bq/g DW
  - before the remediation and
  - after the remediation: over the years 1971 / 1972
- Ra-226 concentrations in pasture grass for each of the ten plots, expressed in Bq/kg DW during summer, of the years 1971 / 1972
- Ra-226 concentrations in cow milk, averaged over the total group and over each of the periods indicated in Table I-IX, expressed in Bq/l.

For each of the concentrations indicated, estimates of the arithmetic mean and the 95% confidence interval (2.5% and 97.5% lower and upper bound estimates) are requested.

A short description of the model applied with equations, and parameter values not indicated in the scenario description, are also required.

I-5. TYPE B SCENARIO DESCRIPTION

Because the inhalation of radon (+ daughter products) in houses is one of the most important pathways, the following impact scenario will be considered:

- a farmer family living on the site, cultivating vegetables in a kitchen garden with contaminated groundwater and keeping dairy and beef cattle on the fields. It is reasonable to assume that the contaminated groundwater is not only used for irrigation, but also as drinking water and that a fraction of the food ingested is obtained from the contaminated site;
- locally produced foodstuffs are: milk, meat, vegetables and potatoes

Two situations will be evaluated:

- the worst situation: a farmer family living on the site, their house is built on the most contaminated piece of land and the well nearby receives ground water coming from the most contaminated area;
- the current situation: a farmer family living on the site, their house is built on the less contaminated piece of the land and the well nearby receives ground water coming from the less contaminated area.

Exposure pathways are:

- inhalation of resuspended particles indoors and outdoors;
- inhalation of exhaled radon indoors and outdoors;
- ingestion of leafy vegetables, potatoes, milk, drinking water, soil and meat;
- external irradiation indoors and outdoors.

I-5.1. Remedial actions

There are several restoration techniques available, like removal of sources, separation of contaminated from uncontaminated material, containment, immobilisation, etc. The selection of the most appropriate remedial action is based on radiological, economical and social factors. In this study the radiological impact is the primary criterion.

The following remedial options will be evaluated, whereby we assume that the farms are built after the remedial option is carried out:

- no action;
- removal of the most contaminated areas (depth of 1 m), whereby the removed soil is replaced by less contaminated soil in the near vicinity. It is assumed that the less contaminated soil contains 0.06 Bq Ra/g;
- covering with a clean soil layer, which contains 0.02 Bq Ra/g (background level).

Immobilisation, used to reduce the mobility of Ra-226 and its uptake by plants is not a suitable technique because it does not limit the radon exhalation from the soil, one of the main exposure pathways.

I-5.1.1. Remedial action 1: Removal of the most contaminated soil

- **Option 1a: removal of sources (bulk removal)**

It was suggested that for the most contaminated areas between the Roerdompstraat and the Kleine Nete, indicated by the numbers 3 to 6 in Figure I-10, the soil should be removed over a depth of 1 m. This means that about 100 000 m^3 soil has to be dumped elsewhere. However, since the existing dumping site is not large enough, a new dumping site needs to be created, involving a lot of costs (labour, material, surveillance) and leading to other exposure scenarios.

In the period 1991-1995, a new detailed radiological survey was carried out, focusing on the most contaminated parts in the village St. Jozef Olen and environment. Also measurements along the Bankloop, between the Roerdompstraat and the Kleine Nete have been carried out. These measurements give a better idea of the current situation and will be used as input data in the modelling assessments of scenario B. The measured dose rate, given in Tables I-XIV, I-XV and I-XVI, will be used as criterion to decide where soil have to be removed. As a minimum dose rate for soil removal, 200 nSv/h (3 times the background dose rate) is taken ; contaminated areas with a dose rate > 200 nSv/h would have to be removed over 1 m depth. Since for a large part of the site considered in this scenario no measurements after deep ploughing are available, a correlation of the recent measurements with the situation before deep ploughing (Figure I-10) was made to estimate the volume of soil that has to be removed. This correlation revealed that roughly the areas indicated by the numbers 4, 5 and 6 have to be removed, which corresponds to approximately 60 000 m^3 soil for the whole site considered in this scenario. The removed soil will partly (only over 0.5 m depth) be replaced by soil of about 0.06 Bq $^{226}Ra/g$, coming from the less contaminated part of the site. Possibly, the removed soil can be dumped on the existing dumping site. However, the volume is still quite large and in order to reduce it, option 1b can be chosen.

- **Option 1b: removal of sources, followed by separation of the contaminated material**

Carrying out a chemical or physical separation can reduce the volume of soil to be disposed of. This will lead to much higher clean-up costs, however these costs may be balanced by lower disposal and surveillance costs for the waste containment system.

If a 50 % removal of radium from the contaminated soil by separation is assumed than only 11 000 m^3 will be higher than the limit value (dose rate > 200 nSv/h) after implementation of the separation technique and has to be brought to the dumping site.

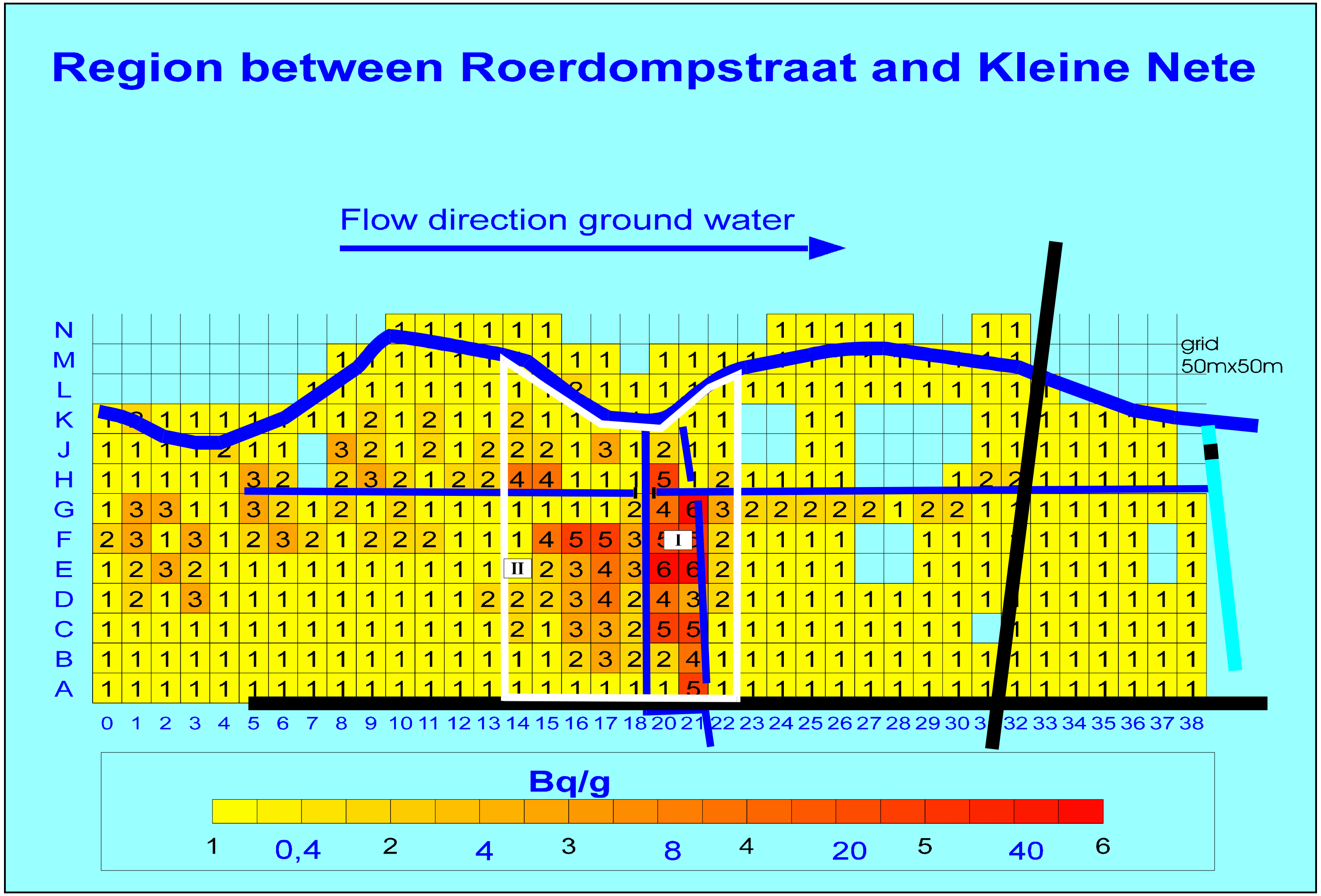


FIG. I-10. Localisation of the site and farms (situation I & II).

The numbers on the figure refer to the radium concentration before deep ploughing.

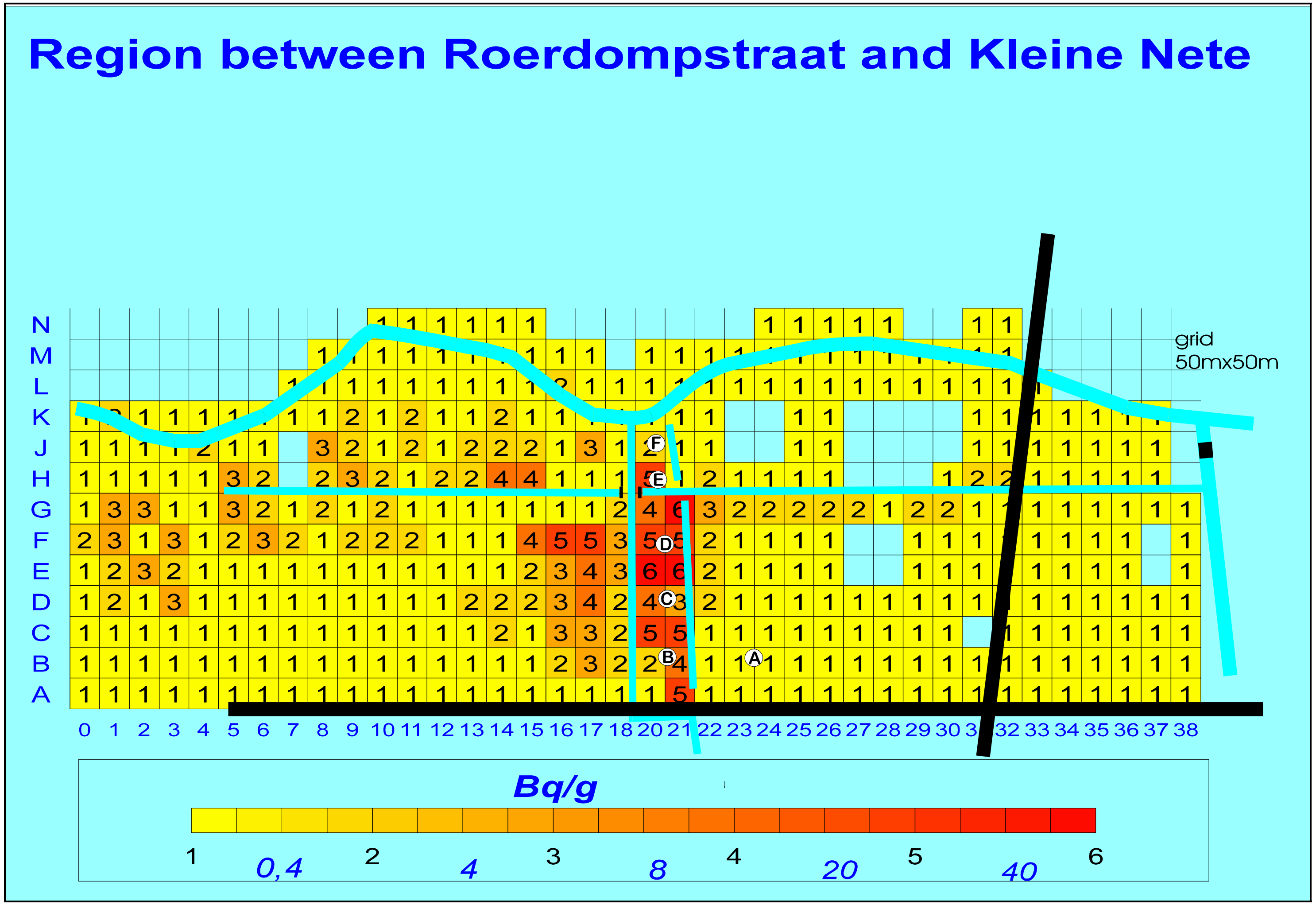


FIG. I-11. Localisation of the soil samples taken on 14th January 1998.

I-5.1.2. Remedial action 2: Covering the whole site with clean soil layer

- **Option 2a: Using one soil type as cover**

In the region, there are several soil types available. Locally, most soils are sandy, peaty sand loamy sand or sandy loam soils, but within 25 km there are also loam and clay soils. To categorise the soils by texture, the following classification is used:

Soil type	% sand (50 µ-2 mm)	% loam (2-50 µ)	% clay (< 2µ)
Sand	83-100	≤ 17	≤ 8
Loamy sand	68 - 91	≤ 32	≤ 17
Sandy loam	15 - 68	15 - 85	≤ 22
Loam	≤ 15	≥ 62	≤ 30
Clay	≤ 83	≤ 70	17 - 45
Heavy clay	≤ 65	≤ 55	≥ 35

As cover, a (heavy) clay soil is preferred because these soils are more efficient in reducing the migration rate of radon than sand or loam soils. However, the soil at the site is a waterlogged, peaty sand soil and to avoid serious drainage problems and also to be able to use the land for agricultural practices, it is not recommendable to use a clay soil.

As cover, a sandy loam soil with an average clay content of 20 % (range: 15–30 %) is chosen. The participants are asked to make calculations for a soil layer of 0.5 m thickness, assuming that the cover will be ploughed over a depth of 30 cm two-yearly, if used as kitchen garden and seven-yearly, if used as pasture.

The reduction factor for the diffusive transport of radon is given by $\exp[-(\lambda_{Rn}/D_e)^{0.5}.L]$ with L the thickness of the layer (m), D_e the effective diffusion coefficient for the soil ($m^2.y^{-1}$) and λ_{Rn} the decay constant of ^{222}Rn (y^{-1}).

No data are available on the effect of a cover on the advection (pressure-driven flow) of radon into buildings, which is mostly a more important entry mechanism for the radon indoors than diffusion.

- **Option 2b: Using a multi-component layer**

Another possibility is to use a multi-component layer, like often is used to cover dumping grounds. The most common multi-component layer is the following:

Top	vegetation/soil layer drainage layer
Bottom	low hydraulic conductivity layer, often a clay layer

The advantage of using such a layer at the Olen site, is that a clay layer can be included without resulting in serious drainage problems. By using a soil layer as top layer , the area may even be suitable for agricultural use. However, the remediation costs will be (much) higher than for option 2a.

Interested participants are asked to choose the materials of the multi-component layer, the sequence and thickness of the different layers and to justify their choice.

I-5.2. Assessment tasks

Only options 1a and 2a of remedial actions 1 and 2 will be considered. Interested participants however can also make calculations or give comments for options 1b and 2b of the remedial actions.

Participants are asked to take the contribution of ^{210}Pb, the long-lived daughter nuclide of ^{226}Ra into account and give the endpoints separately for Ra and Pb, assuming that ^{210}Pb is in equilibrium with ^{226}Ra at year 1.

The endpoints of the calculations for this scenario are the individual doses to an adult farmer, living in situation I (see section I-6.1), after 1, 50, 100, 200 and, if possible 500 years (peak doses, i.e. doses at the time of the maximum may also be given, but are optional) due to:

- external irradiation indoors and outdoors;
- inhalation of resuspended particles indoors and outdoors;
- inhalation of emanated radon indoors and outdoors;
- ingestion of soil;
- ingestion of drinking water obtained from contaminated groundwater (well);
- ingestion of leafy vegetables, potatoes grown on the contaminated soil (contribution through root uptake) and irrigated by contaminated groundwater (contribution through foliar uptake);
- ingestion of milk, meat (contribution through grass, water and soil intake by the cattle).

The concentrations of ^{226}Ra in soil, on which the dose assessments should be based, are those given in I-6.2.4._(Table I-XVIII). The deterministic values for the radium transfer factors soil-to-grass and grass-to-milk are indicated in par. I-6.2.2.2.. Deterministic values for other transfer factors in the food chain are given in section I-6.3.4. Other input information for the deterministic calculations is mainly found in section I-6.3.

The deterministic calculations of doses and concentrations are to be carried out for the following three options:

- no remediation;
- removal of most contaminated soil;
- covering with a clean soil layer of 0.5 m.

In this way, the effectiveness of the remedial actions in terms of dose savings and contamination reductions can be evaluated.

In order to be able to analyse the results for the deterministic calculations, the participants are also asked to give the concentrations in different biosphere compartments, such as:

- concentration of radium and lead in soil (in the upper 1 m layer) for pasture, kitchen-garden (irrigated) and farm;
- concentration of radium and lead in dust (in- and outdoors), grass, leafy vegetables, potatoes, drinking water, milk and meat;
- concentration of radon in air (in- and outdoors);

after 1, 50, 100, 200 and, if possible 500 years for the option without remediation.

For the two other options, only concentrations in soil and in water are asked for.

For the stochastic calculations, participants are asked to calculate the arithmetic mean and the 95% confidence interval (2.5% and 97.5% percentiles) of the individual doses and this for the following two options:

- no remediation;
- covering with a clean soil layer of 0.5 m.

The same exposure pathways are to be considered as for the deterministic calculations, with the exception of dust inhalation and soil ingestion, which are optional. The same applies to peak doses. Uncertainty ranges for input parameters are given in section I-6.4. (Tables I-XXV and I-XXVI).

Participants are also asked to perform a sensitivity analysis in order to identify and rank the input parameters, which have a significant effect on the dose results.

Formulas to fill in information about the model used, deterministic and stochastic modelling results are available. Participants are asked to give a description of their model including a schematic view of the model structure, all assumptions made outside or contrary to the scenario description, method of uncertainty analysis and the dominant contributors to the uncertainty.

I-6. ADDITIONAL INPUT INFORMATION FOR OLEN SCENARIO TYPE B

I-6.1. Assumptions concerning impact scenario

The situation after deep ploughing (1970) will be taken as starting point for the modelling tasks.

I-6.1.1. Farm location

As mentioned in Section I-5, two situations may be considered (only the first situation will be evaluated):

- **Situation I:** farmer family living on the area between the Old and New Bankloop (see Figure I-10).
  The location of the farms (given in Figure I-10) are determined on the basis of the dose rates measured during the period 1991–1995, not on the basis of radium concentrations indicated on Figure I-11 since this figure refers to the situation before deep ploughing.
  dose rate = 1 μSv/h (range: 0.5 - 2 μSv/h) (see Figure I-17).
- **Situation II:** farmer family living along the Roerdompstraat (~ current situation, see Figure I-10)
  dose rate = 150 nSv/h (range: 100 - 200 nSv/h)

In case of a remediation, we assume that the farm will be built after the remedial action is carried out. Furthermore, it is assumed that the ground water flows from west to east (present situation) and that the well, located near the house, takes water from the Kasterlee aquifer.

I-6.1.2. Site for agricultural purposes and exposure pathways

In case of a remediation, the action would mainly be focused on the vicinity of the Bankloop. Therefore to assess the effect of the remedial action on doses, the site considered for this scenario will be limited to a few hundred metres on each side of the Bankloop (New Bankloop) and is marked by the white border in Figure I-10. This is the area flooded frequently in the sixties.

Calculations have to be made, assuming that a small part near the house is used as kitchen garden for the cultivation of potatoes and leafy vegetables. The soil of the kitchen garden has initially the same radium concentration as the soil on which the house is built, but will afterwards be irrigated with contaminated groundwater. The remaining part of the site is used as pasture, leading to doses via ingestion of milk and meat. The pasture will not be irrigated with groundwater.

I-6.2. Site-specific information

I-6.2.1. Soil and aquifer characteristics

- **Soil:** soil density: 320 kg/m^3 before deep ploughing. Sand was added to amend the soil, leading to a soil density of 800 kg/m^3 (range 320–1300 kg/m^3) after deep ploughing.
  porosity: 0.5 (before deep ploughing)
  permeability soil: 1.7E-04 m/s (before deep ploughing)
  recent values of the water content are given in Table I-XVIII

- **Aquifer:** height: 1 m
  Darcy velocity: 3.5 m/y
  depth water table: about 1 metre beneath ground level

I-6.2.2. Radiological measurements (1961–1972)

I-6.2.2.1. Measurements of ^{226}Ra in pasture, in ensilage and uptake by cows during stabling period

TABLE I-X. RADIUM CONCENTRATION IN PASTURE (1970) AND IN ENSILAGE (1971) AFTER DEEP PLOUGHING

	Plot number[a]	Date	[Ra] (Bq/kg dw)
Pasture	1	July 1971	4.16
	2	July 1971	7.78
	3	July 1971	5.93
	4	July 1971	5.41
	5	July 1971	3.53
	6	July 1971	66.4
	unknown	August 1970	118
	unknown	August 1970	55.3
	unknown	August 1970	76.4
Ensilage	unknown	January 1971	35.7
	unknown	February 1971	10.2
	unknown	February 1971	27.5
	unknown	April 1971	17.4
	unknown	December 1971	13.2

[a] for location of plots see Figure I-6.

TABLE I-XI. RADIUM CONCENTRATION IN MILK AFTER DEEP PLOUGHING (MAY 1971–DECEMBER 1972)

Period	Pasture plot(s)	[Ra] (mBq/l)
1/5–5/5/71	4	31.8
6/5–9/5	5	15.9
11/5–17/5	1	11.1
18/5–22/5	2	27.8
23/5–26/5	3	35.9
27/5–1/6	4	24.4
2/6–8/6	5	24.4
9/6–14/6	1	28.8
15/6–17/6	2	31.1
18/6–22/6	3	/
23/6–24/6	4	22.2
26/6–28/6	5	17.8
28/6–30/6	6	34.0
1/7–4/7	2	23.3
4/7–9/7	3+4	29.2
9/7–12/7	3	18.5
12/7–23/7	5+7	28.1
23/7–30/7	7+8	24.0
12/8–27/8	4+5+8	25.2
31/8–9/9	1+2+8	19.6
14/9–4/10	2+3+4+5	25.2
5/10–28/10	1 to 8	19.6
31/10–15/11	4	30.3
16/11–27/11	stable	54.9
29/11–15/12	stable + 1 h on plots	18.9
16/12–30/12	stable	29.6
30/12/71–14/1/72	stable	27.8
15/1–31/1	stable	24.0
1/2–15/2	stable	29.2
16/2–28/2	stable	16.6
1/3–15/3	stable	13.7
16/3–31/3	stable	23.7
1/4–17/4	stable + 1 h on plots	10.7
18/7–1/5	4+5	10.7
2/5–20/5	several	33.3
21/5–31/5	4+5	15.9
1/6–15/6[a]	2	18.5
1/6–15/6[a]	3	21.1
1/6–15/6[a]	9	20.4
1/6–15/6[a]	10	15.5
16/6–30/6	5	15.9
1/7–19/7	9+10	19.6
20/7–10/8	9+10	15.2
10/8–31/8	2+3+4	26.3
1/9–15/9	6	18.1
16/9–22/9	1+2+3+4	27.0
30/9–15/10	stable	23.3
16/10–31/10	stable	18.1
1/11–27/11	stable	18.5
28/11–6/12	stable	14.1
6/12–31/12/72	stable	7.4

[a] Group of cows split over several plots.

TABLE I-XII. MEASUREMENTS OF RADIUM INGESTED BY COWS DURING STABLING PERIOD

Feeding stuff	Uptake (Kg/day/cow)	[Ra] (Bq/kg)	[Ra] ingested (Bq/day/cow)
Ensilage (pasture)	9–10	10.1	90.6–100.6
Pulp	1	0.84	0.84
Cattle cake	5–6	1.18	5.9–6.4
			sum = 97.3–107.8

I-6.2.2.2. Transfer coefficients for ^{226}Ra from water to milk, hay to milk

TABLE I-XIII. TRANSFER COEFFICIENTS (d/l) WATER-MILK, HAY-MILK

	Days[a]	F_m water-milk		F_m hay-milk[b]
Cow 1	7	1.0E-04	Cow 3	5.3E-04
	14	9.0E-05	Cow 4	6.4E-04
	21	9.0E-05	Cow 5	4.1E-04
	26	1.1E-04	Cow 6	7.0E-04
Cow 2	7	2.2E-04		
	14	2.1E-04		
	21	1.9E-04		
	26	1.7E-04		

[a] Number of days that contaminated feed was given.

[b] Mean of transfer coefficients measured from the 8th to the 13th day that contaminated feed was given.

Soil-to-grass concentration factor; 0.083, 0.05 dw/dw (from Table I-VII).

Grass-to-milk transfer factor; 1.1E-04, 1.5E-04, 2.6E-04, 3.4E-04 d/l by intake of 12.5 kg grass/day (from Table I-VII).

I-6.2.3. Results of the radiological assessment study (1991–1995)

(Only the results concerning the site considered from Roerdompstraat to Kleine Nete are always indicated.)

I-6.2.3.1. Dose rate measurements (from foot survey)

(1) At the New Bankloop

Measuring points at the middle of the river (0 m) and at 1.5 m, 2 m and every 2 m up to 10 m distance on both banks from the middle. A plastic scintillator (range: 0.06–1000 µSv/h) was used.

TABLE I-XIV. DOSE RATES ALONG ROERDOMPSTRAAT, FIGURE I-12

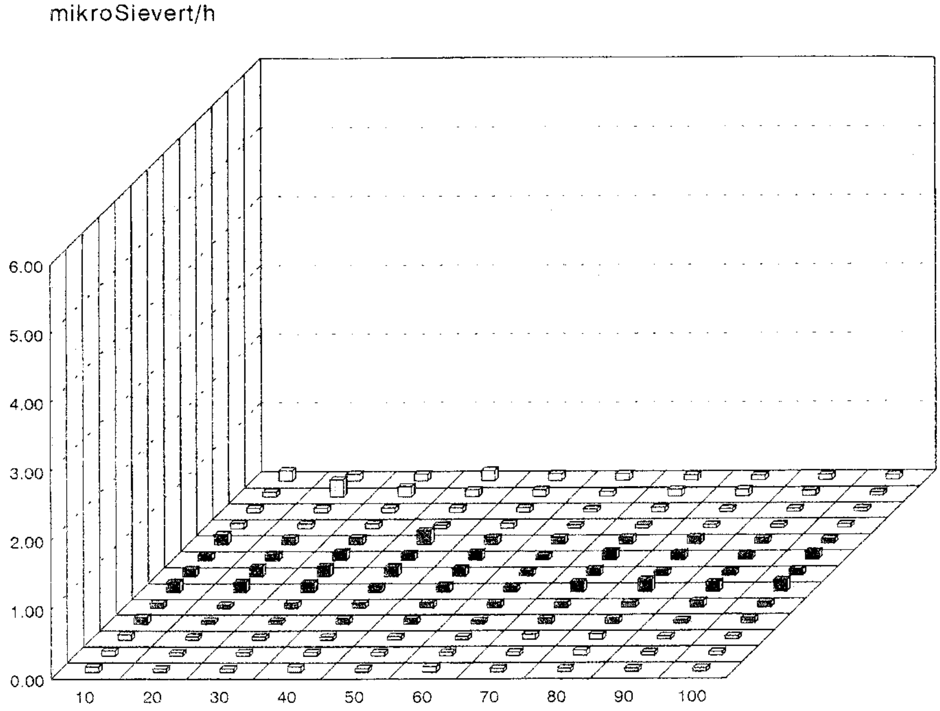
Number of nodal points	Number ≤ 200 nSv/h	Number 200–400 nSv/h	Number 400–800 nSv/h	Number > 800 nSv/h	Number > 200 nSv/h	Mean nSv/h	Max. nSv/h
130	129	1	0	0	1	85	250

TABLE I-XV. DOSE RATES BETWEEN ROERDOMPSTRAAT AND KLEINE NETE, FIGURES I-13 TO I-I-15

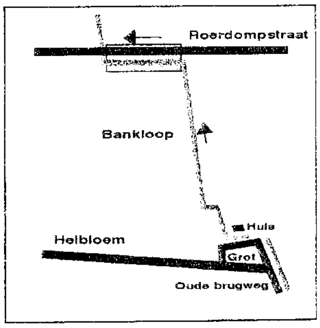
Number of nodal points	Number ≤ 200 nSv/h	Number 200–400 nSv/h	Number 400–800 nSv/h	Number > 800 nSv/h	Number > 200 nSv/h	Mean nSv/h	Max. nSv/h
208	129	76	3	0	79	190	500
192	116	73	3	0	76	190	600
156	153	3	0	0	3	110	400

Stralingsmetingen Olen

Bankloop



-10 m	0.15	0.10	0.10	0.15	0.10	0.10	0.08	0.07	0.08	0.07
-8 m	0.07	0.25	0.15	0.10	0.10	0.07	0.10	0.10	0.08	0.05
-6 m	0.07	0.07	0.07	0.07	0.07	0.05	0.07	0.05	0.05	0.05
-4 m	0.08	0.07	0.07	0.05	0.07	0.05	0.05	0.05	0.05	0.05
-2 m	0.15	0.10	0.10	0.20	0.10	0.10	0.10	0.10	0.08	0.07
-1.5 m	0.09	0.09	0.13	0.10	0.12	0.07	0.13	0.10	0.08	0.11
0	0.10	0.14	0.15	0.14	0.12	0.08	0.10	0.07	0.07	0.09
+1.5 m	0.15	0.15	0.14	0.09	0.10	0.08	0.15	0.18	0.14	0.17
+2 m	0.08	0.05	0.08	0.08	0.08	0.08	0.08	0.08	0.10	0.08
+4 m	0.10	0.05	0.05	0.08	0.08	0.05	0.08	0.08	0.05	0.08
+6 m	0.08	0.05	0.05	0.05	0.05	0.05	0.08	0.08	0.05	0.05
+8 m	0.08	0.05	0.05	0.05	0.05	0.05	0.05	0.08	0.05	0.05
+10 m	0.08	0.05	0.05	0.08	0.05	0.08	0.05	0.05	0.05	0.05

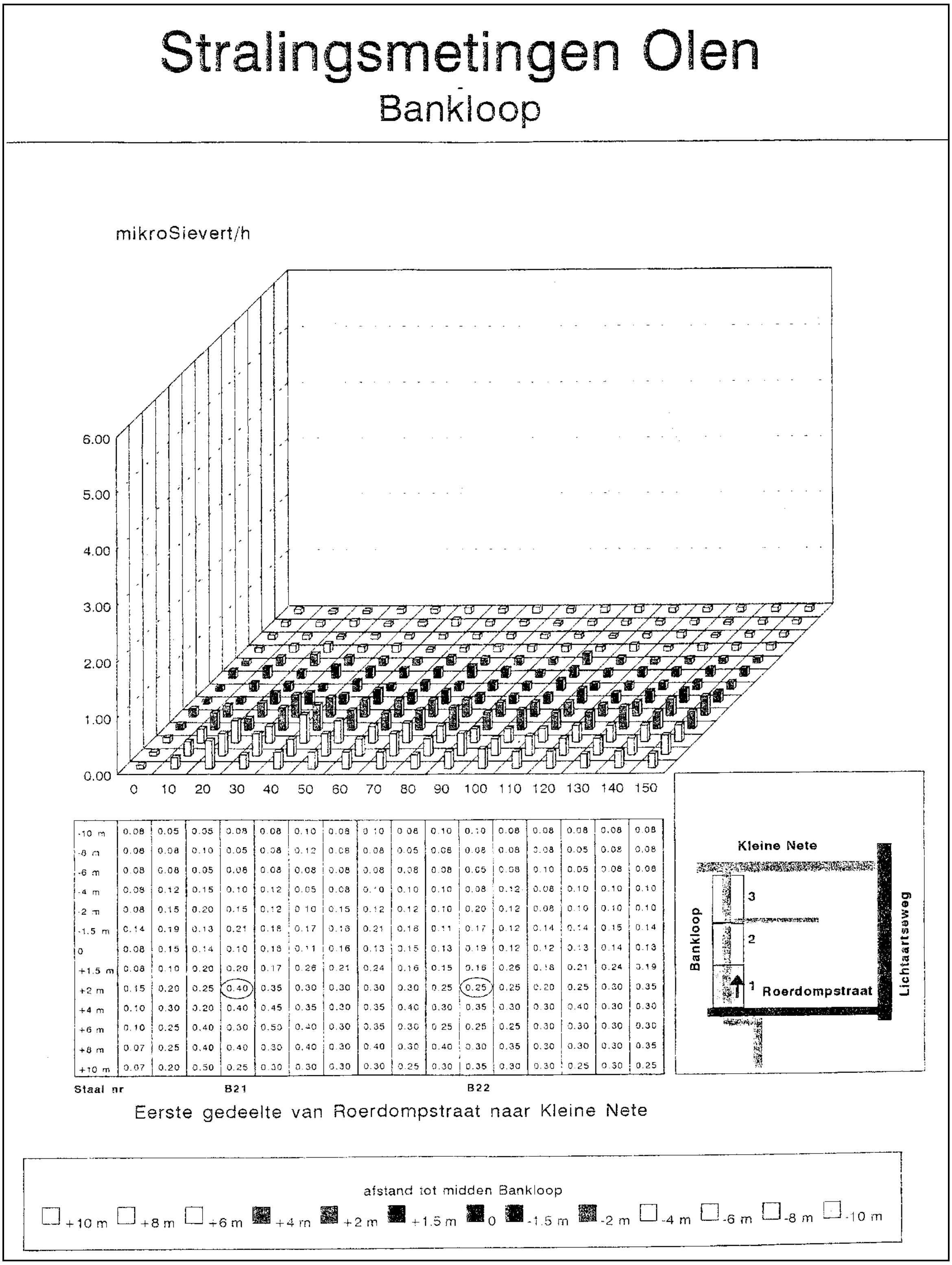


Gedeelte langs de Roerdompstraat

afstand tot midden Bankloop

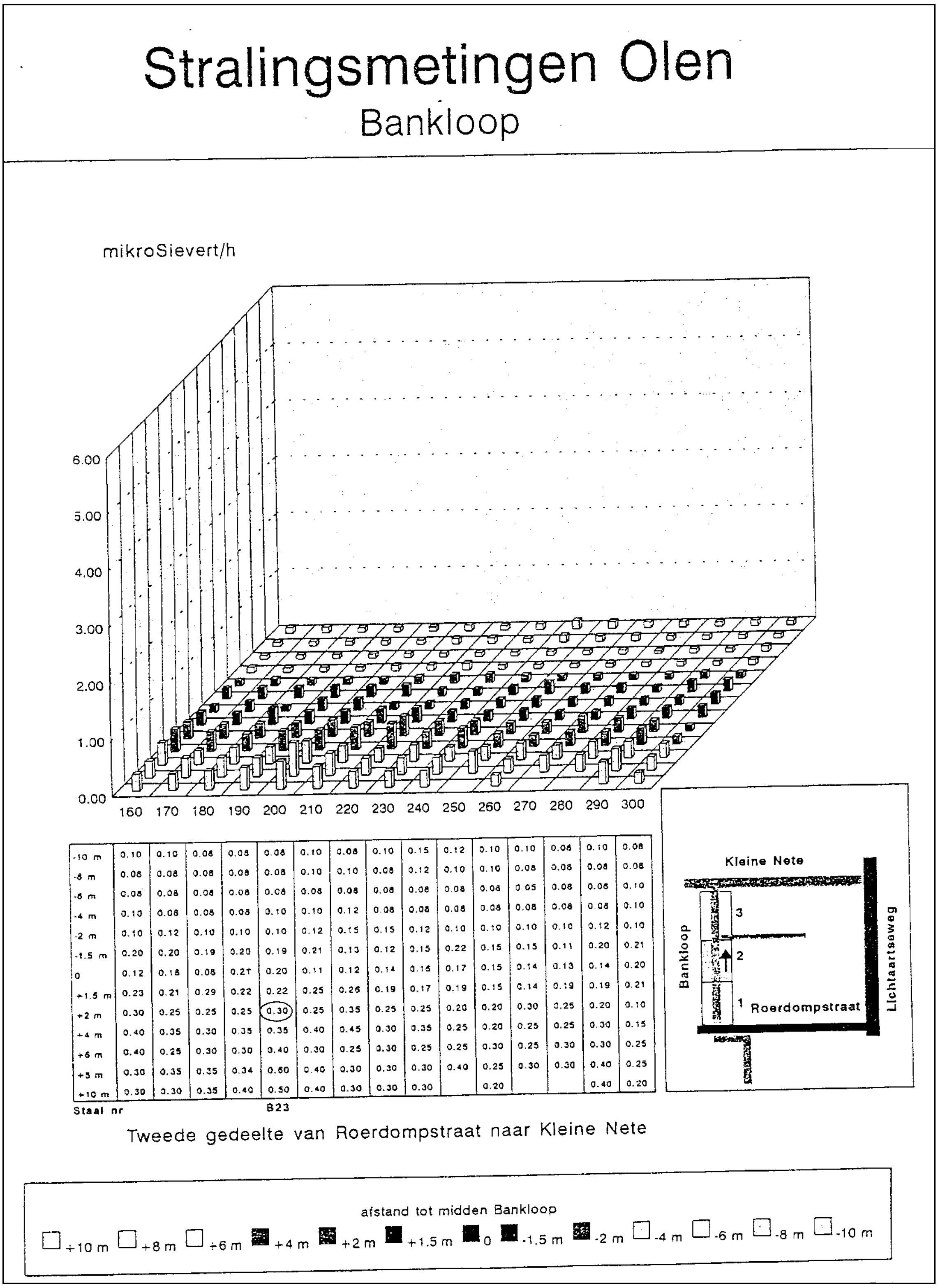
☐ +10 m ☐ +8 m ☐ +6 m ▨ +4 m ▨ +2 m ■ +1.5 m ■ 0 ■ -1.5 m ▨ -2 m ☐ -4 m ☐ -6 m ☐ -8 m ☐ -10 m

FIG. I-12. Dose rate (μSv/h) along the Roerdompstraat.



-10 m	0.08	0.05	0.05	0.08	0.08	0.10	0.08	0.10	0.08	0.10	0.10	0.08	0.08	0.08	0.08	0.08
-8 m	0.08	0.08	0.10	0.05	0.08	0.12	0.08	0.08	0.05	0.08	0.08	0.08	0.08	0.05	0.08	0.08
-6 m	0.08	0.08	0.05	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.05	0.08	0.10	0.05	0.08	0.08
-4 m	0.08	0.12	0.15	0.10	0.12	0.05	0.08	0.10	0.10	0.10	0.08	0.12	0.08	0.10	0.10	0.10
-2 m	0.08	0.15	0.20	0.15	0.12	0.10	0.15	0.12	0.12	0.10	0.20	0.12	0.08	0.10	0.10	0.10
-1.5 m	0.14	0.19	0.13	0.21	0.18	0.17	0.16	0.21	0.16	0.11	0.17	0.12	0.14	0.14	0.15	0.14
0	0.08	0.15	0.14	0.10	0.18	0.11	0.16	0.13	0.15	0.13	0.19	0.12	0.12	0.13	0.14	0.13
+1.5 m	0.08	0.10	0.20	0.20	0.17	0.26	0.21	0.24	0.16	0.15	0.16	0.26	0.18	0.21	0.24	0.19
+2 m	0.15	0.20	0.25	0.40	0.35	0.30	0.30	0.30	0.30	0.25	0.25	0.25	0.20	0.25	0.30	0.35
+4 m	0.10	0.30	0.20	0.40	0.45	0.35	0.30	0.35	0.40	0.30	0.35	0.30	0.30	0.40	0.30	0.30
+6 m	0.10	0.25	0.40	0.30	0.50	0.40	0.30	0.35	0.30	0.25	0.25	0.25	0.30	0.30	0.30	0.30
+8 m	0.07	0.25	0.40	0.40	0.30	0.40	0.30	0.40	0.30	0.40	0.30	0.35	0.30	0.30	0.30	0.35
+10 m	0.07	0.20	0.50	0.25	0.30	0.30	0.30	0.30	0.25	0.30	0.35	0.30	0.30	0.25	0.30	0.25
Staal nr				**B21**							**B22**					

FIG. I-13. Dose rate (μSv/h) along the first part of the Bankloop between Kleine Nete and Roerdompstraat.

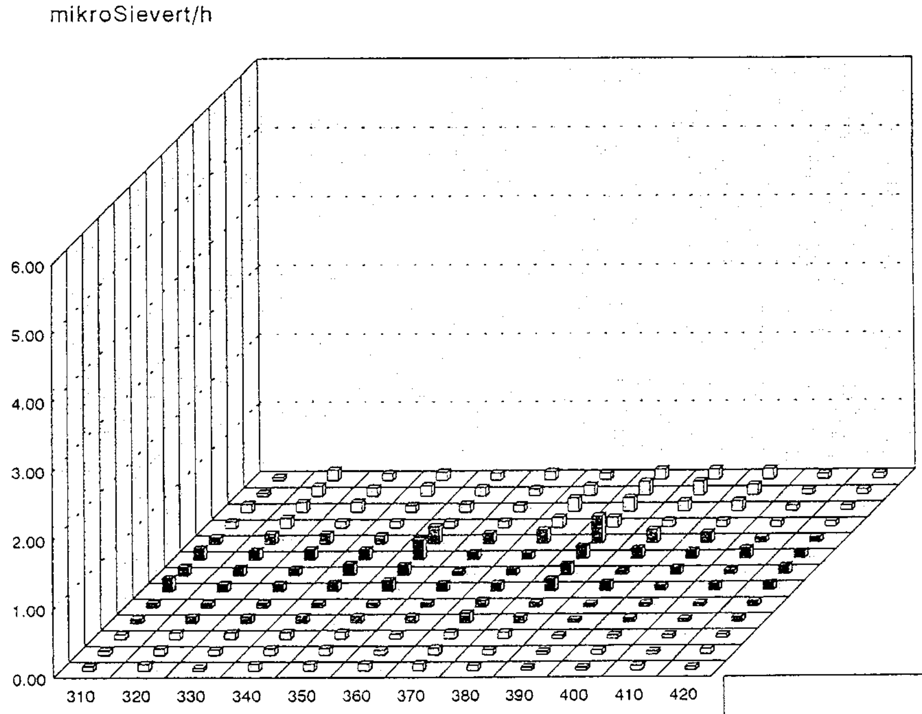


-10 m	0.10	0.10	0.08	0.08	0.08	0.10	0.08	0.10	0.15	0.12	0.10	0.10	0.08	0.10	0.08
-8 m	0.08	0.08	0.08	0.08	0.08	0.10	0.10	0.08	0.12	0.10	0.10	0.08	0.08	0.08	0.08
-6 m	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.05	0.08	0.08	0.10
-4 m	0.10	0.08	0.08	0.08	0.10	0.10	0.12	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.10
-2 m	0.10	0.12	0.10	0.10	0.10	0.12	0.15	0.15	0.12	0.10	0.10	0.10	0.10	0.12	0.10
-1.5 m	0.20	0.20	0.19	0.20	0.19	0.21	0.13	0.12	0.15	0.22	0.15	0.15	0.11	0.20	0.21
0	0.12	0.18	0.08	0.21	0.20	0.11	0.12	0.14	0.16	0.17	0.15	0.14	0.13	0.14	0.20
+1.5 m	0.23	0.21	0.29	0.22	0.22	0.25	0.26	0.19	0.17	0.19	0.15	0.14	0.19	0.19	0.21
+2 m	0.30	0.25	0.25	0.25	0.30	0.25	0.35	0.25	0.25	0.20	0.20	0.30	0.25	0.20	0.10
+4 m	0.40	0.35	0.30	0.35	0.35	0.40	0.45	0.30	0.35	0.25	0.20	0.25	0.25	0.30	0.15
+6 m	0.40	0.25	0.30	0.30	0.40	0.30	0.25	0.30	0.25	0.25	0.30	0.25	0.30	0.30	0.25
+8 m	0.30	0.35	0.35	0.34	0.60	0.40	0.30	0.30	0.30	0.40	0.25	0.30	0.30	0.40	0.25
+10 m	0.30	0.30	0.35	0.40	0.50	0.40	0.30	0.30	0.30		0.20			0.40	0.20
Staal nr					B23										

FIG. I-14. Dose rate (µSv/h) along the second part of the Bankloop between Kleine Nete and Roerdompstraat.

Stralingsmetingen Olen

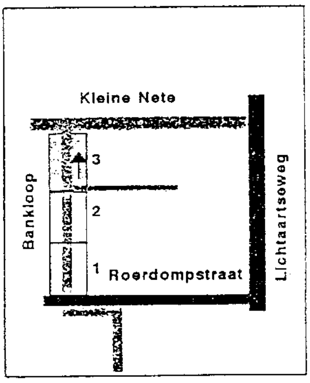
Bankloop



-10 m	0.05	0.15	0.10	0.12	0.10	0.12	0.10	0.15	0.15	0.15	0.08	0.08
-8 m	0.05	0.15	0.12	0.15	0.12	0.10	0.15	0.20	0.20	0.15	0.06	0.08
-6 m	0.12	0.15	0.15	0.10	0.12	0.10	0.20	0.20	0.15	0.15	0.08	0.08
-4 m	0.10	0.15	0.10	0.10	0.10	0.10	0.15	0.15	0.10	0.10	0.08	0.08
-2 m	0.10	0.15	0.15	0.12	0.25	0.15	0.20	0.40	0.20	0.15	0.08	0.08
-1.5 m	0.17	0.14	0.15	0.15	0.29	0.11	0.10	0.19	0.16	0.12	0.15	0.10
0	0.13	0.12	0.10	0.17	0.16	0.06	0.09	0.16	0.08	0.11	0.06	0.13
+1.5 m	0.20	0.11	0.11	0.13	0.16	0.12	0.12	0.17	0.13	0.08	0.10	0.11
+2 m	0.07	0.07	0.07	0.07	0.07	0.07	0.10	0.07	0.05	0.05	0.05	0.06
+4 m	0.07	0.10	0.10	0.10	0.10	0.10	0.15	0.10	0.05	0.07	0.05	0.08
+6 m	0.07	0.10	0.10	0.10	0.10	0.07	0.10	0.10	0.05	0.05	0.05	0.05
+8 m	0.07	0.10	0.08	0.10	0.10	0.07	0.10	0.08	0.05	0.07	0.05	0.08
+10 m	0.07	0.10	0.05	0.10	0.10	0.10	0.10	0.08	0.05	0.05	0.07	0.05

Staal nr B24

Derde gedeelte van Roerdompstraat naar Kleine Nete



afstand tot midden Bankloop

☐ +10 m ☐ +8 m ☐ +6 m ▨ +4 m ▨ +2 m ■ +1.5 m ■ 0 ■ -1.5 m ▨ -2 m ☐ -4 m ☐ -6 m ☐ -8 m ☐ -10 m

FIG. I-15. Dose rate (μSv/h) along the third part of the Bankloop between Kleine Nete and Roerdompstraat.

(2) Pastures on the place of the former bed of the Bankloop

Measuring points in grid with nodal point every 10 m by 10 m

TABLE I-XVI. DOSE RATES OF PASTURES BETWEEN NEW AND OLD BANKLOOP FIGURES I-16 TO I-18

Number of nodal points	Number ≤ 200 nSv/h	Number 200–400 nSv/h	Number 400–800 nSv/h	Number > 800 nSv/h	Number > 200 nSv/h	Mean nSv/h	Max. nSv/h
180	111	57	7	5	69	240	2000
180	35	71	53	21	145	480	5500
192	154	25	7	6	38	180	1500

I-6.2.3.2. Soil sampling and ^{226}Ra measurements

The soil sampling was carried out at certain places where dose rate was measured (section I-6.2.3.1.). Usually, less than 20 cm of the surface soil was sampled. The location of the sampling points is indicated on the Figures I-13 to I-17 by the closest nodal point (surrounded by a circle). Mostly, the circled dose rate is not representative for the sampling place. Most soil samples correspond with a local maximum in the vicinity of the nodal point. There is also only a weak relationship between the measured radium activity and the dose rate at the sampling point, due to:

— the spatial heterogeneity of the radium contamination in the surface layer

— the contribution of the subsurface layer to the dose rate

Consequently, the same dose rate measured at different places may correspond with widely divergent radium activities in the soil samples.

(1) At the New Bankloop

— along Roerdompstraat: no sampling

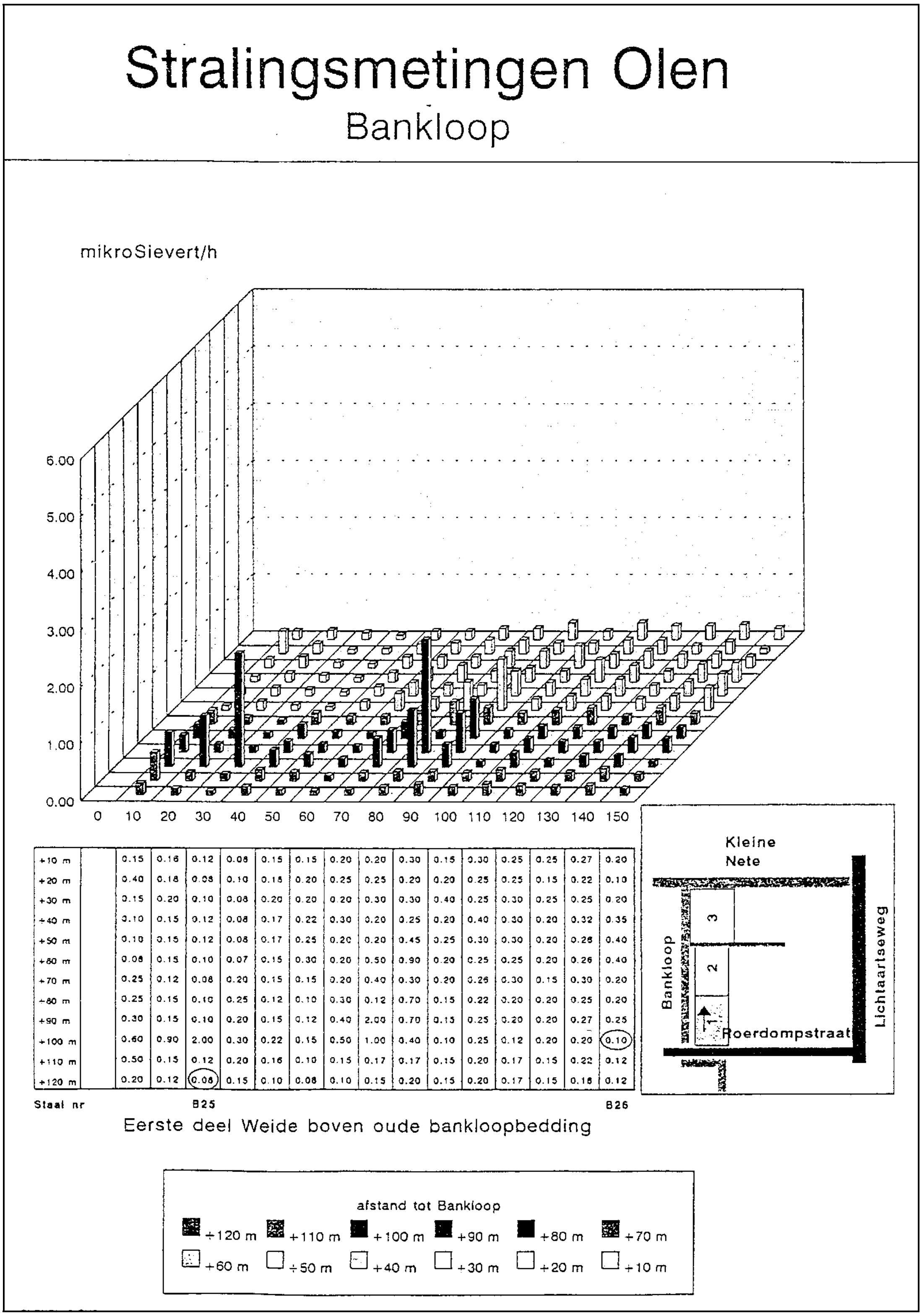
— between Roerdompstraat and Kleine Nete

— results: Figure I-13: B21: 2.5 Bq/g dw ^{226}Ra for 0.2 μSv/h at sampling point
B22: 0.87 Bq/g dw ^{226}Ra for 0.3 μSv/h at sampling point
Figure I-14: B23: 4.4 Bq/g dw ^{226}Ra for 0.3 μSv/h at sampling point
Figure I-15: B24: 1.3 Bq/g dw ^{226}Ra for 0.3 μSv/h at sampling point

(2) Pastures on the former bed of the Bankloop

— results: Figure I-16: B25: 11 Bq/g dw ^{226}Ra for 2 μSv/h at sampling point
B26: 6.3 Bq/g dw ^{226}Ra for 2 μSv/h at sampling point
Figure I-17: B27: 1.5 Bq/g dw ^{226}Ra for 0.5 μSv/h at sampling point
Figure I-18: B28: 1.1 Bq/g dw ^{226}Ra for 0.2 μSv/h at sampling point
B29: 2.2 Bq/g dw ^{226}Ra for 0.2 μSv/h at sampling point
depth profile at B29: 0–25 cm: 2.2 Bq/g dw ^{226}Ra
25–55 cm: 0.57 Bq/g dw ^{226}Ra
55–85 cm: 0.4 Bq/g dw ^{226}Ra

The natural radium concentration in the region varies between 13 and 43 Bq/kg.



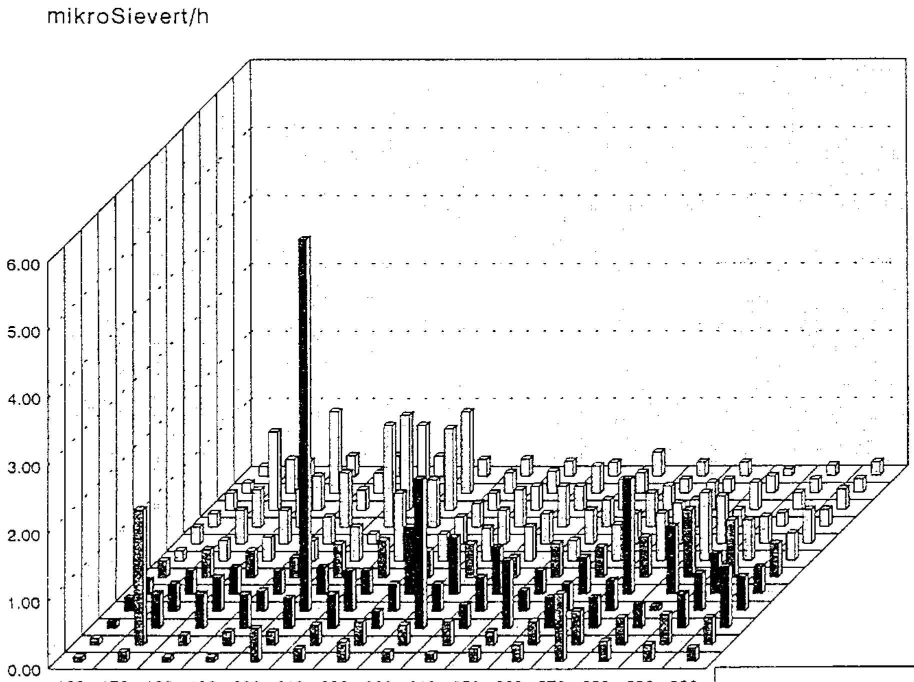
+10 m		0.15	0.16	0.12	0.08	0.15	0.15	0.20	0.20	0.30	0.15	0.30	0.25	0.25	0.27	0.20
+20 m		0.40	0.18	0.08	0.10	0.18	0.20	0.25	0.25	0.20	0.20	0.25	0.25	0.15	0.22	0.10
+30 m		0.15	0.20	0.10	0.08	0.20	0.20	0.20	0.30	0.30	0.40	0.25	0.30	0.25	0.25	0.20
+40 m		0.10	0.15	0.12	0.08	0.17	0.22	0.30	0.20	0.25	0.20	0.40	0.30	0.20	0.32	0.35
+50 m		0.10	0.15	0.12	0.08	0.17	0.25	0.20	0.20	0.45	0.25	0.30	0.30	0.20	0.28	0.40
+60 m		0.08	0.15	0.10	0.07	0.15	0.30	0.20	0.50	0.90	0.20	0.25	0.25	0.20	0.26	0.40
+70 m		0.25	0.12	0.08	0.20	0.15	0.15	0.20	0.40	0.30	0.20	0.26	0.30	0.15	0.30	0.20
+80 m		0.25	0.15	0.10	0.25	0.12	0.10	0.30	0.12	0.70	0.15	0.22	0.20	0.20	0.25	0.20
+90 m		0.30	0.15	0.10	0.20	0.15	0.12	0.40	2.00	0.70	0.15	0.25	0.20	0.20	0.27	0.25
+100 m		0.60	0.90	2.00	0.30	0.22	0.15	0.50	1.00	0.40	0.10	0.25	0.12	0.20	0.20	0.10
+110 m		0.50	0.15	0.12	0.20	0.16	0.10	0.15	0.17	0.17	0.15	0.20	0.17	0.15	0.22	0.12
+120 m		0.20	0.12	0.08	0.15	0.10	0.08	0.10	0.15	0.20	0.15	0.20	0.17	0.15	0.18	0.12
Staal nr				B25												B26

Eerste deel Weide boven oude bankloopbedding

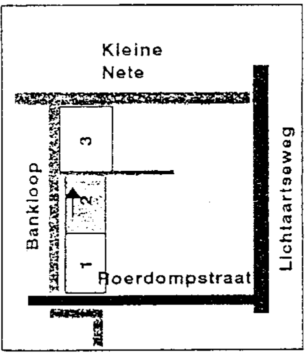
FIG. I-16. Dose rate (μSv/h) of the first part of the pasture between Kleine Nete and Roerdompstraat.

Stralingsmetingen Olen

Bankloop



	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300
+10 m	0.15	0.22	0.30	0.30	0.30	0.25	0.25	0.22	0.20	0.35	0.20	0.20	0.10	0.15	0.20
+20 m	0.15	0.50	1.20	0.30	1.00	1.20	0.30	0.32	0.40	0.30	0.20	0.20	0.25	0.20	0.20
+30 m	0.25	1.15	0.50	0.30	1.40	1.20	0.25	0.35	0.35	0.45	0.35	0.40	0.40	0.25	0.30
+40 m	0.20	0.55	0.55	0.80	1.50	0.70	0.35	0.55	0.60	0.40	0.50	0.40	0.25	0.20	0.25
+50 m	0.25	0.50	0.50	0.40	0.15	0.15	0.40	0.50	0.45	0.50	0.45	0.60	0.70	0.40	0.50
+60 m	0.15	0.30	0.35	0.30	0.50	1.00	0.40	0.48	0.50	0.30	0.53	0.70	1.00	0.60	0.40
+70 m	0.25	0.42	0.40	0.30	0.50	0.55	0.40	0.50	0.30	0.50	0.45	0.60	1.00	0.65	0.50
+80 m	0.20	0.35	0.40	0.35	0.40	0.35	1.00	0.85	0.70	0.35	0.55	1.70	1.00	0.60	0.40
+90 m	0.20	0.40	0.50	0.30	5.50	0.60	0.40	0.40	0.50	0.30	0.40	0.45	0.07	0.55	0.50
+100 m	0.10	0.50	0.50	0.50	0.45	0.50	0.25	2.20	0.35	1.00	0.45	0.45	0.35	0.50	0.90
+110 m	0.10	2.00	0.15	0.20	0.20	0.30	0.35	0.30	0.35	0.20	0.35	0.50	0.40	0.45	0.40
+120 m	0.07	0.15	0.07	0.07	0.50	0.20	0.30	0.15	0.12	0.20	0.25	1.00	0.30	0.25	0.20
Staal nr															B27



Tweede deel Weide boven oude bankloopbedding

afstand tot Bankloop

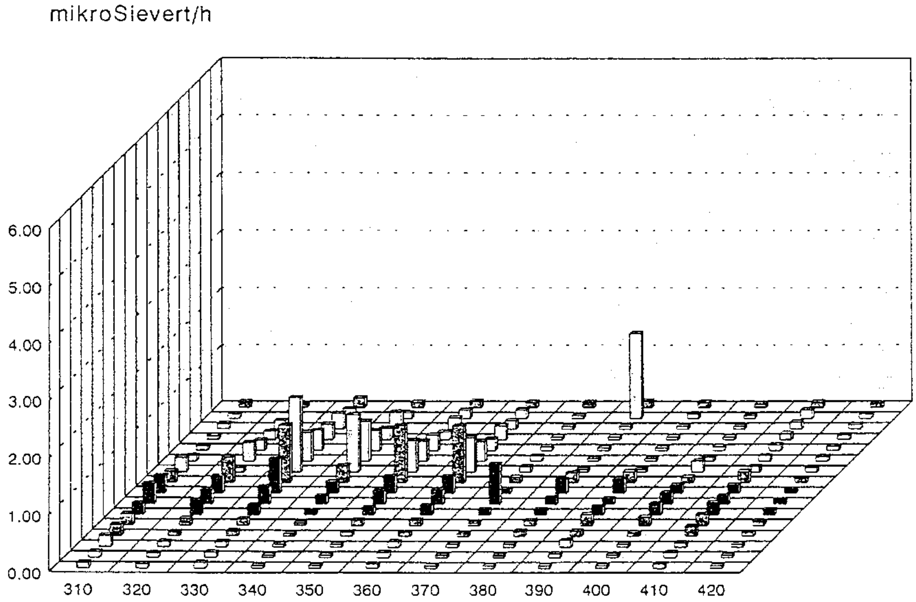
▨ +120 m ▨ +110 m ■ +100 m ■ +90 m ■ +80 m ▨ +70 m

☐ +60 m ☐ +50 m ☐ +40 m ☐ +30 m ☐ +20 m ☐ +10 m

FIG. I-17. Dose rate (µSv/h) of the second part of the pasture between Kleine Nete and Roerdompstraat.

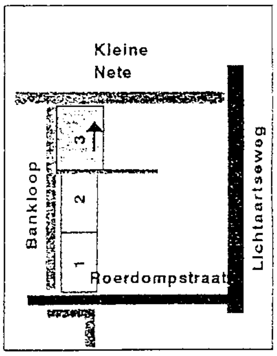
Stralingsmetingen Olen

Bankloop



	310	320	330	340	350	360	370	380	390	400	410	420
+0 m	0.10	0.05	0.17	0.10	0.12	0.10	0.10	0.12	0.10	0.07	0.10	0.08
+10 m	0.08	0.10	0.17	0.10	0.15	0.15	0.05	1.50	0.08	0.05	0.15	0.08
+20 m	0.10	0.15	0.27	0.30	0.20	0.15	0.05	0.05	0.05	0.05	0.12	0.08
+30 m	0.07	0.15	0.27	0.20	0.14	0.25	0.05	0.05	0.05	0.05	0.11	0.08
+40 m	0.08	0.18	0.35	0.35	0.27	0.20	0.07	0.05	0.05	0.07	0.10	0.08
+50 m	0.10	0.32	0.50	0.70	0.35	0.35	0.10	0.05	0.05	0.08	0.10	0.08
+60 m	0.25	0.08	1.30	1.00	0.55	0.60	0.10	0.05	0.05	0.20	0.10	0.08
+70 m	0.20	0.45	1.00	0.30	1.00	1.00	0.10	0.15	0.20	0.10	0.20	0.08
+80 m	0.30	0.30	0.60	0.20	0.30	0.30	0.08	0.25	0.25	0.15	0.15	0.08
+90 m	0.35	0.25	0.30	0.15	0.23	0.25	0.70	0.12	0.10	0.20	0.15	0.05
+100 m	0.20	0.25	0.17	0.07	0.13	0.17	0.10	0.10	0.15	0.20	0.22	0.10
+110 m	0.20	0.12	0.12	0.05	0.10	0.10	0.05	0.10	0.20	0.15	0.20	0.08
+120 m	0.20	0.08	0.10	0.05	0.08	0.08	0.05	0.10	0.10	0.07	0.18	0.08
+130 m	0.20	0.10	0.10	0.05	0.05	0.10	0.05	0.05	0.12	0.05	0.08	0.05
+140 m	0.10	0.08	0.10	0.05	0.05	0.10	0.05	0.05	0.08	0.05	0.10	0.05
+150 m	0.10	0.08	0.10	0.05	0.05	0.08	0.05	0.05	0.05	0.05	0.08	0.05
Staal nr	B28 B29,30,31											

Derde deel Weide boven oude bankloopbedding



afstand tot Bankloop

☐ +150 m ☐ +140 m ☐ +130 m ▨ +120 m ▨ +110 m ■ +100 m ■ +90 m ■ +80 m
▨ +70 m ☐ +60 m ☐ +50 m ☐ +40 m ☐ +30 m ☐ +20 m ☐ +10 m ▨ +0 m

FIG. I-18. Dose rate (µSv/h) of the third part of the pasture between Kleine Nete and Roerdompstraat.

I-6.2.3.3. Measurements of ^{226}Ra in aerosols

The measured values varied between 0.09 and 1.7 μBq/m^3 ^{226}Ra corresponding to an annual committed effective dose between 0.002 and 0.03 μSv/a (negligible).

I-6.2.3.4. Water sampling and ^{226}Ra measurements

Samples of surface water and groundwater have only been taken in the vicinity of the dumping grounds. They have shown the radiological influence from the discharges into those waters to be insignificant. The ^{226}Ra concentrations measured amounted to:

- between 16 and 56 mBq/l in surface waters;
- between 2 and 18 mBq/l in groundwaters (dissolved).

I-6.2.3.5. Measurements of ^{226}Ra in the food chain

- **Milk:** In the period 1971–1972 (1 to 2 years after deep ploughing), milk samples of dairy cows, grazing only on contaminated plots were measured. The assessment of the ^{226}Ra concentrations in the milk was the modelling task of the Olen scenario Type A.
  The ^{226}Ra concentrations measured varied between 10.7 and 35.9 mBq/l (stabling period not included).

  In 1991, samples were taken from two farms with a large milk production (2 × 6 samples).
  During 6 weeks, 0.5 litre milk was sampled per day and at the end of each week these samples were mixed so that finally 6 week samples for each farm were obtained.

  The ^{226}Ra concentrations measured varied between:
  7.5 and 8.6 mBq/l for the first farm (mean = 8.4 (std 0.2))
  9.6 and 14.5 mBq/l for the second farm (mean = 12.4 (std 0.9))

  However, as mentioned earlier, only a small fraction of their pastures and fields were located on contaminated terrain.

- **Maize:** samples from the first farm showed ^{226}Ra concentrations between 0.84 and 1.45 Bq/kg dw (samples were mixed samples, only small fraction was obtained from the contaminated area).
  Samples taken from contaminated terrain: 21.3 and 212 Bq/kg dw (for green parts and roots respectively).

- **Eggs:** from most contaminated chicken-run (along Bankloop): 20.6, 22.6 Bq/kg fw
  from less contaminated chicken-run (along Bankloop): 2.0 Bq/kg fw
  from not contaminated chicken-run (village): 0.12 Bq/kg fw

- **Vegetables:** from kitchen-garden located on not-contaminated ground, but irrigated with water from the Bankloop.

  ^{226}Ra concentrations measured:
  leek: 11 Bq/kg dw
  celery: 5.4 Bq/kg dw
  scorzonera: 17 Bq/kg dw (leaves), 4.3 Bq/kg dw (roots).

I-6.2.3.6. Measurements of ^{226}Ra in milk-teeth (children)

Milk-teeth of children collected in a municipal school close to the former radium plant, showed ^{226}Ra concentrations in the range of the values reported by UNSCEAR for ^{226}Ra in bones. The results were not significantly different from milk-teeth collected in other primary schools of the region.

I-6.2.3.7. Measurement of radon exhalation in houses (dwellings)

Radon concentrations have been measured in all dwellings in the village of St. Jozef Olen and some neighbouring sites (number of houses = 846). In 67 dwellings radon concentrations of 150 Bq/m^3 and more have been measured. In the living and kitchen of one of the houses a maximum of 412 Bq/m^3 has been measured, due to the supply of ^{226}Ra contaminated ground.

I-6.2.3.8. Measurement of radon exhalation in the environment

Radon concentrations in outdoor air have only been measured on and nearby dumping grounds. They are all normal except at dumping ground D1 where an average value of 180 Bq/m^3 at a height of 1.5 m has been measured.

I-6.2.3.9. Measurements of ^{226}Ra in bed sediment and banks of the Bankloop

Bed sediment and banks of the Bankloop have only been sampled upstream of the site considered (upstream of the Roerdompstraat). In the 4 locations closest to the site (between canal and Roerdompstraat) the concentrations in the banks ranged from 240 to 7700 Bq/kg for a depth between 0 and 20 cm and from 30 to 150 Bq/kg between 20 and 40 cm. However they may be much higher than the concentrations at the New Bankloop.

I-6.2.4. Soil profile measurements (1998)

Sampling was done at 6 sampling points (Figure I-11). Soil profiles of 1 m were taken and cut in five slices. The ^{226}Ra concentrations in grass and soil are shown in Tables I-XVII and I-XVIII.

TABLE I-XVII. RADIUM CONCENTRATION IN GRASS SAMPLES

Grass sample	[Ra] (Bq/kg dw)
B	105
C	254
D	111
E	89

TABLE I-XVIII. RADIUM CONCENTRATION IN SOIL SAMPLES

Soil sample	Depth (cm)	[Ra] (Bq/kg dw)	% Moisture	[Ra] (Bq/kg fw)
A1	0–15	65	27	47
A2	15–30	23	25	17
A3	30–50	16	18	13
B1	0–15	734	35	474
B2	15–30	1285	38	794
B3	30–50	3549	51	1745
B4	50–75	33	49	17
B5	75–100	17	19	13
C1	0–15	1827	32	1236
C2	15–30	1710	32	1160
C3	30–50	1243	46	665
C4	50–75	35	51	17
C5	75–100	40	76	10
D1	0–15	2356	33	1569
D2	15–30	1399	28	1004
D3	30–50	4069	54	1867
D4	50–75	60	76	14
D5	75–100	26	69	8
E1	0–15	590	29	416
E2	15–30	590	29	419
E3	30–50	11800	73	3127
E4	50–75	25	45	14
E5	75–100	27	48	14
F1	0–15	267	27	194
F2	15–30	141	21	110
F3	30–50	35	23	27
F4	50–75	68	35	44
F5	75–100	3223	69	1001

I-6.3. Other input information (not site-specific)

I-6.3.1. Occupancy times of population group

— **Child of 5 years:** time staying indoors	7000 h/y
time playing outdoors	500 h/y
time spending on a non-contaminated place elsewhere (e.g. school)	1300 h/y
— **Adult:** time staying indoors	7000 h/y
time working on the fields	1500 h/y
time spending nearby the house	300 h/y
— **Type of houses of residents:** brick houses (normal standard)	
foundation house :	3.5 m depth

I-6.3.2. Consumption by cattle

— **Intake rates of cattle:** grass intake on pasture 10–15 kg dw/d
best estimate 12.5 kg dw/d

daily uptake of water by cow (m^3/d)	0.06
fractional uptake of soil by cow (kg dw/kg dw pasture)	0.04

I-6.3.3. Age-dependent distribution of population and consumption rates

TABLE I-XIX. DISTRIBUTION OF POPULATION ACCORDING TO AGE GROUP IN BELGIUM [9]

Distribution (%)	Age (y)
1.18	< 1
1.18	1 - 2
5.98	2 - 7
6.16	7 - 12
6.52	12 - 17
79.0	> 17

TABLE I-XX. CONSUMPTION RATES FOR CRITICAL GROUP (ADULTS) (kg/y)

Milk	131[a]
Cheese	5.8
Meat	54[a]
Poultry	8.2
Fish	5
Vegetables	56[a]
Fruit	56
Potatoes	122[a]
Eggs	18
Flour (wheat)	81
Water	400

[a] milk, meat, vegetables and potatoes are locally produced food stuffs, the values given are derived from the site.

TABLE I-XXI. CONSUMPTION OF FOOD BY CHILD OF FIVE YEARS RELATIVE TO ADULT CONSUMPTION [10,11]

	Consumption ratio
Cereals	0.49
Meat	0.40
Potatoes	0.45
Green vegetables	0.61
Milk products	1.05
Drinking water	0.5

I-6.3.4. Transfer factors for ^{226}Ra, ^{210}Pb

— **Ra:**	distribution coefficient in root zone soil (m^3/kg)		0.5
	soil-plant concentration factor	leafy vegetables (dw/fw)	1E-02
		potatoes (dw/fw)	1.5E-03
	transfer factor beef (d/kg)		5E-04
— **Pb:**	distribution coefficient in root zone soil (m^3/kg)		0.27
	soil-plant concentration factor	leafy vegetables (dw/fw)	1E-02
		potatoes (dw/fw)	1E-03
		grass (dw/dw)	0.05
	grass-to-milk transfer factor (d/l)		1.5E-04
	transfer factor beef (d/kg)		4E-04

I-6.3.5. Exhalation factors

1 Bq ^{226}Ra / g in soil corresponds to
20 Bq ^{222}Rn/m^3 in outdoor air (measured on one of the dumping sites) [12]
330 Bq ^{222}Rn/m^3 indoor (houses) [12]

I-6.3.6. Dose factors for population

The ingestion and inhalation dose factors given in Tables I-XXII and I-XXIII are the dose factors without taking daughter products into account.

TABLE I-XXII. INGESTION DOSE FACTORS IN SV/BQ (COMMITTED EFFECTIVE DOSE PER UNIT INGESTED ACTIVITY) [13, 14]

Radionuclide	Age group	
	2–7 y	> 17 y
^{226}Ra	$6.2\ 10^{-7}$	$2.8\ 10^{-7}$
^{210}Pb	$2.2\ 10^{-6}$	$6.9\ 10^{-7}$

TABLE I-XXIII. INHALATION DOSE FACTORS IN Sv/Bq (COMMITTED EFFECTIVE DOSE PER UNIT INHALED ACTIVITY – MAXIMUM VALUES (S)) [13, 14]

Radionuclide	Age group	
	2–7 y	> 17 y
^{226}Ra	$1.9\ 10^{-5}$	$9.5\ 10^{-6}$
^{210}Pb	$1.1\ 10^{-5}$	$5.6\ 10^{-6}$

— **^{222}Rn inhalation** (+ daughter products)
31.5 µSv/y per Bq/m^3 at 100 % occupancy and assuming a equilibrium factor of 0.4 [11]

— **External irradiation** [15] (mSv.m^3/Bq.h)
It is assumed that the radium extraction factory discharged radium without daughter products. The daughter products ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po are very short-lived radionuclides (up to a few days) and therefore may be assumed to be in equilibrium with Ra-226. ^{210}Pb has a much longer half-life and therefore is not assumed to be immediately in equilibrium with Ra.

^{226}Ra (+ very short-lived daughter products)	^{210}Pb
$2.4\ 10^{-10}$	$1.5\ 10^{-13}$

Covering with 40 cm clean soil will reduce the γ irradiation with a factor of about 10[a].
Covering with 100 cm clean soil will reduce the γ irradiation with a factor of about 1000[a].
In Annex I formula are given which can be used to calculate the reduction of γ radiation by shielding. There are also several computer programs (e.g. Microshield) available to assess the γ radiation shielding, and databases of the attenuation coefficients can be easily found on internet.

I-6.3.7. Breathing rate data

- breathing rate of adult (m^3/h)

agricultural activities	1.2
residential	0.75–1 (indoor - outdoor)

- inhalable dust concentration in air (kg/m^3)

agricultural activities	1E-07
residential	1.5E-08 – 3E-08 (indoor - outdoor)

- breathing rate at different ages relative to adult data [16]

infant	child
0.18	0.69

I-6.3.8. Intake rate of soil

TABLE I-XXIV. LONG-TERM INTAKE RATE OF SOIL [17]

Age (y)	Soil intake (mg/day)
1–6	200
> 6	50

For short-term outdoors activities, an intake rate of 480 mg/day is recommended [17].

I-6.3.9. Other parameter values

Thickness root zone layer	food crops (m)	0.3
	pasture (m)	0.15

exposure time of food crops to irrigation (days)	60
half-life on food crops due to weathering (days)	30
irrigation rate (m/day)	1E-03
irrigation period (days)	100
shielding factor surfaces (external irradiation) [18, 19]	
agricultural activities	0.7
residential	0.25–0.7 (indoor - outdoor)
interception factor food crops	0.2
yield of leafy vegetables (kg fw /m^2/y)	2
yield of potatoes (kg fw /m^2/y)	2
air exchange rate for the house [20]	0.5 h^{-1}(small rooms) ; 1 h^{-1} (big rooms; > 200 m^3)
porosity concrete [21]	0.2
pore diffusion coefficient radon in concrete[a] ($m^2.y^{-1}$)	6.3
thickness of basement (m) concrete floor and walls below ground level	0.3
emanation fraction in soil [22]	0.25
pore diffusion coefficient radon in soil[a] ($m^2.y^{-1}$)	63.1

I-6.4. Uncertainty ranges of input parameters to be considered in the uncertainty analysis

TABLE I-XXV. RADIONUCLIDE DEPENDENT PARAMETERS

Parameter	Ra-226		Rn-222		Pb-210	
	Mean	Range/pdf	Mean	Range/pdf	Mean	Range/pdf
Diffusion coeff. in soil[a] (m^2/y)	1.0E-05	(0.2–5)E-05 triangular	63.1	20–200 triangular	5E-06	(0.1–2)E-05 triangular
K_d in soil (m^3/kg)	0.5	0.05–5 loguniform	/	/	0.27	0.025–2.5 loguniform
Emanation fraction ε (-)	/	/	0.25	0.1–0.4 uniform	/	/
Soil-to-plant TF						
pasture (dw/dw)	0.08	(1–30)E-02	/	/	0.05	0.02–0.2
leafy veg. (dw/fw)	0.01	(0.1–10)E-02	/	/	0.01	(3–20)E-03
potatoes (dw/fw)	1.5E-03	(0.2–15)E-03 logtriangular	/	/	1E-03	(0.3–3)E-03 triangular
Grass-to-milk TF (d/l)	2.0E-04	(0.5–10)E-04 triangular	/	/	1.5E-04	(0.5–10)E-04 triangular
Grass-to-beef TF (d/kg)	5.0E-04	(0.1 -2)E-03 logtriangular	/	/	4.0E-04	(1–10)E-04 triangular
Translocation factor potatoes [23]	0.1	0.001–0.15 logtriangular	/	/	0.1	0.001–0.15 logtriangular

[a] Apparent diffusion coefficient; takes into account the retardation due to adsorption processes.

TABLE I-XXVI. RADIONUCLIDE INDEPENDENT PARAMETERS

Parameters	Mean/Mode	Range/pdf
Density of soil, after deep ploughing (kg/m^3)	800	320–1300 triangular
Moisture of soil (-)	0.3	0.15–0.5 triangular
Inhalable dust concentration in air (kg/m^3)		
Outdoors + Agricultural activities	1.0E-07	(0.2–5)E-07
Outdoors	3.0E-08	(0.5–10)E-08
Indoors	1.5E-08	(0.25–5)E-08 triangular
Thickness of root zone layer		
Pasture	0.15	0.1–0.3
Potatoes, leafy vegetables	0.3	0.2–0.5 triangular
Ventilation of house (h^{-1})	0.5	0.2–1 triangular
Pore diffusion coefficient radon in concrete (m^2/y)	6.3	1–15 triangular
Thickness of basement (m)	0.3	0.1–0.5 triangular
Daily uptake of pasture by cattle (kg dw/d)	12.5	10–15 triangular
Daily uptake water by cow (m^3/d)	0.06	0.04–0.08 uniform

TABLE I-XXVI. (CONTINUED)

Parameters	Mean/Mode	Range/pdf
Fractional uptake of soil by cattle (kg dw/kg dw pasture)	0.04	0.01–0.1 triangular
Yield of vegetation (kg/m^2/y)		
Leafy vegetables (fresh)	2	0.8–4.0
Potatoes (fresh)	2	0.8–4.0 triangular
Interception factor food crops (-)	0.2	0.1–0.5 triangular
Infiltration velocity (mm/y)	100	40–150 uniform
Irrigation time (d)	100	30–150 triangular
Irrigation rate (m/d)	1.0E-03	(0.3–2)E-03 triangular
Weathering decay constant (d^{-1})	0.023	0.015–0.04 triangular

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ANNEX I
ASSESSMENT OF GAMMA RADIATION SHIELDING

In order to describe the attenuation of radiation through shielding matter we introduce the quantity called fluence rate. The fluence rate Φ gives the intensity of the radiation at a certain point i.e. the number of photons passing per unit surface per time.

The photon fluence rate Φ ($\mathrm{cm}^{-2}.\mathrm{s}^{-1}$) after passing a distance τ through a homogeneous medium can be written as:

$$\Phi(\tau) = \Phi_0 \cdot B \cdot e^{-\mu \cdot \tau}$$

with Φ_0 the photon flux rate of the incoming beam, μ the linear attenuation coefficient which is function of the material composition and photon energy and *B* the build-up factor which is function of the photon energy and the distance travelled through the absorbing material.

The shielding depends on the geometry of the source.

— For a point source;

the photon fluence rate at a dose point which is a distance ρ from the source is given as:

$$\Phi = \frac{S \cdot B \cdot e^{-b}}{4 \cdot \pi \cdot \rho^2}$$

with *S* ($\mathrm{n.s}^{-1}$) the source strength representing the number of photons emitted by the source per unit of time.

b represents the main free paths. It is a dimensionless term which represents the attenuation effectiveness of a shield. The higher the value, the higher the radiation attenuation. The value of *b* is found using:

$$b = \sum \mu_i \cdot \tau_i$$

With μ_i the attenuation coefficient of the material *i* and τ_i the distance travelled following the source-dose point line-of-sight through the material *i*.

— For a volume source;

the photon fluence rate at a dose point near a volume source can be determined by considering the volume source as consisting of a number of point sources. By adding the contribution of every point source to the dose at the dose point we find the photon fluence rate at the dose point from the entire source.

$$\Phi = \int_V \frac{S \cdot B \cdot e^{-b}}{4 \cdot \pi \cdot \rho^2} \cdot dV$$

where *S* represents the source strength per unit volume.

APPENDIX II

DETAILED MODEL DESCRIPTIONS AND PREDICTIONS

This appendix contains the model predictions and descriptions provided by the exercise participants. These contributions have not been edited by the IAEA Secretariat or the Working Group Chairman, but are provided in the form in which they were submitted. The contributions are presented in alphabetical order of the name of the model.

II-1. OLEN SCENARIO TYPE A:
DETAILED MODEL DESCRIPTIONS AND PREDICTIONS

II-1.1. CLRP

II-1.1.1. General model description

II-1.1.1.1. Name of model, model developer(s) and model user(s)

Model name:	Concentration Levels Rapid Predictions (CLRP)
Model developer(s):	Pawel Krajewski, Central Laboratory for Radiological Protection, Department of Radiation Hygiene, Warsaw, Poland
Name of model user:	Pawel Krajewski

II-1.1.1.2. Intended purpose of the model in radiation assessment

The model CLRP was created in 1989 as a part of research project "LONG-LIVED POST-CHERNOBYL RADIOACTIVITY AND RADIATION PROTECTION CRITERIA FOR RISK REDUCTION" performed in co-operation with U.S. Environmental Protection Agency. The aim of this project was to examine the fate of long-lived radionuclides in the terrestrial ecosystem [1, 2]. Following the next years the model was intensively developed and extended for other radionuclides especially for iodine [3].

The aim of this code is to simulate the transport of radionuclides through environment to human's body due to examine the fate of some radionuclides in the ecosystem. The Input Parameters Data Base of the code has been created that allows to evaluate the radiological impact for: I, Cs, Ru, Te, Sr. One is able to set up to 20 radionuclides of 44 elements.

All dynamic processes are described by differential formulas and are solved numerically. Radionuclides concentrations in the particular components of terrestrial ecosystem e.g. soil, vegetation, animal tissues and animal products are calculated as a function of time following calculated deposition from the atmosphere. The model considers seasonal changes in the biomass of vegetation and animal diets, also specific ploughing and crop-harvest dates. Human dietary data are included to permit calculation of time -dependent radionuclide ingestion rates as well as critical organ content of radionuclide for seven different age group of population.

Program enables to calculate doses from the following pathways: external (cloud, ground exposure); internal (inhalation, ingestion) and is designed to make able the simulation of many different radiological situations (chronic or acute releases) and dose affecting countermeasures as some diet components ban, buildings shielding as well as stable iodine prophylactics.

During the 1989–1995 period the CLRP code performance for ^{137}Cs was check out in a frame of the International IAEA programme." Validation of models for the transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" on he base of two "blind" scenarios CB and S [4].

Since 1995 the validation of the CLRP v.4.4 for ^{137}Cs and ^{131}I has started in a frame of International Programme: BIOMOVS II – BIOspheric MOdel Validation Study, PHASE II in the Working Group: Effect of Modellers Interpretation on Model Uncertainties Biomovs II.

The CLRP code was qualified as one of the three codes that has taken part in this programme. Final results of BIOMOVS II programme were presented and published.

II-1.1.1.3. Model type (equilibrium, dynamical, numerical, analytical,...)

All dynamic processes are described by exponential formulas and are solved numerically.

The new version of the computer code CLRP (Concentration Levels Rapid Predictions) has been written in the Visual Basic Language for Excel 7.0 for Windows 95 as an Ad-In application and consists with dialogs and programs that enable to communicate with one Scenario File simultaneously. Scenario File comprises a set of worksheets of Excel 7.0- one pair of worksheets for particular component input and prediction data. More detailed information one can find in [5].

II-1.1.1.4. Method used for deriving uncertainty estimates

The uncertainty estimates given for the OLEN scenario were derived by personal judgement of the range of uncertainty of some model parameters. Item yield of the grass, cow diet, pasture-milk transfer factor. For all parameters log-normal distribution was assumed. The CLRP code calculates overall uncertainty range using error propagation method. Unhomogeneity of Radium concentration in soil for particular plots was taken in to account.

II-1.1.1.5. Description of model (procedures, parameters, main equations)

Please see Figure II-1.1.1.

II-1.1.1.6. Assumptions concerning parameter values used in different components of the model

— **Ra concentration of the upper 10 cm before remediation**

Best estimate – average of each grid points located in plot (Figure II-1.1.2).

Uncertainty ranges of 95% confidence interval have been estimated from grid point's measurement assuming lognormal distribution.

- *Ploughing effect*

Dilution factor was estimated base on scenario information (Scenario Description paragraph 4.1). The reduction of Ra-226 concentration in the root soil layer of 25 cm after deep ploughing was estimated at least by factor 3. Figure II-1.1.3 illustrates the method of estimation.

THE RADIONUCLIDE TRANSPORT PATHWAYS CONSIDERED BY CLRP MODEL.
THE MAIN COMPONENTS OF THE HUMAN ECOSYSTEM ARE PRESENTED:
DYNAMIC PROCESSES ARE MARKED BY DOUBLE ARROWS
DISCRETE EVENTS BY SINGLE ARROWS
CIRCLES INDICATE POSSIBLE COUNTERMEASURES SIMULATED BY THE MODEL.

Program enables to calculate doses from the following pathways: external (cloud, ground exposure); internal (inhalation, ingestion) and is designed to make able the simulation of many different radiological situations (chronic or acute releases) and dose affecting countermeasures as some diet components ban, buildings shielding as well as stable iodine prophylactics.

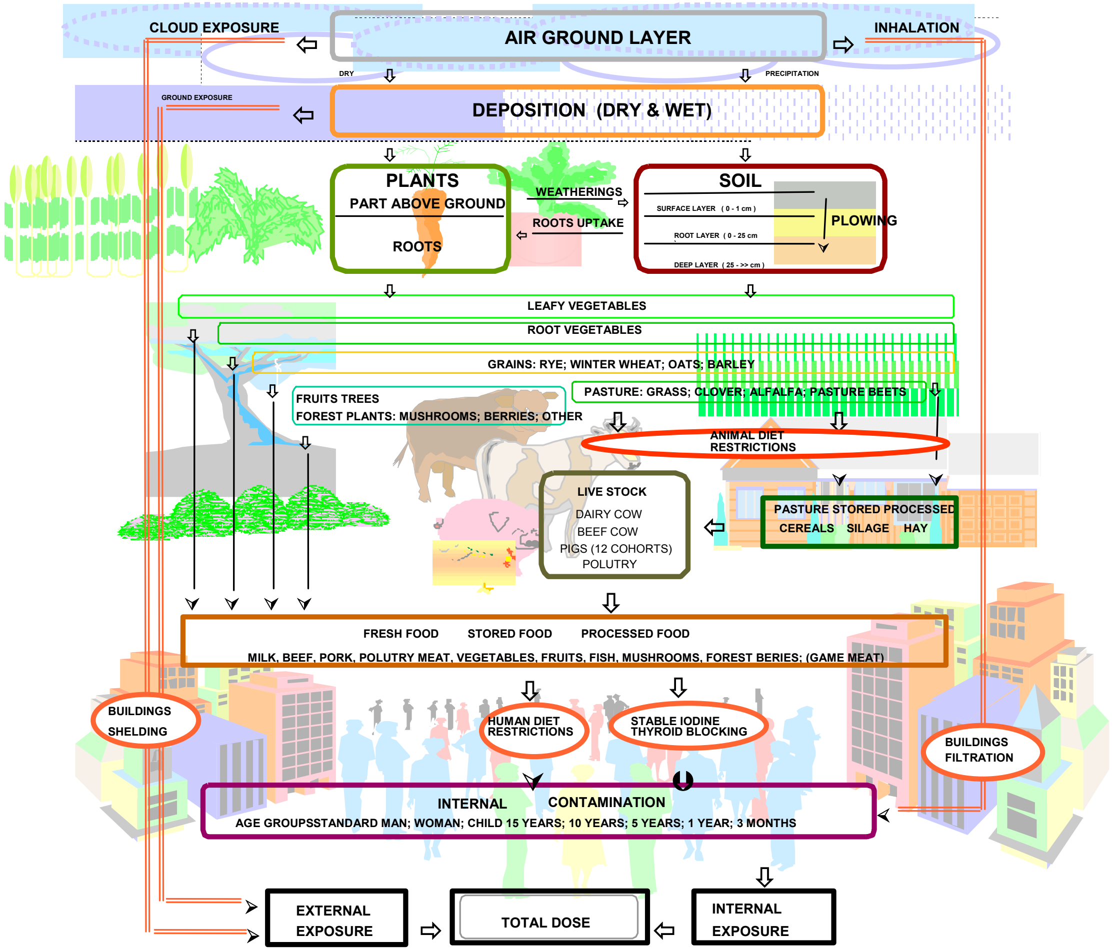

FIG. II-1.1.1. Description of the CLRP model.

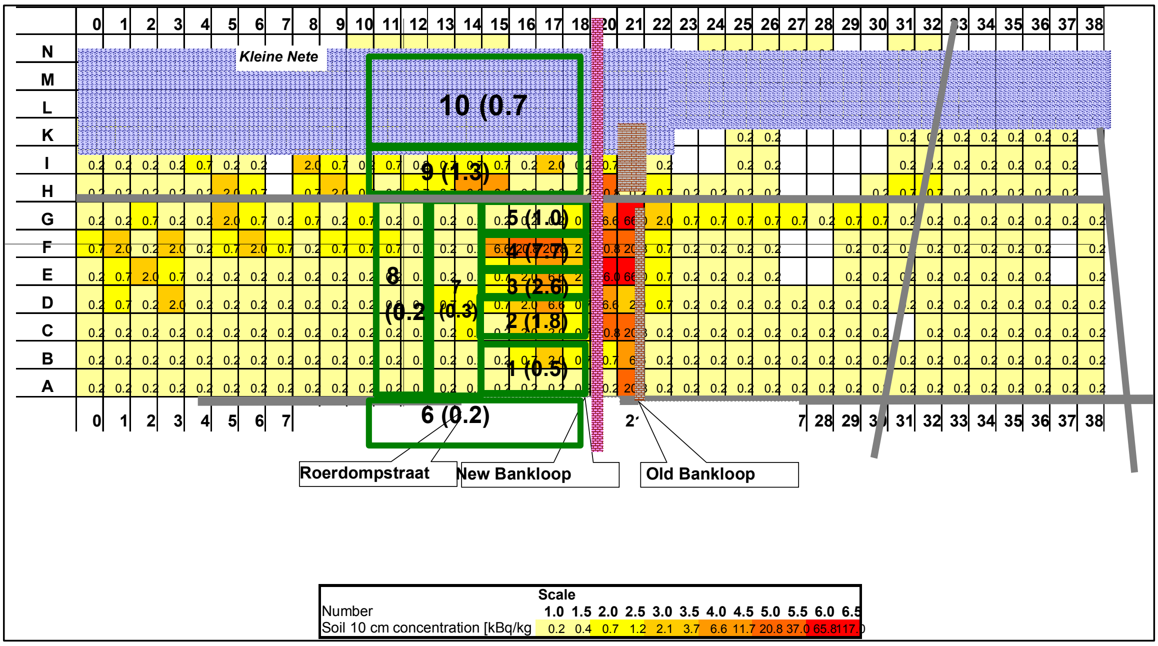

FIG. II-1.1.2. Reconstruction of ^{226}Ra concentration in 10 cm layer for Plots 1-10.

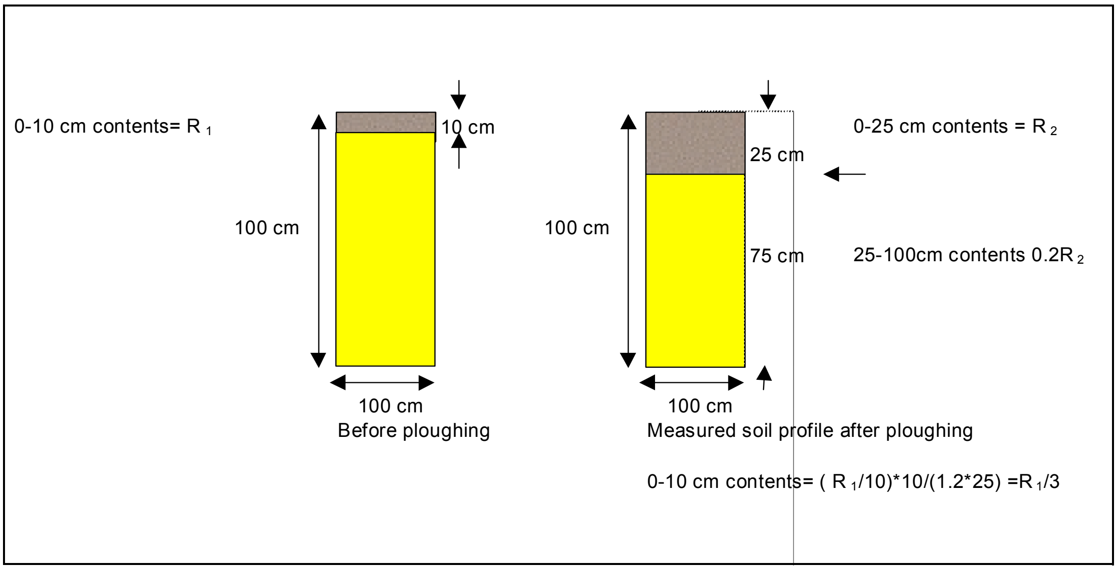

FIG. II-1.1.3. Deep ploughing effect estimation.

- *Uncertainty estimates of radium concentration in root zone before and after deep ploughing*

The average radium concentration in soil and its uncertainty ranges before deep ploughing have been estimated on the base of grid point's measurement assuming log-normal distribution for each plot separately. In this case arithmetic mean Q_a from the mean of the log-normal distribution μ and its variance σ^2, one can estimate as:

$$\overline{O}_a = \exp(\mu + \frac{\sigma^2}{2})$$

The 95% confidence interval bounds of the Q_a are calculated by multiplying Q_a by so called uncertainty factor UF as:

$$\overline{O}_{95\,\%\,Upper} = \overline{O}_a \times UF$$

$$\overline{O}_{95\,\%\,Lower} = \overline{O}_a / UF$$

where:

$$UF = \exp\left(1.645 \times \sqrt{\left(\frac{\sigma^2}{n} + \frac{\sigma^4}{2(n-1)}\right)}\right)$$

n- number of data

- *(Safety Series No.100)*

For all plots UF values have been in a range 1.5–3 and reflected not homogenous distribution of radium ^{226}Ra concentration in soil in the each plot. Because the deep ploughing as well as possible harrowing could have made the concentration of ^{226}Ra in soil more homogenous then, I have made *personal judgement* that there has been no reason to make uncertainty ranges wider. I have made an assumption that deep ploughing might act as smoothing matrix over several squares of grid. The 95% uncertainty range of dilution factor was estimated by personal judgement. I estimated the deep ploughing effect as dilution by factor 3 (best estimate value) with uncertainty ranges from 1.9 to 4.8 (Uncertainty factor=1.6), assuming lognormal distribution factor.

The average values and 95% uncertainty ranges of ^{226}Ra concentration in root zone soil before and after deep ploughing are presented in Table II-1.1.I. These values have been used for grass calculation.

- *Soil to grass transfer factor*

Calculation of Ra-226 concentration in grass was calculated assuming soil-to plant transfer factor equal to 0.12 [Bq/g DW/Bq/g/DW] This value has been compared with values withdrawn from scenario description[1]: 0.083[Bq/g_{DW}/Bq/g/$_{DW}$], 0.05[Bq/g $_{DW}$/Bq/g/$_{DW}$]) respectively. A higher value was assumed to take into account different soil textures (more sand) after deep ploughing.

95% uncertainty range for the best estimate has been evaluated equal to (0.075–0.192) assuming lognormal distribution. Uncertainty factor = 1.6

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[1] See Table I-VII (Appendix I).

TABLE II-1.1.I. SUMMARY OF BEST ESTIMATE VALUES USED FOR SELECTED MODEL PARAMETERS (THE UNCERTAINTY RANGES ARE GIVEN IN PARENTHESES)

Parameter		CLRP 95% confidence interval of uncertainty ranges
soil to grass concentration ratio (dw/dw)	value pdf type	0.12[a] (0.075–0.192) [gsd 1.6] lognormal
intake by cattle during grazing period Ic (kg dw/d)	value pdf type	15 (12.5–18) [gsd 1.2] lognormal
intake by cattle during stabling period (Bq/d)	value pdf type	100 (80–120) [gsd 1.2] lognormal
equilibrium grass to milk factor Fm (d/l)	value pdf type	1.86E-04 (1.16E-04–3.00E-04) [gsd 1.6] lognormal
grass to milk concentration ratio Ic * Fm (kg/l)	value pdf type	/
dilution factor due to deep ploughing	value pdf type	3 (1.9–4.8) [gsd 1.6] lognormal

[a] Value was adjusted from 0.08 to 0.12, taking into account different soil textures (more sand) after deep ploughing.

- *Transfer ^{226}Ra to milk*

Intake ->milk equilibrium transfer factor was evaluated as mean from data given in scenario description (Table I-VII). Results of calculation are presented below:

	Experimental Pasture			
Intake [15 kg DW]	375	375	165	165
Milk [Bq/L]	0.033	0.047	0.036	0.047
Milk factor [d/L]	8.800E-05	1.253E-04	2.182E-04	2.848E-04
	95% confidence interval			
	Mean	Lower bound	Upper bound	Urf
	1.86E-04	1.16E-04	3.00E-04	1.6

Obtained Intake->milk transfer factor 1.86E-04 [d/L] appears to be substantially lower than recommended values in the Handbook of Parameters Values for the Prediction of Radionuclide Transfer in Temperate Environments TRS No. 364: expected value 1.3E-3, range: 1.00E-04 – 1.30E-03 [d/L] or reported in Safety Series No. 57 : 6.00E-04 [d/L]. 95% uncertainty ranges have been estimated assuming lognormal distribution equal to: 1.16E-04 – 3.00E-04.

^{226}Ra concentration in milk was calculated using retention function according formula:

$$Milk_{^{226}Ra}(t) = \int C_{pasture}(t) \cdot Q_{cow}(t) \cdot \Re(\tau - t) d\tau$$

where:

$C_{pasture}(t)$ is the ^{226}Ra concentration in pasture grass – dependent on plot where cows grazed for the particular period;

$Q_{cow}(t)$ is the daily consumption of pasture changed with winter and spring season;

$\Re(t)$ is the retention function of Ra in milk:

$$\Re(t) = F_m \cdot (\lambda_r + \lambda_b) \cdot e^{-(\lambda_r + \lambda_b)\cdot t}$$

where:

Fm is the equilibrium transfer factor of Ra from intake to cow's milk (1.86E-04 dl^{-1});
λ_r is the ^{226}Ra decay constant equal to 1.18608E-06 d^{-1} ($T_{1/2}$=1600 y);
λ_b is the biological decay constant equal to 1.47E-02 d^{-1} ($T_{1/2}$=47 d).

There was no statistical evaluation of λ_b.

For winter period (stable) daily intake of 100 Bq/d was assumed (10 kg dw.× 10 Bqkg^{-1}) base on Scenario description with uncertainty (80–120).

- *Grass concentration for different time periods that have been used for milk calculation*

The cows' grazing pattern was applied base on scenario description. ^{226}Ra concentration was calculated as it has been described in previous chapter. The ^{226}Ra concentration in grass and resulted ^{226}Ra concentration in milk is presented in Table II-1.1.II.

In the last column of the Table II-1.1.II the milk/intake factor was calculated. The discrepancies with in the factors in the table and as well as with assumed equilibrium intake ->milk factor value (1.86E-4) have been caused by the fact that cows had been grazed in not equilibrium conditions e.g. changing differently contaminated plots every several days. The retention function used in calculation with long biological half time has resulted in accumulation of radium from previous plots.

There is a matter of discussion if the selected function is valid but on the other hand can we use equilibrium transfer factor for highly non-equilibrium conditions?

II-1.1.2. Results of model predictions

For ^{226}Ra in milk calculation previously submitted the 95% uncertainty range of the average took in to account only: uncertainty for soil->grass factor, cow's consumption rate and intake->milk transfer factor but not uncertainty bound with deep ploughing dilution factor. In Table II-1.1.II the 95% uncertainty ranges including deep ploughing are submitted.

The second correction has been made in the milk calculation during the "stable" period where wrongly only 1/3 of the 100 Bq intake suggested in scenario had been assumed.

II-1.1.3. Sensitivity analysis

A sensitivity analysis was not performed.

TABLE II-1.1.II. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL BEFORE DEEP PLOUGHING (Bq/g dw)

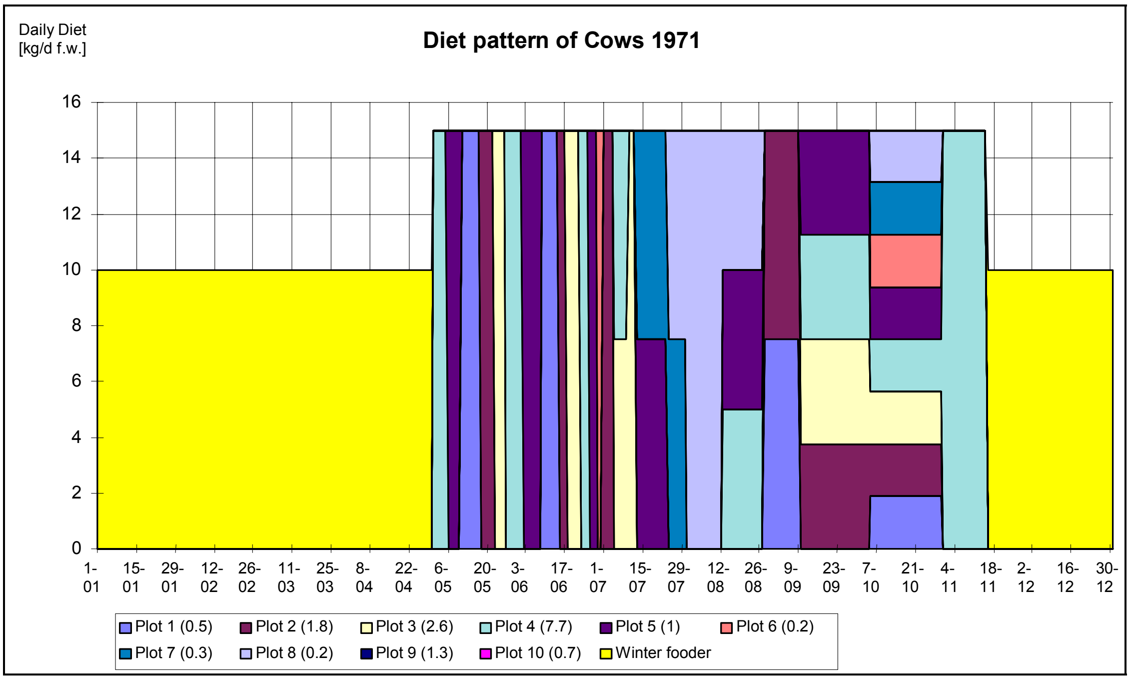
Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	0.50	0.2	1.0
2	1.80	0.9	3.7
3	2.60	1.3	5.00
4	7.70	3.7	15.5
5	1.00	0.4	2.4
6	0.20	0.1	0.4
7	0.30	0.1	0.6
8	0.20	0.1	0.4
9	1.30	0.6	3.7
10	0.70	0.3	1.5

TABLE II-1.1.III. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL AFTER DEEP PLOUGHING (1971) (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	0.17	0.11	0.27
2	0.60	0.38	0.96
3	0.87	0.54	1.39
4	2.57	1.61	4.11
5	0.33	0.21	0.53
6	0.07	0.04	0.11
7	0.10	0.06	0.16
8	0.07	0.04	0.11
9	0.43	0.27	0.69
10	0.23	0.14	0.37

TABLE II-1.1.IV. ^{226}Ra CONCENTRATIONS IN PASTURE AFTER DEEP PLOUGHING (JULY 1971) (Bq/kg dw)

Plot number	[Ra] pasture	95% Confidence interval	
		Lower bound	Upper bound
1	13	6	28
2	70	33	148
3	106	50	223
4	317	150	667
5	40	19	84
6	8	4	17
7	12	6	25
8	8	4	17
9	53	25	111
10	28	13	59



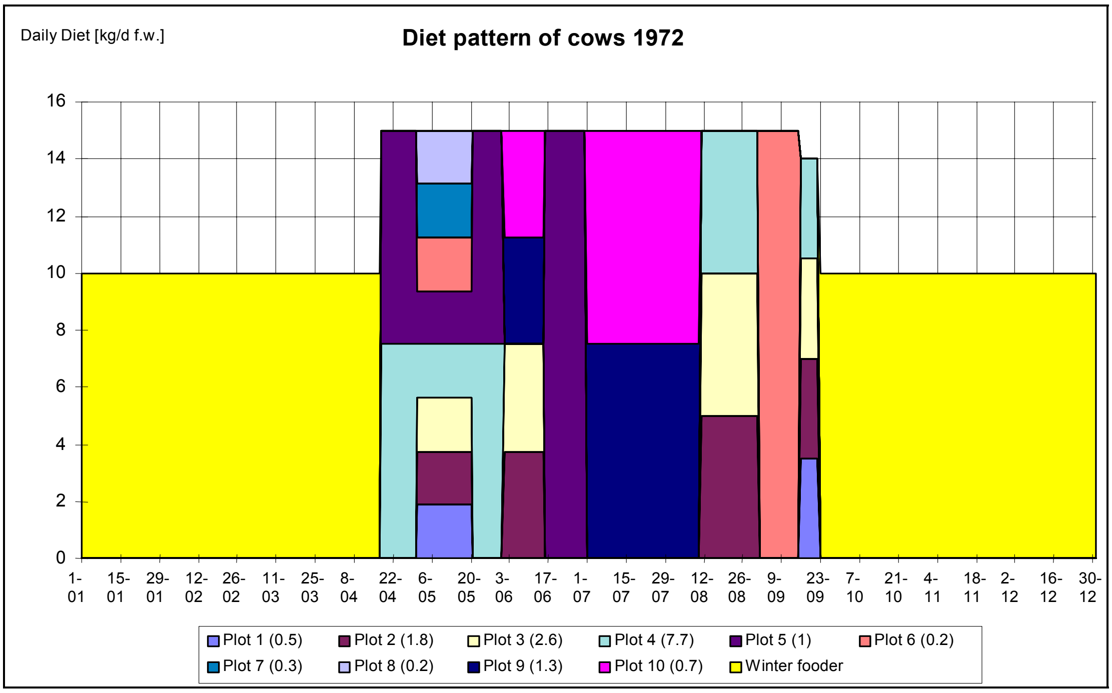


FIG. II-1.1.4. Location of the cows on the different plots during 1971–972.

TABLE II-1.1.V. ^{226}Ra GRASS AND MILK CONCENTRATION

Feeding period		Pasture plot(s) number										Daily consumption of pasture [kg/d d.m.]	^{226}Ra concentration in grass calculated for the particular plot and assumed for winter period [Bq/kg dry.m.]	Number days for the particular feeding period	^{226}Ra concentration in milk after deep ploughing [Bq/L]			
															95% confidence interval			Milk/ Intake factor
from	to	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**				**Average for period specified**	lower bound	upper bound	
01 05 1971	05 05 1971				4							15	317	**5**	**0.027**	***0.009***	***0.077***	**5.68E-06**
06 05 1971	09 05 1971					5						15	40	**4**	**0.055**	***0.019***	***0.157***	**9.17E-05**
11 05 1971	17 05 1971	1										15	13	**7**	**0.056**	***0.020***	***0.160***	**2.87E-04**
18 05 1971	22 05 1971		2									15	70	**5**	**0.058**	***0.020***	***0.165***	**5.52E-05**
23 05 1971	26 05 1971			3								15	106	**4**	**0.068**	***0.024***	***0.194***	**4.28E-05**
27 05 1971	01 06 1971				4							15	317	**6**	**0.100**	***0.036***	***0.285***	**2.10E-05**
02 06 1971	08 06 1971					5						15	40	**7**	**0.140**	***0.049***	***0.399***	**2.33E-04**
09 06 1971	14 06 1971	1										15	13	**6**	**0.130**	***0.046***	***0.371***	**6.67E-04**
15 06 1971	17 06 1971		2									15	70	**3**	**0.130**	***0.046***	***0.371***	**1.24E-04**
18 06 1971	22 06 1971			3								15	106	**5**	**0.130**	***0.046***	***0.371***	**8.18E-05**
23 06 1971	24 06 1971				4							15	317	**2**	**0.140**	***0.049***	***0.399***	**2.94E-05**
26 06 1971	28 06 1971					5						15	40	**3**	**0.160**	***0.056***	***0.456***	**2.67E-04**
28 06 1971	30 06 1971						6					15	8	**3**	**0.160**	***0.056***	***0.456***	**1.33E-03**
01 07 1971	04 07 1971		2									15	70	**4**	**0.160**	***0.056***	***0.456***	**1.52E-04**
04 07 1971	09 07 1971			3	4							15	211	**6**	**0.170**	***0.060***	***0.485***	**5.37E-05**
09 07 1971	12 07 1971			3								15	106	**4**	**0.190**	***0.067***	***0.542***	**1.19E-04**
12 07 1971	23 07 1971					5		7				15	26	**12**	**0.180**	***0.063***	***0.513***	**4.62E-04**
23 07 1971	30 07 1971							7	8			15	10	**8**	**0.160**	***0.056***	***0.456***	**1.07E-03**
12 08 1971	27 08 1971				4	5			8			15	122	**16**	**0.150**	***0.053***	***0.428***	**8.22E-05**
31 08 1971	09 09 1971	1	2						8			15	31	**10**	**0.160**	***0.056***	***0.456***	**3.49E-04**
14 09 1971	04 10 1971		2	3	4	5						15	133	**21**	**0.190**	***0.067***	***0.542***	**9.52E-05**
05 10 1971	28 10 1971	1	2	3	4	5	6	7	8			15	72	**24**	**0.210**	***0.074***	***0.599***	**1.95E-04**
31 10 1971	15 11 1971				4							15	317	**16**	**0.260**	***0.091***	***0.741***	**5.47E-05**
16 11 1971	27 11 1971	stable										10	10	**12**	**0.300**	***0.105***	***0.855***	**3.00E-03**
27 11 1971	15 12 1971	stable + 1 h on plots										10	10	**19**	**0.240**	***0.084***	***0.684***	**2.40E-03**
15 12 1971	30 12 1971	stable										10	10	**16**	**0.190**	***0.067***	***0.542***	**1.90E-03**
30 12 1971	14 01 1972	stable										10	10	**16**	**0.150**	***0.053***	***0.428***	**1.50E-03**
15 01 1972	31 01 1972	stable										10	10	**17**	**0.120**	***0.042***	***0.342***	**1.20E-03**
01 02 1972	15 02 1972	stable										10	10	**15**	**0.012**	***0.004***	***0.034***	**1.20E-04**
16 02 1972	28 02 1972	stable										10	10	**13**	**0.013**	***0.005***	***0.037***	**1.29E-04**
01 03 1972	15 03 1972	stable										10	10	**15**	**0.014**	***0.005***	***0.039***	**1.38E-04**
16 03 1972	31 03 1972	stable										10	10	**16**	**0.014**	***0.005***	***0.041***	**1.44E-04**
01 04 1972	17 04 1972	stable										10	10	**17**	**0.015**	***0.005***	***0.043***	**1.50E-04**
18 04 1972	01 05 1972				4	5						15	179	**14**	**0.111**	***0.039***	***0.316***	**4.15E-05**
02 05 1972	20 05 1972	several										15	72	**19**	**0.087**	***0.031***	***0.248***	**8.09E-05**
21 05 1972	31 05 1972				4	5						15	179	**11**	**0.120**	***0.042***	***0.342***	**4.48E-05**
01 06 1972	15 06 1972		2	3						9	10	15	114	**15**	**0.150**	***0.053***	***0.428***	**8.78E-05**
16 06 1972	30 06 1972					5						15	40	**15**	**0.150**	***0.053***	***0.428***	**2.50E-04**
01 07 1972	19 07 1972									9	10	15	40	**19**	**0.140**	***0.049***	***0.399***	**2.32E-04**
20 07 1972	10 08 1972									9	10	15	40	**22**	**0.130**	***0.046***	***0.371***	**2.16E-04**
10 08 1972	31 08 1972		2	3	4							15	164	**22**	**0.160**	***0.056***	***0.456***	**6.50E-05**
01 09 1972	15 09 1972							6				15	8	**15**	**0.180**	***0.063***	***0.513***	**1.50E-03**
16 09 1972	22 09 1972	1	2	3	4							15	191	**7**	**0.170**	***0.060***	***0.485***	**5.94E-05**
30 09 1972	15 10 1972	stable										10	10	**16**	**0.140**	***0.049***	***0.399***	**1.40E-03**
16 10 1972	31 10 1972	stable										10	10	**16**	**0.110**	***0.039***	***0.314***	**1.10E-03**
01 11 1972	27 11 1972	stable										10	10	**27**	**0.085**	***0.030***	***0.242***	**8.50E-04**
28 11 1972	06 12 1972	stable										10	10	**9**	**0.066**	***0.023***	***0.188***	**6.60E-04**
06 12 1972	31 12 1972	stable										10	10	**26**	**0.053**	***0.019***	***0.151***	**5.30E-04**

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II-1.2. DOSDIM

II-1.2.1. General model description

II-1.2.1.1. Name of model, model developer(s) and model user(s)

Name of model:	DOSDIM (Dose Distribution Model)
Model developer(s):	P. Govaerts, N. Lewyckyj, Th. Zeevaert, SCK/CEN, Department Radiation Protection, Radiological Assessments, Mol, Belgium
Name of model user:	L. Sweeck

II-1.2.1.2. Intended purpose of the model in radiation assessment

To assess the impact to man from routine and accidental releases

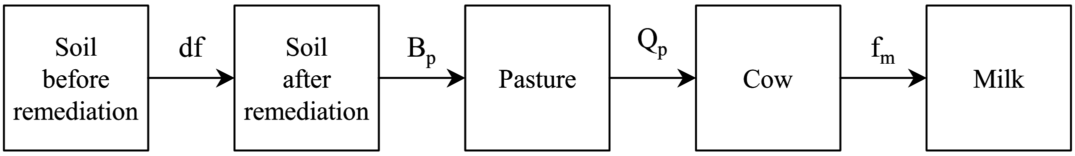
II-1.2.1.3. Model type (equilibrium, dynamical, numerical, analytical,...)

To estimate the ^{226}Ra concentration in milk, a compartmental, partly dynamic transfer model was used. In this model, five compartments can be distinguished; the soil compartment before remediation, the soil compartment after remediation, the plant (pasture) compartment, the animal (cow) compartment and milk compartment. The equations are taken from the DOSDIM model [1–3]. The ^{226}Ra concentration in the milk was calculated daily during the period 1/5/71 till 31/12/72. It was assumed that before this period, the cows were stabled at least several weeks, justifying the use of an equilibrium approach to estimate the initial ^{226}Ra concentration in milk.

II-1.2.1.4. Method used for deriving uncertainty estimates

For the parameter uncertainty analysis, the Latin Hypercube Sampling method was used [4]. For each parameter, a statistic distribution (e.g. triangular, lognormal,...) was defined. 4800 runs were made (until the endpoint values change less than 1%).

II-1.2.1.5. Schematic view



II-1.2.1.6. Description of model (procedures, parameters, main equations)

The following equations were used to estimate the ^{226}Ra concentration in milk:

- *^{226}Ra concentration of the root zone soil layer before remediation:*

$$[\mathrm{Ra}]_{\mathrm{root\ zone}} = [\mathrm{Ra}]_{\mathrm{upper\ 10\ cm}} * \mathrm{f}$$

whereby f = upper 10 cm of soil/root depth

- *^{226}Ra concentration of the root zone layer after remediation:*

  $$[\mathrm{Ra}]_{\text{root zone after remediation}} = [\mathrm{Ra}]_{\text{root zone before remediation}} / \mathrm{df}$$

  whereby df is a dilution factor between 1 and 100 (with as lower limit $[\mathrm{Ra}]_{\text{root zone}}$ equal to background value 0.02 Bq/g dw)

- *^{226}Ra concentration in pasture:*

  $$[\mathrm{Ra}]_{\text{pasture}} = B_p * [\mathrm{Ra}]_{\text{root zone after remediation}}$$

  whereby B_p is soil-to-plant transfer coefficient

- *^{226}Ra uptake by cow:*

  $$I_{\text{cow}} = Q_p * [\mathrm{Ra}]_{\text{pasture}}$$

  whereby Q_p is the daily consumption of pasture

- *^{226}Ra concentration in milk:*

  $$[\mathrm{Ra}]_{\text{milk}} = I_{cow} * \int_0^t f_m(t-T) * dT$$

  with $f_m(t) = a * e^{-(\alpha+\lambda)\cdot t}$

  $$\begin{aligned} &\alpha = \text{biological decay constant} \\ \text{whereby}\quad &a = \text{grass-to-milk coefficient; } a = F_m * (\lambda + \alpha) \\ &F_m = \textit{equilibrium transfer}\text{ factor to cow's milk} \end{aligned}$$

II-1.2.1.7. Assumptions concerning parameter values used in different components of the model

- *Ra concentration of the upper 10 cm before remediation:*

  best estimate = weighted average of each $[\mathrm{Ra}]_{\text{grid}}$ located in plot;

  min. and max. values estimated from measured Ra concentration range (based on our expert judgement);

  triangular distribution.

- *root depth* between 10 and 25 cm (best-estimate 15 cm, triangular distribution);

- *ploughing effect* dilution factor between 1 and 100 (lower limit = background $[\mathrm{Ra}]_{\text{soil}}$, logtriangular distribution.

After remediation, a dilution factor has to be taken into consideration to calculate the ^{226}Ra concentration in the upper soil layer. In the worst case, no dilution of the ^{226}Ra concentration in the upper soil layer is assumed (dilution factor df = 1). In the best case, almost all radium is situated at a depth of more than 25 cm (beneath the root length). Based on the background (0.02 Bq/g dw), we assume a dilution factor of 100. As best estimate, we consider a homogeneous distribution of ^{226}Ra over 1 m depth, the dilution factor is then given by 6.7 (df = ploughing depth / best estimate root depth).

- downwards migration of Ra during 1967 to 1971 is negligible;
- *soil-to-plant transfer factor B_p:*

  best estimate 0.065 dw/dw (arithmetic mean of the 2 values given in the scenario description);

  lognormal distribution, gsd 2.2 derived from literature review.
- *transfer factor to milk F_m:*

  equilibrium F_m: best estimate 2.15E-04 d/l

  lognormal distribution, gsd 2, derived from literature review [5].

  $\alpha = 0.3519\ d^{-1}$, derived from [6].
- *daily consumption of pasture Q_p:*

  triangular distribution, range between 10–15 kg dw/d, best estimate 12.5 kg dw/d
- *intake during stable period*

  triangular distribution, range between 80–120 Bq/d, best estimate 100 Bq/d

II-1.2.2. Results of model predictions

TABLE II-1.2.I. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL BEFORE DEEP PLOUGHING (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	1.23	0.32	2.42
2	2.79	0.81	5.03
3	4.47	1.13	8.60
4	8.90	2.53	18.19
5	2.57	0.64	5.04
6	0.13	0.04	0.25
7	0.59	0.13	1.22
8	0.51	0.09	1.15
9	2.77	0.68	5.12
10	0.54	0.11	1.18

TABLE II-1.2.II. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL AFTER DEEP PLOUGHING (1971) (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	0.22	0.02	0.87
2	0.49	0.03	1.96
3	0.78	0.05	3.30
4	1.57	0.10	6.42
5	0.45	0.03	1.85
6	0.03	0.02	0.09
7	0.10	0.02	0.44
8	0.09	0.02	0.39
9	0.49	0.03	1.91
10	0.10	0.02	0.41

TABLE II-1.2.III. ^{226}Ra CONCENTRATIONS IN PASTURE AFTER DEEP PLOUGHING (JULY 1971) (Bq/kg dw)

Plot number	[Ra] Pasture	95% Confidence interval	
		Lower bound	Upper bound
1	18.5	0.67	98.3
2	42.3	1.36	224.4
3	68.2	1.89	352.3
4	135.5	4.09	726.7
5	39.1	1.12	205.2
6	2.6	0.30	10.7
7	9.0	0.41	45.8
8	7.9	0.41	40.0
9	42.0	1.24	217.4
10	8.4	0.43	42.8

In Table II-1.2.IV, the measured ^{226}Ra concentrations are given. These results represent the Ra concentration of composed milk samples over the given time period. Also the results of the model predictions (mean, 5th and 95th percentile) are summarised in Table II-1.2.IV.

TABLE II-1.2.IV. ^{226}Ra CONCENTRATIONS IN MILK AFTER DEEP PLOUGHING (1971–1972) (Bq/l)

Period	Exp. data	Predicted data		
		Mean	95% Confidence interval	
			Lower bound	Upper bound
1/5–5/5/71	0.032	0.30	0.008	1.81
6/5–9/5	0.016	0.25	0.006	1.48
11/5–17/5	0.011	0.10	0.002	0.58
18/5–22/5	0.028	0.12	0.002	0.69
23/5–26/5	0.036	0.19	0.004	1.08
27/5–1/6	0.024	0.38	0.008	2.37
2/6–8/6	0.024	0.23	0.005	1.33
9/6–14/6	0.029	0.10	0.002	0.57
15/6–17/6	0.031	0.11	0.002	0.62
18/6–22/6	/	0.19	0.004	1.09
23/6–24/6	0.022	0.32	0.007	1.89
26/6–28/6	0.018	0.20	0.005	1.17

TABLE II-1.2.IV. (CONTINUED)

Period	Exp. data	Predicted data		
		Mean	95% Confidence interval	
			Lower bound	Upper bound
28/6–30/6	0.034	0.13	0.003	0.71
1/7–4/7	0.023	0.13	0.003	0.76
4/7–9/7	0.029	0.26	0.006	1.56
9/7–12/7	0.019	0.28	0.006	1.63
12/7–23/7	0.028	0.12	0.003	0.70
23/7–30/7	0.024	0.05	0.001	0.28
12/8–27/8	0.025	0.20	0.004	1.20
31/8–9/9	0.020	0.10	0.002	0.57
14/9–4/10	0.025	0.23	0.005	1.33
5/10–28/10	0.020	0.15	0.003	0.85
31/10–15/11	0.030	0.42	0.009	2.63
16/11–27/11	0.054	0.11	0.009	0.62
29/11–15/12	0.019	0.03	0.005	0.08
16/12–30/12	0.030	0.03	0.005	0.08
30/12/71–14/1/72	0.028	0.03	0.005	0.09
15/1–31/1	0.024	0.03	0.005	0.09
1/2–15/2	0.029	0.03	0.005	0.09
16/2–28/2	0.017	0.03	0.005	0.09
1/3–15/3	0.014	0.03	0.005	0.09
16/3–31/3	0.024	0.03	0.005	0.09
1/4–17/4	0.011	0.03	0.005	0.08
18/4–1/5	0.011	0.26	0.008	1.52
2/5–20/5	0.033	0.15	0.003	0.89
21/5–31/5	0.016	0.27	0.006	1.60
1/6–15/6*	0.019	0.18	0.003	1.01
1/6–15/6*	0.021	0.21	0.005	1.19
1/6–15/6*	0.020	0.18	0.004	0.98
1/6–15/6*	0.016	0.14	0.003	0.78
16/6–30/6	0.016	0.13	0.003	0.75
1/7–19/7	0.020	0.09	0.002	0.54
20/7–10/8	0.015	0.09	0.002	0.52
10/8–31/8	0.026	0.25	0.006	1.52
1/9–15/9	0.018	0.05	0.002	0.30
16/9–22/9	0.027	0.16	0.004	0.95
30/9–15/10	0.023	0.04	0.007	0.16
16/10–31/10	0.018	0.03	0.006	0.09
1/11–27/11	0.019	0.03	0.006	0.09
28/11–6/12	0.014	0.03	0.006	0.09
6/12–31/12	0.007	0.03	0.006	0.09

II-1.2.3. Sensitivity analysis

All the model parameters considered in the uncertainty analysis are linear correlated. Hence, the sensitivity ranking of the parameters will be according to the size of their uncertainty ranges. The three most sensitive parameters in decreasing order are: deep ploughing effect, soil-to-grass transfer factor and grass-to-milk transfer factor.

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II-1.3. OLENRAD-A

II-1.3.1. General model description

II-1.3.1.1. Name of model, model developer(s) and model user(s)

Name of model:	OLENRAD-A
Model developer(s):	Alexander Kryshev and Tatiana Sazykina, Institute of Experimental Meteorology, "SPA Typhoon", Kaluga Region, Obninsk, Russian Federation
Name of model user:	Alexander Kryshev

II-1.3.1.2. Intended purpose of the model in radiation assessment

Estimation of effectiveness of the remediation actions.

II-1.3.1.3. Model type (equilibrium, dynamical, numerical, analytical,...)

An equilibrium model was used to calculate the transfer from soil to pasture grass and from grass to milk.

II-1.3.1.4. Method used for deriving uncertainty estimates

Analytical estimation on the basis of uncertainty of the model parameters.

II-1.3.1.5. Description of model (procedures, parameters, main equations)

— *Assumptions:*

(1) Remediation actions led up to the uniform distribution of radioactivity in the soil profile (0-100 cm).

(2) Equilibrium model was used to estimate the radionuclide transfer from soil to pasture grass and from grass to milk.

— *Equations:*

$$C_{soil}^{after}=k_{eff}*C_{soil}^{before} \quad (1)$$

where C_{soil}^{after} -concentration of ^{226}Ra in upper 10-cm layer of soil after the remediation action of deep ploughing, C_{soil}^{before} – before remediation action, k_{eff} – coefficient of mixing due to deep ploughing.

$$C_{grass}^{after}=k_{soil\text{-}grass}*C_{soil}^{after} \quad (2)$$

where C_{grass}^{after} – concentration of ^{226}Ra in pasture grass, $k_{soil\text{-}grass}$ – the coefficient of the radionuclide transfer from soil to pasture grass.

$$C_{milk}^{after}=k_{grass\text{-}milk}*C_{grass}^{after} \quad (3)$$

where C_{milk}^{after} – concentration of ^{226}Ra in milk, $k_{grass\text{-}milk}$ – the coefficient of the radionuclide transfer from pasture grass to milk.

— *Parameters:*

k_{eff}=0.1
$k_{soil\text{-}grass}$=0.05±0.03
$k_{grass\text{-}milk}$=0.003±0.002
intake by cows during the winter (stable) period: 100±50 Bq/day

II-1.3.1.6. Assumptions concerning parameter values used in different components of the model

The weighted-averaged values of ^{226}Ra concentration in soil before the remediation actions for 9 plots indicated in the scenario were estimated on the basis of information presented in Figure I-6 of the scenario description (Appendix I).

The values of the transfer coefficients $k_{soil\text{-}grass}$ and $k_{grass\text{-}milk}$ were estimated on the basis of data of measurements presented in Section I-3 of the scenario description (Appendix I).

II-1.3.2. Results of model predictions

TABLE II-1.3.I. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL BEFORE DEEP PLOUGHING (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	0.6	0.3	0.9
2	3.6	1.5	5.7
3	4.6	1.1	7.1
4	7.8	3.1	12.5
5	3.4	0.7	6.1
6	0.2	0.2	0.2
7	0.5	0.2	0.8
8	0.3	0.2	0.4
9	2.4	0.6	5.2
10	0.3	0.2	0.4

TABLE II-1.3.II. ^{226}Ra CONCENTRATIONS IN THE ROOT ZONE SOIL AFTER DEEP PLOUGHING (1971) (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	0.06	0.03	0.09
2	0.36	0.15	0.57
3	0.46	0.11	0.71
4	0.78	0.31	1.25
5	0.34	0.07	0.61
6	0.02	0.02	0.02
7	0.05	0.02	0.08
8	0.03	0.02	0.04
9	0.24	0.06	0.52
10	0.03	0.02	0.04

TABLE II-1.3.III. ^{226}Ra CONCENTRATIONS IN PASTURE AFTER DEEP PLOUGHING (JULY 1971) (Bq/kg dw)

Plot number	[Ra] Pasture	95% Confidence interval	
		Lower bound	Upper bound
1	3	0.7	5.3
2	18	3	33
3	23	1	45
4	39	2	76
5	17	2	32
6	1	0.4	1.6
7	2.5	0.4	4.9
8	1.5	0.4	2.6
9	12	1	23
10	1.5	0.5	2.5

TABLE II-1.3.IV. ^{226}Ra CONCENTRATIONS IN MILK AFTER DEEP PLOUGHING (1971–1972) (Bq/l)

Period	[Ra] Milk	95% Confidence interval	
		Lower bound	Upper bound
1/5–5/5/71	0.117	0.005	0.229
6/5–9/5	0.051	0.003	0.099
11/5–17/5	0.009	0.001	0.017
18/5–22/5	0.054	0.004	0.104
23/5–26/5	0.069	0.003	0.135
27/5–1/6	0.117	0.005	0.229
2/6–8/6	0.051	0.003	0.099
9/6–14/6	0.009	0.001	0.017
15/6–17/6	0.054	0.004	0.104
18/6–22/6	0.069	0.003	0.135
23/6–24/6	0.117	0.005	0.229
26/6–28/6	0.051	0.003	0.099
28/6–30/6	0.003	0.001	0.005
1/7–4/7	0.054	0.004	0.104
4/7–9/7	0.093	0.003	0.183
9/7–12/7	0.069	0.003	0.135
12/7–23/7	0.029	0.002	0.056
23/7–30/7	0.007	0.001	0.013
12/8–27/8	0.058	0.003	0.113
31/8–9/9	0.023	0.002	0.044
14/9–4/10	0.073	0.004	0.142
5/10–28/10	0.007	0.001	0.013
31/10–15/11	0.117	0.005	0.229
16/11–27/11	0.003	0.001	0.005
29/11–15/12	0.02	0.016	0.024
16/12–30/12	0.02	0.016	0.024
30/12/71–14/1/72	0.02	0.016	0.024
15/1–31/1	0.02	0.016	0.024
1/2–15/2	0.02	0.016	0.024
16/2–28/2	0.02	0.016	0.024
1/3–15/3	0.02	0.016	0.024
16/3–31/3	0.02	0.016	0.024
1/4–17/4	0.02	0.016	0.024
18/4–1/5	0.084	0.004	0.164
2/5–20/5			
21/5–31/5	0.084	0.004	0.164
1/6–15/6[*]	0.054	0.004	0.104

TABLE II-1.3.IV. (CONTINUED)

Period	[Ra] Milk	95% Confidence interval	
		Lower bound	Upper bound
1/6–15/6*	0.069	0.003	0.135
1/6–15/6*	0.036	0.002	0.070
1/6–15/6*	0.005	0.001	0.009
16/6–30/6	0.051	0.003	0.099
1/7–19/7	0.020	0.002	0.038
20/7–10/8	0.020	0.002	0.038
10/8–31/8	0.080	0.004	0.156
1/9–15/9	0.003	0.001	0.005
16/9–22/9	0.062	0.002	0.122
30/9–15/10	0.02	0.004	0.036
16/10–31/10	0.02	0.004	0.036
1/11–27/11	0.02	0.004	0.036
28/11–6/12	0.02	0.004	0.036
6/12–31/12	0.02	0.004	0.036

*group of cows split over several plots

II-1.3.3. Sensitivity analysis

The calculations are based on a static model, and the model predictions are directly proportional to the values of the transfer coefficients. Three model parameters are considered to have uncertainties: average value of Ra-226 concentration in soil, coefficient of radionuclide transfer from soil to pasture grass, and coefficient of radionuclide transfer from grass to cow milk. The model is equally sensitive to the deviations in each of these parameters, because the model result is proportional to the multiplication of parameters.

II-1.4. RISKOLEN

II-1.4.1. General model description

II-1.4.1.1. Name of model, model developer(s) and model user(s)

Name of model:	RiskOlen
Model developer(s):	Peter Lietava, Waste Disposal Dept., Nuclear Research Institute Rez, plc, Rez, Czech Republic
Name of model user:	Peter Lietava

II-1.4.1.2. Intended purpose of the model in radiation assessment

The model has been developed for the BIOMASS Theme 2, Olen case scenario. The calculations are performed in MS Excel 5.0 environment, with help of add-in program @RISK. @RISK allows to define uncertain values in Excel as probability distributions using about 30 new functions. Distribution functions can be added to any number of cells and formulas throughout the worksheet and can include arguments which are cell references and expressions. Based on defined input data for Olen test case scenario the code can evaluate the environmental effects of remedial actions at Olen site. The endpoint of radiation assessment is the Ra-226 concentration in milk obtained from cows grazed at the contaminated pastures nearby the Olen radium extraction site.

II-1.4.1.3. Model type (equilibrium, dynamical, numerical, analytical ...)

Partly dynamical, analytical model.

II-1.4.1.4. Method used for deriving uncertainty estimates

Latin Hypercube sampling method for each stochastic output parameter described with help of statistical distribution (uniform, lognormal or triangular). To achieve the convergence of solution about 3000 runs have been performed for each output parameter.

II-1.4.1.5. Description of model (procedures, parameters, main equations)

The assessment endpoint is the concentration of Ra-226 in milk. Scenario description contains the site survey results of Ra-226 concentration in soil in the region between Roerdompstraat and Kleine Nete.

The evaluation of deep ploughing is based on available information's about this remedial procedure. The Ra-226 concentration in root zone is calculated as:

$$C_{after} = C_{before} \cdot DP \qquad (1)$$

where:

C_{after} is the Ra-226 concentration in soil after deep ploughing [Bq/g];
C_{before} is the Ra-226 concentration in soil before deep ploughing [Bq/g],
DP is the deep ploughing dilution factor [-].

The Ra-226 concentration in pasture is calculated as:

$$C_{pasture} = C_{after} \,.\, B_V \tag{2}$$

where:

$C_{pasture}$ is the Ra-226 concentration in pasture [Bq/g];
C_{after}- is the Ra-226 concentration in soil after deep ploughing [Bq/g];
B_V is the soil-to-plant transfer factor [Bq/g DW / Bq/g DW].

To obtain the Ra-226 concentration in milk, the contaminant concentration in pasture is multiplied by daily consumption rate of pasture and by the pasture – milk transfer factor:

$$C_{milk} = C_{pasture} \,.\, INT.\, K_{milk} \tag{3}$$

where:

C_{milk} is the Ra-226 concentration in milk [Bq/l];
$C_{pasture}$ is the Ra-226 concentration in pasture [Bq/g];
INT is the daily intake of grass [kg/d];
K_{milk} is the pasture – milk transfer factor [d/l].

II-1.4.1.6. Assumptions concerning parameter values used in different components of the model

— Ra-226 concentration in soil before remedial action is based on Figures I-6 of Olen case A scenario (Appendix I). This figure shows the localisation the pasture plots on Ra-226 soil concentration map (see Figure II-1.4.2). Each pasture plot contains several grid elements with different relative concentration values as it is showed on Table II-1.4.I. Unfortunately the relative value vs. soil concentration scale allows only a limited estimate of Ra-226 soil concentration in each grid element. The pasture plot No. 6 is placed outside the region shown on Figure II-1.4.1, in sector 2 between the Roerdompstraat and the Kempisch Kanaal. The Ra-226 soil concentration has been estimated with help of helicopter survey results (Figure I-8 of Appendix I). The survey identified a limited area with higher Ra-226 concentration (about 240 cps) at this pasture plot. Therefore it has been assumed, that about 2 grid elements out of 24 have higher soil concentration value than other elements.

— The effect of deep ploughing on Ra-226 distribution in soil has been evaluated with help of the information from Olen case scenario description (Appendix I) – technique of deep ploughing and Ra-226 depth distribution. The vertical Ra-226 concentration profile showed that the deep ploughing has reduced the initial concentration in root zone about 4.3 times. The estimate of deep ploughing effect from technical files concerning the remedial action shows the reduction of original concentration about 10–20 times. Therefore the used dilution factor for deep ploughing efficiency was described as a uniform distribution with min. value of 4.3 and max. value of 20. For further calculations of Ra-226 concentration in milk it was assumed, that the plot No. 6, lying outside the region between Roerdompstraat and Kleine Nete, had been remediated by the deep ploughing technology.

— The values of Ra-226 concentrations in soil, pasture and milk from experimental pasture (Table I-VII, Appendix I) correspond to the soil-to-plant transfer factor of 0.083 and 0.05 and to the pasture-milk transfer factor of 8.8E-05 to 2.8E-04 d/l. The range of the soil-to-plant transfer factor from [1] (expected value – 8.0E-02, 95% confidence interval 1.6E-02–4.0E-01) corresponds to the lognormal distribution with mean value of 0.17 and standard deviation of 0.22. This distribution is in good agreement with both experimental values. The distribution function for pasture-milk transfer factor was derived from experimental values – triangular distribution with min. value of 8.8E-05 d/l, most likely value of 1.19E-04 d/l and max. value of 2.85E-04 d/l.

- Distribution function for daily pasture intake is based on values from Olen case scenario (Chapter I-4, Appendix I) – uniform distribution within the range of 10–15 kg/d DW.
- The Ra-226 intake during the stabling period was estimated from value of 100 Bq/d as it had been published in Olen case scenario (Chapter I-4, Appendix I) – a triangular distribution function with min. value of 20 Bq/d, most likely value of 100 Bq/d and max. value of 200 Bq/d was used.

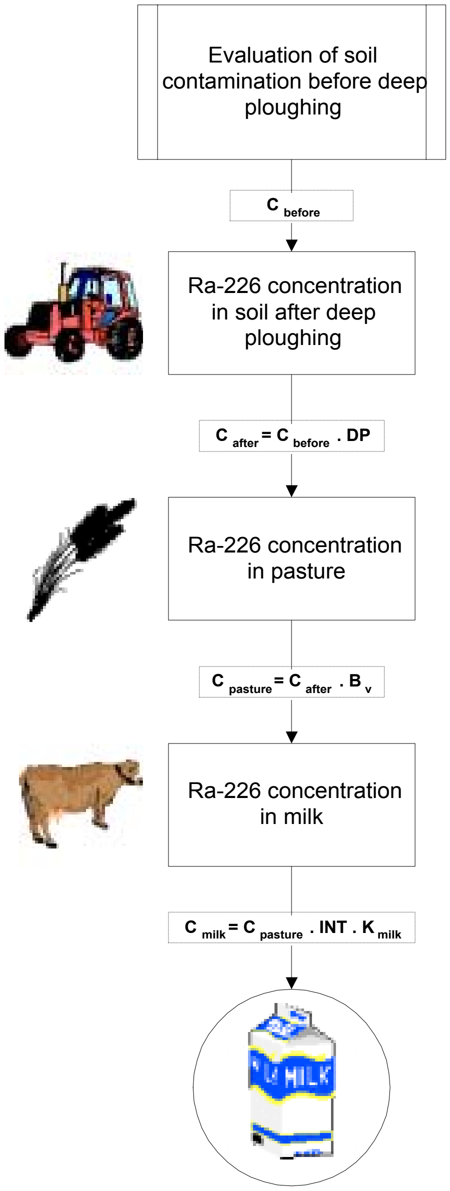

FIG. II-1.4.1. Flowchart of RiskOlen code.

TABLE II-1.4.I. PASTURE PLOT VS. GRID ELEMENT TABLE

Plot No.	No. of elements with concentration level						Plot Area
	1	2	3	4	5	6	[m^2]
1	5	2	1	0	0	0	20000
2	1	2	2.5	0.5	0	0	15000
3	0	1.5	1.5	1	0	0	10000
4	0	0.5	1.5	1	1	0	10000
5	4	0	0.5	0.5	1	0	15000
6	22	0	2	0	0	0	60000
7	11	3	0	0	0	0	35000
8	16	0.6	0	0	0	0	41500
9	4.6	4.5	0.6	3	0	0	31750
10	10.5	3	0.3	0	0	0	34500

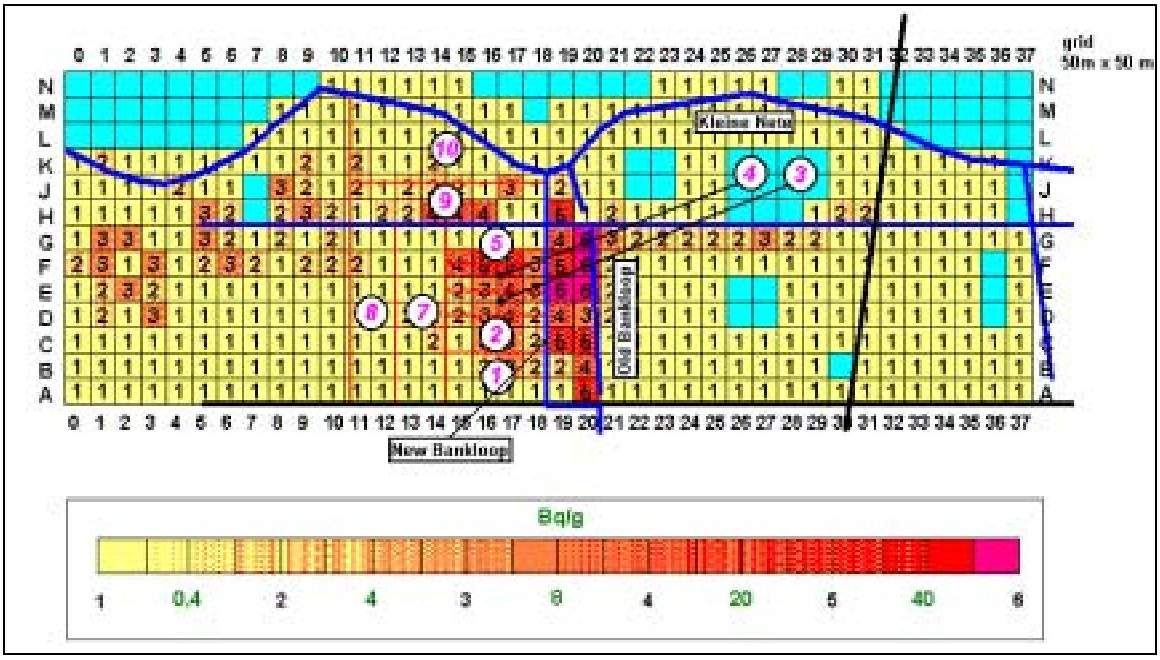

FIG. II-1.4.2. Localisation of pasture plots.

The Ra-226 soil concentrations are defined with help of scale on Figure II-1.4.2 as:

TABLE II-1.4.II. DISTRIBUTION FUNCTION FOR Ra-226 SOIL CONCENTRATION

Relative value vs. concentration scale	
Relative value	Ra-226 soil concentration [Bq/g]
1	triang (0,0.2,0.4)
2	triang (0.4,2.2,4)
3	triang (4,6,8)
4	triang (8,14,20)
5	triang (20,30,40)
6	triang (40,45,50)

II-1.4.2. Results of model predictions

TABLE II-1.4.III. Ra-226 CONCENTRATIONS IN ROOT ZONE BEFORE THE REMEDIATION

Plot No.	Ra-226 concentration in root zone before deep ploughing		
	Lower bound	Mean [Bq/g]	Upper bound
1	0.99	1.43	1.83
2	3.49	4.43	5.36
3	5.10	6.58	8.01
4	11.04	13.53	15.86
5	5.38	6.80	8.16
6	0.48	0.68	0.87
7	0.29	0.63	0.95
8	0.11	0.27	0.43
9	3.17	4.44	5.65
10	0.41	0.76	1.09

TABLE II-1.4.IV. Ra-226 CONCENTRATIONS IN ROOT ZONE AFTER THE REMEDIATION

Plot No.	Ra-226 concentration in root zone after deep ploughing		
	Lower bound	Mean [Bq/g]	Upper bound
1	0.06	0.14	0.32
2	0.21	0.43	0.96
3	0.30	0.65	1.44
4	0.65	1.32	3.00
5	0.32	0.66	1.47
6	0.03	0.07	0.15
7	0.02	0.06	0.15
8	0.01	0.03	0.07
9	0.19	0.44	0.97
10	0.03	0.07	0.17

TABLE II-1.4.V. Ra-226 CONCENTRATIONS IN PASTURE BEFORE THE REMEDIATION

Plot No.	Ra-226 concentration in pasture before deep ploughing		
	Lower bound	Mean [Bq/kg]	Upper bound
1	20.67	241.63	1032.74
2	61.54	757.62	3275.95
3	94.64	1155.35	4676.18
4	202.27	2288.92	9548.63
5	98.59	1157.06	5056.30
6	10.25	116.18	501.64
7	7.29	106.94	467.64
8	3.46	45.11	209.25
9	66.60	747.21	3021.47
10	10.41	128.00	532.13

TABLE II-1.4.VI. Ra-226 CONCENTRATIONS IN PASTURE AFTER THE REMEDIATION

Plot No.	Ra-226 concentration in pasture after deep ploughing		
	Lower bound	Mean [Bq/kg]	Upper bound
1	1.59	23.97	128.83
2	4.73	74.50	362.30
3	7.82	110.32	516.54
4	15.62	218.09	1028.21
5	7.41	111.98	506.63
6	0.76	11.71	61.79
7	0.58	10.34	49.72
8	0.23	4.65	19.87
9	4.66	72.94	343.81
10	0.80	13.39	68.28

The pasture concentration for time periods, when cows have been grazed on several plots, was calculated as the weighted average from Ra-226 concentration in pasture after deep ploughing and the area of pasture plots:

$$C_{\text{mixed plots}} = \Sigma\, C_{\text{plot}}.\, A_{\text{plot}} / \Sigma\, A_{\text{plot}} \qquad (4)$$

where:

C_{plot} is the Ra-226 concentration in grass on separate plot [Bq/kg];
A_{plot} is the area of each plot [m^2].

After the normalization the milk to grass concentration ratio achieves a constant value of 0,00233 Bq/l / Bq/kg for every time period when cows grazed outdoors.

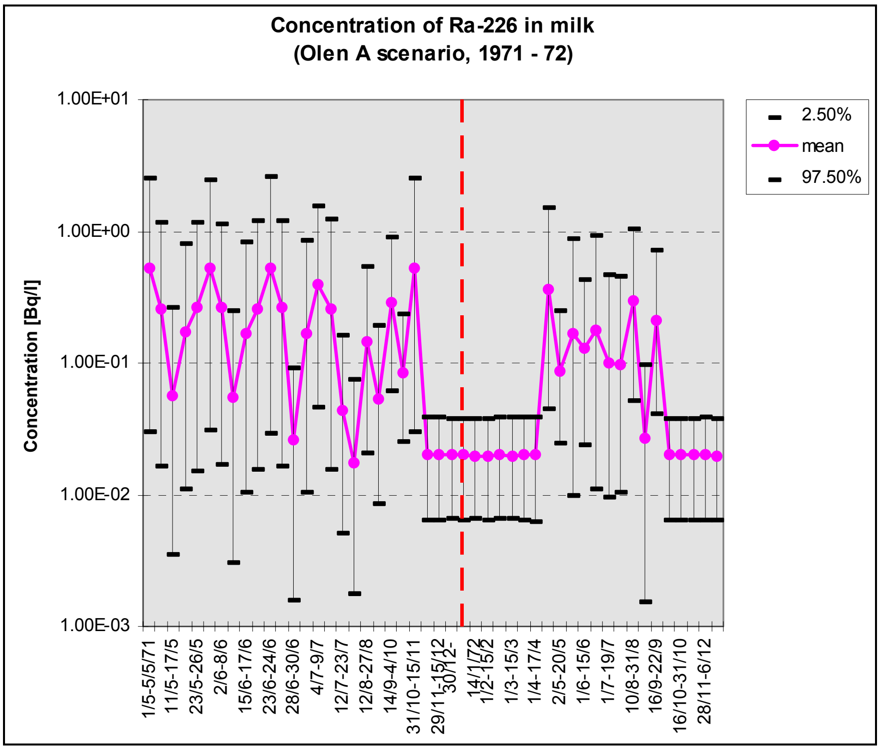

FIG. II-1.4.3. Concentration of Ra-226 in milk for Olen case, Scenario A.

TABLE II-1.4.VII. Ra-226 CONCENTRATIONS IN GRASS AND MILK (ITALIC WRITTEN VALUES ARE THE DAILY RADIUM INTAKE VALUES FOR THE STABLING PERIOD IN Bq)

Period	Pasture concentration		Ra-226 concentration in milk	
[d/m/y]	[Bq/kg]	lower bound	mean [Bq/l]	upper bound
1/5-5/5/71	218.092	0.03	0.53	2.49
6/5-9/5	111.982	0.01	0.26	1.32
11/5-17/5	23.966	0.00	0.06	0.26
18/5-22/5	74.496	0.01	0.17	0.87
23/5-26/5	110.317	0.01	0.26	1.29
27/5-1/6	218.092	0.03	0.52	2.28
2/6-8/6	111.982	0.01	0.26	1.38
9/6-14/6	23.966	0.00	0.06	0.25
15/6-17/6	74.496	0.01	0.17	0.80
18/6-22/6	110.317	0.01	0.26	1.26
23/6-24/6	218.092	0.03	0.53	2.38
26/6-28/6	111.982	0.02	0.26	1.26
28/6-30/6	11.709	0.00	0.03	0.09
1/7-4/7	74.496	0.01	0.17	0.77
4/7-9/7	164.204	0.05	0.39	1.62
9/7-12/7	110.317	0.01	0.26	1.33
12/7-23/7	18.560	0.01	0.04	0.20
23/7-30/7	7.253	0.00	0.02	0.07
12/8-27/8	60.957	0.02	0.14	0.50
31/8-9/9	23.396	0.01	0.05	0.18
14/9-4/10	121.625	0.06	0.29	0.82
5/10-28/10	36.272	0.02	0.09	0.23
31/10-15/11	218.092	0.03	0.53	2.57
16/11-27/11	*106.667*	0.01	0.02	0.04
29/11-15/12	*106.667*	0.01	0.02	0.04
16/12-30/12	*106.667*	0.01	0.02	0.04
30/12-14/1/72	*106.667*	0.01	0.02	0.04
15/1-31/1	*106.667*	0.01	0.02	0.04
1/2-15/2	*106.667*	0.01	0.02	0.04
16/2-28/2	*106.667*	0.01	0.02	0.04
1/3-15/3	*106.667*	0.01	0.02	0.04
16/3-31/3	*106.667*	0.01	0.02	0.04
1/4-17/4	*106.667*	0.01	0.02	0.04
18/4-1/5	154.426	0.04	0.37	1.31
2/5-20/5	36.272	0.02	0.09	0.23
21/5-31/5	74.496	0.01	0.17	0.73
1/6-15/6	54.778	0.02	0.13	0.40
16/6-30/6	72.938	0.01	0.18	0.81
1/7-19/7	41.930	0.01	0.10	0.40
20/7-10/8	41.930	0.01	0.10	0.40
10/8-31/8	125.758	0.05	0.30	1.04
1/9-15/9	11.709	0.00	0.03	0.09
16/9-22/9	88.743	0.04	0.21	0.70
30/9-15/10	*106.667*	0.01	0.02	0.04
16/10-31/10	*106.667*	0.01	0.02	0.04
1/11-27/11	*106.667*	0.01	0.02	0.04
28/11-6/12	*106.667*	0.01	0.02	0.04
6/12-31/12	*106.667*	0.01	0.02	0.04

II-1.4.3. Uncertainty and sensitivity analysis

From a mathematical point of view the RiskOlen code is based on a linear model as described in Chapter II-1.4.1.1. Therefore a sensitivity analysis has not been performed. The attention has been focused on the stochastic evaluation of selected critical input parameters – deep ploughing dilution factor and initial Ra concentration in root zone, and uncertainty analysis for these two parameters. The aim of the uncertainty analysis was to answer the question, how can the selection of distribution function affect the final results of safety assessment.

In the first step three distribution functions and their parameters for deep ploughing dilution factor have been selected so that they approximately cover the range from 4.3 to 20:

- uniform distribution (4.3, 20);
- triangular distribution (4.3, 12.15, 20);
- lognormal (12.98, 7.55).

The triangular distribution is based on estimates of the absolute minimum and maximum of dilution factor. For the lognormal distribution we have assumed, that there is a non-zero probability, that the realistic value of dilution factor lies outside the interval of 4.3 to 20. Therefore these two values represent 0.025 and 0.975 quantiles and the lognormal distribution function corresponds to the cumulative probability of 0% for the value of dilution factor of 1, 2.5% for 4.3, 50% for 12.15, 7.5% for 20% and 100% for dilution factor of 100.

The results obtained by using the uniform distribution function for dilution factor and triangular distribution function for initial Ra concentration in root zone have been used as reference results. Table II-1.4.VIII shows the differences between the Ra-226 concentration in grass for triangular and lognormal distribution function and reference Ra-226 concentration.

TABLE II-1.4.VIII. MEAN VALUES OF Ra-226 CONCENTRATIONS IN GRASS AFTER DEEP PLOUGHING – I

Plot No.	Uncertainty analysis for Ra-226 concentration in grass after deep ploughing		
	reference results (uniform distribution) [Bq/kg]	difference for triangular distribution [%]	difference for lognormal distribution [%]
1	23.97	-11.83	1.85
2	74.50	-11.19	5.49
3	110.32	-9.43	5.14
4	218.09	-3.50	14.26
5	111.98	-11.86	12.44
6	11.71	-10.60	3.99
7	10.34	-10.68	4.57
8	4.65	-9.89	2.56
9	72.94	-11.90	3.49
10	13.39	-15.07	2.18

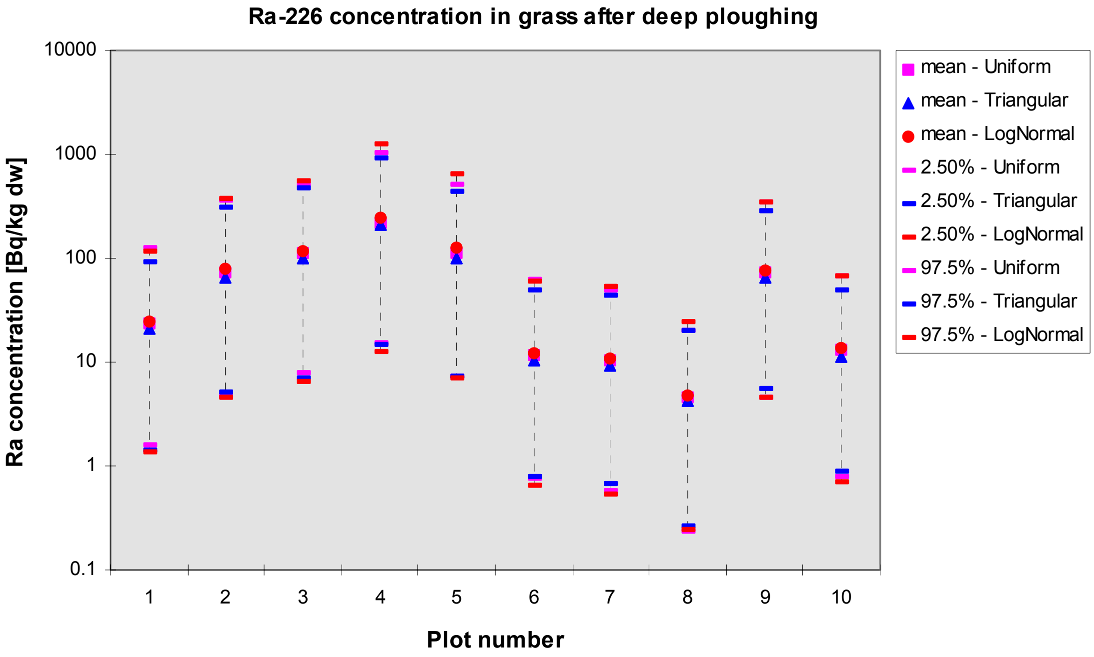

FIG. II-1.4.4. Uncertainty analysis for Ra-226 concentrations in root zone after deep ploughing.

As it can be seen from Table II-1.4.VIII, the use of different types of distribution functions can significantly change the mean values of Ra-226 concentrations in grass and Ra-226 concentration in milk. The triangular distribution function for dilution factor causes a decrease of mean values for about 10 %, while the use of lognormal distribution function increases the mean Ra-226 concentration for less than 6 % (except plot No. 4 and 5). The tendency of these results is not unexpected. The uniform distribution function overestimates the effect of deep ploughing in comparison with triangular distribution, because the value of density function for the whole dilution factor interval is equal. The situation is different for the lognormal distribution. The contribution of low values of dilution factor (1–4.3) with cumulative probability of 2.5% slightly dominates over the contribution of high values of dilution factor (20–100) to the mean Ra-226 concentration and therefore the concentration in grass is higher for each plot than the reference results.

The comparison for Ra-226 concentration in milk shows, that the values are in general lower than the reference concentration. The differences of final results for triangular and lognormal distribution are almost identical. The application of two additional stochastic parameters to the Ra-226 concentration in grass (intake by cattle, grass-to-milk factor) does not significantly affect these differences. Depending on plots used for grazing of cows in different time periods the concentration in milk is lower than the reference results for triangular distribution function for about 5 – 11%. The results based on the lognormal distribution of dilution factor are higher for about 3 – 8%. In general higher differences from reference results can be seen for time periods, when cows grazed plots No. 4 and 5 for lognormal distribution of dilution factor (e.g. 1/5 – 5/5, 6/5 – 9/5, 27/5 – 1/6, 2/6 – 8/6, ...).

A second set of uncertainty analysis calculations has been performed for the evaluation of the influence of distribution functions for initial Ra-226 concentration in root zone before deep ploughing. As in previous case following three groups of distribution functions and their parameters have been used for the quantification of root zone contamination in scale sections according to the Figure II-1.4.2:

- uniform distribution;
- triangular distribution (reference results);
- lognormal distribution.

TABLE II-1.4.IX. RESULTS OF UNCERTAINTY ANALYSIS FOR Ra-226 CONCENTRATIONS IN MILK – I

Period	Ra-226 concentration in milk		
[d/m/y]	reference results (uniform distribution) [Bq/l]	difference for triangular distribution [%]	difference for lognormal distribution [%]
1/5-5/5/71	0.53	-7.88	7.34
6/5-9/5	0.26	-5.91	8.07
11/5-17/5	0.06	-10.63	-1.21
18/5-22/5	0.17	-7.00	5.95
23/5-26/5	0.26	-11.71	6.61
27/5-1/6	0.52	-8.84	8.20
2/6-8/6	0.26	-8.62	5.91
9/6-14/6	0.06	-8.44	3.01
15/6-17/6	0.17	-6.25	8.13
18/6-22/6	0.26	-10.69	5.11
23/6-24/6	0.53	-8.70	4.81
26/6-28/6	0.26	-8.04	5.14
28/6-30/6	0.03	-2.57	6.70
1/7-4/7	0.17	-7.31	6.82
4/7-9/7	0.39	-10.08	6.77
9/7-12/7	0.26	-10.13	6.28
12/7-23/7	0.04	-8.15	5.32
23/7-30/7	0.02	-11.82	3.04
12/8-27/8	0.14	-7.13	7.44
31/8-9/9	0.05	-7.10	5.05
14/9-4/10	0.29	-7.76	6.77
5/10-28/10	0.09	-12.65	1.64
31/10-15/11	0.53	-9.19	5.24
16/11-27/11	0.02	stable	stable
29/11-15/12	0.02	stable	stable
16/12-30/12	0.02	stable	stable
30/12-14/1/72	0.02	stable	stable
15/1-31/1	0.02	stable	stable
1/2-15/2	0.02	stable	stable
16/2-28/2	0.02	stable	stable
1/3-15/3	0.02	stable	stable
16/3-31/3	0.02	stable	stable
1/4-17/4	0.02	stable	stable
18/4-1/5	0.37	-7.23	6.71
2/5-20/5	0.09	-9.18	4.74
21/5-31/5	0.17	-6.78	7.15
1/6-15/6	0.13	-9.79	4.65
16/6-30/6	0.18	-11.07	5.36

TABLE II-1.4.IX. (CONTINUED)

Period [d/m/y]	Ra-226 concentration in milk		
	reference results (uniform distribution) [Bq/l]	difference for triangular distribution [%]	difference for lognormal distribution [%]
1/7-19/7	0.10	-10.54	4.59
20/7-10/8	0.10	-9.58	5.13
10/8-31/8	0.30	-8.51	7.42
1/9-15/9	0.03	-2.57	6.70
16/9-22/9	0.21	-9.32	6.13
30/9-15/10	0.02	stable	stable
16/10-31/10	0.02	stable	stable
1/11-27/11	0.02	stable	stable
28/11-6/12	0.02	stable	stable
6/12-31/12	0.02	stable	stable

The parameters for each distribution function have been evaluated according to the Figure II-1.4.5.

The parameters of lognormal distribution have been defined with help of BestFit software package [3]. The parameters of distribution functions for each scale segment are summed up in Table II-1.4.X.

The comparison of output parameters (Ra-226 concentration in grass and milk) with the reference results shows, that there are small differences for uniform distribution of scale segments – max. 5% for Ra-226 concentration in milk. This fact is caused by overlapping the minimum and maximum values for both distribution functions – uniform and triangular. These values have been used by the generation of lognormal distribution as 2.5% and 97.5% quantiles. As the boundaries of lognormal function have been used the closest values of soil concentration according to the Figure II-1.4.5, e.g. for scale segment No. 3 values of 0.4 Bg/g and 20 Bq/g. Therefore the lognormal functions cover wider range of initial Ra-226 concentrations and cause bigger differences between results and reference concentrations.

The performed uncertainty analysis proved the importance of the proper evaluation of biological study results performed in years 1961–67, when the soil contamination had been measured before deep ploughing in the region between Roerdompstraat and Kleine Nete. Depending on the used distribution function and its parameters the final Ra-226 concentration in milk can be up to 50–70% higher than the reference results. In comparison with these results the importance of the value of dilution factor is lower. The variation of Ra-226 concentration in milk does not exceed -13% to +8% interval.

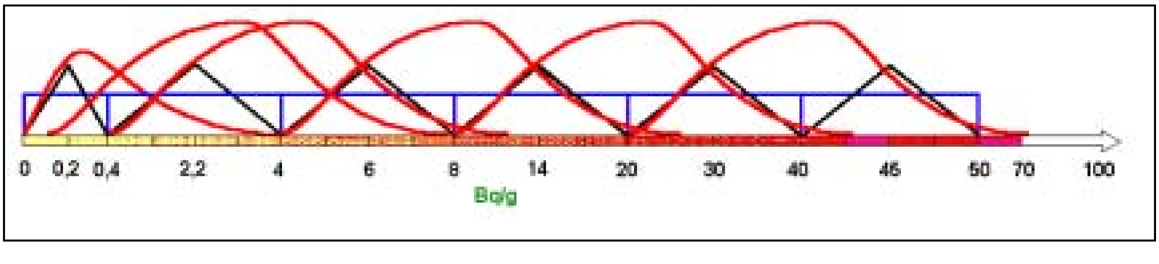

FIG. II-1.4.5. Distribution functions for Ra-226 concentration in root zone (not in scale).

TABLE II-1.4.X. PARAMETERS OF LOGNORMAL DISTRIBUTION FUNCTIONS FOR Ra-226 CONCENTRATION SCALE SEGMENTS

Scale segment	Parameters of lognormal distribution function Mean [Bq/g]	Standard deviation [Bq/g]	2.5% quantile [Bq/g]	97.5% quantile [Bq/g]
1	0.42	0.56	0.05	1
2	3.3	5	0.2	6
3	7.28	4.74	2.2	14
4	16.28	8.62	6	30
5	29.88	11.14	14	45
6	47.87	13.47	30	70

TABLE II-1.4.XI. MEAN VALUES OF Ra-226 CONCENTRATIONS IN GRASS AFTER DEEP PLOUGHING – II

Plot No.	Uncertainty analysis for Ra-226 concentration in grass after deep ploughing Reference results (triangular distribution) [Bq/kg]	Difference for uniform distribution [%]	Difference for lognormal distribution [%]
1	23.97	-0.53	50.43
2	74.50	-0.64	33.23
3	110.32	-3.18	15.43
4	218.09	0.54	9.02
5	111.98	-0.49	3.81
6	11.71	-0.43	42.92
7	10.34	1.35	67.16
8	4.65	0.02	90.22
9	72.94	1.45	25.41
10	13.39	1.00	58.09

TABLE II-1.4.XII. RESULTS OF UNCERTAINTY ANALYSIS FOR Ra-226 CONCENTRATIONS IN MILK – II

Period [d/m/y]	Ra-226 concentration in milk reference results (triangular distribution) [Bq/l]	difference for uniform distribution [%]	difference for lognormal distribution [%]
1/5-5/5/71	0.53	0.55	6.11
6/5-9/5	0.26	5.82	5.50
11/5-17/5	0.06	-2.33	34.22
18/5-22/5	0.17	0.39	28.34
23/5-26/5	0.26	-5.89	20.64
27/5-1/6	0.52	-0.12	7.07
2/6-8/6	0.26	4.42	3.36
9/6-14/6	0.06	-0.94	40.82
15/6-17/6	0.17	1.45	27.03
18/6-22/6	0.26	-2.26	21.12
23/6-24/6	0.53	-0.18	6.81
26/6-28/6	0.26	5.64	3.62
28/6-30/6	0.03	2.08	44.25
1/7-4/7	0.17	-0.76	26.00
4/7-9/7	0.39	-0.61	10.83
9/7-12/7	0.26	-3.62	24.79
12/7-23/7	0.04	0.33	16.02
23/7-30/7	0.02	-3.67	68.82

TABLE II-1.4.XII. (CONTINUED)

Period [d/m/y]	Ra-226 concentration in milk reference results (triangular distribution) [Bq/l]	difference for uniform distribution [%]	difference for lognormal distribution [%]
12/8-27/8	0.14	3.16	10.18
31/8-9/9	0.05	0.15	38.17
14/9-4/10	0.29	1.91	11.85
5/10-28/10	0.09	0.23	23.20
31/10-15/11	0.53	0.55	6.11
16/11-27/11	0.02	stable	stable
29/11-15/12	0.02	stable	stable
16/12-30/12	0.02	stable	stable
30/12-14/1/72	0.02	stable	stable
15/1-31/1	0.02	stable	stable
1/2-15/2	0.02	stable	stable
16/2-28/2	0.02	stable	stable
1/3-15/3	0.02	stable	stable
16/3-31/3	0.02	stable	stable
1/4-17/4	0.02	stable	stable
18/4-1/5	0.37	2.63	6.84
2/5-20/5	0.09	-1.52	21.95
21/5-31/5	0.17	-2.30	30.56
1/6-15/6	0.13	-1.44	26.66
16/6-30/6	0.18	-1.70	23.38
1/7-19/7	0.10	0.54	33.92
20/7-10/8	0.10	-0.21	34.15
10/8-31/8	0.30	-0.26	16.71
1/9-15/9	0.09	2.08	44.25
16/9-22/9	0.21	-2.25	17.82
30/9-15/10	0.02	stable	stable
16/10-31/10	0.02	stable	stable
1/11-27/11	0.02	stable	stable
28/11-6/12	0.02	stable	stable
6/12-31/12	0.02	stable	stable

References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Reports Series No. 364, IAEA, Vienna (1994).

[2] @RISK – Advanced Risk Analysis for Spreadsheets, Guide to Using @RISK, Palisade Corp. (1996).

[3] BestFit – Probability Distribution Fitting for Windows.

II-1.5. TAMDYN

II-1.5.1. General model description

II-1.5.1.1. Name of model, model developer(s) and model user(s)

Name of model:	the model and procedure developed for the special case to the simulation and uncertainty analysis code of TAMDYN (TAM DYNamic)
Model developer(s):	Béla Kanyár, University of Veszprém, Department of Radiochemistry, Veszprém, Hungary
Name of model user:	Béla Kanyár

II-1.5.1.2. Intended purpose of the model in radiation assessment

Modelling of the radionuclide transport in the environment, uncertainty prediction, sensitivity analysis, education

II-1.5.1.3. Model type (equilibrium, dynamic, numerical, analytical,...)

The main part of the model type is a dynamic type, namely simulation of systems defined by ordinary differential equations. The differential equations are solved numerically by the Runge-Kutta-Fehlberg method.

II-1.5.1.4. Method used for deriving uncertainty estimates

Monte-Carlo method. The distributions of the parameters were three-angular and normal ones. The uncertainty ranges of the parameters TF(soil-pasture), K_d, water flow into soil and feeding profile were derived from the scenario description. The values and ranges of the transport coefficients in the cow were mainly assessed by personal judgement, taking into consideration that the F_m (milk transfer) should be 0.0004 d/l in steady state.

II-1.5.1.5. Description of model (procedures, parameters, main equations)

The concentrations before ploughing are given in the scenario description in Figure I-6 (Appendix I). Averages were provided in all the plots. The Ra-concentrations in the root zone soil after the remediation action (deep ploughing) were given in the scenario description. The effect of the remediation was assessed from the K_d-values and the soil profile measurement made in 1991–1993. Depending on the K_d the upper soil (0–15 cm) contamination after remediation was only 2–3 times less than the concentration before. In case of a perfect mixing in 1 m deep layer it should be 6.7 times less. Therefore the uncertainty (mainly the bias) of the assessed concentration after the remediation must be high.

Neither the downward released activity from the root soil nor the wash-off from the surface has not been taken into account following the ploughing.

II-1.5.1.6. Mathematical forms of the model used

$$C_s(t) = C_s(0) . \exp[-(\lambda_r + \lambda_l).t]$$

$$C_P(t) = TF \cdot C_s(t)$$

$$dq_{GIT}/dt = Q \cdot C_p(t) - (\lambda_{excr} + \lambda_{GIT\text{-}Plasma} + \lambda_r) \cdot q_{GIT}$$

$$dq_{Plasma}/dt = \lambda_{GIT\text{-}Plasma} \cdot q_{GIT} + \lambda_{Surf.bone\text{-}Plasma} \cdot q_{Surf.bone} - (\lambda_{urin.excr.} + \lambda_{Plasma\text{-}Surf.bone} + \lambda_{Milk\ excr.} + \lambda_r) \cdot q_{Plasma}$$

$$dq_{surf.bone}/dt = \lambda_{Plasma\text{-}Surf.bone} \cdot q_{Plasma} - (\lambda_{Surf.bone - Plasma} + \lambda_{Surf.bone - Bone} + \lambda_r) \cdot q_{Surf.bone}$$

$$dq_{Bone}/dt = \lambda_{Surf.bone\text{-}Bone} \cdot q_{Surf.bone} - \lambda_r \cdot q_{Bone}$$

$$C_{milk}(t) = \lambda_{Plasma\text{-}Milk} \cdot q_{Plasma}/V_{milk}$$

where:

C_p	is the Ra-conc. in pasture (dry, Bq/kg);
C_s	is the Ra-conc. in soil (dry, Bq/kg);
λ_r	is the rate constant of the radioactive decay (d^{-1});
λ_l	is the leaching and downward transport coefficient from the root soil layer, and:

$$\lambda_l = .I_{net} / (h_{root\ soil} . K_d . m . p . \rho) ,$$

where:

I_{net}	is the net flow of water downward into the soil (equal to the rain) (m/d),
K_d	is the concentration factor (m^3/kg),
M	is the moisture of the root soil (0-1),
p	is the porosity (0-1),
ρ	is the density of the root soil (kg/m^3),
$h_{root\ soil}$	is the thickness of the root soil layer (m);

TF	is the bioaccumulation factor, soil to pasture;
Q	is the feeding (kg/d, dry);
$\lambda_{i\text{-}j}$	is the linear transport coefficients (d^{-1}), from compartment i to j;
q_i	is the activity in the i-th compartment (tissue), (Bq);
V_{milk}	is the daily milk produced by the cow (l/d).

The daily Ra-226 intake of the cow was defined as the product of daily feed (8-20 kg, normal distributed for uncertainty) and the concentration in the pasture.

The Ra-226 kinetics in the pasture-cow-milk pathway was modelled by a linear compartmental system given in Figure II-1.5.1. The parameters are in Table II-1.5.I. Other parameters – mainly the soil ones – are presented in Table II-1.5.II.

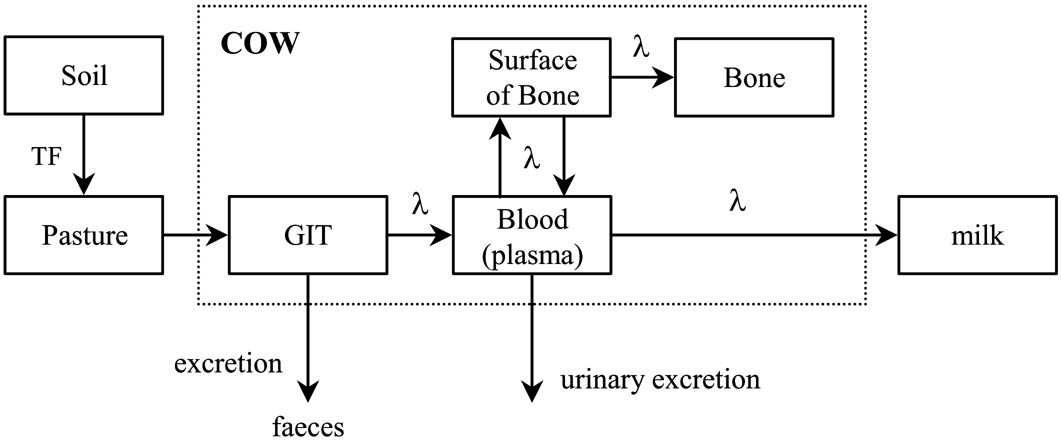

FIG. II-1.5.1. Compartmental system used to modelling the Ra-226 kinetics in the cow.

TABLE II-1.5.I. PARAMETERS USED IN THE "COW MODEL", ALL OF THEM WITH TRIANGULAR DISTRIBUTION FOR UNCERTAINTY ANALYSIS

Parameter	Mean value	Minimum	Maximum
TF(-)	0.05	0.02	0.15
λ (excretion)	2.0	0.5	5.0
λ (git-blood plasma)	0.2	0.05	0.5
λ (urinary excretion)	0.5	0.15	1.5
λ (milk excretion)	0.2	0.05	0.5
λ (blood-bone surface)	10.0	3.0	25
λ (bone surface-blood)	0.5	0.1	1.5
λ (bone surface-bone)	0.3	0.1	1.0

TABLE II-1.5.II. OTHER PARAMETERS

Parameter	Mean value	Minimum	Maximum	Type of distribution
Thickness of root soil layer (m)	0.15	–	–	constant
Water inflow rate (m/d)	2.0E-3	0.7E-3	5.0E-3	triangul.
Moisture	0.3	0.2	0.4	normal
Porosity	0.5	0.3	0.7	normal
density of root soil (kg/m^3)	0.5	0.3	0.7	normal
Feeding of the cow (kg/d, dry)	12.5	7.0	20.0	normal
Direct ingestion of cow, in winter (Bq/d)	100	30	300	triangul.

The K_d value was varying from soil to soil plots (0.15-2.5 m^3/kg). For uncertainty analysis the min and max values of it were 0.25 and 2.5 times the mean value, the type of distribution three-angular.

During the investigated period (1-2 years) the product of $(\lambda_r + \lambda_l).t \ll 1$ therefore $C_s(t) \approx C_s(0)$. It means the loss of the activity from the root soil layer is negligible.

II-1.5.2. Results of model predictions

TABLE II-1.5.III. Ra-226 CONCENTRATIONS IN THE ROOT ZONE SOIL BEFORE DEEP PLOUGHING (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval	
		Lower bound	Upper bound
1	1.2	0.80	2.4
2	2.0	0.80	3.2
3	2.3	1.6	3.3
4	3.3	2.5	4.2
5	1.4	0.82	1.7
6	0.30	0.15	0.4
7	1.1	0.83	1.7
8	0.92	0.80	1.7
9	1.6	0.80	3.2
10	1.0	0.81	1.7

TABLE II-1.5.IV. Ra-226 CONCENTRATIONS IN THE ROOT ZONE SOIL AFTER DEEP PLOUGHING, 1971 (Bq/g dw)

Plot number	[Ra] Root zone soil	95% Confidence interval lower bound upper bound	
		Lower bound	Upper bound
1	0.56	0.18	1.2
2	0.94	0.30	2.0
3	1.1	0.34	2.3
4	1.4	0.46	3.3
5	0.68	0.21	1.4
6	0.19	0.06	1.9
7	0.62	0.19	1.1
8	0.51	0.17	0.92
9	0.94	0.31	1.6
10	0.60	0.19	1.0

TABLE II-1.5.V. Ra-226 CONCENTRATIONS IN PASTURE AFTER DEEP PLOUGHING (JULY 1971) (Bq/kg dw)

Plot number	[Ra] Pasture	95% Confidence interval lower bound upper bound	
		Lower bound	Upper bound
1	30	13	66
2	50	18	89
3	56	21	110
4	75	28	260
5	34	11	70
6	11	4.8	19
7	29	11	63
8	27	9.5	46
9	54	17	110
10	29	10	55

TABLE II-1.5.VI. Ra-226 CONCENTRATIONS IN MILK AFTER DEEP PLOUGHING (1971–1972) (Bq/l)

Period	[Ra] Milk	95% Confidence interval	
		Lower bound	Upper bound
1/5–5/5/ 71	0.18	0.042	0.73
6/5–9/5	0.15	0.034	0.48
11/5–17/5	0.11	0.026	0.20
18/5–22/5	0.12	0.032	0.24
23/5–26/5	0.14	0.036	0.42
27/5–1/6	0.21	0.042	0.54
2/6–8/6	0.13	0.030	0.32
9/6–14/6	0.072	0.017	0.20
15/6–17/6	0.13	0.031	0.28
18/6–22/6	0.14	0.031	0.35
23/6–24/6	0.16	0.037	0.49
26/6–28/6	0.12	0.027	0.4
28/6–30/6	0.07	0.015	0.20
1/7–4/7	0.10	0.029	0.32
4/7–9/7	0.15	0.035	0.54
9/7–12/7	0.12	0.0241	0.39
12/7–23/7	0.10	0.022	0.31
23/7–30/7	0.07	0.015	0.26
12/8–27/8	0.11	0.024	0.40
31/8–9/9	0.10	0.023	0.25
14/9–4/10	0.13	0.030	0.4
5/10–28/10	0.07	0.016	0.21
31/10–15/11	0.10	0.024	0.51
16/11–27/11	0.017	0.0039	0.037
29/11–15/12	0.019	0.0048	0.038
16/12–30/12	0.007	0.0018	0.022
30/12–14/1 /72	0.009	0.0020	0.021
15/1–31/1	0.009	0.0018	0.022
1/2–15/2	0.009	0.0022	0.021
16/2–28/2	0.009	0.0021	0.023
1/3–15/3	0.009	0.0021	0.020
16/3–31/3	0.009	0.0021	0.022
1/4–17/4	0.0085	0.0019	0.021
18/4–1/5	0.14	0.035	0.41
2/5–20/5	0.11	0.025	0.27
21/5–31/5	0.082	0.022	0.27
1/6–15/6	0.11	0.024	0.26
16/6–30/6	0.097	0.023	0.23
1/7–19/7	0.073	0.016	0.19
20/7–10/8	0.071	0.016	0.18
10/8–31/8	0.14	0.032	0.36
1/9–15/9	0.021	0.0047	0.058
16/9–22/9	0.13	0.039	0.38
30/9–15/10	0.011	0.0024	0.034
16/10–31/10	0.0093	0.0022	0.024
1/11–27/11	0.0093	0.0021	0.022
28/11–6/12	0.0093	0.0021	0.023
6/12–31/12	0.0098	0.0022	0.024

II-1.5.3. Sensitivity analysis results

The *sensitivities* of the concentration in milk with respect to the main parameters were assessed in the following four time periods:

a. Pasture period, 1971 Summer;

b. Stable period, 1991-72 Winter;

c. Pasture period, 1992 Summer;

d. Stable, 1972 Winter.

First all the parameters were varied and then only the 3 most sensitive ones were selected and others were taken as constants. From that last running the results are shown in Table II-1.5.VII.

The uncertainties of the absolute percentages given in the table might be 3–5.

According to the data in the table the largest contribution to the Ra-226 concentration in milk has the transport coefficient from blood to milk. The next two ones are the uptake from GIT to the plasma and the transfer factor from soil to pasture during the grazing periods. Both of the coefficients λ (git-blood plasma) and λ (blood plasma-milk) represent the F_m value in steady state.

From the running of varying all the parameters the contributions of the feeding (Q), the $\lambda_{\text{excretion}}$ and the $\lambda_{\text{blood-bone surface}}$ are about 5-15 %, the other parameters (K_d, moisture, porosity etc.) less than 5 %.

TABLE II-1.5.VII. AVERAGE SENSITIVITIES (%) GOT BY MONTE CARLO*

Parameter period	TF	λ (git-blood plasma)	λ (blood plasma-milk)
a.	28	31	37
b.	< 1	41	52
c.	34	28	36
d.	< 1	43	51

* 100 × determination coefficient, where: determination coefficient = r^2 and r: partial correlation coefficient.

II-2. OLEN SCENARIO TYPE B:
DETAILED MODEL DESCRIPTIONS AND PREDICTIONS

II-2.1. CLRP-RAD

II-2.1.1. General model description

II-2.1.1.1. Name of model, model developer(s) and model user(s)

Model name:	CLRP_Rad
Model developer(s):	Pawel Krajewski, Central Laboratory for Radiological Protection, Department of Radiation Hygiene, Warsaw, Poland
Name of model user:	Pawel Krajewski

II-2.1.1.2. Intended purpose of the model in radiation assessment

Modelling of the radium transport in environment. The model has been specially designed for the BIOMASS Theme 2 Scenario Olen-B exercise.

II-2.1.1.3. Model type (equilibrium, dynamic, numerical, analytical,...)

Dynamic model of Ra-226 and Pb-210 transport in soil layers. Equilibrium model of external, ingestion and inhalation pathways. The differential equation are solved numerically, by the first order Runge-Kutta method.

II-2.1.1.4. Method used for deriving uncertainty estimates

Monte-Carlo method. The commercially available package Crystal Ball 2000 has been used. Latin hypercube sampling with the specified precision 2% for 97.5% percentile of statistics.

II-2.1.1.5. Description of model (procedures, parameters, main equations, scheme)

General comments

The description of procedures and equations used for dose calculation is presented in the following paragraphs in order of significance of exposure pathways (dose values obtained in deterministic calculation). The applied parameters and combined with them uncertainty ranges are summarised in chapter II-2.1.4. (Tables II-2.1.XVIII to II-2.1.XXVI). The discrepancy between the input parameters that have been used in dose calculations and values of item proposed in Scenario (if such discrepancy occurred) is discussed and remarked by italic text below the equations related to these parameters. Term Scenario used further in the text means the scenario description given in Appendix I of this report.

The basic model feature is ability of evaluation of ^{226}Ra, ^{222}Rn and ^{210}Pb behaviour in six soil layers of different thickness. This approach allows calculating doses for the inhomogeneous deep profile of radium in soil and takes into account the different soil proprieties within the particular layer.

The different soil proprieties for three variants of remedial action, namely: “no remediation”, “removal of most contaminated soil”, “covering with a clean soil layers 0.5 m” have been considered.

The radium concentrations in the particular soil layers L, at the time T have been evaluated by numerically solving diffusion equation:

$$\frac{dC^{L}{}_{Ra}(T)}{dt} = \frac{d}{dx}\left(D_{Ra} \frac{dC^{L}{}_{Ra}(T)}{dx} \right) - (\lambda_r + \lambda^{L}{}_{lch}) C^{L}{}_{Ra}(T)$$

$$\frac{dC^{L}{}_{Ra}(T)}{dt} = \frac{d}{dx}\left(D_{Ra} \frac{dC^{L}{}_{Ra}(T)}{dx} \right) - (\lambda_r + \lambda^{L}{}_{lch}) C^{L}{}_{Ra}(T) \qquad (1)$$

where:

$C^{L}{}_{Ra}(T)$	is the ^{226}Ra concentration in the soil layer L [Bq kg^{-1}] in the specified periods of time, namely: 1 year, 50 years, 100 years, 500 years;
D_{Ra}	is the diffusion coefficient in soil (m^2 y^{-1}] (chapter I-6.4., Appendix I);
λ_r	is the ^{226}Ra radioactive decay constant;
$\lambda^{L}{}_{lch}$	is the leach rate constant [y^{-1}] in the soil l layer.

^{226}Ra diffusion coefficient in soil has been applied both for deterministic and stochastic calculation without considering any differences in soil layers proprieties : D=1×10^{-5} [m^2 y^{-1}], D_{Ra}={ likeliest= 1×10^{-5}; pdf-triangular; 2×10^{-6}; 5×10^{-5}} respectively. It has been taken from Scenario. However, proposed in Scenario triangular distribution of D_{Ra} gives the mean value of D_{Ra} = 2.07 [m^2 y^{-1}] and produces different results in stochastic and deterministic calculation.

^{226} Ra-leach rate $\lambda^{L}{}_{lch}$, is given by:

$$\lambda^{L}{}_{lch} = \frac{I_{nfr}}{\theta_{vol} \times Th^{L} \times R_d{}^{L}}$$

$$\lambda^{L}{}_{lch} = \frac{I_{nfr}}{\theta_{vol} \times Th^{L} \times R_d{}^{L}} \qquad (2)$$

where:

I_{nfr}	is the infiltration rate [m y^{-1}];
θ_{vol}	is the volumetric water content of contaminated zone [dimensionless];
Th^{L}	is the thickness of contaminated layer L, (see Figure II-2.1.1).

The infiltration rate for contaminated zone has been calculated with the following formula [2]:

$$I_{nfr} = (1 - C_{ev}) \times \left[\left(1 - C_{runoff} \right) \times P_r + I_{arr} \right] \qquad (3)$$

where:

C_{ev}	is the evapotranspiration coefficient;
C_{runoff}	is the runoff coefficient;
P_r	is the precipitation rate [m y^{-1}].

It has been assumed that the annual irrigation rate $I_{arr,}$ is product of irrigation rate and irrigation time expressed as a fraction time of the year:

$$I_{arr} = I_{rr} \times I_{rt} / 365$$

The precipitation rate Pr = 0.76 m y^{-1} (annual rainfall) has been taken based on Scenario information.

The irrigation rate I_{rr} = {3.6×10^{-1} m y^{-1}; $1.1\times10^{-1}\div7.3\times10^{-1}$ m y^{-1}; pdf-triangular} and irrigation time I_{rt} = {100 days; 30÷150 days; pdf-triangular} results the annual irrigation rate I_{arr} = {1.20E-01 m y-1; 5.11E-02÷ 1.83E-01}

The runoff coefficient C_{runoff} = 0.2 was obtained base on Gray 1970 data [2, 3], assuming flat land, open sandy loam, cultivated land.

According to Equation (3), the calculated value of infiltration rate $I_{nfr,}$= 3.65×10-1 m y-1 and was higher than value proposed in Scenario 0.1 m y^{-1}.

The retardation factor $R^L{}_d$, in the layer L is given by:

$$R^L{}_d = 1 + \frac{\rho^L \times K^L{}_d}{\theta_{vol}} \tag{4}$$

where:

ρ^L	is the soil density of the particular layer L;
$K^L{}_d$	is the distribution coefficient in the particular soil layer[2] L;
θ_{vol}	is the volumetric water content of the contaminated zone.

The volumetric water content is the product of the saturated water content (equal to the total porosity of the soil materials p_t) and the saturation ratio of the contaminated zone R_s:

$$\theta_{vol} = p_t \times R_s \tag{5}$$

The saturation ratio R_s has been estimated for the whole contaminated zone by equation:

$$R_s = \left(\frac{I}{K_{sat}} \right)^{\frac{1}{2b+3}} \tag{6}$$

where:

b	is the soil specific exponential parameter;
K_{sat}	is the saturated hydraulic conductivity [m y^{-1}];
I_{nfr}	is the infiltration rate [m y^{-1}].

---

[2] The radionuclide equilibrium concentration ratio of the absorbed radionuclide (in soil) to the desorbed radionuclide in water.

Based on Scenario information, and literature preview, K_{sat} value for loamy sand soil has been selected as follows:

$$K_{sat} = \{3500 \text{ m y}^{-1};\ 1000 \div 5500;\ \text{pdf= triangular; likeliest } 4000\}[2].$$

The retardation factors R^L_d and leach rates λ^L_{lch} have been calculated for each particular soil layers taking in to account the different soil proprieties for the variants of remedial action considered in Scenario, namely: "no remediation", "removal of most contaminated soil", "covering with a clean soil layers 0.5 m".

Assumed soil proprieties i.e. soil porosity, soil moisture, soil bulk densities are given (Tables II-2.1.XVIII to II-2.1.XXI) respectively.

The resulting ^{226}Ra leach rates are presented in Table II-2.1.I. They do not change more than factor 2, however they reflect kind of compromise between site specific and literature default values of input parameters.

— *^{210}Pb transport in soil*

^{210}Pb a long live daughter products of ^{226}Ra (Half-life 22.3 y) gets equilibrium with ^{226}Ra after about 200 years since the time of pure radium release.

Assuming that, the highest release had been occurred in 1936, and considering the starting date of calculation as the year in which the last soil profiles were taken e.g. 1998, one can obtain the equilibrium factor between ^{226}Ra and ^{210}Pb in the first, 50-th, 100-th, 200-th and 500-th year of calculation as: 0.86, 0.97, 0.99, 1, 1 respectively. The equilibrium factor for the first year 0.86 differs slightly comparing with item indicated in scenario" ^{210}Pb is at equilibrium with ^{226}Ra after one years of calculation".

The ^{210}Pb doses have been calculated assuming that ^{210}Pb concentration in soil has the same vertical profile that radium. This simplification neglects the fact that about of 20 percent of ^{210}Pb might follow radon emanating from soil and gets radon concentration profile in soil.

The long term ^{210}Pb concentration in soil layers has been calculated using the different ^{210}Pb leach rates than items for ^{226}Ra assuming the higher distribution coefficients Kd of ^{210}Pb (Table II-2.1.II).

TABLE II-2.1.I. ^{226}Ra LEACH RATES FOR DIFFERENT SOIL LAYERS DEPENDING ON REMEDIAL ACTION APPLIED

No Action		Removing		Capping	
Soil layers	Leaching rates Ra-226	Soil layers	Leaching rates Ra-226	Soil layers	Leaching rates Ra-226
0-15 cm	1.64E-03 1/y	0-15 cm	6.63E-04 1/y	0-50 cm	1.35E-04 1/y
15-30 cm	1.01E-03 1/y	15-30 cm	6.13E-04 1/y	50-65 cm	6.63E-04 1/y
30-50 cm	6.02E-04 1/y	30-50 cm	4.60E-04 1/y	65-80 cm	1.33E-03 1/y
50-75 cm	3.13E-04 1/y	50-75 cm	3.68E-04 1/y	80-100 cm	9.19E-04 1/y
75-100 cm	3.31E-04 1/y	75-100 cm	3.68E-04 1/y	100-125 cm	3.68E-04 1/y
100-150 cm	1.19E-04 1/y	100-150 cm	1.84E-04 1/y	125-150 cm	3.68E-04 1/y
150-200 cm	1.63E-04 1/y	150-200 cm	1.84E-04 1/y	150-200 cm	1.84E-04 1/y

TABLE II-2.1.II. ^{210}Pb LEACH RATES FOR DIFFERENT SOIL LAYERS DEPENDING ON REMEDIAL ACTION PERFORMED

No Action		Removing		Capping	
Soil layers	Leaching rates Ra-226	Soil layers	Leaching rates Ra-226	Soil layers	Leaching rates Ra-226
0-15 cm	3.03E-03 1/y	0-15 cm	1.33E-03 1/y	0-50 cm	2.70E-04 1/y
15-30 cm	1.87E-03 1/y	15-30 cm	1.23E-03 1/y	50-65 cm	1.33E-03 1/y
30-50 cm	1.20E-03 1/y	30-50 cm	9.19E-04 1/y	65-80 cm	2.46E-03 1/y
50-75 cm	6.26E-04 1/y	50-75 cm	7.35E-04 1/y	80-100 cm	1.70E-03 1/y
75-100 cm	6.61E-04 1/y	75-100 cm	7.35E-04 1/y	100-125 cm	7.35E-04 1/y
100-150 cm	2.38E-04 1/y	100-150 cm	3.68E-04 1/y	125-150 cm	7.35E-04 1/y
150-200 cm	3.27E-04 1/y	150-200 cm	3.68E-04 1/y	150-200 cm	3.68E-04 1/y

— *Radon concentration outdoor/indoor, radon inhalation doses*

The radon concentration and flux along a one dimensional direction within multiple layers of radium contaminated soil and cover material were calculated by using one dimensional radon diffusion equations:

$$D_{Rn}^{L}\frac{d^{2}C^{L}(x)}{dx^{2}}-\lambda C^{L}(x)+f^{L}=0 \tag{7}$$

$$\Phi(x)^{L}=-p_{t}{}^{L}D^{L}\frac{dC^{L}(x)}{dx} \tag{8}$$

where:

$C^L(x)$	is the ^{222}Rn concentration per unit volume in the pore space of layer L [Bq m^{-3}];
$\Phi^L(x)$	is the radon flux per unit area of porous medium in layer L [Bq m^{-2} s^{-1}];
λ	is the decay constant of ^{222}Rn [s^{-1}];
D^L	is the diffusion coefficient of ^{222}Rn in the particular layer) [m^2 s^{-1}];
$p_t{}^L$	is the total porosity of the medium, (interstitial volume/total volume in particular layer L) [dimensionless];
f^L	is the rate of radon production in the particular layer [Bq m^{-3} s^{-1}].

The rate of radon production f^L, is given by:

$$f^{L}=\frac{\varepsilon\times\rho^{L}\times C^{L}_{Rn-222}\times\lambda}{p_{t}{}^{L}} \tag{9}$$

where:

ε	is the radon emanation coefficient[3] [dimensionless];
λ	is the decay constant of ^{222}Rn [s^{-1}];
ρ^L	is the bulk density of soil material in the particular layer L;
$C^L{}_{Ra-226}$	is the ^{226}Ra concentration in soil [Bq kg^{-1}];
p^L	is the total porosity of the soil layer L.

---

[3] The fraction of radon generated by radium decay that escapes from the soil particles.

The boundary condition of Equations (7) and (8) are as follows:

C^H(x= H –the total layers height) = 0 - the radon concentration at the
air-ground interface is zero

Φ^L(0 – bottom of the boundary) – the radon flux is zero at the bottom of boundary,

C^L (x= H^L) = C^{L+1}(x= H^{L+1}) - the radon concentration is continuous
across the medium interfaces,

Φ^L (x= H^L) = Φ_{L+1}(x= H^{L+1}) - the radon flux is continuous
across the medium interfaces. (10)

The equations (7) and (8), together with boundary conditions (10), have been solved numerically and radon flux Φ^H at air-ground interface has been calculated [4].

The radon diffusion coefficients have been calculated considering the changes in soil proprieties in different layers, using the Rogers formula:

$$D_{soil}^{Rn-222} = D_{air}^{Rn-222} \times p_t^L \exp(-6 \times R_S \times p_L - 6 \times R_S^{14 p_t^L}) \quad (11)$$

where:

D^{Rn-222}_{air} is the radon diffusion coefficient in air ($m^2\ s^{-1}$);

p_t^L is the total porosity of particular soil layer L;

R_s is the saturation ratio defined as the ratio of water content over the total porosity [dimensionless].

The calculated ^{222}Rn diffusion coefficient fits in a range of ($37 \div 44\ m^2\ y^{-1}$) depending on the particular soil layers, and is lower than recommended in Scenario default value of 63.1 $m^2\ y^{-1}$.

The ^{222}Rn emanation coefficient has been estimated based on Scenario information that *^{226}Ra concentration in soil of 1 Bq g^{-1} yields to the ^{222}Rn concentration in indoor and outdoor air of 20 Bq m^{-3} and 330 Bq m^{-3} respectively (paragraph I-6.3.5 of Appendix I).* Assuming outdoor and indoor conditions i.e. buildings size, air exchange rate, average annual wind speed etc. according to Scenario description, one can obtain a higher ^{222}Rn emanation coefficient than item suggested in Scenario (0.45 instead of 0.25[4]). The ^{222}Rn emanation coefficient $\varepsilon = 0.45$ yields the radon concentration in outdoor, indoor air equal to 20 Bq m^{-3}, 200 Bq m^{-3} respectively and appears to be more consistent with measurements data. The $\varepsilon = 0.25$ gives lower values of ^{222}Rn concentration in outdoor and indoor air of 7 Bq m^{-3} and 100 Bq m^{-3} respectively.

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[4] Unknown source.

TABLE II-2.1.III. ^{222}Rn DIFFUSION COEFFICIENT IN PARTICULAR SOIL LAYERS DEPENDING ON THE REMEDIAL ACTION APPLIED

No Action		Removing		Capping	
Soil layers	^{222}Rn diffusion coefficient	Soil layers	^{222}Rn diffusion coefficient	Soil layers	^{222}Rn diffusion coefficient
0-15 cm	1.40E-06 (m^2/s)	0-15 cm	1.38E-06 (m^2/s)	0-50 cm	1.18E-06 (m^2/s)
15-30 cm	1.38E-06 (m^2/s)	15-30 cm	1.38E-06 (m^2/s)	50-65 cm	1.38E-06 (m^2/s)
30-50 cm	1.37E-06 (m^2/s)	30-50 cm	1.38E-06 (m^2/s)	65-80 cm	1.38E-06 (m^2/s)
50-75 cm	1.40E-06 (m^2/s)	50-75 cm	1.38E-06 (m^2/s)	80-100 cm	1.38E-06 (m^2/s)
75-100 cm	1.33E-06 (m^2/s)	75-100 cm	1.38E-06 (m^2/s)	100-125 cm	1.38E-06 (m^2/s)
100-150 cm	1.40E-06 (m^2/s)	100-150 cm	1.38E-06 (m^2/s)	125-150 cm	1.38E-06 (m^2/s)
150-200 cm	1.39E-06 (m^2/s)	150-200 cm	1.38E-06 (m^2/s)	150-200 cm	1.38E-06 (m^2/s)

The annual average radon concentration in outdoor air $\hat{C}_{out}$:

$$\hat{C}_{out} = \frac{\Phi^{H} \times F_{out}}{\lambda \times H_{mix}} \times \left[1 - \exp\left(- \frac{\lambda \times L_{eff}}{2 \times u_{wind}} \right) \right] \tag{12}$$

where:

Φ^H is the radon flux at air-ground interface outdoor [Bq m^{-2} s^{-1}];

F_{out} is the outdoor area correction factor (lateral dispersion effect), this factor is equal to for area > 100 m^2;

H_{mix} is the height in to which radon plume is uniformly mixed (2 m);

λ is the decay constant of Rn-222 [s^{-1}];

L_{eff} is the effective length of contaminated area equal to 37 m for area of 1500 m^2;

u_{wind} is the average annual wind speed [m s^{-1}] [5].

The annual average radon concentration in indoor building air $\hat{C}_{in}$:

$$\hat{C}_{in} = \frac{\left(\frac{\Phi_{in}^{H} \times F_{in}}{\Gamma_{vol/area}} \times \nu \times \hat{C}_{out} \right)}{\lambda + \nu} \tag{13}$$

where:

Φ^{in}_{H} is the radon flux at air-floor interface indoor;

$\Gamma_{vol/area}$ is the ratio of the interior volume of the house to the floor area of the house [m];

ν is the air exchange rate (1 h^{-1});

F_{in} is the indoor area factor.

$$F_{in} = 1 + {4D_f} \Big/ {\sqrt{A^{interior}_{house}}} \tag{14}$$

where:

D_f is the depth of foundation [m];

$A^{interior}_{house}$ is the interior surface area of the house floor [m^2].

---

[5] Evaluated base on scenario description given in Appendix I of this report

The two story family house was assumed.

The indoor radon from water use was neglected because of small contribution to the radon in the air indoors (expected 10^{-4} of radon concentration in air [5].

The summary of used parameters is given in Table II-2.1.XXIII.

The doses from Rn-222 inhalation outdoor and indoor:

$$D_{inh}^{indoor/outdoor} = C_{^{222}Rn}^{indoor/outdoor} \times DCF_{^{222}Rn} \times O^{indoor/outdoor} \tag{15}$$

where:

$C^{indoor/outdoor}$ is the ^{222}Rn concentration in indoor/outdoor air;
$DCF_{Rn\text{-}222}$ is the dose conversion factor;
$O^{indoor/outdoor}$ is the occupancy factor.

^{222}Rn inhalation dose conversion factor $DCF_{Rn\text{-}222}$ of 3.15×10^{-2} mSv y^{-1} Bq m^{-3} (at 100% occupancy and equilibrium factor 0.4) has been used.

For simplicity of calculation, the same value of $DCF_{Rn\text{-}222}$ has been applied for indoor and outdoor condition, although in the outdoor air condition the equilibrium factor between radon and radon progenies is close to unity (1÷0.8) and the different DCF should be applied.

The summary of used parameters is given in Table II-2.1.XXIII.

— *External ground radiation exposure*

The effective dose equivalent for the external ground radiation pathway has been calculated as the effective dose equivalent for the standard source multiplied by the environmental transport factor E^L that can be expressed by formula [6]:

$$E^L = \rho^L \times O \times \Pi \times S \times A \times D^L \times C^L \tag{16}$$

where:

ρ_L is the bulk density of soil in the particular layer L [kg m^{-3}];
O is the occupancy factor (indoor 0.795, 0.205 outdoor) [dimensionless];
Π is the shielding factor (outdoor 0.7, indoor 0.25) [dimensionless];
S^6 is the shape factor (1) [dimensionless];
A^7 is the area factor (1) [dimensionless].

The depth factor D_L (Th_L, ρ_L), is a function of layer thickness and density as given by:

$$\mathrm{D}^L(\mathrm{Th}^L, \rho^L) = 1 - \exp(-\kappa^L \times \rho^L \times Th^L) \tag{17}$$

---

[6] Used for the noncircular-shape area factor- for scenario purposes estimated as 0.75 (0.6; 1), for a large surface the contamination is close to unity.

[7] Calculated for a circular-area-equivalent contaminated zone. For area more than 1000 m^2 this factor is close to unity.

where:

Th^L is the thickness of contaminated layer L;
$\kappa^L(\rho^L)$ is the empirical parameter that is function of the layer L bulk density;
C^L (Cd^L, ρ^L) is the cover factor for contaminated zone that is approximated by the formula:

$$\mathrm{C}^L(\mathrm{Cd}^L, \rho^L) = 1 - \exp(-\kappa^L \times \rho^L \times Cd^L) \tag{18}$$

where:

Cd^L is the depth of cover [m] (see Figure II-2.1.1);
$\kappa^L(\rho^L)$ is the empirical parameters as a function of layer bulk density.

Empirical parameter κ^L is calculated by linear extrapolation of tabulated depth factors for standard soil density 1000 kg m^{-3} and 1800 kg m^{-3}:

$$\kappa^L(\rho^L) = \frac{-\ln\left[1 - D^L(\rho^L)_{Th^L=0.15}\right]}{0.15 \times \rho^L}$$

Tabulated values for Ra-226+D and Pb-210+D are presented in tables below:

TABLE II-2.1.IV. DEPTH FACTORS $D^L(\rho, Th)$ FOR Ra-226+DAUGHTERS

Density ρ		
1000.00 kg/m3 Thickness = 0.15 m	1000.00 kg/m3 Thickness = 0.50 m	1000.00 kg/m3 Thickness = 1.00 m
0.63	0.92	1
Density ρ		
1800.00 kg/m3 Thickness = 0.15 m	1800.00 kg/m3 Thickness = 0.50 m	1800.00 kg/m3 Thickness = 1.00 m
0.85	1	1

TABLE II-2.1.V. DEPTH FACTORS $D^L(\rho, Th)$ FOR Pb-210+DAUGHTERS

Density ρ		
1000.00 kg/m3 Thickness = 0.15 m	1000.00 kg/m3 Thickness = 0.50 m	1000.00 kg/m3 Thickness = 1.00 m
0.88	1	1
Density ρ		
1800.00 kg/m3 Thickness = 0.15 m	1800.00 kg/m3 Thickness = 0.50 m	1800.00 kg/m3 Thickness = 1.00 m
0.97	1	1

TABLE II-2.1.VI. EFFECTIVE DOSE EQUIVALENT OF THE STANDARD SOURCE (INFINITY DEPTH) FOR Ra-226 +D[a]

Soil bulk density	
1.00 g/cm3	1.80 g/cm3
4.19E-06 (mSv/yr)/(Bq/m3)	2.31E-06 (mSv/yr)/(Bq/m3)

[a] Value recommended in scenario for Ra-226 (chapter I-6.3.6, Appendix I) was equal to 2.10E-06 mSv/yr/(Bq/m3).

TABLE II-2.1.VII. EFFECTIVE DOSE EQUIVALENT OF THE STANDARD SOURCE (INFINITY DEPTH) FOR Pb-210 +D[b]

Soil bulk density	
1.00 g/cm3 1.32E-09 (mSv/yr)/(Bq/m3)	1.80 g/cm3 6.24E-10 (mSv/yr)/(Bq/m3)

[b] Value recommended in Scenario for Pb-210 (chapter I-6.3.6, Appendix I) was equal to 1.31E-09 (mSv/yr)/(Bq/m3)

The standard source is a contaminated zone of infinite depth with no cower [2]. The actual source is approximated by a cylindrical contaminated zone of radius R and located at distance H below the ground surface.

The summary of used parameters for external ground exposure pathway is given in Table II-2.1.XXIV.

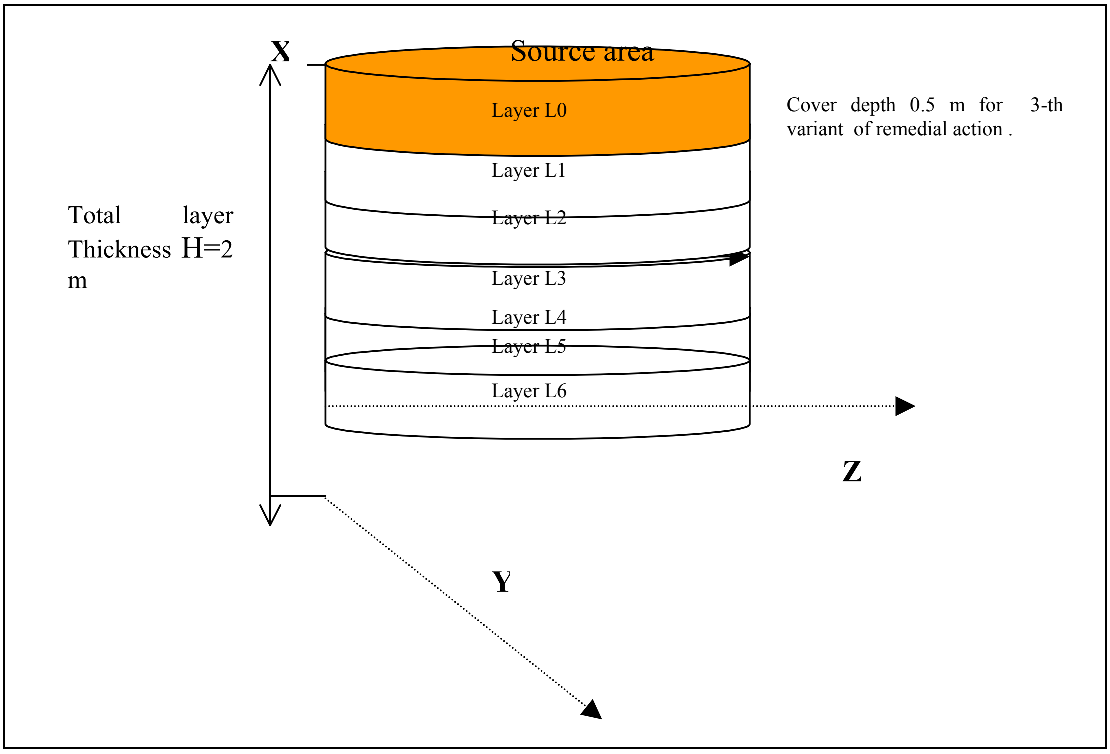

FIG. II-2.1.1. Geometry of contaminated zone.

— *^{226}Ra and ^{210}Pb dust inhalation*

The doses due to airborne dust of ^{226}Ra and ^{210}Pb inhalation are given by:

$$D_{inh\_dust}^{indoor/outdoor} = C_{^{226}Ra/^{210}Pb}^{indoor/outdoor} \times Bh^{indoor/outdoor} \times DCF_{^{226}Ra/^{210}Pb} \qquad (19)$$

where:

$C^{indoor/outdoor}{}_{Ra\text{-}226/Pb\text{-}210}$ is the airborne dust concentration (indoor, outdoor) of ^{226}Ra and ^{210}Pb respectively;

$Bh^{indoor/outdoor}$ is the annual intake of air ($m^3\ y^{-1}$) (indoor/outdoor respectively).

The annual intake of air for indoor and outdoor conditions are:

$$B_h^{indoor} = Time_{indoor} \times Bh^{residential}{}_{rate} \tag{20}$$

Based on Scenario data: B_{indoor}= 5250 m3 y^{-1} and $B_{outdoor}$=2160 m3 y^{-1}

$DCF_{Ra\text{-}226/Pb\text{-}210}$ is the Committed Effective Dose Equivalent Conversion Factors for inhalation:

$DCF_{Ra\text{-}226}$ = 9.5E-03 (mSv/Bq);
$DCF_{Pb\text{-}210}$ = 5.6E-03 (mSv/Bq).

The airborne dust concentration outdoor $C^{air(outdoor)}{}_{Ra\text{-}226/Pb\text{-}210}$, has been evaluated base on the mass loading model by:

$$C^{air(outdoor)}_{Ra-226/Pb-210} = C^{soil}_{Ra-226/Pb-210} \times C_f \times F_{cd} \times S_{area} \tag{21}$$

where:

$C^{soil}{}_{Ra\text{-}226/Pb\text{-}210}$ is the concentration of ^{226}Ra and ^{210}Pb in the first (0-15 cm) soil layer;

C_f stands for average mass loading factor of airborne contaminated soil particles, the C_f default value of 2.00E-07 kg m^3 was assumed [3];

F_{cd} is the depth factor defined as the fraction of resuspendable soil particles at the ground surface.

Assuming, that the mixing of the soil will occur within a layer of thickness much lower then the thickness of contaminated zone the depth factor F_{cd} = 1.

S_{area} denotes the fraction of airborne dust that is contaminated;

S_{area} can be determined from:

$$S_{area} = \frac{\sqrt{A}}{\sqrt{A} + Dl} \tag{22}$$

where:

A is the area of contaminated zone (1500 m^2);

Dl is the dilution length, default value of 3 m has been assumed.

That gives S_{area} factor of 0.928 and relatively higher inhalable dust concentration in air for agricultural activities comparing with the value indicated in Scenario (1.86 instead of 1 respectively)

The airborne dust concentration indoor $C^{air(indoor)}{}_{Ra\text{-}226/Pb\text{-}210}$ is given by:

$$C^{air(indoor)} = C^{air(outdoor)} \times B_{filtr}$$

where:

B_{filtr} is the house filtration factor (dimensionless).

B_{filtr} value of 15% has been estimated from Scenario data as a ratio of inhalable dust concentration in air indoor to inhalable concentration in air outdoor i.e. 1.5×10^{-8} kg m^{-3} to 1×10^{-7} kg m^{-3} respectively.

The summary of used parameters for dust inhalation pathway is shown in Table II-2.1.XXV.

— *Ingestion dose*

The annual dose due to ingestion from Ra-226 and Pb-210 was calculated according formula:

$$D_{ing} = E_{ing}^{Ra-226/Pb-210} \times \sum_i I_i \times C_i^{Ra-226/Pb-210} \tag{23}$$

where:

D_{ing} is the annual ingestion dose [mSv y^{-1}];
$E_{ing}^{Ra-226/Pb-210}$ is the Committed Effective Dose Equivalent Conversion Factor[8] [mSv Bq^{-1}];
E_{ing}^{Ra-226} = 2.80×10^{-4} mSv Bq^{-1};
E_{ing}^{Pb-210} = 6.9×10^{-4} mSv Bq^{-1};
I_i is the annual ingestion rate of food i [kg y^{-1}];
$C_i^{Ra-226/Pb-210}$ is the activity concentration in food product i of Ra-226 and Pb-210 respectively.

Following Scenario description, only ingestion of several products has been considered e.g. leafy vegetables, potatoes, milk and beef. The ingestion rate of leafy vegetation has been assumed as 17 kg/per year[9] instead of 56 kg as indicated in the Scenario because it stands for a total amount of vegetables consumed.

Activity concentration in leafy vegetables and potatoes is expressed in Bq kg^{-1} dry weight.

A foliar interception of leafy vegetables and potatoes has been neglected in calculation due to assumption that high uncertainty combined with the soil to plant transfer factor might overlap the rather weak effect of foliar interception.

II-2.1.1.6. Assumptions concerning parameters values, exposure pathways, etc.:

— *Evaluation of Ra-226 soil concentration profile*

Based on the results of measurements of ^{226}Ra concentration in soil (Table II-2.1.VIII) (given in Scenario), the lognormal mean and standard deviation have been calculated for each soil layer. The validity of lognormal distribution of measurements data has been check out by Chi-squared method using Batch Fit tool of statistical package Cristal Ball 2000 [1]. The Ch-squared p value of 0.753 has been obtained for the measurements of ^{226}Ra concentrations in the first soil layer (0-20 cm). This indicates a close fit to the lognormal distribution. Poor statistics of measurements for the next layers make impossible to perform the test, but the same assumption about lognormal distribution was applied for the deeper layers.

The results of statistical evaluation of Ra-226 in soil measurements are presented in Tables II-2.1.VIII and II-2.1.XXVII.

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[8] The dose conversion factors aggregated for intake of principal radionuclide together with radionuclides of the associated decay chain in equilibrium.

[9] Polish data of leafy vegetables consumption rate.

— *Ra-226 external dose rate above ground model validation*

The external dose calculation method was validated base on the dose rate measurements in the test region[10] (Table II-2.1.VIII and Figure II-2.1.2). The results of comparison suggest more consistent information in the Scenario description (see Section II-2.1.3).

Additionally, the cumulative distribution of external dose rate above ground, resulting from assumed ^{226}Ra concentrations in soil, has been generated by stochastic tool (LHS, precision 2% at 99% confidence, 22 000 trials) and compared with the distribution evaluated from measurements data (Table I-XVI, Appendix I). Result of stochastic simulation of external dose rates is presented on Figure II-2.1.3 and comparison of cumulative distributions on Figure II-2.1.4. The satisfactory agreement between both distributions has been obtained, however the measured dose rates distribution is shifted *to lower doses* comparing with the distribution of dose rates generated from ^{226}Ra concentration in soil. It might indicate that the evaluated ^{226}Ra concentrations in soil are somewhat higher than items representative for whole contaminated area (Situation II). Nevertheless, the conservative assumption about ^{226}Ra contamination might be reasonable for radiological protection purposes.

— *Parametric analysis of Ra-226 external dose rates above ground model*

The parametric analysis has been performed to identify variables that have the most effect on the forecast of the Ra-226 external ground dose rates. Tornado chart tool of Crystall Ball 2000 has been used.

The results in Figure II-2.1.5 show the greatest swing in the dose rate forecasts values for the ^{226}Ra concentration in (0–15 cm), (30–50 cm), (15–13 cm) layers respectively (in descending order).

The next parameter of significant impact is the soil bulk density in the first (0–15 layer) and shape area factor. The remaining parameters have insignificant impact.

— *Parametric analysis of radon concentration in outdoor air model*

Similar approach has been applied to identify the model parameters influencing the radon concentration in outdoor air. The results on Figure II-2.1.6 show the greatest swing in the radon concentration for the ^{226}Ra concentration in (30–50 cm), (0–15 cm), (15–30 cm) layers respectively (in descending order).

The next important parameter, but of minor impact, is the radon emanation coefficient and soil bulk density in the first (0–15 layer). The others parameters have small impact on ^{222}Rn concentration in outdoor air, although the area of contaminated zone has influence on radon concentration in outdoor air.

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[10] Scenario paragraph I-6.2.3.2, Appendix I.

TABLE II-2.1.VIII. COMPARISON OF EXTERNAL Ra-226 DOSE RATES: CALCULATED FROM MEASURED Ra-226 CONCENTRATION IN SOIL AND MEASURED ABOVE THE GROUND

Situation I (Olen Scenario B)

Sample Identification (Localisation)	**A**	**B**	*B* *B21*	*B* *B22*	*B* *B25*	*B* *B26*	**C**	**D**	*D* B27	*D* B23	**E**	**F**	*FE* B24	*FE* B28	*FE* B29
Figure Number	Fig. I-16	Fig. I-16	Fig. I-13	Fig. I-13	Fig. I-16	Fig. I-16	Fig. I-17	Fig. I-17	Fig. 22	Fig. I-18	Fig. I-18	Fig. I-18	Fig. I-15	Fig. I-15	Fig. I-18
Soil profile depth [cm]	Measured Ra-226 concentration in the particular layers [Bq kg^{-1}]														
0-15	65	734	2500	870	11000	6300	1827	2356	1500	4400	590	267	1300	1100	2200
15-30	23	1285					1710	1399			590	141			570
30-50	16	3549					1243	4069			11800	35			400
50-75		33					35	60			25	68			
75-100		17					40	26			27	3223			
Total Dose rate from Ra-226 (evaluated + background)[a] [μSv h^{-1}]	**8.14E-02**	**4.98E-01**	**4.78E-01**	**1.88E-01**	**1.86E+00**	**1.10E+00**	**5.24E-01**	**7.57E-01**	**2.70E-01**	**6.56E-01**	**9.69E-01**	**1.42E-01**	**2.43E-01**	**2.17E-01**	**4.32E-01**
Dose rate readout from Scenario[μSv h^{-1}]	*1.00E-01*	*3.00E-01*[b] ÷ *7.00E-01*	*4.00E-01*[c] ***2.00E-01***[d]	*2.50E-0*[c] ***3.00E-01***[d]	*8.00E-02*[c] ***2.00E+00***[d]	*1.00E-01*[c] ***2.00E+00***[d]	*2.50E-01*[b] ÷ *1.00E+00*	*4.00E-01*[b] ÷ *1.00E+00*	*2.00E-01*[c] ***5.00E-01***[d]	*3.00E-01*[c] ***3.00E-01***[d]	*3.00E-01*[b] ÷ *1.00E+00*	*5.00E-02*[b] ÷ *1.20E-01*	*4.00E-01*[c] ***3.00E-01***[d]	*7.00E-02*[c] ***2.00E-01***[d]	*2.50E-01*[c] ***2.00E-01***[d]
Radon Rn-222 concentration in outdoor air [Bq m^{-3}]	**3.86E-01**	**2.36E+01**	**1.19E+01**	**3.21E+00**	**5.25E+01**	**3.00E+01**	**1.81E+01**	**3.25E+01**	**5.52E+00**	**1.62E+01**	**6.00E+01**	**1.06E+01**	**4.79E+00**	**4.05E+00**	**1.17E+01**

[a] Background of 0.07 [μSv h^{-1}] was assumed- Lieve Sweeck private communication.

[b] Estimated from Figure of the Scenario description by modeller.

[c] Circle values.

[d] Reported in Scenario values.

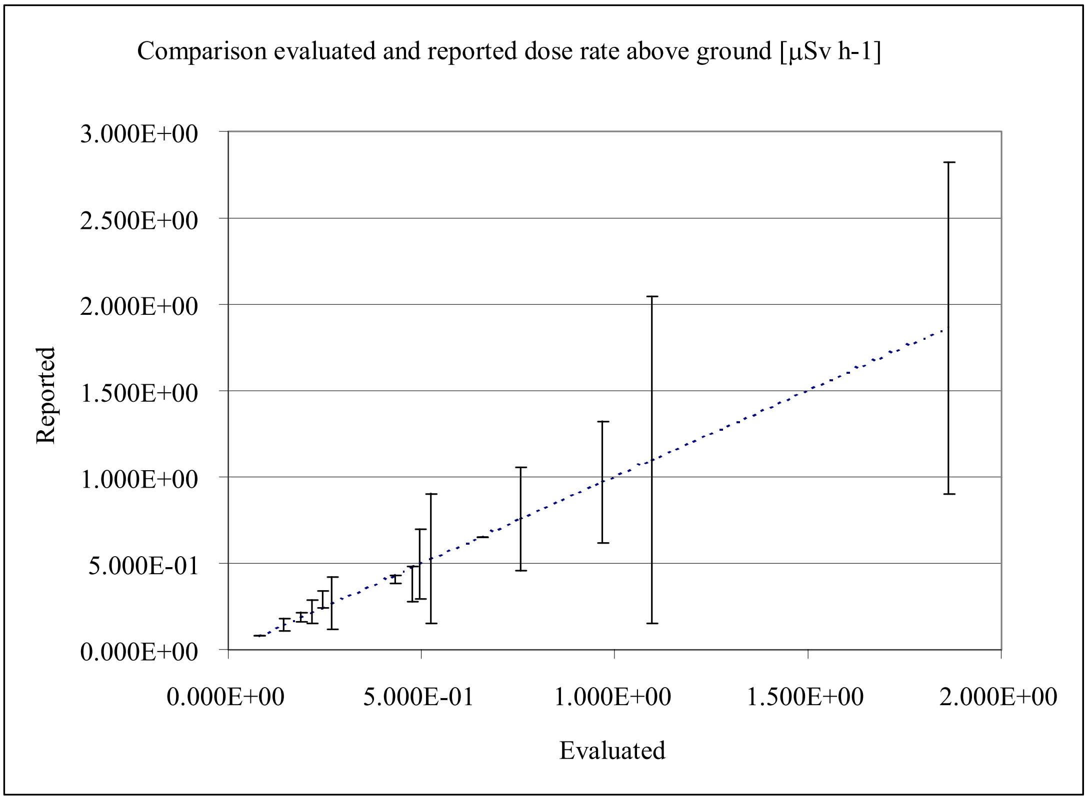

FIG. II-2.1.2. Comparison of Ra-226 dose rates: evaluated by model and reported in Scenario.

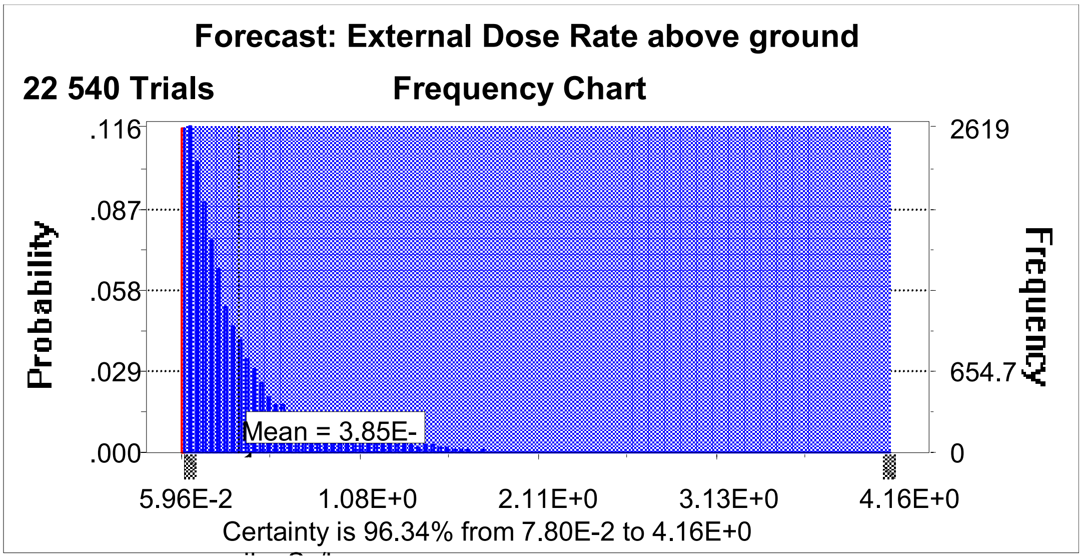

FIG. II-2.1.3. Distribution of external dose rate from Ra-226 as a function of variability of Ra-226 concentration in the particular soil layers and soil density (LHS, 22 540 trials).

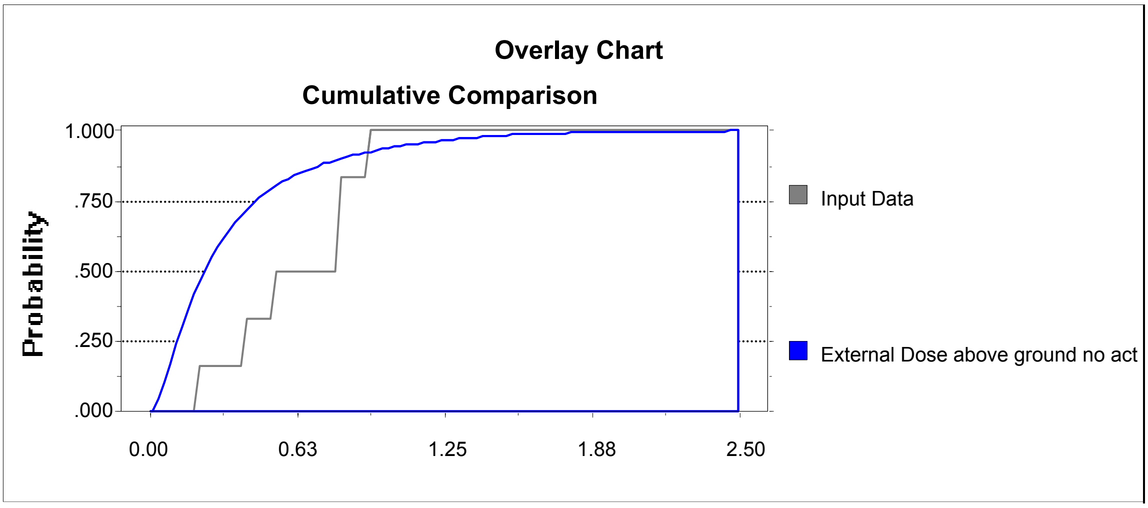

FIG. II-2.1.4. Comparison of cumulative distribution.

TABLE II-2.1.IX. RESULTS OF CHI-SQUARED TEST

Data Series:	1
Chi-squared p-value:	0.753004316
Distribution:	**2862.989**
Best fit:	Lognormal

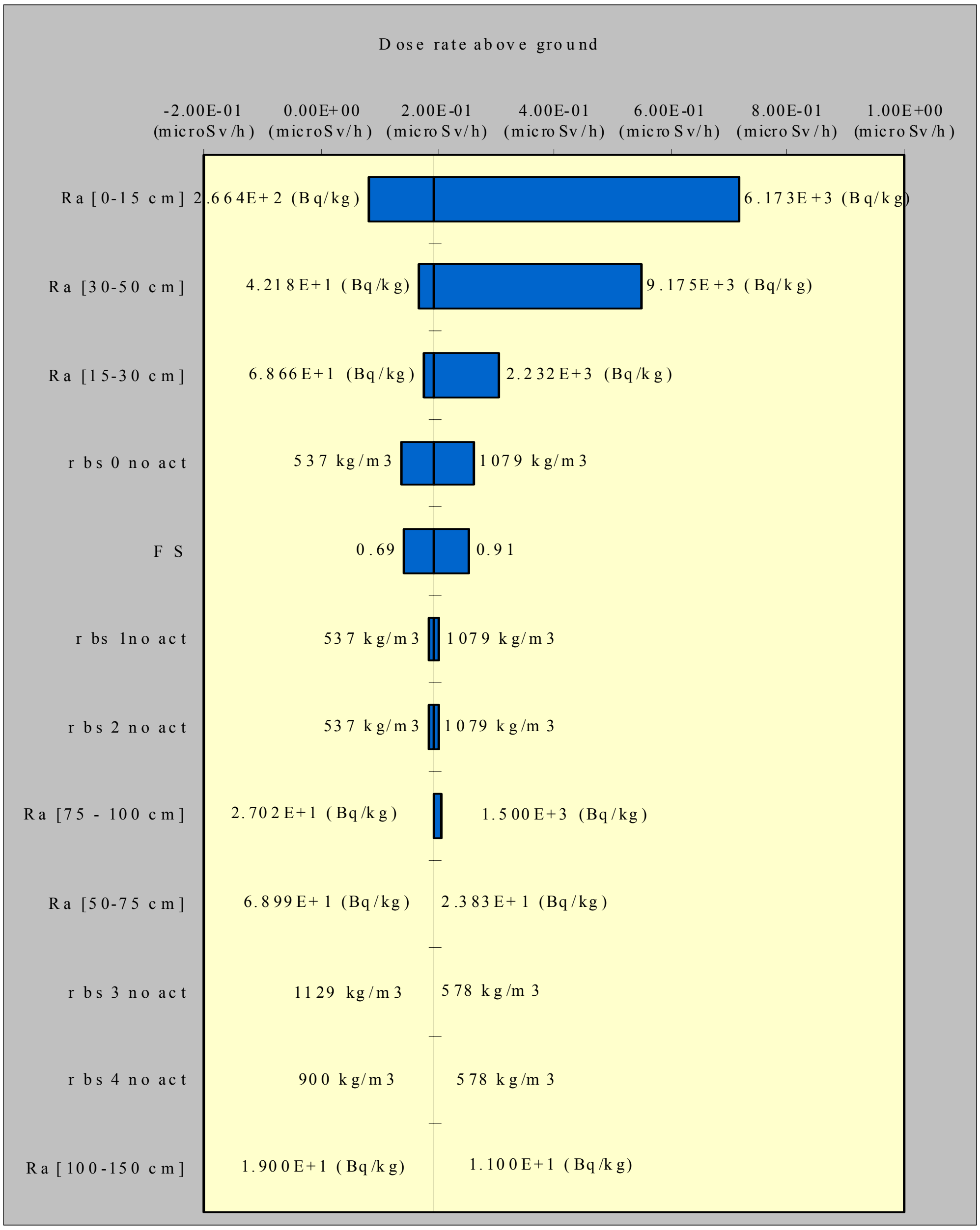

FIG. II-2.1.5. Parametric analysis of ^{226}*Ra external dose rate model (Tornado Chart).*

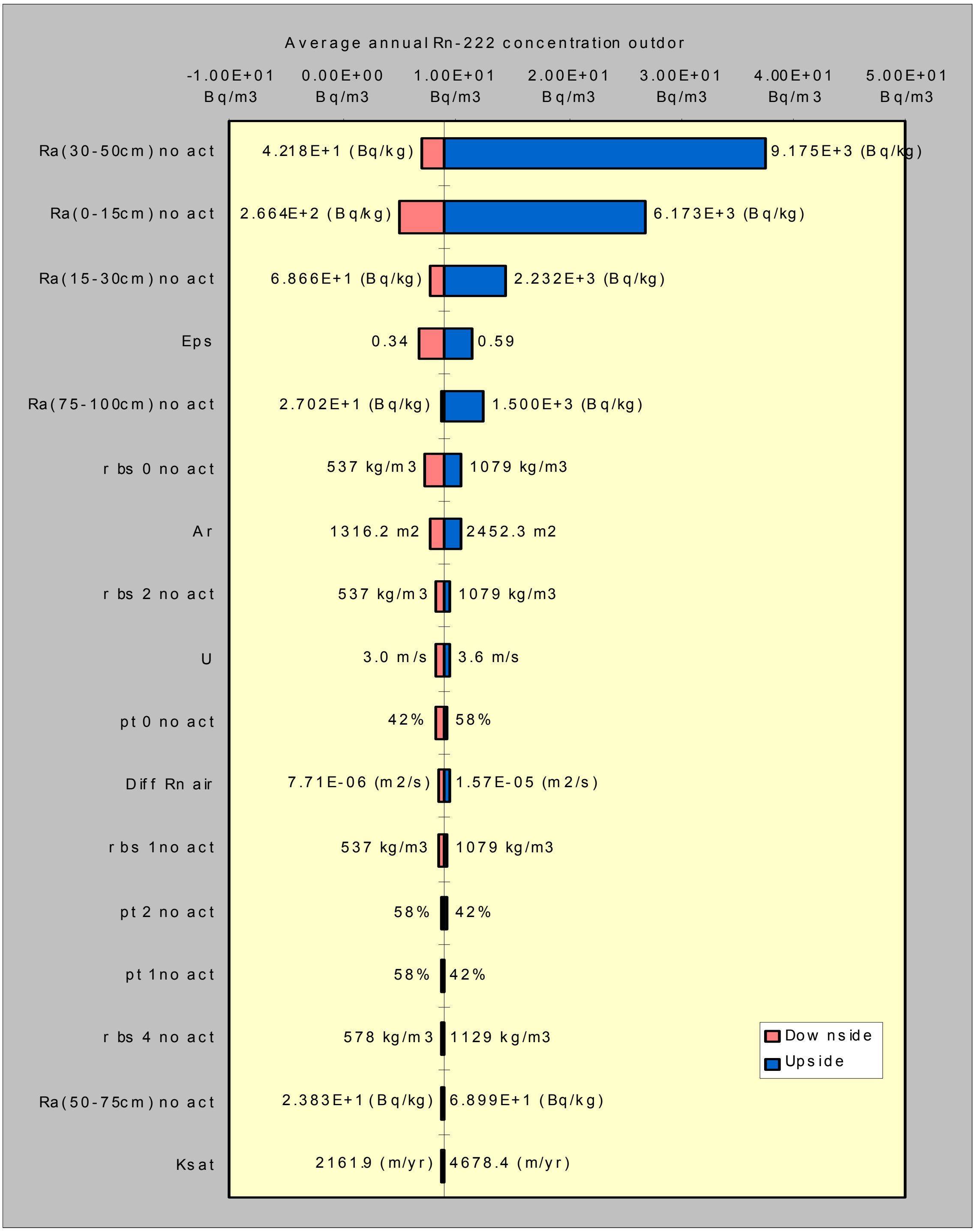

FIG. II-2.1.6. Parametric analysis of ^{222}Rn concentration in outdoor air (Tornado Chart).

II-2.1.2. Description of uncertainty method and results of sensitivity analysis

Stochastic calculation was performed using commercially available stochastic package Cristall Ball 2000 that enables user to use electronic spreadsheet model.

The summary of input parameters and uncertainty ranges is given in chapter II-2.1.4.

The uncertainty analysis has been performed for the endpoints specified in Scenario template sheet: situation I, two variants of remedial action: "no remedial action" and "covering with a clean soil layer of 0.5 m". Latin Hypercube Sampling with sample size of 500 intervals has been performed.

The arithmetic mean and 2.5% and 97.5% percentile of confidence interval have been calculated with a precision control of 2% for 97.5% percentile. The total number of trials was 58 000.

The examples of calculation are presented in the tables and figures below. Several cases have been considered: the total[11] effective dose for (^{226}Ra&^{210}Pb) in the first and 500-th year if no remedial action would be introduced, the total effective dose for (^{226}Ra&^{210}Pb) if covering with a clean soil layer of 0.5 m would be applied.

Implementation of covering the contaminated zone with a clean soil layer of 0.5 m reduces the total effective dose for (^{226}Ra&^{210}Pb) by factor of 3 (from 8.5 mSv y^{-1} to 2.84 mSv y^{-1} in the first year and from 3.5 mSv y^{-1} to 1.2 mSv y^{-1} in the 500-th year). The probability distribution of total dose is lognormal alike and the 97.5 % percentile of dose distribution after the first year of remedial action is no grater than 12 mSv y^{-1}.

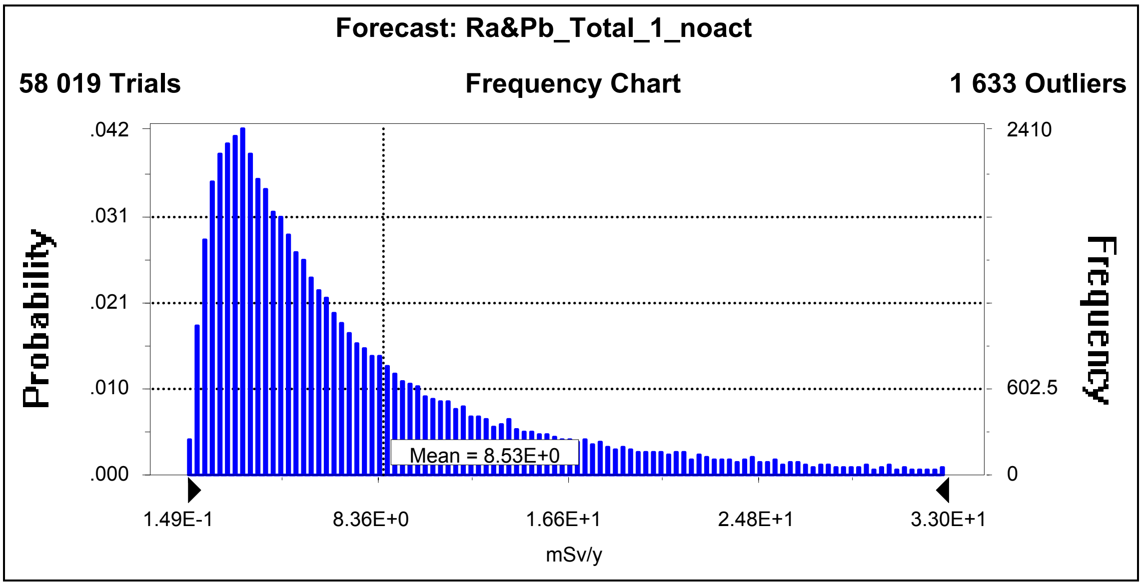

FIG. II-2.1.7. Distribution of the total effective dose for ^{226}Ra&^{210}Pb after one year. (Situation I; no remedial action).

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[11] For the all pathways specified in the Scenario description.

TABLE II-2.1.X. DESCRIPTIVE STATISTICS FOR THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER ONE YEAR. (SITUATION I; NO REMEDIAL ACTION)

Trials	58019	
Statistics:	Value	Precision
Mean	8.53E+00	1.18%
Median	5.41E+00	1.24%
Mode	–	
Standard Deviation	9.41E+00	2.37%
Variance	8.86E+01	
Skewness	3.20	
Kurtosis	20.62	
Coeff. of Variability	1.10	
Range Minimum	1.49E-01	
Range Maximum	1.79E+02	
Range Width	1.79E+02	
Mean Std. Error	3.91E-02	

TABLE II-2.1.XI. PERCENTILES FOR DISTRIBUTION OF THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER ONE YEAR. (SITUATION I; NO REMEDIAL ACTION)

Percentile	mSv/y	Precision
0.0%	1.49E-01	
2.5%	8.37E-01	
5.0%	1.13E+00	
50.0%	5.41E+00	1.24%
95.0%	2.64E+01	1.70%
97.5%	3.44E+01	1.70%
100.0%	1.79E+02	

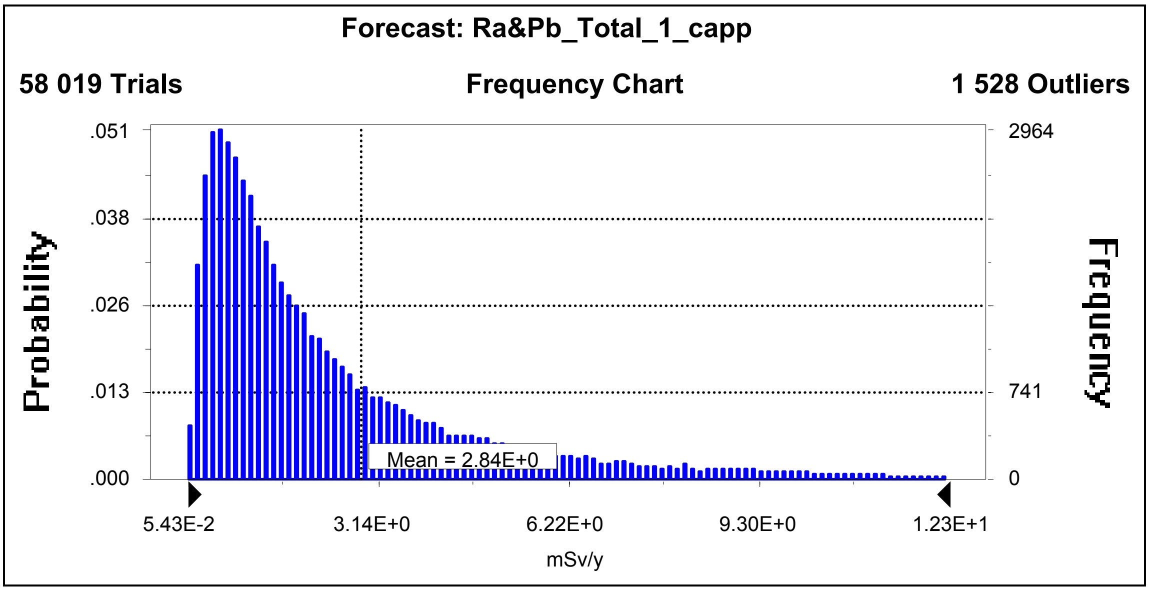

FIG. II-2.1.8. Distribution of the total effective dose for ^{226}Ra&^{210}Pb after one year. (Situation I; covering with a clean soil layer of 0.5 m).

TABLE II-2.1.XII. DESCRIPTIVE STATISTICS FOR THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER ONE YEAR. (SITUATION I; COVERING WITH A CLEAN SOIL LAYER OF 0.5 M)

Trials	58019	
Statistics:	Value	Precision
Mean	2.84E+00	1.38%
Median	1.66E+00	1.28%
Mode	–	
Standard Deviation	3.67E+00	3.26%
Variance	1.35E+01	
Skewness	4.39	
Kurtosis	38.07	
Coeff. of Variability	1.29	
Range Minimum	5.43E-02	
Range Maximum	8.02E+01	
Range Width	8.02E+01	
Mean Std. Error	1.52E-02	

TABLE II-2.1.XIII. PERCENTILES FOR DISTRIBUTION OF THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER ONE YEAR. (SITUATION I; NO REMEDIAL ACTION)

Percentile	mSv/y	Precision
0.0%	5.43E-02	
2.5%	2.55E-01	
5.0%	3.33E-01	
50.0%	1.66E+00	1.28%
95.0%	9.28E+00	1.78%
97.5%	1.27E+01	1.78%
100.0%	8.02E+01	

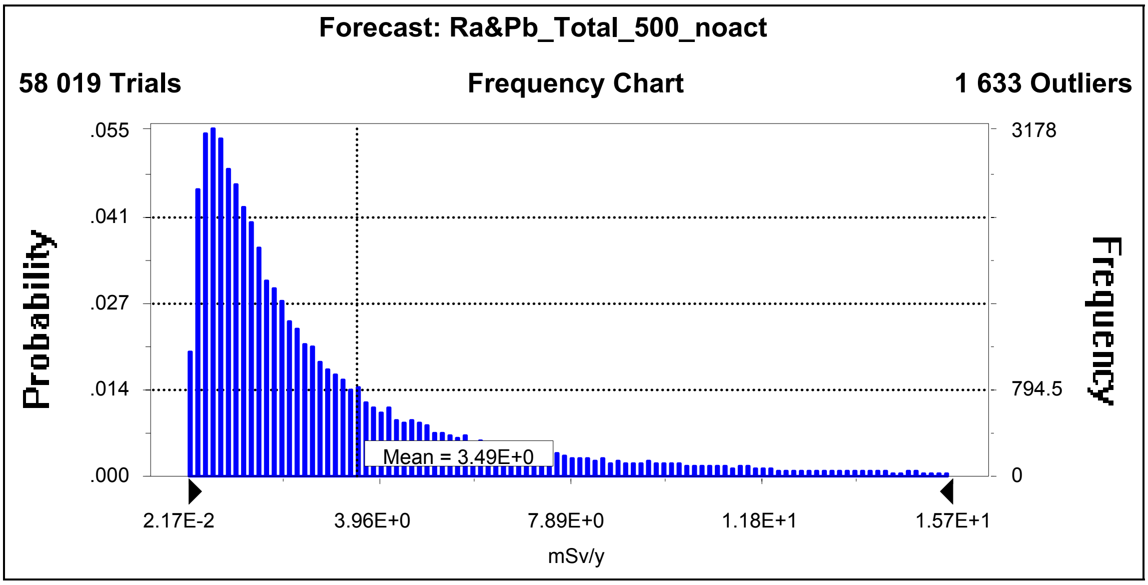

FIG. II-2.1.9. Distribution of the total effective dose for ^{226}Ra&^{210}Pb after 500 year. (Situation I; no remedial action)

TABLE II-2.1.XIV. DESCRIPTIVE STATISTICS FOR THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER 500 YEAR. (SITUATION I; NO REMEDIAL ACTION)

Trials	58019	
Statistics:	Value	Precision
Mean	3.49E+00	1.45%
Median	1.90E+00	1.50%
Mode	–	
Standard Deviation	4.72E+00	3.00%
Variance	2.23E+01	
Skewness	4.08	
Kurtosis	32.47	
Coeff. of Variability	1.35	
Range Minimum	2.17E-02	
Range Maximum	1.09E+02	
Range Width	1.09E+02	
Mean Std. Error	1.96E-02	

TABLE II-2.1.XV. DESCRIPTIVE STATISTICS FOR THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER 500 YEAR. (SITUATION I; NO REMEDIAL ACTION)

Percentile	mSv/y	Precision
0.0%	2.17E-02	
2.5%	2.02E-01	
5.0%	2.88E-01	
50.0%	1.90E+00	1.50%
95.0%	1.21E+01	1.97%
97.5%	1.65E+01	1.97%
100.0%	1.09E+02	

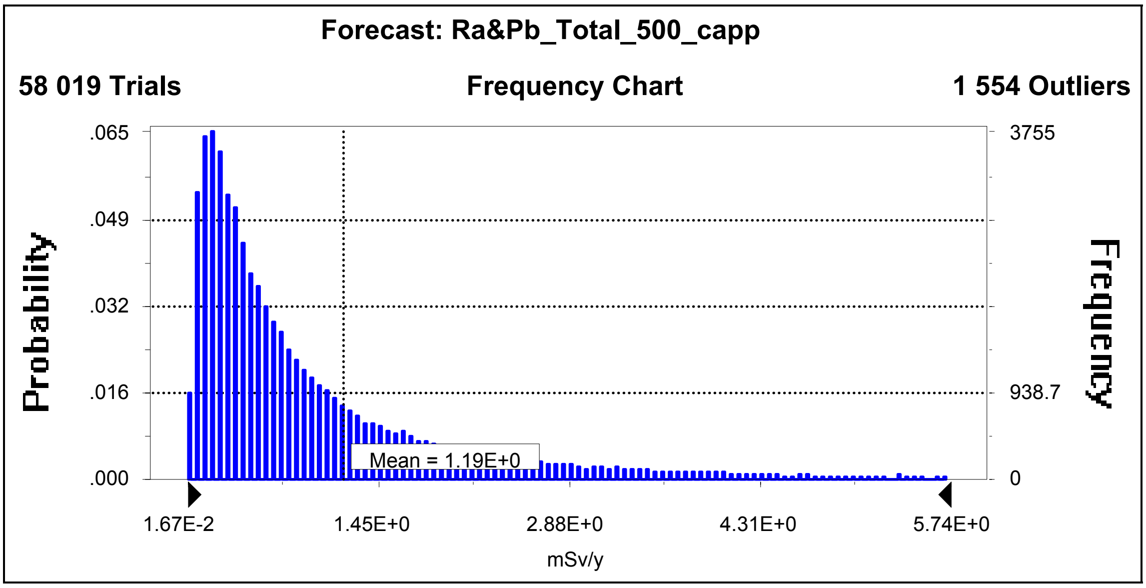

FIG. II-2.1.10. Distribution of the total effective dose for ^{226}Ra and ^{210}Pb after 500 year. (Situation I; covering with a clean soil layer of 0.5 m)

TABLE II-2.1.XVI. DESCRIPTIVE STATISTICS FOR THE TOTAL EFFECTIVE DOSE FOR ^{226}Ra AND ^{210}Pb AFTER 500 YEAR. (SITUATION I; COVERING WITH A CLEAN SOIL LAYER OF 0.5 M)

Trials	58019	
Statistics:	Value	Precision
Mean	1.19E+00	1.58%
Median	6.19E-01	1.39%
Mode	–	
Standard Deviation	1.75E+00	3.46%
Variance	3.07E+00	
Skewness	4.85	
Kurtosis	42.92	
Coeff. of Variability	1.47	
Range Minimum	1.67E-02	
Range Maximum	3.63E+01	
Range Width	3.63E+01	
Mean Std. Error	7.27E-03	

TABLE II-2.1.XVII. PERCENTILES FOR DISTRIBUTION OF THE TOTAL EFFECTIVE DOSE FOR ^{226}RA AND ^{210}PB AFTER 500 YEAR. (SITUATION I; NO REMEDIAL ACTION)

Percentile	mSv/y	Precision
0.0%	1.67E-02	
2.5%	8.59E-02	
5.0%	1.13E-01	
50.0%	6.19E-01	1.39%
95.0%	4.12E+00	1.92%
97.5%	5.94E+00	1.92%
100.0%	3.63E+01	

II-2.1.3. General comments, problems encountered

II-2.1.3.1. Concerning the evaluation of measurements data

There are several important sets of measurements/data that can be used as a base for dose assessment and validation of dose prediction:

1. The measurements performed in the period (1991-1995):
    1.1. The measurements of ^{226}Ra concentration in soil – deep profile taken up to 1 meter from 6 locations (A, B, C, D, E, F)[12] in (Table I-XVIII of Scenario (Appendix I)) . The dose rate above ground for the points A, B, C, D, E, F is not given in Scenario but approximate dose might be evaluated from Figures I-13, I-14, I-15 if location of these points was more accurate known.

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[12] Recommended as a basic input information in Scenario, but unfortunately there is no information about the dose rate above these sampling point.

1.2. The measurements of ^{226}Ra concentration in soil- about 0.2 meter deep sample between Roerdompstraat and Kleine Nete from 4 locations (B21, B22, B23, B24), together with dose rate information above the sampling point (par. I-6.2.3.2. of the Scenario (Appendix I)), as well as a wide survey results of dose rate measurements (Figures I-13, I-14, I-15 of the Scenario)

1.3. The measurements of ^{226}Ra concentration in soil- about 0.2 meter deep sample on the former bed of the Bankloop from 5 locations (B25, B26, B27, B28, B29) together with dose rate information above the sampling point (par. I-6.2.3.2. of the Scenario (Appendix I)) as well as a wide survey results of dose rate measurements (Figures I-16, I-17, I-18 of the Scenario (Appendix I)).

Unfortunately there is no correspondence between indicated in par. I-6.2.3.2 (Appendix I) *reported dose rate* and circled dose rate for locations mentioned above:

B21 (Figure 18) – (circle values 0.4 μSv h^{-1} ; reported values 0.2 μSv h^{-1})
B22 (Figure 18) – (circle values 0.025 μSv h^{-1} ; reported values 0.03 μSv h^{-1})
B25 (Figure 21) – (circle values 0.08 μSv h^{-1} ; reported values 2 μSv h^{-1}) !?
B26 (Figure 21) – (circle values 0.1 μSv h^{-1} ; reported values 2 μSv h^{-1}) !?
B27 (Figure 19) – (circle values 0.2 μSv h^{-1} ; reported values 0.5 μSv h^{-1})
B24 (Figure 23) – (circle values 0.4 μSv h^{-1} ; reported values 0.3 μSv h^{-1})
B28 (Figure 20) – (circle values 0.07 μSv h^{-1} ; reported values 0.2 μSv h^{-1})
B29 (Figure 23) – (circle values 0.25 μSv h^{-1} ; reported values 0.2 μSv h^{-1})

Therefore the method of dose rate evaluation above ground for this particular location might be described.

2. Statistical evaluation of dose rates survey (Table I-XV, Table I-XVI of the Scenario (Appendix I)

There is also some information less related to the modelled site (Situation I) that can only show the order of magnitude of input parameters, as follow:

1. Exhalation factors specific for that area (approximately) (paragraph I-6.3.5 of the Scenario (Appendix I)) It was estimated that Ra-226 concentration in soil of 1 Bq kg^{-1} (uniformly distributed over infinite depth ?) corresponds to 20 Bq m^{-3} outdoor and 300 Bq m^{-3} outdoor[13].

   Assuming that the indoor and outdoor conditions according to the Scenario, one can apply higher radon Rn-222 emanation ratio than values suggested in scenario ($\varepsilon = 0.25$[14]). The radon Rn-222 emanation ratio $\varepsilon = 0.45$ yields to radon concentration in outdoor, indoor air equal to 20 Bq m^{-3}, 200 Bq m^{-3} respectively, instead of values 7 Bq m^{-3} , 100 Bq m^{-3} calculated for $\varepsilon = 0.25$.

2. Measurements of radon exhalation in dwellings in the village of St. Olen (paragraph I-6.2.3.7 of the Scenario (Appendix I)). The average Rn-222 concentration in indoor air of 150 Bq m^{-3} was obtained but it doses not help to much for the validation of predicted radon concentration for specified in Scenario tasks (Situation I and II) as the Ra-226 soil concentration for St. Olen site remains unknown.

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[13] Personal communication.

[14] Unknown source.

3. Measurements of radon exhalation in the environment (paragraph I-6.2.3.7 of the Scenario (Appendix I)). Numerous measurements of radon concentrations above the dumping grounds (more than 100) were performed, but there is only information in Scenario that the measured levels of radon were normal ??

   A maximum value of 180 Bq m^{-3} was reached near dump D1. It responds to radium concentration in soil of about 15 000 Bq kg^{-1} (uniform layer 0-100 cm) and is slightly higher than the maximal reported values for another sites (point E – the Ra-226 concentration was equal to 11 000 Bq kg^{-1}).

4. Results of monitoring survey (1971–1972), concerning measurements of Ra-226 concentration in milk and another agricultural products. The area of sampling was more related to the Site II of Scenario and but measurements data can be applied in evaluation of transfer factors in agricultural environment pathway.

II-2.1.3.2. Concerning probability density function of input parameters and uncertainty ranges

In some cases (see chapter II-2.1.4.) uncertainty range for triangular pdf yield different mean value than it is indicated in scenario. (Tables I-XXV and I-XXVI of Scenario (Appendix I)). The men value are more related to the likeliest value of the distribution. The reason for selecting particular pdf function might be explained, for instant: soil to plant transfer factors for ^{226}Ra (logtriangular), item for ^{210}Pb (triangular), grass-to-beef TF for ^{226}Ra (logtriangular), grass-to-beef TF for ^{210}Pb (triangular).

II-2.1.3.3. Concerning Scenario itself

A complex but very instructive scenario with various exposure pathways to be considered. About 500 end points for deterministic calculation and 175 end points for stochastic calculation (assuming limited variant of Scenario).

More observed data related to the modelled site would be useful, especially date of radon concentration in open area as well as more precise location of existing soil samples together with external dose rate measurements.

II-2.1.4. Summary of input parameters and uncertainty ranges

TABLE II-2.1.XVIII. SOIL BULK DENSITY

	Depth of soil layers	Deterministic calculation	Stochastic Calculation					Scenario recommended values					Tips
				PDF[a]	Distribution parameters				PDF	Distribution parameters			
		best value	Mean		Minimum	Likeliest	Maximum	Mean		Minimum	Likeliest	Maximum	
Soil bulk density (without remedial action) [kg m^3]	0-15 cm	800.00	806.7	pdf:Triangular	320.00	800.00	1300.00	800.00	pdf:Triangular	320.00	800.00	1300.00	b
	15-30 cm	800.00	806.7		320.00	800.00	1300.00						
	30-50 cm	800.00	806.7		320.00	800.00	1300.00						
	50-75 cm	1000.00	873.33		320.00	1000.00	1300.00						
	75-100 cm	1000.00	873.33		320.00	1000.00	1300.00						
	100-150 cm	1000.00	873.33		320.00	1000.00	1300.00						
	150-200 cm	1000.00	873.33		320.00	1000.00	1300.00						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil bulk density (removal of contaminated soil) [kg m^3]	0-15 cm	800	806.7	pdf:Triangular	320.00	800.00	1300.00						
	15-30 cm	1000	873.33		320.00	1000.00	1300.00						
	30-50 cm	1000	873.33		320.00	1000.00	1300.00						
	50-75 cm	1000	873.33		320.00	1000.00	1300.00						
	75-100 cm	1000	873.33		320.00	1000.00	1300.00						
	100-150 cm	1000	873.33		320.00	1000.00	1300.00						
	150-200 cm	1000	873.33		320.00	1000.00	1300.00						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil bulk density (capping with clean soil of 0.5 m) [kg m^3]	0-50 cm	1000	873.33	pdf:Triangular:	320.00	1000.00	1300.00						
	50-65 cm	800	806.7		320.00	800.00	1300.00						
	65-80 cm	800	806.7		320.00	800.00	1300.00						
	80-100 cm	1000	873.33		320.00	1000.00	1300.00						
	100-125 cm	1000	873.33		320.00	1000.00	1300.00						
	125-150 cm	1000	873.33		320.00	1000.00	1300.00						
	150-200 cm	1000	873.33		320.00	1000.00	1300.00						

[a] Probability density function.

[b] The soil bulk density has been considered higher for deeper layers > 0.5 m based on Geology information shown on Figure: I.5. of Scenario. Additionally, the density of capping layers has been set to higher value (1000 kg/m3 instead of 800).

TABLE II-2.1.XIX. SOIL POROSITY

	Depth of soil layers	Deterministic calculation	Stochastic Calculation					Scenario recommended values					Tips
				PDF[a]	Distribution parameters				PDF	Distribution parameters			
		best value	Mean		Minimum	Likeliest	Maximum	Mean		Minimum	Likeliest	Maximum	
Soil total porosity (without remedial action) [%]	0-15 cm	50%	50%	pdf:Triangular	35%	50%	65%	50%	not indicated	not indicated			b
	15-30 cm	50%	50%		35%	50%	65%						
	30-50 cm	50%	50%		35%	50%	65%						
	50-75 cm	50%	50%		35%	50%	65%						
	75-100 cm	50%	50%		35%	50%	65%						
	100-150 cm	50%	50%		35%	50%	65%						
	150-200 cm	50%	50%		35%	50%	65%						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil total porosity (removal of contaminated soil) [%]	0-15 cm	50%	50%	pdf:Triangular	35%	50%	65%						
	15-30 cm	50%	50%		35%	50%	65%						
	30-50 cm	50%	50%		35%	50%	65%						
	50-75 cm	50%	50%		35%	50%	65%						
	75-100 cm	50%	50%		35%	50%	65%						
	100-150 cm	50%	50%		35%	50%	65%						
	150-200 cm	50%	50%		35%	50%	65%						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil total porosity (capping with clean soil of 0.5 m) [%]	0-50 cm	30%	37%	pdf:Triangular:	25%	30%	55%						
	50-65 cm	50%	50%		35%	50%	65%						
	65-80 cm	50%	50%		35%	50%	65%						
	80-100 cm	50%	50%		35%	50%	65%						
	100-125 cm	50%	50%		35%	50%	65%						
	125-150 cm	50%	50%		35%	50%	65%						
	150-200 cm	50%	50%		35%	50%	65%						

[a] Probability density function.

[b] The soil porosity of 50% (before deep ploughing) has been reported in Scenario. The porosity values for stochastic calculation was selected base on literature preview. The texture of Sandy loam was assumed.

TABLE II-2.1.XX. SOIL MOISTURE

	Depth of soil layers	Deterministic calculation	Stochastic Calculation					Scenario recommended values					Tip
				PDF[a]	Distribution parameters				PDF	Distribution parameters			
		best value	Mean		Minimum	Likeliest	Maximum	Mean		Minimum	Likeliest	Maximum	
Soil moisture (without remedial action) [%]	0-15 cm	30%	32%	pdf:Triangular	15%	30%	50%	30%	pdf:Triangular	15%	30%	50%	b
	15-30 cm	30%	32%		15%	30%	50%						
	30-50 cm	30%	32%		15%	30%	50%						
	50-75 cm	45%	48%		40%	45%	60%						
	75-100 cm	45%	48%		40%	45%	60%						
	100-150 cm	60%	60%		45%	60%	75%						
	150-200 cm	60%	60%		45%	60%	75%						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil moisture (removal of contaminated soil) [%]	0-15 cm	30%	32%	pdf:Triangular	15%	30%	50%						
	15-30 cm	30%	32%		15%	30%	50%						
	30-50 cm	30%	32%		15%	30%	50%						
	50-75 cm	45%	48%		40%	45%	60%						
	75-100 cm	45%	48%		40%	45%	60%						
	100-150 cm	60%	60%		45%	60%	75%						
	150-200 cm	60%	60%		45%	60%	75%						
		best value	Mean		Minimum	Likeliest	Maximum						
Soil moisture (capping with clean soil of 0.5 m) [%]	0-50 cm	30%	32%	pdf:Triangular:	15%	30%	50%						
	50-65 cm	30%	32%		15%	30%	50%						
	65-80 cm	30%	32%		15%	30%	50%						
	80-100 cm	45%	48%		40%	45%	60%						
	100-125 cm	45%	48%		40%	45%	60%						
	125-150 cm	60%	60%		45%	60%	75%						
	150-200 cm	60%	60%		45%	60%	75%						

[a] Probability density function.

[b] The soil moisture of 30% for whole soil layers has been recommended in Scenario. The values applied in calculation have been evaluated base on the soil moisture measurements Table I-XVIII (Appendix I), where higher values of 60% have been measured for deeper layers.

TABLE II-2.1.XXI. Ra-226 DISTRIBUTION COEFFICIENT K_d

	Depth of soil layers	Deterministic calculation	Stochastic Calculation				Scenario recommended values				Tip
				PDF[a]	Distribution parameters			PDF	Distribution parameters		
		The best value	Mean		from value	95% tile	Mean		Minimum	Maximum	
Distribution coefficient Kd (without remedial action) [m3 kg-1]	0-15 cm	0.5	0.55	pdf: exponential	0.05	1.5	0.5	pdf: loguniform	0.05	5	[b]
	15-30 cm	0.5	0.55		0.05	1.5					
	30-50 cm	1	1		0.05	3					
	50-75 cm	1	1		0.05	3					
	75-100 cm	1	1		0.05	3					
	100-150 cm	1	1		0.05	3					
	150-200 cm	1	1		0.05	3					
		The best value	Mean		from	95% tile					
Distribution coefficient Kd (removal of contaminated soil) [m3 kg-1]	0-15 cm	1	1	pdf: exponential	0.05	3					
	15-30 cm	1	1		0.05	3					
	30-50 cm	1	1		0.05	3					
	50-75 cm	1	1		0.05	3					
	75-100 cm	1	1		0.05	3					
	100-150 cm	1	1		0.05	3					
	150-200 cm	1	1		0.05	3					
		The best value	Mean		from	95% tile					
Distribution coefficient Kd (capping with clean soil of 0.5 m) [m3 kg-1]	0-50 cm	0.5	0.5	pdf: exponential	0.05	1.5					
	50-65 cm	0.5	0.5		0.05	1.5					
	65-80 cm	0.5	0.5		0.05	1.5					
	80-100 cm	1	1		0.05	3					
	100-125 cm	1	1		0.05	3					
	125-150 cm	1	1		0.05	3					
	150-200 cm	1	1		0.05	3					

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[a] Probability density function.

[b] The distribution coefficient K_d of 1 has been assumed for deeper soil layers with lower pH and higher clay contents.

TABLE II-2.1.XXII. PARAMETERS OF Ra-226 AND Pb-210 TRANSPORT IN SOIL

	Deterministic calculation	Stochastic Calculation					Scenario recommended values					Tip
			PDF[a]	Distribution parameters				PDF	Distribution ranges			
Ra-226 diffusion coefficient in soil [m^2 y^{-1}]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	
	1.00E-05	2.07E-05		2.00E-06	1.00E-05	5.00E-05	1.00E-05		2.00E-06	1.00E-05	5.00E-05	b
Pb-210 diffusion coefficient in soil [m^2 y^{-1}]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	
	5.00E-06	8.66E-06		1.00E-06	5.00E-06	2.00E-05			1.00E-06	5.00E-06	2.00E-05	
Yearly rainfall [m y^{-1}]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	c
	0.76	0.76		0.53	0.76	1.00	0.76		0.53	0.76	1.00	
Saturated hydraulic conductivity [m y^{-1}]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	This parameter has been applied for a leach rate calculation and has not been reported in Scenario					
	4000	3500		1000	4000	5500						
Irrigation rate [m d-1]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	
	1.00E-03	1.10E-03		3.00E-04	1.00E-03	2.00E-03	1.10E-03		3.00E-04	1.00E-03	2.00E-03	d
Irrigation time [d]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	
	1.00E+02	9.33E+01		3.00E+01	1.00E+02	1.50E+02	9.33E+01		3.00E+01	1.00E+02	1.50E+02	

[a] Probability density function.

[b] It is impossible to set triangular pdf with the range and the mean specified. You can only set likeliest instead of mean value.

[c] Values evaluated from Table I.2: Precipitation data during the period 1968-1983 Appendix I Scenario Olen A.

[d] differences between mean and likeliest value.

TABLE II-2.1.XXIII. PARAMETERS OF ^{222}Rn CONCENTRATION IN OUTDOOR/INDOOR AIR

	Deterministic calculation	Stochastic Calculation					Scenario recommended values					
			PDF[a]	Distribution parameters				PDF	Distribution ranges			Tips
Rn-222 diffusion coefficient in air [m2 s-1][b]	best value	Mean	pdf: Lognormal	Mean	Std. Dev.							
	1.10E-05	2.00E-06		2.00E-06	1.00E-05							
Rn-222 diffusion coefficient in soil [m^2 y-1]							Mean	pdf: Triangular	Minimum	Likeliest	Maximum	c
							94.37		20	63.1	200	
Radon emanation fraction in soil [dimensionless]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Uniform	Minimum	Likeliest	Maximum	d
	0.45	0.47		0.25	0.45	0.70	0.25		0.1	0.25	0.4	
Interior surface area of the house floor [m^2]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	no detailed indication					
	100.0	116.7		50.0	100.0	200.0						
Interior volume of the house [m^3]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	brick houses, no detailed indication					
	1000.0	1100		800.0	1000.0	1500.0						
Air exchange rate for the house [s^{-1}]	best value	Mean		Minimum	Likeliest	Maximum		no indication	Maximum	Minimum		
	2.78E-04	2.93E-04		1.00E-04	2.78E-04	5.00E-04			2.78E-04	1.3E-04		
Thickness of the basement concentrate floor [m]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	
	0.3	0.3		0.1	0.3	0.5	0.3		0.1	0.3	0.5	
Area of contaminated Zone [m^2]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	Evaluated from Scenario information (Figures)					
	1 500.0	1833.3		1 000.0	1 500.0	3 000.0						
Annual average wind speed [m s-1]	best value	Mean	pdf: Lognormal	Mean	Std. Dev.		Evaluated from Scenario Appendix I, Site meteorological data					
	3	3.3		3.3	0.2							

[a] Probability density function.

[b] Taken from [4].

[c] Differences between mean and likeliest value.

[d] Evaluated based on Scenario data.

TABLE II-2.1.XXIV. Ra-226 AND Pb-210 EXTERNAL EXPOSURE PATHWAY

	Deterministic calculation	Stochastic Calculation					Scenario recommended values			Comments
			PDF[a]	Distribution parameters				PDF	Distribution ranges	
Building shielding factor indoor [dimensionless]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	The best value	no indication		
	0.25	0.27		0.15	0.25	0.40	0.25			
Building shielding factor outdoor [dimensionless]		Mean	pdf: Triangular	Minimum	Likeliest	Maximum	The best value	no indication		
	0.7	0.7		0.40	0.70	1.00	0.7			
Shape area factor[b] [dimensionless]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum				
	0.79	0.8		0.60	0.79	1.00				
Average annual time spent indoor [h]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	the best value			
	7000	6667		5000	7000	8000	7000			
Average annual time spent outdoor (on fields) [h]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	the best value			
	1 500	1 333		800	1 500	1 700	1 500			
Average annual time spent outdoor (near the house) [h]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum	the best value			
	300	300		200	300	400	300			

[a] Probability density function.

[b] Value evaluated base on probable shape of contamination (Helicopter survey).

TABLE II-2.1.XXV. Ra-226 AND Pb-210 DUST INHALATION

	Deterministic calculation	Stochastic Calculation					Scenario recommended values			Comments
			PDF[a]	Distribution parameters				PDF	Distribution ranges	
House filtration factor[b] [dimensionless]	best value	Mean	pdf: Triangular	Minimum	Likeliest	Maximum				
	0.15	0.15		0.05	0.15	0.25				
Breathing rate of adult for agricultural activities [$m^3\,h^{-1}$]	best value						best value			
	1.2						1.2			
Breathing rate of adult for residential activities [$m^3\,h^{-1}$]	best value						best value			
	0.75						0.75			

[a] Probability density function.

[b] Value evaluated from Scenario data (inhalable dust concentration in air, par. I-6.3.7).

TABLE II-2.1.XXVI. RA-226 AND PB-210 INGESTION PATHWAY

	Deterministic calculation	Stochastic Calculation					Scenario recommended values					Tips
			PDF[a]	Distribution parameters				PDF	Distribution ranges			
Ra-226 transfer coefficients soil to leafy vegetables [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Maximum		b
	6.67E-02	1.78E-02	Lognormal	6.7E-03	6.7E-01		1.0E-02	Logtriangular	1.0E-02	1.0E-01		
Pb-210 transfer coefficients soil to leafy vegetables [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Likeliest	Maximum	b
	6.09E-02	6.09E-02	Lognormal	2.00E-02	1.33E-01		1.0E-02	Triangular	3.0E-03	1.0E-02	2.0E-02	
Ra-226 transfer coefficients soil to pasture [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Maximum		
	8.00E-02	9.35E-02	Lognormal	1.00E-02	3.00E-01		8.00E-02	Logtriangular	1.0E-02	3.00E-01		
Pb-210 transfer coefficients soil to pasture [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Likeliest	Maximum	c
	5.00E-02	8.08E-02	Lognormal	2.00E-02	2.00E-01		9.0E-02	Triangular	2.0E-02	5.00E-02	2.0E-01	
Ra-226 transfer coefficients soil to potatoes [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Maximum		b
	7.50E-03	7.74E-03	Lognormal	1.00E-03	7.50E-02		1.5E-03	Logtriangula	2.0E-04	1.5E-02		
Pb-210 transfer coefficients soil to potatoes [dw/dw]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Likeliest	Maximum	
	5.00E-03	6.6E-03	Lognormal	1.50E-03	1.50E-02		1.43E-03	Triangular	3.0E-4	1.0E-03	3.0E-3	c
Ra-226 transfer coefficients grass to milk [d kg-1]	best value	Mean	pdf:	Minimum	Likeliest	Maximum	Mean	pdf:	Minimum	Likeliest	Maximum	
	2.00E-04	4.17E-04	Triangular	5.00E-05	2.02E-04	1.00E-03	4.17E-04	Triangular	5.00E-05	2.02E-04	1.00E-03	
Ra-226 transfer coefficients grass to beef [d kg-1]	best value	Mean	pdf:	Minimum	Likeliest	Maximum	Mean	pdf:	Minimum	Maximum		
	5.00E-04	8.68E-04	Triangular	1.00E-04	5.05E-04	2.00E-03	5.00E-04	Logtriangular	1.00E-04	2.00E-03		
Pb-210 transfer coefficients grass to beef [d kg-1]	best value	Mean	pdf:	5% - tile	95% - tile		Mean	pdf:	Minimum	Likeliest	Maximum	
	4.00E-04	4.00E-04	Lognormal	1.00E-04	1.00E-03		5.00E-04	Triangular	1.00E-04	4.00E-04	1.00E-03	
Grass consumption rate [kg dw d-1]	best value	Mean	pdf:	Minimum	Likeliest	Maximum	Mean	pdf:	Minimum	Likeliest	Maximum	
	12.50	12.50	Triangular	10.00	12.50	15.00	12.50	Triangular	10.00	12.50	15.00	

[a] Probability density function.

[b] TF (dw/fw).

[c] Differences between mean and likeliest value.

TABLE II-2.1.XXVII. Ra-226 CONCENTRATION IN SOIL

	Depth of soil layers	Deterministic calculation	Stochastic Calculation				
				PDF[a]	Distribution parameters		
		The best value	Mean		Mean	Log Mean	Log Std. Dev.
Ra-225 soil concentration (without remedial action) [Bq kg^{-1}]	0-15 cm	2.467E+03	2.467E+03	pdf: lognormal	2.467E+03	7.216E+00	1.263E+00
	15-30 cm	8.220E+02	8.220E+02		8.220E+02	6.094E+00	1.554E+00
	30-50 cm	3.028E+03	3.028E+03		3.028E+03	6.473E+00	2.502E+00
	50-75 cm	4.400E+01	4.400E+01		4.400E+01	3.717E+00	4.236E-01
	75-100 cm	6.677E+02	6.677E+02		6.677E+02	4.231E+00	2.172E+00
		The best value		pdf: uniform	Mean	Min	Max
	100-150 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
	150-200 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
		The best value	Mean	pdf: log normal	Mean	Log Mean	Log Std. Dev.
Ra-225 soil concentration (removal of contaminated soil) [Bq kg^{-1}]	0-15 cm	4.400E+01	4.400E+01		4.400E+01	3.717E+00	4.236E-01
	15-30 cm	6.677E+02	6.677E+02		6.677E+02	4.231E+00	2.172E+00
		The best value	Mean	pdf: uniform	Mean	Min	Max
	30-50 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
	50-75 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
	75-100 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
	100-150 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
	150-200 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
		The best value	Mean	pdf: uniform	Mean	Min	Max
Ra-225 soil concentration (capping with clean soil of 0.5 m) [Bq kg^{-1}]	0-50 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01
		The best value	Mean	pdf: lognormal	Mean	Log Mean	Log Std. Dev.
	50-65 cm	2.467E+03	2.467E+03		2.467E+03	7.216E+00	1.263E+00
	65-80 cm	8.220E+02	8.220E+02		8.220E+02	6.094E+00	1.554E+00
	80-100 cm	3.028E+03	3.028E+03		3.028E+03	6.473E+00	2.502E+00
	100-125 cm	4.400E+01	4.400E+01		4.400E+01	3.717E+00	4.236E-01
	125-150 cm	6.677E+02	6.677E+02		6.677E+02	4.231E+00	2.172E+00
				pdf: uniform	Mean	Min	Max
	150-200 cm	2.000E+01	2.000E+01		2.000E+01	1.000E+01	3.000E+01

[a] Probability density function.

II-2.1.5. Results of model predictions

Deterministic model calculations

Concentrations in the different compartments - Situation I (maximum values = optional)

1. Without remedial action

Ra-226 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	garden	farm	indoors	outdoors	outdoors agricult(*)	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	2,45E+03	1,63E+03	1,58E+03	6,82E-05	4,55E-04	#N/A	1,96E+02	#N/A	1,23E+01	#N/A	1,09E+02	#N/A	1,00E+01	4,90E-01	1,23E+00	2,08E+02	1,84E+01
50	2,26E+03	1,51E+03	1,49E+03	6,30E-05	4,20E-04	#N/A	1,81E+02	#N/A	1,13E+01	#N/A	1,01E+02	#N/A	1,04E+01	4,53E-01	1,13E+00	1,96E+02	1,73E+01
100	2,09E+03	1,40E+03	1,39E+03	5,81E-05	3,87E-04	#N/A	1,67E+02	#N/A	1,05E+01	#N/A	9,32E+01	#N/A	1,12E+01	4,17E-01	1,04E+00	1,84E+02	1,63E+01
200	1,77E+03	1,19E+03	1,23E+03	4,94E-05	3,29E-04	#N/A	1,42E+02	#N/A	8,95E+00	#N/A	7,96E+01	#N/A	1,25E+01	3,55E-01	8,86E-01	1,62E+02	1,44E+01
500	1,09E+03	7,44E+02	8,47E+02	3,03E-05	2,02E-04	#N/A	8,71E+01	#N/A	5,58E+00	#N/A	4,96E+01	#N/A	1,53E+01	2,18E-01	5,44E-01	1,12E+02	9,94E+00
Maximum																	

Pb-210 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	garden	farm	indoors	outdoors	outdoors agricult	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	2,12E+03	1,41E+03	1,37E+03	5,89E-05	3,93E-04	#N/A	1,06E+02	#N/A	7,06E+00	#N/A	8,59E+01	#N/A	5,00E+00	1,98E-01	5,29E-01
50	2,20E+03	1,47E+03	1,44E+03	6,11E-05	4,08E-04	#N/A	1,10E+02	#N/A	7,34E+00	#N/A	8,93E+01	#N/A	5,28E+00	2,06E-01	5,49E-01
100	2,07E+03	1,39E+03	1,39E+03	5,77E-05	3,85E-04	#N/A	1,04E+02	#N/A	6,94E+00	#N/A	8,45E+01	#N/A	5,07E+00	1,94E-01	5,18E-01
200	1,77E+03	1,19E+03	1,23E+03	4,94E-05	3,29E-04	#N/A	8,86E+01	#N/A	5,97E+00	#N/A	7,26E+01	#N/A	5,50E+00	1,66E-01	4,43E-01
500	1,09E+03	7,44E+02	8,47E+02	3,03E-05	2,02E-04	#N/A	5,44E+01	#N/A	3,72E+00	#N/A	4,53E+01	#N/A	6,90E+00	1,02E-01	2,72E-01
Maximum															

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Ra-226 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	garden	farm	indoors	outdoors	outdoors agricult(*)	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	5,99E+01	5,99E+01	5,99E+01	1,67E-06	1,11E-05	#N/A	4,79E+00	#N/A	4,49E-01	#N/A	3,99E+00	#N/A	1,00E+01	1,20E-02	2,99E-02	1,16E+01	1,03E+00
50	5,67E+01	5,69E+01	5,73E+01	1,58E-06	1,05E-05	#N/A	4,54E+00	#N/A	4,27E-01	#N/A	3,79E+00	#N/A	1,00E+01	1,13E-02	2,84E-02	1,11E+01	9,83E-01
100	5,37E+01	5,40E+01	5,47E+01	1,49E-06	9,96E-06	#N/A	4,29E+00	#N/A	4,05E-01	#N/A	3,60E+00	#N/A	1,00E+01	1,07E-02	2,68E-02	1,06E+01	9,42E-01
200	4,81E+01	4,87E+01	4,99E+01	1,34E-06	8,92E-06	#N/A	3,85E+00	#N/A	3,65E-01	#N/A	3,25E+00	#N/A	1,01E+01	9,62E-03	2,40E-02	9,78E+00	8,66E-01
500	3,45E+01	3,57E+01	3,80E+01	9,62E-07	6,41E-06	#N/A	2,76E+00	#N/A	2,68E-01	#N/A	2,38E+00	#N/A	1,01E+01	6,91E-03	1,73E-02	7,59E+00	6,72E-01
Maximum																	

Pb-210 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	garden	farm	indoors	outdoors	outdoors agricult	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	5,17E+01	5,17E+01	5,17E+01	1,44E-06	9,60E-06	#N/A	2,59E+00	#N/A	2,59E-01	#N/A	3,15E+00	#N/A	5,00E+00	4,85E-03	1,29E-02
50	5,50E+01	5,52E+01	5,56E+01	1,53E-06	1,02E-05	#N/A	2,75E+00	#N/A	2,76E-01	#N/A	3,36E+00	#N/A	5,37E+00	5,16E-03	1,38E-02
100	5,33E+01	5,37E+01	5,44E+01	1,49E-06	9,90E-06	#N/A	2,67E+00	#N/A	2,69E-01	#N/A	3,27E+00	#N/A	5,25E+00	5,00E-03	1,33E-02
200	4,81E+01	4,87E+01	4,99E+01	1,34E-06	8,92E-06	#N/A	2,40E+00	#N/A	2,44E-01	#N/A	2,97E+00	#N/A	5,18E+00	4,51E-03	1,20E-02
500	3,45E+01	3,57E+01	3,80E+01	9,62E-07	6,41E-06	#N/A	1,73E+00	#N/A	1,79E-01	#N/A	2,18E+00	#N/A	6,33E+00	3,24E-03	8,64E-03
Maximum															

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

Ra-226 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	garden	farm	indoors	outdoors	outdoors agricult(*)	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	2,00E+01	2,00E+01	1,58E+03	5,58E-07	3,72E-06	#N/A	1,60E+00	#N/A	1,50E-01	#N/A	1,34E+00	#N/A	1,00E+01	4,01E-03	1,00E-02	7,05E+01	6,24E+00
50	2,06E+01	2,06E+01	1,48E+03	5,73E-07	3,82E-06	#N/A	1,65E+00	#N/A	1,54E-01	#N/A	1,37E+00	#N/A	1,06E+01	4,11E-03	1,03E-02	6,66E+01	5,90E+00
100	2,10E+01	2,10E+01	1,38E+03	5,84E-07	3,89E-06	#N/A	1,68E+00	#N/A	1,57E-01	#N/A	1,40E+00	#N/A	1,12E+01	4,20E-03	1,05E-02	6,28E+01	5,56E+00
200	2,15E+01	2,15E+01	1,22E+03	5,99E-07	3,99E-06	#N/A	1,72E+00	#N/A	1,61E-01	#N/A	1,43E+00	#N/A	1,23E+01	4,30E-03	1,08E-02	5,61E+01	4,97E+00
500	2,14E+01	2,14E+01	8,36E+02	5,95E-07	3,97E-06	#N/A	1,71E+00	#N/A	1,60E-01	#N/A	1,42E+00	#N/A	1,47E+01	4,27E-03	1,07E-02	4,03E+01	3,57E+00
Maximum																	

Pb-210 concentration

Years	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg **d.w.**)		Potatoes (Bq/kg **d.w.**)		Leafy vegetables (Bq/kg **d.w.**)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	garden	farm	indoors	outdoors	outdoors agricult	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	1,73E+01	1,73E+01	1,36E+03	4,82E-07	3,21E-06	#N/A	8,66E-01	#N/A	8,66E-02	#N/A	1,05E+00	#N/A	5,00E+00	1,62E-03	4,33E-03
50	2,00E+01	2,00E+01	1,43E+03	5,56E-07	3,70E-06	#N/A	9,98E-01	#N/A	9,98E-02	#N/A	1,21E+00	#N/A	5,27E+00	1,87E-03	4,99E-03
100	2,08E+01	2,08E+01	1,38E+03	5,80E-07	3,87E-06	#N/A	1,04E+00	#N/A	1,04E-01	#N/A	1,27E+00	#N/A	5,05E+00	1,95E-03	5,21E-03
200	2,15E+01	2,15E+01	1,22E+03	5,99E-07	3,99E-06	#N/A	1,08E+00	#N/A	1,08E-01	#N/A	1,31E+00	#N/A	5,53E+00	2,02E-03	5,38E-03
500	2,14E+01	2,14E+01	8,36E+02	5,95E-07	3,97E-06	#N/A	1,07E+00	#N/A	1,07E-01	#N/A	1,30E+00	#N/A	6,93E+00	2,00E-03	5,34E-03
Maximum															

Deterministic model calculations

Individual doses for adult for Olen site (mSv/y) - Situation I (maximum values = optional)

1. Without remedial action

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	3,40E-03	9,34E-03	7,54E-01	5,43E-01	5,21E+00	1,19E-01	7,78E-02		8,37E-02		1,12E-03	1,80E-02	1,85E-02		**6,84E+00**
50	3,14E-03	8,62E-03	7,04E-01	5,07E-01	4,90E+00	1,12E-01	7,20E-02		7,75E-02		1,17E-03	1,66E-02	1,71E-02		**6,42E+00**
100	2,90E-03	7,95E-03	6,57E-01	4,73E-01	4,60E+00	1,05E-01	6,65E-02	neglected	7,16E-02	neglected	1,25E-03	1,53E-02	1,58E-02		**6,02E+00**
200	2,46E-03	4,14E-03	5,71E-01	4,11E-01	4,06E+00	9,25E-02	5,68E-02		6,12E-02		1,40E-03	1,30E-02	1,34E-02		**5,29E+00**
500	1,51E-03	4,14E-03	3,78E-01	2,72E-01	2,81E+00	6,40E-02	3,54E-02		3,81E-02		1,71E-03	7,98E-03	8,23E-03		**3,62E+00**
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	2,94E-03	8,06E-03	2,25E-04	1,62E-04	1,51E-01		1,19E-01		1,38E-03	1,79E-02	1,97E-02		**3,20E-01**
50	3,05E-03	8,36E-03	2,35E-04	1,69E-04	1,57E-01		1,24E-01		1,46E-03	1,86E-02	2,05E-02		**3,33E-01**
100	2,88E-03	7,90E-03	2,23E-04	1,61E-04	1,49E-01	neglected	1,17E-01	neglected	1,40E-03	1,76E-02	1,93E-02		**3,15E-01**
200	2,46E-03	6,75E-03	1,94E-04	1,40E-04	1,28E-01		1,00E-01		1,52E-03	1,50E-02	1,65E-02		**2,71E-01**
500	1,51E-03	4,14E-03	1,35E-04	8,33E-05	7,97E-02		6,26E-02		1,90E-03	9,22E-03	1,01E-02		**1,69E-01**
Maximum													

2. After implementing remedial action 1 (removal of contaminated soil)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	8,31E-05	2,28E-04	2,72E-02	1,96E-02	2,90E-01	6,61E-03	2,85E-03		3,07E-03		1,12E-03	4,39E-04	4,53E-04		**3,52E-01**
50	7,88E-05	2,16E-04	2,59E-02	1,86E-02	2,78E-01	6,34E-03	2,71E-03		2,92E-03		1,12E-03	4,16E-04	4,29E-04		**3,37E-01**
100	7,45E-05	2,04E-04	2,47E-02	1,78E-02	2,67E-01	6,07E-03	2,57E-03	neglected	2,77E-03	neglected	1,12E-03	3,94E-04	4,06E-04		**3,23E-01**
200	6,68E-05	1,83E-04	2,24E-02	1,61E-02	2,45E-01	5,58E-03	2,32E-03		2,50E-03		1,13E-03	3,53E-04	3,63E-04		**2,96E-01**
500	4,80E-05	1,32E-04	1,68E-02	1,21E-02	1,90E-01	4,33E-03	1,70E-03		1,83E-03		1,14E-03	2,53E-04	2,61E-04		**2,29E-01**
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	4,23E-08	1,16E-07	7,38E-06	5,31E-06	5,54E-03		4,35E-03		1,38E-03	4,38E-04	4,82E-04		**1,22E-02**
50	4,51E-08	1,24E-07	7,89E-06	5,68E-06	5,92E-03		4,65E-03		1,48E-03	4,66E-04	5,13E-04		**1,30E-02**
100	4,37E-08	1,20E-07	7,68E-06	5,53E-06	5,75E-03	neglected	4,52E-03	neglected	1,45E-03	4,52E-04	4,97E-04		**1,27E-02**
200	3,93E-08	1,08E-07	6,99E-06	5,03E-06	5,22E-03		4,10E-03		1,43E-03	4,07E-04	4,48E-04		**1,16E-02**
500	2,83E-08	7,76E-08	5,39E-06	3,43E-06	3,83E-03		3,01E-03		1,75E-03	2,93E-04	3,22E-04		**9,21E-03**
Maximum													

3. After implementing remedial action 2 (capping with clean soil layer of 50 cm)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	2,78E-05	7,64E-05	1,19E-01	8,56E-02	1,77E+00	4,02E-02	9,54E-04		1,03E-03		1,12E-03	1,47E-04	1,52E-04		**2,01E+00**
50	2,86E-05	7,83E-05	1,11E-01	8,02E-02	1,67E+00	3,80E-02	9,79E-04		1,05E-03		1,19E-03	1,51E-04	1,55E-04		**1,90E+00**
100	2,91E-05	7,99E-05	1,04E-01	7,51E-02	1,57E+00	3,59E-02	9,99E-04	neglected	1,07E-03	neglected	1,26E-03	1,54E-04	1,59E-04		**1,79E+00**
200	2,99E-05	8,19E-05	9,15E-02	6,59E-02	1,41E+00	3,20E-02	1,02E-03		1,10E-03		1,37E-03	1,58E-04	1,63E-04		**1,60E+00**
500	2,97E-05	8,14E-05	6,29E-02	4,53E-02	1,01E+00	2,30E-02	1,02E-03		1,10E-03		1,64E-03	1,57E-04	1,62E-04		**1,15E+00**
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	1,42E-08	3,89E-08	1,57E-05	1,13E-05	1,85E-03		1,46E-03		1,38E-03	1,47E-04	1,61E-04		**5,03E-03**
50	1,63E-08	4,48E-08	1,67E-05	1,20E-05	2,14E-03		1,68E-03		1,45E-03	1,69E-04	1,86E-04		**5,65E-03**
100	1,71E-08	4,68E-08	1,61E-05	1,16E-05	2,23E-03	neglected	1,75E-03	neglected	1,39E-03	1,77E-04	1,94E-04		**5,78E-03**
200	1,76E-08	4,83E-08	1,44E-05	1,04E-05	2,30E-03		1,81E-03		1,53E-03	1,82E-04	2,00E-04		**6,05E-03**
500	1,75E-08	4,80E-08	1,07E-05	7,54E-06	2,29E-03		1,80E-03		1,91E-03	1,81E-04	1,99E-04		**6,40E-03**
Maximum													

Stochastic model calculations

Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

Without remediation

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**3,25E-03**	*1,34E-04*	*1,62E-02*	**8,51E-03**	*3,84E-04*	*4,17E-02*	**8,48E-01**	*7,93E-02*	3,39E+00	**5,48E-01**	*5,01E-02*	*2,20E+00*
100	**2,44E-03**	*9,00E-05*	*1,24E-02*	**6,37E-03**	*2,61E-04*	*3,18E-02*	**6,60E-01**	*5,80E-02*	2,69E+00	**4,26E-01**	*3,64E-02*	*1,75E+00*
500	**1,07E-03**	*3,29E-06*	*6,33E-03*	**2,80E-03**	*9,18E-06*	*1,61E-02*	**3,22E-01**	*1,55E-02*	1,52E+00	**2,08E-01**	*1,00E-02*	*9,72E-01*
Maximum												

Pb-210 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**2,81E-03**	*1,16E-04*	*1,39E-02*	**7,35E-03**	*3,32E-04*	*3,60E-02*	**2,52E-04**	*2,28E-05*	*1,03E-03*	**1,63E-04**	*1,43E-05*	*6,72E-04*
100	**2,71E-03**	*1,09E-04*	*1,35E-02*	**6,33E-03**	*2,60E-04*	*3,16E-02*	**2,23E-04**	*1,88E-05*	*9,26E-04*	**1,44E-04**	*1,19E-05*	*5,96E-04*
500	**1,07E-03**	*3,29E-06*	*6,33E-03*	**2,80E-03**	*9,18E-06*	1,61E-02	**1,18E-04**	*5,12E-06*	*5,45E-04*	**6,59E-05**	*2,96E-06*	*3,05E-04*
Maximum												

Ra-226 calculations

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptak	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**6,18E+00**	*4,89E-01*	*2,75E+01*	**1,51E-01**	*1,53E-02*	*6,25E-01*	**2,11E-01**	*1,84E-03*	*1,37E+00*				**1,12E-03**	*5,60E-04*	*2,24E-03*
100	**4,95E+00**	*3,67E-01*	*2,28E+01*	**1,21E-01**	*1,16E-02*	*5,22E-01*	**1,59E-01**	*1,32E-03*	*1,04E+00*		neglected		**8,77E-04**	*2,56E-04*	*2,07E-03*
500	**2,61E+00**	*1,30E-01*	*1,33E+01*	**6,35E-02**	*4,05E-03*	*3,10E-01*	**7,02E-02**	*2,89E-04*	*4,84E-01*				**4,37E-04**	*3,38E-05*	*1,52E-03*
Maximum															

Pb-210 calculations

	Leafy vegetables						Drinking water		
	Root uptake	95% confidence interval		Foliar uptak	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**1,51E-01**	*9,42E-03*	*6,92E-01*				**2,38E-03**	*1,19E-03*	*4,77E-03*
100	**1,31E-01**	*7,67E-03*	*6,04E-01*				**2,15E-03**	*6,27E-04*	*5,06E-03*
500	**5,86E-02**	*1,34E-03*	*3,06E-01*				**1,08E-03**	*8,33E-05*	*3,74E-03*
Maximum									

Ra-226 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**8,64E-02**	*2,20E-03*	*4,51E-01*				**4,35E-02**	*4,15E-04*	*2,82E-01*	**3,74E-02**	*3,62E-04*	*2,43E-01*			
100	**6,49E-02**	*1,58E-03*	*3,43E-01*				**3,25E-02**	*2,90E-04*	*2,14E-01*	**2,80E-02**	*2,48E-04*	*1,86E-01*			
500	**2,88E-02**	*3,36E-04*	*1,69E-01*				**1,42E-02**	*1,68E-05*	*1,01E-01*	**1,23E-02**	*1,44E-05*	*8,77E-02*			
Maximum															

Pb-210 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit				Mean	Lower limit	Upper limit	Mean					
1	**1,44E-01**	*7,22E-03*	*7,05E-01*				**7,80E-02**	*1,28E-03*	*4,77E-01*	**3,25E-02**	*4,62E-04*	*2,02E-01*			
100	**1,25E-01**	*5,85E-03*	*6,22E-01*				**6,72E-02**	*9,86E-04*	*4,17E-01*	**2,80E-02**	*3,64E-04*	*1,79E-01*			
500	**5,58E-02**	*1,12E-03*	*3,06E-01*				**2,97E-02**	*4,87E-05*	*2,05E-01*	**1,23E-02**	*1,85E-05*	*8,27E-02*			
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
8,11E+00	*7,69E-01*	*3,34E+01*	**6,45E+00**	*5,71E-01*	*2,76E+01*	**3,33E+00**	*1,87E-01*	*1,61E+01*			

Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
4,19E-01	*3,25E-02*	*1,88E+00*	**3,63E-01**	*2,67E-02*	*1,65E+00*	**1,62E-01**	*4,56E-03*	*8,45E-01*			

Ra-226 & Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
8,53E+00	*8,36E-01*	*3,45E+01*	**6,81E+00**	*6,29E-01*	*2,84E+01*	**3,49E+00**	*2,02E-01*	*1,65E+01*			

Stochastic model calculations
Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

Covering with 0,5 m clean soil layer

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**2,00E-05**	*8,56E-06*	*3,56E-05*	**5,24E-05**	*3,19E-05*	*7,58E-05*	**1,26E-01**	*1,68E-02*	*4,70E-01*	**8,13E-02**	*1,06E-02*	*3,05E-01*
100	**2,36E-05**	*8,97E-06*	*5,31E-05*	**6,17E-05**	*3,22E-05*	*1,30E-04*	**9,99E-02**	*1,31E-02*	*3,84E-01*	**6,45E-02**	*8,31E-03*	*2,49E-01*
500	**2,69E-05**	*5,78E-06*	*9,90E-05*	**7,04E-05**	*1,83E-05*	*2,50E-04*	**5,20E-02**	*5,48E-03*	*2,25E-01*	**3,35E-02**	*3,48E-03*	*1,45E-01*
Maximum												

Pb-210 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**1,02E-08**	*4,36E-09*	*1,81E-08*	**2,67E-08**	*1,62E-08*	*3,86E-08*	**1,61E-05**	*2,72E-06*	*5,96E-05*	**1,04E-05**	*1,70E-06*	*3,85E-05*
100	**1,38E-08**	*5,25E-09*	*3,11E-08*	**3,61E-08**	*1,89E-08*	*7,61E-08*	**1,52E-05**	*2,55E-06*	*5,73E-05*	**9,79E-06**	*1,60E-06*	*3,67E-05*
500	**1,59E-08**	*3,41E-09*	*5,83E-08*	**4,15E-08**	*1,08E-08*	*1,48E-07*	**9,30E-06**	*1,34E-06*	*3,81E-05*	**5,83E-06**	*7,99E-07*	*2,38E-05*
Maximum												

Ra-226 calculations

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**2,56E+00**	*1,91E-01*	*1,18E+01*	**6,26E-02**	*6,09E-03*	*2,73E-01*	**1,92E-03**	*4,39E-05*	*1,13E-02*				**2,70E-03**	*7,92E-05*	*1,55E-02*
100	**2,05E+00**	*1,49E-01*	*9,65E+00*	**5,03E-02**	*4,73E-03*	*2,25E-01*	**2,27E-03**	*4,80E-05*	*1,35E-02*				**2,10E-03**	*5,83E-05*	*1,22E-02*
500	**1,06E+00**	*6,32E-02*	*5,50E+00*	**2,61E-02**	*1,99E-03*	*1,28E-01*	**2,58E-03**	*3,92E-05*	*1,62E-02*				**9,99E-04**	*1,70E-05*	*6,20E-03*
Maximum															

Pb-210 calculations

	Leafy vegetables						Drinking water		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**1,39E-03**	*3,50E-04*	*3,81E-03*				**5,75E-03**	*1,69E-04*	*3,30E-02*
100	**1,89E-03**	*4,32E-04*	*5,68E-03*				**5,14E-03**	*1,43E-04*	*2,98E-02*
500	**2,16E-03**	*3,07E-04*	*8,81E-03*				**2,46E-03**	*4,20E-05*	*1,53E-02*
Maximum									

Ra-226 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	confidence interval		95% confidence interval			95% confidence interval				95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**7,97E-04**	*5,69E-05*	*2,42E-03*				**2,69E-04**	*1,26E-05*	*1,35E-03*	**2,30E-04**	*1,15E-05*	*1,14E-03*			
100	**9,38E-04**	*6,13E-05*	*3,05E-03*				**3,18E-04**	*1,36E-05*	*1,64E-03*	**2,72E-04**	*1,25E-05*	*1,37E-03*			
500	**1,07E-03**	*4,91E-05*	*4,79E-03*				**3,65E-04**	*1,06E-05*	*2,09E-03*	**3,11E-04**	*9,78E-06*	*1,75E-03*			
Maximum															

Pb-210 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	confidence interval		95% confidence interval			95% confidence interval				95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	**1,33E-03**	*2,44E-04*	*4,24E-03*				**4,76E-04**	*4,69E-05*	*1,83E-03*	**1,98E-04**	*1,64E-05*	*8,69E-04*			
100	**1,80E-03**	*3,03E-04*	*6,15E-03*				**6,46E-04**	*5,85E-05*	*2,62E-03*	**2,68E-04**	*2,04E-05*	*1,21E-03*			
500	**2,06E-03**	*2,21E-04*	*9,12E-03*				**7,43E-04**	*4,49E-05*	*3,62E-03*	**3,08E-04**	*1,57E-05*	*1,60E-03*			
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
2,83E+00	*2,50E-01*	*1,26E+01*	**2,27E+00**	*1,95E-01*	*1,03E+01*	**1,18E+00**	*8,28E-02*	*5,91E+00*			

Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
9,17E-03	*2,14E-03*	*3,66E-02*	**9,77E-03**	*2,30E-03*	*3,63E-02*	**7,76E-03**	*1,41E-03*	*3,06E-02*			

Ra-226 & Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
2,84E+00	*2,55E-01*	*1,27E+01*	**2,28E+00**	*2,00E-01*	*1,03E+01*	**1,19E+00**	*8,59E-02*	*5,94E+00*			

II-2.1.6. Sensitivity analysis

Ra &Pb Sensitivity Data	No remediation			Capping			Removal of contaminated soil		
	1y	100y	500y	1y	100y	500y	1y	100y	500y
Ra[80-100 cm]Capp	0,01	0,01	0,01	0,51	0,51	0,46	0,00	0,01	0,00
Ra[50-65 cm]Capp	0,00	0,00	0,00	0,47	0,45	0,38	0,01	0,01	0,01
pt 0 capp	0,00	0,00	-0,01	0,23	0,22	0,18	0,01	0,01	0,01
Ai	0,16	0,15	0,14	0,19	0,19	0,18	0,42	0,41	0,37
Eps	0,13	0,13	0,11	0,17	0,16	0,15	0,36	0,35	0,32
Ra[65-80 cm]Capp	-0,01	-0,01	-0,01	0,16	0,16	0,13	0,00	0,00	0,00
Diff Rn conc	0,13	0,13	0,11	0,14	0,14	0,13	0,32	0,32	0,29
Diff Rn air	0,04	0,05	0,05	0,13	0,13	0,12	0,19	0,19	0,18
Ra[125-150 cm]Capp	0,00	0,00	0,00	0,12	0,13	0,16	0,00	0,00	0,00
r_bs_1 capp	0,00	0,00	-0,01	0,09	0,10	0,12	0,00	0,00	0,00
r_bs_3 capp	0,02	0,02	0,02	0,06	0,07	0,09	0,00	0,00	0,00
r_bs_2 capp	0,00	0,00	-0,01	0,04	0,04	0,06	0,01	0,02	0,01
Ar	0,02	0,02	0,02	0,02	0,02	0,02	0,03	0,03	0,03
r_bs_5 capp	0,01	0,01	0,01	0,02	0,02	0,03	0,00	0,00	0,00
Ksat	-0,01	0,00	-0,01	0,02	0,02	0,02	0,04	0,04	0,05
gr bf Pb	0,01	0,01	0,01	0,02	0,02	0,02	0,01	0,01	0,01
Ra[30-50 cm] Remv	0,01	0,01	0,01	0,02	0,02	0,01	0,09	0,09	0,08
FB out	0,01	0,01	0,01	0,02	0,02	0,02	0,03	0,03	0,02
Kd 1 capp	0,00	0,00	0,00	0,01	0,09	0,25	0,01	0,01	0,01
r_bs_0 capp	-0,01	-0,01	0,00	0,01	0,02	0,04	0,01	0,01	0,00
pt 1no act	0,00	0,00	0,00	0,01	0,01	0,01	0,01	0,01	0,01
FB in	0,02	0,01	0,01	0,01	0,01	0,02	0,03	0,03	0,02
Ra[0-15 cm] No Act	0,58	0,55	0,42	0,01	0,01	0,01	0,01	0,01	0,01
Ra[0-50 cm]Capp	-0,01	-0,01	-0,01	0,01	0,01	0,02	0,00	0,00	-0,01
Ra[150-200 cm] Remv	0,00	0,00	0,00	0,01	0,01	0,01	0,02	0,02	0,02
pot Pb	0,02	0,02	0,02	0,01	0,01	0,01	0,03	0,03	0,03
FS	0,06	0,05	0,05	0,01	0,01	0,02	0,07	0,07	0,06
r_bs_4 capp	0,00	0,00	0,00	0,01	0,01	0,01	-0,01	-0,01	0,00
r_bs_0 remv	0,01	0,00	0,00	0,01	0,01	0,01	0,15	0,16	0,16
past Pb	0,01	0,02	0,02	0,01	0,01	0,02	0,02	0,02	0,01
pt 4 capp	0,00	0,00	0,00	0,01	0,01	0,01	0,01	0,01	0,02
Kd 4 capp	0,00	0,00	0,01	0,01	0,01	0,02	0,00	0,00	0,01
ms0 no act	0,00	0,00	0,00	0,01	0,01	0,01	0,02	0,03	0,03
ms4 capp	0,00	0,00	-0,01	0,01	0,01	0,01	-0,01	-0,01	-0,01
Filtr	-0,01	-0,01	0,00	0,01	0,01	0,01	0,00	0,00	0,01
r bs 1no act	0,04	0,03	0,03	0,01	0,01	0,01	0,01	0,01	0,01
Ra[75-100 cm] No Act	0,11	0,12	0,14	0,01	0,01	0,00	-0,01	-0,01	0,00
ms2 remv	0,01	0,01	0,01	0,01	0,00	0,00	0,01	0,01	0,01
r_bs_6 capp	0,00	0,00	0,00	0,01	0,01	0,01	0,01	0,01	0,00
Kd 2 remv	0,00	0,00	0,00	0,01	0,01	0,00	0,01	0,05	0,14
ms2 capp	-0,01	-0,01	-0,01	0,01	0,01	0,01	0,01	0,01	0,01
Kd 3 capp	0,00	0,01	0,01	0,01	0,04	0,15	0,02	0,02	0,02
Kd 1no act	-0,01	-0,01	-0,01	0,01	0,00	0,00	0,00	0,00	0,00
pot	0,01	0,01	0,02	0,01	0,01	0,00	0,02	0,02	0,01
Ra[50-75 cm] Remv	0,01	0,01	0,01	0,01	0,01	0,01	0,08	0,08	0,07
ms4 no act	0,00	0,00	0,00	0,01	0,01	0,01	-0,01	-0,01	-0,01
Ra[100-125 cm]Capp	-0,01	-0,01	-0,01	0,01	0,00	0,01	-0,01	-0,01	0,00

(Continued)

Kd 4 remv	0,02	0,02	0,01	0,01	0,01	0,02	0,03	0,05	0,10
Kd 3 no act	0,00	0,00	-0,01	0,01	0,01	0,00	0,00	0,00	0,00
Kd 5 capp	0,02	0,01	0,01	0,01	0,01	0,04	0,00	0,00	0,00
ms4 remv	0,00	0,00	0,00	0,00	0,01	0,01	0,00	0,00	0,00
ms0 remv	0,01	0,01	0,01	0,00	0,01	0,01	0,01	0,01	0,00
rbs2 no act	0,06	0,06	0,06	0,00	0,00	0,01	0,00	0,00	0,00
ms3 no act	0,00	-0,01	-0,01	0,00	0,00	0,00	0,01	0,01	0,00
lveg Pb	0,02	0,02	0,02	0,00	0,01	0,00	0,02	0,02	0,02
Time in door	0,01	0,01	0,01	0,00	0,01	0,00	0,02	0,02	0,02
Kd 4 no act	0,00	0,00	0,00	0,00	0,00	0,01	-0,01	0,00	0,00
cat diet	0,01	0,01	0,01	0,00	0,01	0,00	0,01	0,01	0,01
Kd 0 remv	-0,02	-0,01	-0,01	0,00	0,00	0,00	-0,01	0,08	0,22
past	0,01	0,01	0,01	0,00	0,00	0,00	0,02	0,01	0,01
pt 0 remv	0,00	0,01	0,01	0,00	0,00	-0,01	0,14	0,13	0,10
pt 3 remv	0,00	0,00	0,00	0,00	0,00	0,00	-0,03	-0,03	-0,04
rbs4 no act	0,01	0,02	0,02	0,00	0,00	0,01	0,01	0,01	0,01
r_bs_1 remv	-0,01	0,00	0,00	0,00	0,00	0,00	0,10	0,11	0,12
Kd 3 remv	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,11
Time near the house	0,00	0,00	-0,01	0,00	0,00	0,00	-0,02	-0,02	-0,02
Ra[30-50 cm] No Act	0,49	0,50	0,51	0,00	0,00	0,01	0,01	0,01	0,01
Kd 5 no act	0,01	0,01	0,00	0,00	0,00	0,00	0,01	0,01	0,00
r_bs_2 remv	0,00	-0,01	-0,01	0,00	0,00	0,00	0,09	0,10	0,10
U	0,00	0,00	0,01	0,00	0,00	0,00	0,01	0,01	0,01
rbs3 no act	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
Kd 2 no act	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00
ms1 remv	0,00	-0,01	-0,01	0,00	0,00	0,00	0,02	0,02	0,02
pt 2 capp	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	-0,01
pt 6 no act	0,00	0,00	0,00	0,00	0,00	0,00	-0,01	0,00	0,00
Yearly raifall	0,01	0,01	0,00	0,00	-0,02	-0,06	0,00	-0,03	-0,08
Ra[100-150 cm] Remv	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,04	0,04
lveg	0,04	0,05	0,04	0,00	0,00	0,01	0,05	0,05	0,04
ms0 capp	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00
pt 2 remv	-0,01	-0,01	-0,01	0,00	0,00	0,00	-0,04	-0,04	-0,05
pt 6 remv	0,00	0,00	0,00	0,00	0,00	0,00	-0,01	-0,01	-0,01
Kd 2 capp	0,00	0,00	0,00	0,00	0,03	0,09	0,00	0,00	0,00
Kd 6 capp	0,01	0,01	0,01	0,00	0,00	0,01	0,01	0,01	0,01
r_bs_3 remv	0,01	0,01	0,01	0,00	0,00	0,00	0,07	0,08	0,10
r_bs_5 remv	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,03	0,04	0,04
gr ml Pb	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01
Kd 0 capp	-0,01	-0,01	-0,01	0,00	0,00	0,02	0,00	0,00	0,00
pt 4 remv	-0,02	-0,02	-0,01	0,00	0,00	0,00	-0,04	-0,04	-0,04
pt 0 no act	0,05	0,05	0,05	0,00	0,00	0,00	0,01	0,01	0,01
Ra[150-200 cm] No Act	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,00	-0,01	0,00
Ra[15-30 cm] Remv	0,01	0,01	0,01	0,00	0,00	0,00	0,09	0,09	0,08
pt 5 remv	-0,01	-0,01	-0,01	0,00	0,00	0,00	-0,03	-0,03	-0,03
Ra[0-15 cm] Remv	0,00	0,00	0,00	0,00	0,00	0,00	0,14	0,13	0,11
gr ml	0,01	0,01	0,00	0,00	0,00	-0,01	0,01	0,00	0,00
pt 2 no act	-0,03	-0,03	-0,03	0,00	0,00	0,00	0,00	0,00	0,00
ms3 remv	0,00	-0,01	-0,01	0,00	0,00	0,00	0,00	-0,01	-0,01
Ra[150-200 cm]Capp	0,00	-0,01	-0,01	0,00	0,00	0,00	0,00	0,00	-0,01

(Continued)

Kd 5 remv	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,03
Kd 1 remv	0,02	0,02	0,01	0,00	0,00	0,00	0,01	0,07	0,19
rbs5 no act	0,00	0,00	0,00	0,00	0,00	-0,01	-0,01	-0,01	-0,01
ms5 no act	0,00	0,00	0,00	0,00	0,00	0,00	-0,01	-0,01	0,00
Diff cf	0,00	0,00	-0,01	0,00	0,00	0,02	0,01	0,01	0,00
ms1 capp	-0,02	-0,01	-0,01	0,00	0,00	-0,01	0,00	0,00	-0,01
pt 3 no act	0,00	0,00	0,00	0,00	-0,01	0,00	-0,01	-0,01	-0,01
Ra[100-150 cm] No Act	0,00	0,00	0,01	-0,01	0,00	0,00	0,01	0,01	0,01
gr bf	-0,01	0,00	0,00	-0,01	0,00	0,00	0,00	0,01	0,01
ms3 capp	-0,01	-0,01	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
Diff cf Pb	-0,01	0,00	0,00	-0,01	0,00	0,00	-0,01	-0,01	-0,01
r_bs_4 remv	-0,01	-0,01	0,00	-0,01	0,00	0,01	0,05	0,06	0,08
Kd 6 remv	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,01	0,01	0,02
ms2 no act	-0,01	-0,01	-0,01	-0,01	0,00	0,00	-0,01	-0,01	-0,01
r_bs_6 remv	-0,02	-0,01	-0,01	-0,01	-0,01	-0,01	0,01	0,01	0,01
rbs0 no act	0,11	0,10	0,08	-0,01	-0,01	-0,01	0,00	0,00	0,00
ms5 capp	-0,01	0,00	-0,01	-0,01	-0,01	-0,01	-0,01	-0,01	-0,01
ms1no act	0,00	-0,01	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
Ra[75-100 cm] Remv	-0,02	-0,02	-0,02	-0,01	-0,01	-0,01	0,03	0,04	0,04
Ra[50-75 cm] No Act	0,00	0,00	0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
pt 4 no act	-0,02	-0,02	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,00
pt 1 remv	-0,01	-0,01	0,00	-0,01	-0,01	-0,01	-0,04	-0,05	-0,06
ms5 remv	0,00	0,00	0,00	-0,01	-0,01	-0,02	-0,01	-0,01	0,00
pt 6 capp	0,00	0,00	0,01	-0,01	-0,01	0,00	0,00	0,00	0,00
ms6 remv	0,00	0,00	0,00	-0,01	-0,01	-0,01	0,00	0,00	-0,01
ms6 no act	0,01	0,01	0,01	-0,01	-0,01	-0,01	-0,01	-0,01	-0,01
I time	0,01	0,01	0,00	-0,01	-0,02	-0,03	0,00	-0,02	-0,03
Kd 0 no act	-0,01	-0,01	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
Kd 6 no act	-0,01	0,00	0,01	-0,01	-0,02	-0,02	-0,01	-0,01	-0,01
ms6 capp	0,00	0,00	0,00	-0,01	-0,01	-0,01	-0,01	0,00	0,00
pt 5 no act	0,01	0,01	0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
rbs6 no act	0,01	0,01	0,01	-0,02	-0,01	-0,01	0,00	0,00	0,00
Ra[15-30 cm] No Act	0,19	0,19	0,16	-0,02	-0,02	-0,01	-0,03	-0,02	-0,02
I rate	-0,01	-0,01	-0,01	-0,02	-0,03	-0,04	-0,01	-0,02	-0,05
pt 5 capp	-0,01	0,00	0,00	-0,02	-0,02	-0,02	0,00	0,00	0,00
pt 3 capp	0,00	0,00	-0,01	-0,03	-0,03	-0,04	0,00	0,00	0,00
Time on fields	-0,01	-0,01	-0,01	-0,03	-0,03	-0,03	-0,03	-0,03	-0,02
pt 1 capp	-0,01	-0,01	0,00	-0,05	-0,05	-0,07	-0,01	-0,01	0,00
DepthB	-0,07	-0,07	-0,06	-0,09	-0,09	-0,09	-0,20	-0,20	-0,18
Vhouse	-0,08	-0,08	-0,08	-0,10	-0,10	-0,10	-0,21	-0,20	-0,18
Vent	-0,18	-0,18	-0,16	-0,22	-0,22	-0,20	-0,48	-0,47	-0,43

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II-2.2. DOSDIM

II-2.2.1. General model description

II-2.2.1.1. Name of model, model developer(s) and model user(s)

Model name:	DOSDIM (DOSe DIstribution Model)
Model developer(s):	Paul Govaerts, Nicolas Lewyckyj, Theo Zeevaert. Adapted by Lieve Sweeck – SCK/CEN, Mol, Belgium
Name of model user:	Lieve Sweeck

II-2.2.1.2. Intended purpose of the model in radiation assessment

To assess the impact to man from routine and accidental releases

II-2.2.1.3. Model type (equilibrium, dynamical, numerical, analytical,...)

A compartmental, partly dynamical model

II-2.2.1.4. Method used for deriving uncertainty estimates

Latin Hypercube Sampling method was used. The mean, ranges and pdf's for the different parameters as given in table I-XXV and I-XXVI (Appendix I) were used.

II-2.2.1.5. Description of model (procedures, parameters, main equations)

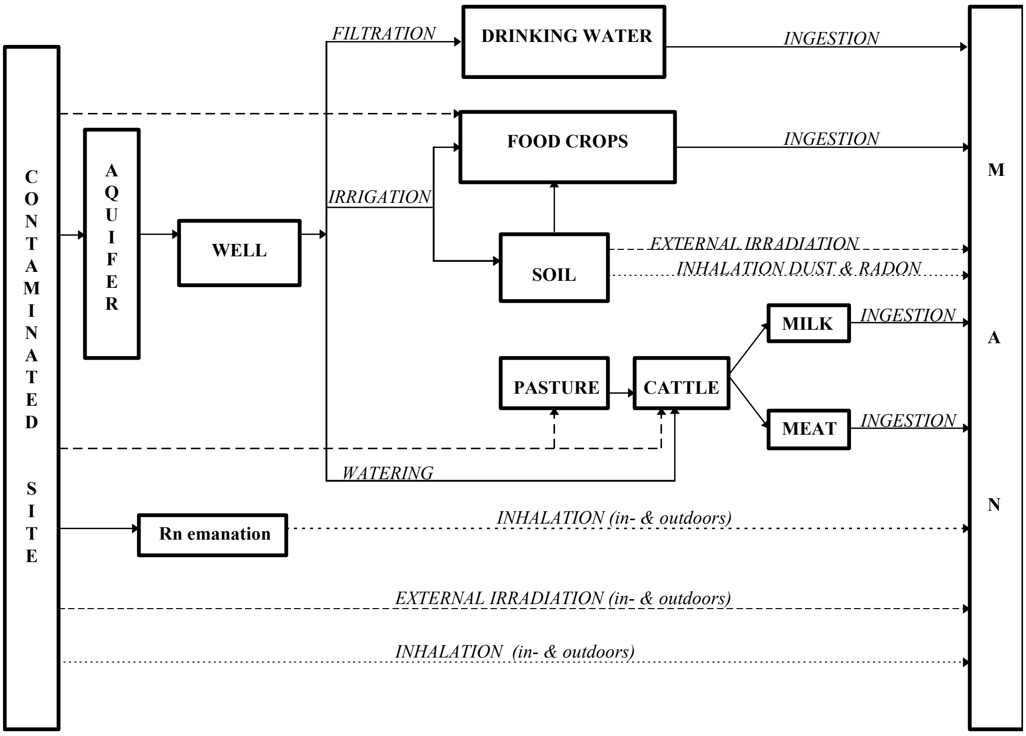

FIG. II-2.2.1. Exposure pathways.

- *Concentrations*

Concentration in soil was estimated from the data given in the Olen B scenario;
For no remediation case:

- Farm and garden: best estimate value 2000 Bq/kg [500–4000; triangular];
- Pasture: 300 Bq/kg [100–1000; triangular];

Cover for remediation 2 case: 20 Bq/kg [10–40; triangular].

Concentration in drinking water (Bq/m^3) is given by:

$$\begin{aligned} C_{soilsolution,i} &= C_{soil,i} / (\theta_s / \rho_s + K_{ds}) \\ C_{aquifer,i} &= C_{soilsolution,i} \cdot I_w / h_a \cdot e^{(-\lambda_i \cdot t)} \cdot (1 - e^{(-\lambda_s * TS)}) / (1 - e^{-\lambda_s * TS}) \\ C_{w,i} &= C_{aquifer,i} / (\theta_a + K_{da} * \rho_a) \end{aligned} \tag{1}$$

where:

$C_{soil,i}$	is the concentration of radionuclide i in soil (Bq/kg);
$C_{soilsolution,i}$	is the concentration of radionuclide i in soil solution (Bq/m^3);
$C_{aquifer,i}$	is the concentration of radionuclide i in aquifer (Bq/m^3);
$C_{w,i}$	is the concentration of radionuclide i in ground water(Bq/m^3);
ρ_s, ρ_a	is the bulk density of root zone soil, aquifer respectively (kg/m^3);
θ_s, θ_a	is the water content of soil, aquifer respectively (-);
K_{ds}, K_{da}	is the distribution coefficient in soil, aquifer respectively (m^3/kg);
I_w	is the infiltration rate (m/y);
h_a	is the height of aquifer (m);
λ_s	is the leaching rate in soil (1/y);
t	is time (y);
TS	is time step t_i-t_{i-1} (y).

Concentration in grass and leafy vegetables (Bq/kg) was estimated by the following equation:

$$C_{lv,i} = C_{w,i} * \frac{I_{rr}}{T_{ir}} * \frac{R}{Y} * \left[1 - \exp(-\lambda_{w,i} * t_e)\right] * \exp(-\lambda_{w,i} * t_h) + \overline{C}_{soil,i} * B_{v,i} \tag{2}$$

whereby the first term represents the foliar adsorption and the second one the root uptake, and:

$T_{ir,v}$	is the irrigation period for food crop (y);
$I_{rr,v}$	is the annual irrigation (m);
R	is the interception factor (-);
Y	is the herbage density of the plant (kg fw m^{-2} for food crops; kg dw m^{-2} for feed crops, pasture);
t_e	is the time during which the plant is externally exposed to irrigation (y)
$\lambda_{w,i}$	is the weathering decay constant (1/y);
t_h	is the time between end of irrigation and harvest (y);
$B_{v,i}$	is the soil-to-plant transfer factor (kg dw kg^{-1} fw for food crops, kg dw kg^{-1} dw for feed crops, pasture).

In case of root crops, only a certain fraction of the activity interception is assumed to reach the edible parts of the plant. This fraction is represented by a translocation factor f_t.

Concentration in root crops (Bq/kg) is given by:

$$C_{v,i} = C_{w,i} * \frac{I_{rr}}{T_{ir}} * \frac{R}{Y} * t_e * f_t + \overline{C}_{soil,i} * B_v \tag{3}$$

Concentration in inhalable dust (Bq/m^3) is given by:

$$C_{dust} = \overline{C}_{soil,i} * C_{da} * f \tag{4}$$

where:

f	is the fraction contaminated soil (f is assumed to be 0.5);
C_{da}	is the dust loading of the air (value dependent on activities in- and outdoors) (kg/m^3);
$\overline{C_{soil,i}}$	average concentration or radionuclide *i* in root zone soil over the year concerned (Bq/kg).

To calculate the inhalation of dust outdoors during agricultural practices (1500 hours outdoors), the soil concentration of pasture was used. For the work in the garden (300 hours), the soil concentration of the garden was used. For indoors, the concentration of the pasture was used, because it was assumed that the dust in air indoors will come from a much larger area than only the soil surrounding the farm.

The concentration in milk and meat (Bq/kg) is given by:

$$\begin{aligned} C_{m,i} &= F_{m,i} * \left\lfloor C_{w,i} * Q_{w,m} + (C_{p,i} + C_{soil,i} * X_s) * Q_p \right\rfloor \\ C_{f,i} &= F_{f,i} * \left\lfloor C_{w,i} * Q_{w,f} + (C_{p,i} + C_{soil,i} * X_s) * Q_p \right\rfloor \end{aligned} \tag{5}$$

where:

$F_{m(f),i}$	is the grass-to-milk(meat) transfer factor of radionuclide i(d/l for milk, d/kg for meat);
$C_{p,i}$	is the concentration of radionuclide i in pasture or feed crops for the cattle (Bq kg^{-1} dw);
Q_p	is the daily pasture intake by the cattle (kg dw d^{-1});
$Q_{w,m(f)}$	is the daily consumption rate of water (m^3 d^{-1});
X	is the fraction of soil eaten (X = 0.04).

The radon concentration (Bq/m^3) is given by:

$$\begin{aligned} C_{radonoutdoors} &= C_{soil} * 20 \\ C_{radonindoors} &= C_{soil} * 330 * f_{layer} \end{aligned} \tag{6}$$

The factor 20 and 330 are measured values. The factor 330 is only accurate for an infinite soil layer. In this case the contaminated layer is much smaller than the foundation depth. Therefore, a dilution factor f_{layer} (= thickness contaminated layer/foundation depth) was used to calculate the radon concentration indoors.

- *Doses*

The ingestion dose (of water, vegetables, milk, meat) is given by:

$$D_{ing} = C_{food} * I_{food} * df_{ing} \tag{7}$$

where:

I_{food}	is the annual individual consumption rate of food stuffs (food crops, milk, meat, drinking water) (kg/y or m^3/y);
$C_{food,i}$	is the concentration of radionuclide i in food stuffs (food crops, milk, meat, drinking water) (Bq/kg or Bq/m^3);
df_{ing}	ingestion dose conversion factor (Sv/Bq).

The ingestion dose of soil is given by:

$$D_{ing} = C_{soil} * I_{soil} * f * df_{ing} \tag{8}$$

where:

f	is the fraction of dust that is contaminated.

The inhalation dose of dust is given by:

$$D_{inh} = C_{dust} * I_a * df_{inh} \tag{9}$$

where:

I_a	is the breathing rate (differs in- and outdoors) (m^3/h);
df_{inh}	is the inhalation dose conversion factor (Sv/Bq).

The inhalation dose of radon is given by:

$$D_{inhRn,y} = C_{radon,y} * T_{\exp,y} * I_{a,y} * df_{inhal\,Rn,y} \tag{10}$$

where:

$D_{inhRn,y}$	is the inhalation dose of radon indoors, outdoors respectively;
$C_{radon,y}$	is the radon concentration in indoors air, outdoors air respectively (Bq/m3);
$T_{exp,y}$	is time of exposure per year indoors, outdoors respectively;
$df_{inhRn,y}$	inhalation dose conversion factor indoors, outdoors respectively (Sv.m^3/Bq.year).

The external irradiation dose is given by:

$$D_{ext} = C_{soil} * \rho_s * T_{\exp} * SF * df_{ext} \tag{11}$$

where:

SF	shielding factor;
df_{ext}	external irradiation dose conversion factor (Sv/Bq).

II-2.2.1.6. Assumptions concerning parameter values used in different components of the model:

It is assumed that Ra and Pb are in equilibrium in the soil, but that they behave different when migrated, taken up by plants, etc.

To produce stochastic results for the Pb concentration in ground water, it is assumed that the maximum concentration is given when for the radioactive decay the decay for radium is used, while for the leaching process the Kd of Pb is used. The minimum is given by using the radioactive decay and leaching out of lead. Our best-estimate value is the mean of the minimum and maximum.

The average radium concentration in the upper clean soil layer after capping is initially background level (20 Bq/kg), but will increase due to bioturbation (transport of about 2 kg soil dw/m^2/y [0,5-4, triangular] from the deep soil to the cover layer).

We adopted a negative correlation between the distribution coefficient in soil and the soil-to-plant transfer factor in the uncertainty and sensitivity analysis.

II-2.2.1.7. Uncertainty and sensitivity analysis

The risk analysis program @Risk [3] was used for the uncertainty and sensitivity analysis. Random parameter values are generated by using the Latin Hypercube sampling method.

II-2.2.2. Results of model predictions

Deterministic calculations

1. Concentrations in the different compartments

To analyse the results also the soil concentrations used for each pathway are required;
(1) soil concentration used to calculate the radionuclide concentration of dust indoors
(2) soil concentration used to calculate the radionuclide concentration of dust outdoors
(3) soil concentration used to calculate external irradiation indoors
(4) soil concentration used to calculate the external irradiation outdoors
(5) soil concentration used to calculate radionuclide concentration in grass
(6) soil concentration used to calculate radionuclide concentration in potatoes
(7) soil concentration used to calculate radionuclide concentration in leafy vegetables
(8) soil concentration used to calculate radionuclide concentration in ground water
(9) soil concentration used to calculate the radon concentration indoors
(10) soil concentration used to calculate the radon concentration outdoors

1. Without remedial action

	Ra-226 concentration Soil (Bq/kg)										*Pb-210 concentration* Soil (Bq/kg)							
Years	(1)	(2)*	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	299	582	1997	582	299	1997	1997	1999	586	582	299	582	1997	582	299	1997	1997	1999
50	270	538	1877	538	270	1879	1879	1933	585	538	270	538	1877	538	270	1878	1878	1933
100	243	496	1762	496	243	1766	1766	1868	571	496	243	496	1762	496	243	1764	1764	1868
200	197	423	1553	423	197	1564	1564	1745	558	423	197	423	1553	423	197	1555	1555	1745
500	105	265	1062	265	105	1096	1096	1421	531	265	105	265	1062	265	105	1066	1066	1421

(*) weighted mean (weight factor: time spent outdoors working on field (1500 hours) or doing less heavy activities (300 hours))

Ra-226 concentration

	Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
Years	indoors	outdoors	outdoors agric.	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	4,5E-06	9,0E-06	3,0E-05	23,95	0,00	3,00	0,02	20,0	1,17E-01	35,9	9,02E-02	2,26E-01	120,9	2,59
50	4,1E-06	8,1E-06	2,7E-05	21,61	0,00	2,82	0,04	18,8	2,08E-01	64,0	8,18E-02	2,05E-01	118,1	2,51
100	3,6E-06	7,3E-06	2,5E-05	19,46	0,00	2,65	0,05	17,7	2,96E-01	91,0	7,41E-02	1,85E-01	115,4	2,42
200	3,0E-06	5,9E-06	2,1E-05	15,77	0,00	2,35	0,08	15,6	4,56E-01	140,6	6,08E-02	1,52E-01	110,1	2,27
500	1,6E-06	3,2E-06	1,2E-05	8,40	0,00	1,64	0,15	11,0	8,36E-01	257,4	3,46E-02	8,65E-02	95,9	1,87

Pb-210 concentration

Years	Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	indoors	outdoors	outdoors agric.	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	4,5E-06	9,0E-06	3,0E-05	14,58	0	2,00	0,04	19,97	0,23	71,4	6,7E-02	1,35E-01
50	4,1E-06	8,1E-06	2,7E-05	12,28	0	1,88	0,07	18,78	0,36	112,3	5,9E-02	1,18E-01
100	3,6E-06	7,3E-06	2,5E-05	10,30	0	1,76	0,09	17,64	0,50	154,4	5,1E-02	1,04E-01
200	3,0E-06	5,9E-06	2,1E-05	7,24	0	1,56	0,14	15,55	0,76	234,2	4,0E-02	8,13E-02
500	1,6E-06	3,2E-06	1,2E-05	2,52	0	1,07	0,25	10,66	1,35	415,9	2,1E-02	4,36E-02

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Years	*Ra-226 concentration* Soil (Bq/kg)										*Pb-210 concentration* Soil (Bq/kg)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	150	135	60	135	150	60	60	60	31	135	150	135	60	135	150	60	60	60
50	135	122	56	122	135	57	57	58	31	122	135	122	56	122	135	57	57	58
100	122	110	53	110	122	54	54	56	31	110	122	110	53	110	122	53	53	56
200	99	90	47	90	99	49	49	52	31	90	99	90	47	90	99	47	47	52
500	53	49	32	49	53	38	38	43	31	49	53	49	32	49	53	32	32	43

Ra-226 concentration

Years	Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	indoors	outdoors	outdoors agric.	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	2,2E-06	4,5E-06	1,5E-05	11,97	0,00	9,0E-02	2,1E-02	0,6	0,11489531	35,4	4,5E-02	1,1E-01	6,2	6,54E-01
50	2E-06	4,1E-06	1,4E-05	10,80	0,00	8,6E-02	2,2E-02	0,6	0,11828035	36,4	4,1E-02	1,0E-01	6,1	6,33E-01
100	1,8E-06	3,6E-06	1,2E-05	9,73	0,00	8,1E-02	2,2E-02	0,5	0,12139457	37,4	3,7E-02	9,2E-02	6,0	6,12E-01
200	1,5E-06	3,0E-06	1,0E-05	7,89	0,00	7,4E-02	2,3E-02	0,5	0,12667009	39,0	3,0E-02	7,5E-02	5,9	5,73E-01
500	7,9E-07	1,6E-06	6,0E-06	4,20	0,00	5,7E-02	2,5E-02	0,4	0,13610368	41,9	1,6E-02	4,1E-02	5,4	4,69E-01

Pb-210 concentration

Years	Inhalable dust (Bq/m3) indoors	outdoors	outdoors agric.	Grass (Bq/kg) root uptake	foliar uptake	Potatoes (Bq/kg) root uptake	foliar uptake	Leafy vegetables (Bq/kg) root uptake	foliar uptake	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
1	2,2E-06	4,5E-06	1,5E-05	7,29	0	6,0E-02	4,1E-02	6,0E-01	2,2E-01	68,7	3,4E-02	6,80E-02
50	2E-06	4,1E-06	1,4E-05	6,14	0	5,7E-02	1,2E-02	5,7E-01	6,4E-02	19,9	2,9E-02	5,82E-02
100	1,8E-06	3,6E-06	1,2E-05	5,15	0	5,3E-02	5,9E-03	5,3E-01	3,2E-02	9,9	2,5E-02	5,03E-02
200	1,5E-06	3,0E-06	9,9E-06	3,62	0	4,7E-02	6,6E-03	4,7E-01	3,6E-02	11,1	1,9E-02	3,81E-02
500	7,9E-07	1,6E-06	5,3E-06	1,26	0	3,2E-02	1,3E-02	3,2E-01	6,8E-02	20,9	8,6E-03	1,73E-02

3. After implementing of remedial action 2 (covering with clean soil layer - option 2a)
Soil type (% clay content): loam (20 % (range 15 - 30%) clay)
3.A. Thickness of soil layer = 0.5 m

Years	*Ra-226 concentration* Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	*Pb-210 concentration* Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	21	28	47	28	21	31	31	2000	585	289	21	28	47	28	21	31	31	2000
50	78	141	449	141	78	435	435	1939	571	381	78	141	449	141	78	435	435	1939
100	111	210	691	210	111	680	680	1874	558	433	111	210	691	210	111	679	679	1874
200	139	268	898	268	139	893	893	1751	531	467	139	268	898	268	139	889	889	1751
500	131	253	855	253	131	870	870	1426	458	407	131	253	855	253	131	849	849	1426

Ra-226 concentration

Years	Inhalable dust (Bq/m3) indoors	outdoors	outdoors agric.	Grass (Bq/kg) root uptake	foliar uptake	Potatoes (Bq/kg) root uptake	foliar uptake	Leafy vegetables (Bq/kg) root uptake	foliar uptake	Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3) indoors	outdoors
1	3,2E-07	6,44E-07	2,15E-06	1,72	0,00	4,6E-02	2,1E-02	3,1E-01	1,1E-01	35,3	6,9E-03	1,7E-02	115,26	1,36
50	1,2E-06	2,33E-06	9,16E-06	5,96	0,00	6,5E-01	3,7E-02	4,4E+00	2,0E-01	61,1	2,3E-02	5,8E-02	112,64	1,76
100	1,7E-06	3,34E-06	1,31E-05	8,19	0,00	1,0E+00	5,3E-02	6,8E+00	2,9E-01	88,2	3,2E-02	7,9E-02	110,04	1,99
200	2,1E-06	4,18E-06	1,59E-05	9,44	0,00	1,3E+00	8,3E-02	8,9E+00	4,5E-01	138,0	3,7E-02	9,3E-02	105,02	2,14
500	2E-06	3,92E-06	1,46E-05	6,89	0,00	1,3E+00	1,5E-01	8,7E+00	8,3E-01	255,3	2,9E-02	7,2E-02	91,40	1,87

Pb-210 concentrations

	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
Years	pasture	garden	farm	indoors	outdoors	outdoors agric.	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	21,47	30,55	30,54	3,2205E-07	6,44E-07	2,15E-06	1,07	0	0,03	4,11E-02	0,31	0,22	68,5	5,44E-03	1,13E-02
50	77,63	435,12	434,22	1,16449E-06	2,33E-06	9,16E-06	3,33	0	0,44	6,27E-02	4,35	0,34	104,6	1,67E-02	3,40E-02
100	111,27	679,18	677,71	1,66905E-06	3,34E-06	1,30E-05	4,09	0	0,68	8,76E-02	6,79	0,47	146,0	2,18E-02	4,44E-02
200	139,46	888,66	886,31	2,09183E-06	4,18E-06	1,55E-05	3,76	0	0,89	1,35E-01	8,89	0,73	224,3	2,32E-02	4,78E-02
500	130,69	849,37	845,32	1,96037E-06	3,92E-06	1,24E-05	1,40	0	0,85	2,42E-01	8,49	1,31	402,6	1,57E-02	3,39E-02

Individual doses for an adult for Olen site (mSv/y)

1. Without remedial action

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			
1	2,24E-04	6,83E-04	6,71E-01	1,41E-01	3,81	8,16E-02	3,13E-01	1,83E-03	1,02E-01	7,36E-04	4,02E-03	3,31E-03	3,41E-03	1,47E-03
50	2,02E-04	6,23E-04	6,31E-01	1,30E-01	3,72	7,89E-02	2,95E-01	3,26E-03	9,63E-02	1,31E-03	7,17E-03	3,00E-03	3,09E-03	1,38E-03
100	1,82E-04	5,68E-04	5,92E-01	1,20E-01	3,64	7,63E-02	2,77E-01	4,63E-03	9,05E-02	1,87E-03	1,02E-02	2,72E-03	2,80E-03	1,30E-03
200	1,48E-04	4,73E-04	5,22E-01	1,03E-01	3,47	7,15E-02	2,45E-01	7,16E-03	8,01E-02	2,88E-03	1,57E-02	2,23E-03	2,30E-03	1,14E-03
500	7,86E-05	2,79E-04	3,57E-01	6,54E-02	3,02	5,89E-02	1,72E-01	1,31E-02	5,62E-02	5,28E-03	2,88E-02	1,27E-03	1,31E-03	7,81E-04
Maximum	2,24E-04	6,83E-04	6,71E-01	1,41E-01	3,81	8,16E-02	3,13E-01	1,83E-03	1,02E-01	7,36E-04	4,02E-03	3,31E-03	3,41E-03	1,47E-03

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			
1	1,32E-04	4,02E-04	4,19E-04	8,81E-05	7,72E-01	8,95E-03	1,68E-01	3,60E-03	1,97E-02	6,06E-03	5,01E-03	2,41E-02
50	1,24E-04	3,67E-04	3,94E-04	8,15E-05	7,26E-01	1,41E-02	1,58E-01	5,67E-03	3,10E-02	5,31E-03	4,40E-03	2,27E-02
100	1,17E-04	3,34E-04	3,70E-04	7,52E-05	6,82E-01	1,94E-02	1,48E-01	7,80E-03	4,26E-02	4,65E-03	3,87E-03	2,13E-02
200	1,03E-04	2,77E-04	3,26E-04	6,43E-05	6,01E-01	2,94E-02	1,31E-01	1,18E-02	6,46E-02	3,61E-03	3,03E-03	1,87E-02
500	7,03E-05	1,60E-04	2,23E-04	4,05E-05	4,12E-01	5,22E-02	8,98E-02	2,10E-02	1,15E-01	1,86E-03	1,62E-03	1,28E-02
Maximum	1,32E-04	4,02E-04	4,19E-04	8,81E-05	7,72E-01	8,95E-03	1,68E-01	3,60E-03	1,97E-02	6,06E-03	5,01E-03	2,41E-02

Total dose :

Ra-226 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	4,71	4,58	4,44	4,19	3,53
pasture+kitchen garden	5,13	4,97	4,82	4,52	3,78

Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	0,06	0,06	0,07	0,09	0,13
pasture+kitchen garden	1,01	0,97	0,93	0,86	0,71

Ra-226 &Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	4,77	4,64	4,51	4,28	3,66
pasture+kitchen garden	6,14	5,94	5,75	5,39	4,49

2. After implementing remedial action 1 (removal of contaminated soil)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			
1	1,12E-04	2,61E-04	2,01E-02	3,26E-02	0,19	2,06E-02	9,40E-03	1,80E-03	3,07E-03	7,25E-04	3,96E-03	1,66E-03	1,71E-03	3,15E-04
50	1,01E-04	2,37E-04	1,89E-02	2,95E-02	0,19	1,99E-02	8,94E-03	1,85E-03	2,92E-03	7,47E-04	4,08E-03	1,50E-03	1,55E-03	2,96E-04
100	9,10E-05	2,15E-04	1,78E-02	2,67E-02	0,19	1,93E-02	8,51E-03	1,90E-03	2,78E-03	7,66E-04	4,19E-03	1,35E-03	1,40E-03	2,78E-04
200	7,38E-05	1,77E-04	1,57E-02	2,19E-02	0,18	1,80E-02	7,74E-03	1,99E-03	2,53E-03	8,00E-04	4,37E-03	1,10E-03	1,14E-03	2,45E-04
500	3,93E-05	1,03E-04	1,07E-02	1,21E-02	0,17	1,48E-02	5,95E-03	2,13E-03	1,94E-03	8,59E-04	4,70E-03	5,96E-04	6,15E-04	1,67E-04
Maximum	1,12E-04	2,61E-04	2,01E-02	3,26E-02	0,19	2,06E-02	9,40E-03	1,80E-03	3,07E-03	7,25E-04	3,96E-03	1,66E-03	1,71E-03	3,15E-04

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			
1	6,60E-05	1,54E-04	1,26E-05	2,04E-05	2,32E-02	8,61E-03	5,05E-03	3,47E-03	1,89E-02	3,06E-03	2,54E-03	7,75E-04
50	5,96E-05	1,39E-04	1,18E-05	1,84E-05	2,19E-02	2,49E-03	4,78E-03	1,00E-03	5,48E-03	2,62E-03	2,17E-03	7,29E-04
100	5,36E-05	1,25E-04	1,11E-05	1,67E-05	2,05E-02	1,24E-03	4,47E-03	4,98E-04	2,72E-03	2,27E-03	1,87E-03	6,84E-04
200	4,35E-05	1,02E-04	9,78E-06	1,36E-05	1,81E-02	1,39E-03	3,93E-03	5,59E-04	3,06E-03	1,72E-03	1,42E-03	6,03E-04
500	2,32E-05	5,48E-05	6,69E-06	7,43E-06	1,24E-02	2,62E-03	2,70E-03	1,05E-03	5,76E-03	7,77E-04	6,45E-04	4,12E-04
Maximum	6,60E-05	1,54E-04	1,26E-05	2,04E-05	2,32E-02	8,61E-03	5,05E-03	3,47E-03	1,89E-02	3,06E-03	2,54E-03	7,75E-04

Total dose :

Ra-226 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	0,28	0,27	0,26	0,25	0,22
pasture+kitchen garden	0,29	0,28	0,27	0,26	0,23

Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	0,03	0,01	0,01	0,01	0,01
pasture+kitchen garden	0,07	0,04	0,03	0,03	0,03

Total dose :

Ra-226 &Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	0,30	0,28	0,27	0,25	0,22
pasture+kitchen garden	0,36	0,32	0,31	0,29	0,25

3. After implementing remedial action 2 (capping with clean soil layer of 50 cm)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking water	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar				
1	1,60E-05	3,93E-05	1,56E-02	6,69E-03	3,63	4,28E-02	4,79E-03	1,80E-03	1,57E-03	7,24E-04	3,96E-03	2,52E-04	2,59E-04	5,79E-05
50	5,57E-05	1,66E-04	1,51E-01	3,42E-02	3,55	5,55E-02	6,82E-02	3,11E-03	2,23E-02	1,25E-03	6,84E-03	8,46E-04	8,72E-04	3,45E-04
100	7,66E-05	2,37E-04	2,32E-01	5,08E-02	3,47	6,27E-02	1,07E-01	4,49E-03	3,48E-02	1,81E-03	9,88E-03	1,17E-03	1,20E-03	5,18E-04
200	8,83E-05	2,89E-04	3,02E-01	6,50E-02	3,31	6,73E-02	1,40E-01	7,02E-03	4,57E-02	2,83E-03	1,55E-02	1,36E-03	1,40E-03	6,65E-04
500	6,45E-05	2,66E-04	2,87E-01	6,21E-02	2,88	5,90E-02	1,36E-01	1,30E-02	4,46E-02	5,23E-03	2,86E-02	1,06E-03	1,09E-03	6,29E-04
Maximum	9,10E-05	2,98E-04	3,14E-01	6,72E-02	3,63	6,73E-02	1,46E-01	7,02E-03	4,76E-02	2,83E-03	1,55E-02	1,40E-03	1,44E-03	6,89E-04

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		potatoes		drinking water	milk	meat	soil ingestion
	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar				
1	9,46E-06	2,32E-05	9,77E-06	4,18E-06	1,18E-02	8,59E-03	2,57E-03	3,46E-03	1,89E-02	4,91E-04	4,20E-04	1,43E-04
50	3,28E-05	9,79E-05	9,43E-05	2,14E-05	1,68E-01	1,31E-02	3,66E-02	5,28E-03	2,89E-02	1,51E-03	1,27E-03	8,51E-04
100	4,51E-05	1,39E-04	1,45E-04	3,17E-05	2,62E-01	1,83E-02	5,72E-02	7,38E-03	4,03E-02	1,97E-03	1,66E-03	1,28E-03
200	5,21E-05	1,66E-04	1,89E-04	4,05E-05	3,43E-01	2,81E-02	7,48E-02	1,13E-02	6,19E-02	2,10E-03	1,78E-03	1,64E-03
500	3,80E-05	1,34E-04	1,80E-04	3,83E-05	3,28E-01	5,05E-02	7,15E-02	2,03E-02	1,11E-01	1,42E-03	1,26E-03	1,55E-03
Maximum	5,36E-05	1,71E-04	1,96E-04	4,19E-05	3,58E-01	5,05E-02	7,79E-02	1,13E-02	6,19E-02	2,16E-03	1,83E-03	1,70E-03

Total dose :

Ra-226 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	3,70	3,80	3,82	3,76	3,32
pasture+kitchen garden	3,71	3,89	3,97	3,96	3,52

Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	0,02	0,03	0,05	0,07	0,12
pasture+kitchen garden	0,05	0,26	0,39	0,53	0,59

Total dose :

Ra-226 &Pb-210 calculations

Agricultural use	1 y	50 y	100 y	200 y	500 y
100% pasture	3,72	3,83	3,87	3,83	3,43
pasture+kitchen garden	3,76	4,15	4,36	4,48	4,10

Stochastic model calculations

Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

No remediation

Ra-226 calculations

Years	Inhalation of dust (optional)						External irradiation					
	Indoors			Outdoors			Indoors			Outdoors		
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	5,30E-04	1,04E-04	1,37E-03	1,91E-03	4,86E-04	4,97E-03	7,33E-01	2,42E-01	1,45E+00	1,84E-01	7,47E-02	3,37E-01
100	4,01E-04	5,27E-05	1,14E-03	1,47E-03	3,05E-04	4,11E-03	6,15E-01	1,63E-01	1,29E+00	1,53E-01	5,29E-02	2,96E-01
500	2,09E-04	1,81E-07	7,88E-04	8,10E-04	7,36E-05	2,74E-03	3,67E-01	8,99E-03	9,73E-01	1,12E-01	3,24E-02	2,38E-01
Maximum												

Pb-210 calculations

Years	Inhalation of dust (optional)						External irradiation					
	Indoors			Outdoors			Indoors			Outdoors		
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	3,13E-04	6,16E-05	8,06E-04	1,13E-03	2,87E-04	2,93E-03	4,58E-04	1,51E-04	9,07E-04	1,15E-04	4,64E-05	2,11E-04
100	2,61E-04	4,65E-05	6,99E-04	8,65E-04	1,68E-04	2,42E-03	3,84E-04	1,02E-04	8,08E-04	9,35E-05	2,59E-05	1,87E-04
500	1,54E-04	3,52E-06	5,06E-04	4,61E-04	6,35E-06	1,63E-03	2,29E-04	5,62E-06	6,08E-04	5,49E-05	1,73E-06	1,43E-04
Maximum												

Ra-226 calculations

Years	Inhalation of radon						Leafy vegetables						Drinking water		
	Indoors			Outdoors			Root			Foliar					
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	6,02E+00	5,61E-01	2,43E+01	1,12E-01	1,44E-02	3,76E-01	0,5195297	4,59E-02	2,185053	5,01E-02	3,58E-05	0,4322536	4,19E-02	4,93E-05	3,04E-01
100	5,71E+00	5,32E-01	2,28E+01	1,05E-01	1,34E-02	3,56E-01	0,406227	4,26E-02	1,4989541	9,90E-02	8,00E-05	0,8392705	9,94E-02	1,26E-04	7,01E-01
500	4,62E+00	4,32E-01	1,86E+01	8,90E-02	1,12E-02	3,03E-01	0,2505286	2,96E-02	0,9438492	0,1507192	1,51E-04	1,2261891	2,23E-01	3,73E-04	1,45E+00
Maximum															

Pb-210 calculations

Years	Leafy vegetables						Drinking water		
	Root			Foliar					
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	0,9203846	0,2735328	1,9225459	0,1548148	1,17E-04	1,1781054	2,40E-01	2,96E-04	1,77E+00
100	0,7689922	0,2003708	1,7033364	0,2924867	2,58E-04	2,2462161	4,56E-01	6,55E-04	3,14E+00
500	0,4625124	1,58E-02	1,3072723	0,5266679	7,45E-04	3,536914	8,34E-01	1,92E-03	4,93E+00
Maximum									

Ra-226 calculations

Years	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root			Foliar											
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	0,1768742	1,83E-02	0,7215797	8,76E-03	1,80E-06	7,99E-02	1,63E-02	2,38E-03	5,26E-02	8,94E-03	1,18E-03	3,10E-02	1,89E-03	9,94E-04	2,93E-03
100	0,1385203	1,67E-02	0,5118193	1,73E-02	4,01E-06	0,1582315	1,23E-02	1,96E-03	3,85E-02	6,73E-03	1,00E-03	2,24E-02	1,57E-03	6,59E-04	2,63E-03
500	8,52E-02	1,15E-02	0,3152024	2,65E-02	7,57E-06	0,24354	5,84E-03	1,00E-03	2,24E-02	4,00E-03	5,33E-04	1,43E-02	9,26E-04	3,18E-05	2,01E-03
Maximum															

Pb-210 calculations

Years	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root			Foliar											
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	0,2627435	0,0692771	0,5942672	2,79E-02	4,90E-06	0,2559075	3,12E-02	4,26E-03	9,79E-02	1,58E-02	3,07E-03	4,52E-02	2,50E-02	6,11E-03	6,15E-02
100	0,2219985	6,11E-02	0,5168545	5,27E-02	1,08E-05	0,4835131	2,24E-02	3,16E-03	6,86E-02	1,14E-02	2,25E-03	3,10E-02	2,07E-02	4,52E-03	5,39E-02
500	0,1490674	2,86E-02	0,3909321	9,48E-02	3,15E-05	0,776954	1,50E-02	1,37E-03	5,77E-02	7,61E-03	9,85E-04	2,64E-02	1,22E-02	3,40E-04	3,85E-02
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
7,83E+00	1,68E+00	2,63E+01	7,31E+00	1,56E+00	2,47E+01	5,91E+00	1,22E+00	1,98E+01

Pb-210 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1,66E+00	4,46E-01	4,79E+00	1,83E+00	3,57E-01	7,09E+00	2,09E+00	1,24E-01	9,98E+00

Ra-226 & Pb-210 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
9,49E+00	2,45E+00	2,88E+01	9,14E+00	2,27E+00	2,71E+01	7,99E+00	1,78E+00	2,38E+01

Remediation 2

Ra-226 calculations

Years	Inhalation of dust (optional)						External irradiation					
	Indoors			Outdoors			Indoors			Outdoors		
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	2,92E-05	7,25E-06	6,51E-05	9,58E-05	2,35E-05	2,20E-04	1,79E-02	8,93E-03	2,97E-02	8,16E-03	4,10E-03	1,37E-02
100	1,67E-04	2,46E-05	5,11E-04	6,32E-04	1,47E-04	1,72E-03	2,42E-01	7,53E-02	4,94E-01	6,37E-02	2,73E-02	1,19E-01
500	1,55E-04	7,66E-07	5,60E-04	7,07E-04	1,66E-04	1,93E-03	2,89E-01	4,70E-02	6,42E-01	8,02E-02	2,86E-02	1,58E-01
Maximum												

Pb-210 calculations

Years	Inhalation of dust (optional)						External irradiation					
	Indoors			Outdoors			Indoors			Outdoors		
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	1,72E-05	4,28E-06	3,84E-05	5,65E-05	1,39E-05	1,30E-04	1,12E-05	5,58E-06	1,85E-05	5,10E-06	2,56E-06	8,57E-06
100	9,87E-05	1,45E-05	3,01E-04	3,69E-04	7,34E-05	1,02E-03	1,52E-04	4,71E-05	3,09E-04	3,96E-05	1,59E-05	7,46E-05
500	9,11E-05	4,51E-07	3,30E-04	3,61E-04	2,09E-05	1,15E-03	1,81E-04	2,94E-05	4,01E-04	4,67E-05	9,27E-06	1,00E-04
Maximum												

Ra-226 calculations

Years	Inhalation of radon						Leafy vegetables						Drinking water		
	Indoors			Outdoors			Root			Foliar					
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1	5,63E+00	4,82E-01	2,41E+01	5,65E-02	7,19E-03	1,89E-01	8,71E-03	8,45E-04	3,49E-02	2,70E-02	1,99E-05	2,07E-01	4,50E-02	5,08E-05	3,28E-01
100	5,01E+00	4,32E-01	2,12E+01	8,25E-02	1,02E-02	2,77E-01	1,65E-01	1,52E-02	6,96E-01	6,30E-02	5,02E-05	4,75E-01	1,05E-01	1,28E-04	7,46E-01
500	3,19E+00	2,51E-01	1,36E+01	7,77E-02	9,13E-03	2,72E-01	1,84E-01	2,24E-02	6,91E-01	1,42E-01	1,52E-04	1,02E+00	2,37E-01	3,88E-04	1,50E+00
Maximum															

Pb-210 calculations

Years	Leafy vegetables						Drinking water		
	Root			Foliar					
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1,00E+00	1,57E-02	5,74E-03	3,12E-02	1,51E-01	1,16E-04	1,18E+00	2,51E-01	2,89E-04	1,71E+00
1,00E+02	3,13E-01	7,84E-02	7,35E-01	2,82E-01	2,52E-04	2,09E+00	4,70E-01	6,29E-04	3,08E+00
5,00E+02	3,64E-01	6,39E-02	8,82E-01	5,15E-01	7,48E-04	3,58E+00	8,63E-01	1,88E-03	5,02E+00
Maximum									

Ra-226 calculations

Years	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root			Foliar											
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1,00E+00	3,00E-03	3,71E-04	1,19E-02	4,61E-03	1,02E-06	4,31E-02	1,02E-03	1,12E-04	4,48E-03	5,70E-04	6,04E-05	2,57E-03	7,01E-05	4,15E-05	1,04E-04
1,00E+02	5,66E-02	6,16E-03	2,12E-01	1,07E-02	2,57E-06	1,00E-01	4,40E-03	5,83E-04	1,41E-02	2,45E-03	3,05E-04	8,99E-03	6,54E-04	2,67E-04	1,24E-03
5,00E+02	6,30E-02	9,08E-03	2,15E-01	2,42E-02	7,76E-06	2,08E-01	5,84E-03	3,05E-04	8,99E-03	2,78E-03	3,38E-04	1,04E-02	7,44E-04	1,71E-04	1,39E-03
Maximum															

Pb-210 calculations

Years	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root			Foliar											
	Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
1,00E+00	4,42E-03	1,32E-03	9,42E-03	2,58E-02	5,13E-06	2,39E-01	3,33E-03	2,73E-04	1,79E-02	1,72E-03	2,11E-04	8,43E-03	1,73E-04	1,02E-04	2,56E-04
1,00E+02	8,81E-02	1,91E-02	2,24E-01	4,83E-02	1,12E-05	4,38E-01	9,87E-03	1,12E-03	3,55E-02	5,10E-03	7,98E-04	1,69E-02	1,61E-03	6,61E-04	3,07E-03
5,00E+02	1,03E-01	1,64E-02	2,66E-01	6,46E-03	3,11E-06	5,31E-02	1,14E-02	5,96E-04	5,10E-02	5,87E-03	3,73E-04	2,38E-02	1,83E-03	4,22E-04	3,43E-03
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
5,80E+00	6,16E-01	2,44E+01	5,81E+00	9,40E-01	2,21E+01	4,30E+00	8,82E-01	1,48E+01

Pb-210 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
4,53E-01	1,18E-02	3,01E+00	1,22E+00	1,33E-01	5,97E+00	1,87E+00	1,32E-01	8,95E+00

Ra-226 & Pb-210 calculations

1 y			100 y			500 y		
Mean	95% confid. interval		Mean	95% confid. interval		Mean	95% confid. interval	
	lower limit	upper limit		lower limit	upper limit		lower limit	upper limit
6,26E+00	7,31E-01	2,46E+01	7,03E+00	1,31E+00	2,38E+01	6,17E+00	1,39E+00	1,84E+01

II-2.2.3. Sensitivity analysis

Table: Ranking of the three most sensitive parameters for the total dose (Ra&Pb)

1. Without remedial action

from most to less sensitive	parameter
1	exhalation factor indoors
2	radium concentration farm/garden
3	soil-to-plant TF(Pb) for leafy vegetables

2. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

from most to less sensitive	parameter
1	exhalation factor indoors
2	radium concentration farm/garden
3	soil-to-plant TF(Pb) for leafy vegetables/potatoes

References

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[2] INTERNATIONAL ATOMIC ENERGY AGENCY. Measurement and calculation of radon releases from uranium mill tailings, Technical Reports Series No. 333, IAEA, Vienna (1992).

[3] @RISK, Guide for using @Risk, Risk analysis and simulation add-in for Ms Excel or Lotus 1-2-3, Windows Version, July 1997. Palisade corporation.

II-2.3. OLENRAD-B

II-2.3.1. General model description

II-2.3.1.1. Name of model, model developer(s) and model user(s)

Model name:	OLENRAD-B
Model developer(s):	Tatiana Sazykina, Alexander Kryshev, SPA "Typhoon", Obninsk, Kaluga Region, Russian Federation
Name of model user(s):	Tatiana Sazykina, Alexander Kryshev, SPA "Typhoon", Obninsk, Kaluga Region, Russian Federation

II-2.3.1.2. Intended purpose of the model in radiation assessment

Assessment of dose to representatives of rural population, inhabiting the territory, contaminated with ^{226}Ra.

Evaluation of effectiveness of different countermeasures.

II-2.3.1.3. Model type

Analytical formulas with empirical values of some parameters

II-2.3.1.4. Method used for deriving uncertainty estimates

Analytical estimation on the basis of uncertainties in the contamination levels and uncertainties in the model parameters

II-2.3.1.5. Description of model (procedures, parameters, main equations, scheme)

The annual doses to representatives of rural population (adult man and child of 5 years old), inhabiting the ^{226}Ra contaminated territory, are calculated. The calculations are based on the multiple pathway approach. The annual dose is calculated as a sum of the doses from the following pathways: external irradiation from soil, inhalation of dust, consumption of contaminated foodstuff (including consumption of soil), inhalation of daughter product of radium decay – ^{222}Rn.

II-2.3.1.6. Basic equations and parameters

— *Annual dose of external irradiation from ^{226}Ra contaminated soil*

$$P_{ext} = D_{ext} (T_{out} \text{ x } Shield_{out} + T_{in} \text{ x } Shield_{in}) \quad (1)$$

where:

P_{ext} is the annual dose of external irradiation from ^{226}Ra contaminated soil, mSv year^{-1};
D_{ext} is the dose rate of gamma-irradiation from soil, μSv/h; (D_{ext}=1 μSv/h (0.5-2 μSv/h) without remediation on most contaminated site of Olen place);
T_{out} is the time staying outdoors (adult – 1800 h/y; child – 500 h/y);
T_{in} is the time staying indoors (adult – 7000 h/y; child – 8300 h/y);
$Shield_{out}$ is the shielding factor for external irradiation, staying outdoor ($Shield_{out}$=0.75);
$Shield_{in}$ is the shielding factor for external irradiation , staying indoor ($Shield_{in}$=0.25).

— *Annual dose from inhalation of 226Ra contaminated aerosols*

$$P_{dust} = D_{inh,dust} \text{ x } A_{aer} \text{ x } [V_{breath,out} \text{ x } T_{out} \text{ x } C_{dust,out} + V_{breath,in} \text{ x } T_{in} \text{ x } C_{dust,out}] \quad (2)$$

where:

P_{dust} is the annual dose from inhalation of ^{226}Ra contaminated dust;
$D_{inh,dust}$ is the dose conversion factor for inhalation of ^{226}Ra (9.5×10^{-6} Sv/Bq for adult, and 1.9×10^{-5} Sv/Bq for child);
$V_{breath,out}$ is the breathing rate outdoors (adult – 1 m^3/h; child – 0.69 m^3/h);
$V_{breath,in}$ is the breathing rate indoors (adult – 0.75 m^3/h; child – 0.51 m^3/h);
$C_{dust,out}$ is the concentration of dust in the local air outdoors (3×10^{-8} kg/m^3);
$C_{dust,in}$ is the concentration of dust in the local air indoors (1.5×10^{-8} kg/m^3);
A_{aer} is the ^{226}Ra activity in aerosols (0.09-1.7 µBq/m^3).

— *Annual dose from ingestion of food, contaminated with 226Ra*

$$P_{ing} = D_{ing} \text{ x } [\Sigma Ration_i \text{ x } TC_{Ra,i} \text{ x } A_{soil} + Water_{ing} \text{ x } A_{water} + Soil_{ing}] \quad (3)$$

where:

P_{ing} is the annual dose from ingestion of food, contaminated with ^{226}Ra ;
D_{ing} is the dose conversion factor for ingestion of ^{226}Ra (adult – 2.8×10^{-7} Sv/Bq; child – 6.2×10^{-7} Sv/Bq);
$Ration_i$,$Water_{ing}$, $Soil_{ing}$ is the annual consumption of different food items (kg/y):

Food type	Adult	Child (in % of adult consumption)
Milk	131	105%
Meat	54	40%
Potatoes	122	45%
Leafy vegetables	56	61%
Water	400	
Soil ingestion	50 mg/day	200 mg/day

A_{water} is the activity of ^{226}Ra in water (16-56 mBq/L in surface water, 2-18 Bq/L in underground water);
$TC_{Ra,i}$ is the coefficient of ^{226}Ra transfer from soil to food:
Grass to milk transfer factor $2.15\text{x}10^{-4}$ (d/L);
Soil to leafy vegetables 0.01 (dw/fw);
Soil to potatoes transfer factor - $1.5\text{x}10^{-3}$ (dw/fw);
Cow ingestion to beef transfer factor $5\text{x}10^{-4}$ (d/kg).

— *Annual dose from inhalation of radon*

$$P_{inh,Rn} = D_{inh,Rn} \text{ x } [V_{breath,out} \text{ x } T_{out} \text{ x } A_{Rn,out} + V_{breath,in} \text{ x } T_{in} \text{ x } A_{Rn,in}] \quad (4)$$

where:

$D_{inh,Rn}$ is the annual dose from inhalation of radon with concentration in air 1 Bq/m^3 (31 µSv/y);
$A_{Rn,out}$ is the activity of radon outdoors (1000 Bq/kg of ^{226}Ra in soil corresponds to 20 Bq/m^3 of radon in the open air).

The radon exhalation from soil may be calculated by the following formulas.

— *Exhalation of radon from a soil layer of big thickness*

$$R= \lambda_{Rn} \text{ x } F_{Rn} \text{ x } A_{Ra,soil} \text{ x } \rho_{soil} \text{ x } L_{Rn} \tag{5}$$

where:

R	is the exhalation rate of radon from soil (Bq m^{-2} s^{-1});
λ_{Rn}	is the decay constant for ^{222}Rn (2.1×10^{-6} s^{-1});
F_{Rn}	is the emanation coefficient (0.2);
ρ_{soil}	is the soil density (1.6×10^3 kg/m^3);
L_{Rn}	is the diffusion length of radon in soil (m),

$L_{Rn}= (D_{eff}\, \lambda_{Rn}^{-1} \Delta\rho_{soil}^{-1})^{0.5}$, D_{eff} - effective diffusion coefficient, m^2/s ($D_{eff}=5\times10^{-7}$); $\Delta\rho_{soil}$ – soil porosity ($\Delta\rho_{soil}=0.25$).

— *Exhalation of radon from a soil layer of definite thickness L_{layer}*

$$R= \lambda_{Rn} \times F_{Rn} \times A_{Ra,soil} \times \rho_{soil} \times L_{Rn} \times \tanh (0.5L_{layer}/ L_{Rn}) \tag{6}$$

Equilibrium concentration of radon in a ventilated room is calculated by a formula:

$$A_{Rn,room}= R \times k \times S/V(\lambda_{Rn} +\lambda_{vent}) \tag{7}$$

where:

S, V	is the square and volume of a room;
R	is the exhalation from soil;
k	is the coefficient of radon flux retardation by concrete foundation (k=0.25 for concrete layer with small fractures);
λ_{vent}	is the ventilation rate (for example 1 $hour^{-1}$).

II-2.3.1.7. Long-term predictions (assumptions and equations)

— *Main assumptions for the cases*

1. No remediation.
2. Remediation action –removal of most contaminated soil - option 1a , and filling by soil with ^{226}Ra concentration 60 Bq/kg).

It is assumed, that every year a surface layer of the thickness Δh is removed by wind , and the equivalent value of dust Δh is deposited on soil from the atmospheric air. The activity of ^{226}Ra in the atmospheric dust is C_{norm} (background level 20 Bq/kg). It is assumed also, that the upper 0.5 m of soil is plugged (mixed) every year. These processes lead to the decrease of the activity of ^{226}Ra in soil.

The equation, describing these processes is as follows:

$$dC/dt = -(\Delta h/h +\lambda)(C - C_{norm})$$

$$C(t)= C_{norm} +[C(0)- C_{norm}]\text{x}EXP[-(\Delta h/h +\lambda)t] \tag{8}$$

where:

C(t)	is the ^{226}Ra activity in soil (upper 0.5 m);

h=0.5 m (the thickness of the mixed layer of soil);

Δh= 1 millimeter per year;

λ	is the decay rate for ^{226}Ra.

— *Main assumptions for the case*

3. Remedial action -Capping with clean soil layer of 0.5 m thickness

It is assumed, that the lower contaminated soil layer of thickness 0.5 m is gradually mixed with the upper (clean) soil layer of 0.5 m thickness. This process is determined by several reasons : bioturbation due to activity of worms, fluctuations of the ground water levels, diffusion, etc. For simplicity, the activity of ^{226}Ra is assumed to be uniformly distributed within each soil compartment.

The equations, describing the process, are as follows:

$$dC_1/dt = \alpha\,(C_2-C_1)$$
$$dC_2/dt = -\alpha\,(C_2-C_1)$$
$$C_1+C_2=0.5(C_1^0+C_2^0) \tag{9}$$

where:

C_1, C_2 are activities of ^{226}Ra in the upper layer of soil (0.5 m) and lower soil layer (0.5 m);

C_1^0, C_2^0 are initial activities of ^{226}Ra in the upper layer of soil (0.5 m) and lower soil layer (0.5 m); C_1^0= 20 Bq/kg; , C_2^0=2356 Bq/kg.

The process of soil mixing is considered to be much more intensive, than the radioactive decay of ^{226}Ra , or weathering of soil. It is assumed, that the total mixing of the clean and contaminated soil layers occurs within 100 years after the remediation action, so the value of α is: α=0.023 year^{-1}.

The dynamics of ^{226}Ra activity in the upper layer of soil is described by the formula:

$$C^1(t)= 0.5(C_1^0- C_2^0)EXP(-\alpha\ t) + 0.5(C_1^0+ C_2^0) \tag{10}$$

For the periods of time t>100 years, the dynamics of ^{226}Ra activity in the upper layer of soil is determined mainly by the process of weathering (see assumptions for the case 1 and 2), and also by the radioactive decay of ^{226}Ra.

II-2.3.2. Uncertainty estimations

II-2.3.2.1. Uncertainty of predictions without remediation measures

The uncertainty in estimation of doses from food consumption, dust inhalation, external irradiation are directly determined by the uncertainty in the estimated values of ^{226}Ra activity in soil. According to experimental data, the uncertainty in soil contamination level is about 50%: 2000±1000 Bq ^{226}Ra /kg soil. Taking into account other factors, the doses, associated with food consumption, dust inhalation, external irradiation have the uncertainty within the factor of 2.

The main contribution to the total dose without remediation measures is inhalation of ^{222}Rn in houses. The uncertainty in predictions of ^{222}Rn concentration in the rooms is rather high, and depend of many factors, such as volume of rooms, ventilation rate, fractures in the concrete foundation of houses, etc. The exact values of these parameters are not available, the expert estimation of uncertainty in dose from radon inhalation is within the factor of 10.

II-2.3.2.2. Uncertainty of predictions with remediation measures

Uncertainty in predictions of doses from food consumption, dust inhalation, external irradiation are mainly determined by the processes of soil layers mixing and weathering.

II-2.3.3. Results of model predictions

Deterministic model calculations.Modelers: Dr.T.Sazykina & A.Kryshev . September 2000.
Concentrations in the different compartments - Situation I (maximum values = optional)

To analyse the results also the soil concentrations used for each pathway are required;
(1) soil concentration used to calculate the radionuclide concentration of dust indoors
(2) soil concentration used to calculate the radionuclide concentration of dust outdoors
(3) soil concentration used to calculate external irradiation indoors
(4) soil concentration used to calculate the external irradiation outdoors
(5) soil concentration used to calculate radionuclide concentration in grass
(6) soil concentration used to calculate radionuclide concentration in potatoes
(7) soil concentration used to calculate radionuclide concentration in leafy vegetables
(8) soil concentration used to calculate radionuclide concentration in ground water
(9) soil concentration used to calculate the radon concentration indoors
(10) soil concentration used to calculate the radon concentration outdoors

1. Without remedial action

Ra-226 concentration

Years	Soil (Bq/kg)										Inhalable dust (Bq/m3)		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	indoors	outdoors	outdoors agricult(*)
1	2,4E+03	2,4E+03	2,4E+03	2,4E+03	2,4E+03	1,9E+03	1,9E+03	***	2,4E+03	2,4E+03	3,5E-05	7,0E-05	
50	2,3E+03	2,3E+03	2,3E+03	2,3E+03	2,3E+03	1,9E+03	1,9E+03		2,3E+03	2,3E+03	3,5E-05	6,9E-05	
100	1,9E+03	1,9E+03	1,9E+03	1,9E+03	1,9E+03	1,5E+03	1,5E+03		1,9E+03	1,9E+03	2,7E-05	5,4E-05	
200	1,5E+03	1,5E+03	1,5E+03	1,5E+03	1,5E+03	1,2E+03	1,2E+03		1,5E+03	1,5E+03	2,2E-05	4,4E-05	
500	7,3E+02	7,3E+02	7,3E+02	7,3E+02	7,3E+02	5,8E+02	5,8E+02		7,3E+02	7,3E+02	1,1E-05	2,2E-05	
Maximum													

***. Contamination of drinking water was taken from experimental data, decrease with time is associated with radioactive decay only.

Years	Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	1,2E+02	-	2,9E+00		1,9E+01		5,0E+01	3,0E-02	6,0E-02	7,8E+02	4,7E+01
50	1,2E+02		2,9E+00		1,9E+01		4,9E+01	2,9E-02	5,9E-02	7,7E+02	4,7E+01
100	9,2E+01		2,3E+00		1,5E+01		4,8E+01	2,3E-02	4,7E-02	6,2E+02	3,7E+01
200	7,3E+01		1,8E+00		1,2E+01		4,6E+01	1,9E-02	3,7E-02	4,8E+02	3,0E+01
500	3,6E+01		9,0E-01		5,8E+00		4,0E+01	9,0E-03	1,9E-02	2,4E+02	1,5E+01
Maximum											

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Ra-226 concentration

Years	Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	Inhalable dust (Bq/m3) indoors	outdoors	outdoors agricult(*)
1	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	***	6,0E+01	6,0E+01	9,0E-07	1,8E-06	1,8E-06
50	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01		5,5E+01	5,5E+01	8,2E-07	1,6E-06	1,6E-06
100	5,1E+01	5,1E+01	5,1E+01	5,1E+01	5,1E+01	5,1E+01	5,1E+01		5,1E+01	5,1E+01	7,6E-07	1,5E-06	1,5E-06
200	4,4E+01	4,4E+01	4,4E+01	4,4E+01	4,4E+01	4,4E+01	4,4E+01		4,4E+01	4,4E+01	6,6E-07	1,3E-06	1,3E-06
500	3,2E+01	3,2E+01	3,2E+01	3,2E+01	3,2E+01	3,2E+01	3,2E+01		3,2E+01	3,2E+01	4,8E-07	9,6E-07	9,6E-07
Maximum	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01		6,0E+01	6,0E+01			

***. Contamination of drinking water was taken from experimental data, decrease with time is associated with radioactive decay only.

Grass (Bq/kg) root uptake	foliar uptake	Potatoes (Bq/kg) root uptake	foliar uptake	Leafy vegetables (Bq/kg) root uptake	foliar uptake	Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3) indoors	outdoors
3,0E+00		9,2E-02		6,0E-01		5,0E+01	7,2E-04	1,5E-03	2,0E+01	1,1E+00
2,7E+00		8,4E-02		5,5E-01		4,9E+01	6,6E-04	1,3E-03	1,8E+01	1,0E+00
2,5E+00		7,8E-02		5,1E-01		4,8E+01	6,1E-04	1,2E-03	1,7E+01	9,7E-01
2,2E+00		6,7E-02		4,4E-01		4,6E+01	5,2E-04	1,1E-03	1,5E+01	8,3E-01
1,6E+00		4,9E-02		3,2E-01		4,0E+01	3,8E-04	8,0E-04	1,1E+01	6,1E-01

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

Ra-226 concentration

Years	Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	Inhalable dust (Bq/m3) indoors	outdoors	outdoors agricult(*)
1	2,0E+01	2,0E+01	2,0E+01	2,0E+01	2,0E+01	2,0E+01	2,0E+01	***	2,0E+01	2,0E+01	3,0E-07	5,9E-07	
50	8,2E+02	8,2E+02	8,2E+02	8,2E+02	8,2E+02	7,0E+02	7,0E+02		8,2E+02	8,2E+02	1,2E-05	2,4E-05	
100	9,0E+02	9,0E+02	9,0E+02	9,0E+02	9,0E+02	7,2E+02	7,2E+02		9,0E+02	9,0E+02	1,3E-05	2,7E-05	
200	6,2E+02	6,2E+02	6,2E+02	6,2E+02	6,2E+02	5,0E+02	5,0E+02		6,2E+02	6,2E+02	9,2E-06	1,8E-05	
500	3,0E+02	3,0E+02	3,0E+02	3,0E+02	3,0E+02	2,4E+02	2,4E+02		3,0E+02	3,0E+02	4,4E-06	8,9E-06	
Maximum													

***. Contamination of drinking water was taken from experimental data, decrease with time is associated with radioactive decay only.

Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
9,9E-01		3,0E-02		2,0E-01		5,0E+01	2,4E-04	5,0E-04	6,6E+00	3,8E-01
4,1E+01		1,1E+00		7,0E+00		4,9E+01	9,8E-03	2,0E-02	2,7E+02	1,6E+01
4,5E+01		1,1E+00		7,2E+00		4,8E+01	1,1E-02	2,2E-02	3,0E+02	1,7E+01
3,1E+01		7,7E-01		5,0E+00		4,6E+01	7,4E-03	1,5E-02	2,0E+02	1,2E+01
2,5E+01		3,7E-01		2,4E+00		4,0E+01	3,6E-03	7,5E-03	9,9E+01	5,7E+00

Stochastic results

Table: Ranking of the three most sensitive parameters for the total dose (Ra&Pb)

1. Without remedial action

from most to less sensitive	parameter
1	Inhalation Rn indoor
2	External irradiation outdoor
3	Leafy vegetables,root uptake

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

from most to less sensitive	parameter
1	Inhalation Rn indoor
2	External irradiation outdoor
3	Leafy vegetables,root uptake

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

from most to less sensitive	parameter
1	Inhalation Rn indoor
2	External irradiation outdoor
3	Leafy vegetables,root uptake

Deterministic model calculations. Modellers: Dr.T.Sazykina & A.Kryshev (with revisions, September 2000)
Individual doses for adult for Olen site (mSv/y) - Situation I (maximum values = optional)

1. Without remedial action

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	1,70E-03	1,10E-03	0,7	1,8	4,9	3,00E-01	0,3		0,1		5,60E-03	3,00E-03	1,00E-03	1,20E-02	8,1
50	1,70E-03	1,10E-03	0,7	1,8	4,9	3,00E-01	0,3		9,90E-02		5,50E-03	3,00E-03	9,90E-04	1,18E-02	8
100	1,30E-03	8,60E-04	0,6	1,4	3,9	2,00E-01	0,24		7,90E-02		5,30E-03	2,40E-03	7,90E-04	9,50E-03	6,4
200	1,10E-03	6,80E-04	0,4	1,1	3	1,80E-01	0,184		6,20E-02		5,10E-03	1,90E-03	6,20E-04	7,40E-03	5
500	5,00E-04	3,40E-04	0,2	0,6	1,5	1,00E-01	0,095		3,10E-02		4,48E-03	9,00E-04	3,10E-04	3,70E-03	2,5
Maximum															

2. After implementing remedial action 1 (removal of contaminated soil)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	4,10E-05	2,80E-05	1,70E-02	4,60E-02	0,13	7,40E-03	9,50E-03		2,50E-03		5,60E-03	7,60E-05	2,50E-05	3,00E-04	0,21
50	3,80E-05	2,60E-05	1,60E-02	4,20E-02	0,12	6,90E-03	8,60E-03		2,30E-03		5,50E-03	7,00E-05	2,30E-05	2,80E-04	0,19
100	3,50E-05	2,40E-05	1,40E-02	3,90E-02	0,11	5,50E-03	8,00E-03		2,10E-03		5,30E-03	6,50E-05	2,10E-05	2,60E-04	0,18
200	3,00E-05	2,10E-05	1,30E-02	3,40E-02	0,1	5,40E-03	6,80E-03		1,90E-03		5,10E-03	5,60E-05	1,90E-05	2,20E-04	0,16
500	2,10E-05	1,50E-05	9,00E-03	2,40E-02	0,07	4,40E-03	5,00E-03		1,30E-03		4,48E-03	4,00E-05	1,30E-05	1,60E-04	0,11
Maximum															

3. After implementing remedial action 2 (capping with clean soil layer of 50 cm)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water			ingestion	
1	1,40E-05	9,00E-06	5,90E-03	1,50E-02	2,5	3,00E-02	3,10E-03		8,40E-04		5,60E-03	2,50E-05	8,40E-06	1,00E-04	2,6
50	5,70E-04	3,70E-04	5,80E-03	1,40E-02	2,5	2,90E-02	0,11		3,40E-02		5,50E-03	1,00E-03	3,40E-04	4,10E-03	2,7
100	6,30E-04	4,10E-04	4,70E-03	1,20E-02	2	2,30E-02	0,113		3,80E-02		5,35E-03	1,10E-03	3,70E-04	4,50E-03	2,2
200	4,30E-04	2,80E-04	3,70E-03	9,00E-03	1,6	1,80E-02	7,70E-02		2,60E-02		5,10E-03	8,00E-04	2,60E-04	3,10E-03	1,7
500	2,10E-04	1,40E-04	1,80E-03	4,60E-03	0,8	9,00E-03	3,70E-02		1,30E-02		4,48E-03	3,70E-04	2,60E-04	1,50E-03	0,8
Maximum															

Stochastic model calculations. Modellers: Dr.T.Sazykina & A.Kryshev
Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

Without remediation

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1							7,00E-01	0,4	1,4	1,8	9,00E-01	3,6
100							6,00E-01	0,3	1,2	1,4	7,00E-01	2,8
500							2,00E-01	0,1	0,4	6,00E-01	3,00E-01	1,2
Maximum												

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	4,9	0,5	50	0,3	1,00E-01	0,6	0,3	1,50E-01	0,6				5,60E-03	2,80E-03	1,12E-02
100	3,9	0,4	40	0,2	1,00E-01	0,4	0,2	1,00E-01	0,4				4,40E-03	2,00E-03	8,80E-03
500	1,5	1,00E-01	15	1,00E-01	1,00E-02	0,2	0,1	1,00E-02	0,2				1,70E-03	8,00E-04	3,40E-03
Maximum															

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	0,1	5,00E-02	0,2				3,00E-03	1,50E-03	6,00E-03	1,00E-03	5,00E-04	2,00E-03			
100	7,90E-02	4,00E-02	1,58E-01				2,40E-03	1,20E-03	4,80E-03	7,90E-04	4,00E-04	1,60E-03			
500	3,10E-02	1,50E-02	6,20E-02				9,00E-04	4,50E-04	1,80E-04	3,10E-04	1,50E-04	6,20E-04			
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
8,1	2	56	6,4	1,6	44	2,5	0,8	17			

Stochastic model calculations . Modellers:Dr.T.Sazykina & A.Kryshev
Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

Covering with 0,5 m clean soil layer

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1							5,90E-03	3,00E-03	1,20E-02	1,50E-02	8,00E-03	3,00E-02
100							4,70E-03	2,40E-03	9,00E-03	1,20E-02	6,00E-03	2,40E-02
500							1,80E-03	9,00E-04	3,60E-03	4,60E-03	2,30E-03	9,00E-03
Maximum												

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,5	0,25	25	3,00E-02	1,50E-02	6,00E-02	2,50E-03	1,30E-03	5,00E-03				5,60E-03	2,80E-03	1,10E-02
100	2	0,2	20	2,30E-02	1,20E-02	4,60E-02	0,11	6,00E-02	0,2				4,40E-03	2,20E-03	9,00E-03
500	0,8	0,08	10	9,00E-03	4,50E-03	1,80E-02	3,70E-02	1,60E-02	8,00E-02				1,70E-03	7,00E-04	4,00E-03
Maximum															

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	8,40E-04	4,20E-04	1,70E-03				2,50E-05	1,20E-05	5,00E-05	8,40E-06	4,20E-06	1,68E-05			
100	3,80E-02	2,00E-02	7,60E-02				1,10E-03	6,00E-04	2,20E-03	3,70E-04	1,80E-04	7,40E-04			
500	1,30E-02	6,00E-03	2,60E-02				3,70E-04	1,80E-04	7,40E-04	2,60E-04	1,30E-04	5,20E-04			
Maximum															

Total dose:

Ra-226 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
2,6	0,3	25	2,2	0,3	20	0,8	0,1	10			

II-2.4. RESRAD-OFFSITE

II-2.4.1. General model description

II-2.4.1.1. Name of model, model developer(s) and model user(s)

Model name:	RESRAD-OFFSITE (Residual Radioactivity Dose Assessment Code for Off-site Receptors)
Model developer(s):	Charley Yu and Emmanuel K. Gnanapragasam, Environmental Assessment Division Argonne National Laboratory, Argonne, Illinois, United States of America

Name of model user(s): Emmanuel K. Gnanapragasam and Charley Yu

II-2.4.1.2. Intended purpose of the model in radiation assessment

To estimate the radiological dose and excess cancer risk to an individual or population situated directly above and/or near contaminated land. RESRAD-OFFSITE, which is an extension of the RESRAD (ONSITE) model, takes into account radiological doses to off-site receptors.

II-2.4.1.3. Model type (equilibrium, dynamic, numerical, analytical,...)

In general, RESRAD-OFFSITE is an equilibrium model. Analytical expressions are used; some of these analytical expressions can be directly evaluated whereas others require numerical evaluation techniques.

II-2.4.1.4. Method used for deriving uncertainty estimates

The RESRAD-OFFSITE has probabilistic (uncertainty) analysis capability built into it. The user can select form 27 different distributions that are available in the code and can then specify the statistical parameters to define the distribution. The user also has a choice of two sampling schemes; simple random sampling and Latin hypercube sampling. The samples generated for each uncertain or probabilistic variable are grouped together to form the input data sets in a manner chosen by the user; either random grouping or grouping where the input variables are correlated with each other (as closely as possible) according to the pair wise (rank) correlation coefficients specified by the user. Each of these input sets are used in RESRAD-OFFSITE runs (performed automatically by the code) and a set of outputs are produced and saved in binary and ASCII files. This output data set is then analyzed to produce probabilistic statistics and plots for peak dose. The statistics include the mean, the standard deviation, the maximum, the minimum and a table of various percentiles of the peak dose from each or all exposure pathways. The plots include the cumulative distribution function (cdf) and scatter plots between each of the selected outputs and each probabilistic input. At the user's request, a correlation and regression analysis will also be produced to give the partial correlation coefficients (PCC), standardized regression coefficients (SRC), partial rank correlation coefficients (PRCC), and the standardized rank regression coefficient (SRRC) between each of the selected outputs and each of the probabilistic inputs. Some of this information is also available for the user requested times.

II-2.4.1.5. Description of model (procedures, parameters, main equations, scheme)

RESRAD-OFFSITE is a multimedia computer code developed by Argonne National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE) for use in evaluating radioactively contaminated sites. The RESRAD-OFFSITE code is an extension of the RESRAD (onsite) code, which has been widely used in the United States and abroad (Yu, 1999). The RESRAD code (Yu et al., 1993b) implements the methodology described in DOE's manual for developing residual radioactive material guidelines and calculates radiation dose and excess lifetime cancer risk to a chronically exposed individual at a site with residual contamination. The RESRAD-OFFSITE code focuses on radioactive contaminants in soil and their transport in air, water, and biological media to a receptor located directly on the contaminated soil or away from the contamination. Nine exposure pathways are considered in RESRAD-OFFSITE: direct exposure; inhalation of particulates and radon; and ingestion of plant foods, meat, milk, aquatic foods, water, and soil. Figure II-2.4.1 illustrates conceptually the exposure pathways considered in RESRAD-OFFSITE. RESRAD-OFFSITE calculates time-integrated annual dose, soil cleanup guidelines, radionuclide concentrations, and lifetime cancer risks as a function of time. The code estimates at which time the peak dose occurs for each radionuclide and for all radionuclides summed. The RESRAD-OFFSITE code permits sensitivity analysis for various parameters. Graphics are used to show the sensitivity analysis results. Text reports are provided for users to view the deterministic analysis results through a text viewer. RESRAD-OFFSITE has about 200 parameters. Detailed discussion on the parameters and models used in the RESRAD-OFFSITE code can be found in many RESRAD supporting documents (Yu et al. 1993a, Yu et al. 1993b, Yu et al. 2000).

II-2.4.1.6. Description of uncertainty method and results of analysis

— *Inputs*

All but one of the statistical distributions specified in this scenario were already available in the code, the log triangular distribution was not. The code was updated to include the log triangular distribution. The code is capable of performing simple random sampling (SRS) and Latin hypercube sampling (LHS). A Latin hypercube sample of 1000 observation was used.

Some of the individual probabilistic inputs specified in the scenario corresponded to multiple inputs in RESRAD-OFFSITE, these inputs are the water soil distribution coefficient of each radionuclide in various soil layers; the density, and moisture content of soil at different locations and layers; the irrigation rate, the root depth and the weathering decay constant for leafy vegetables and for potatoes; and the foliar interception factors for air borne and water borne contaminants for the different types of vegetation. The version of the code that was used to model this scenario did not have the capability to specify that the same set of probabilistic samples be used for multiple inputs. These multiple inputs were specified to have the same distribution and statistical parameters as the single input specified in the scenario. In order to ensure that the sample values chosen for these multiple parameters were similar, they were stipulated to be strongly correlated with a rank correlation coefficient of 0.99999.

Conversely, there were two pairs of probabilistic inputs specified in the scenario that correspond to single inputs in RESRAD-OFFSITE. An example of this are the irrigation time (in days per year) and the irrigation rate (in m/d) which have to be combined to get the irrigation applied per year which is the RESRAD-OFFSITE input. Three repetitions of 250 samples were produced for irrigation time and for irrigation rate and were paired together so that they were uncorrelated. Each pair of irrigation time and irrigation rate was multiplied to produce 750 samples of irrigation applied per year. The cumulative distribution function of these 750 values was plotted and was approximated by an eight point linearly interpolated cdf as shown in Figure II-2.4.2.

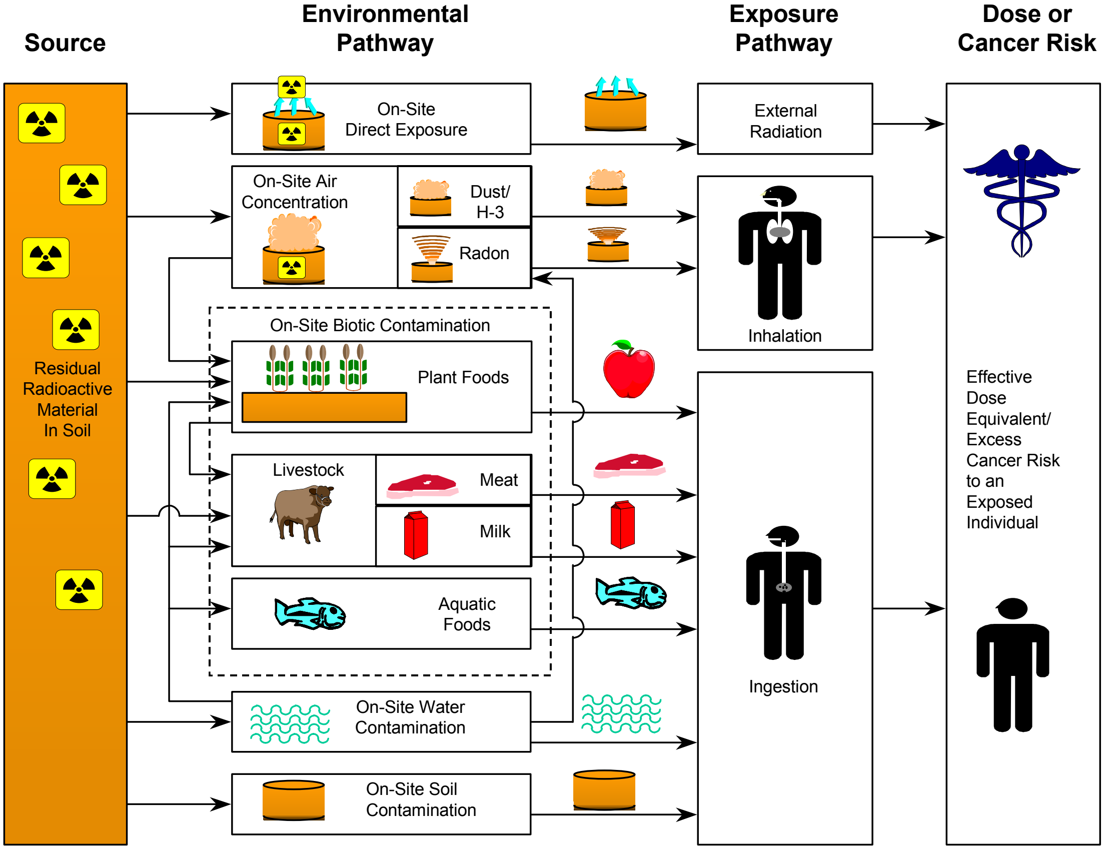


FIG. II-2.4.1. *Graphical Representation of Pathways Considered in RES.*

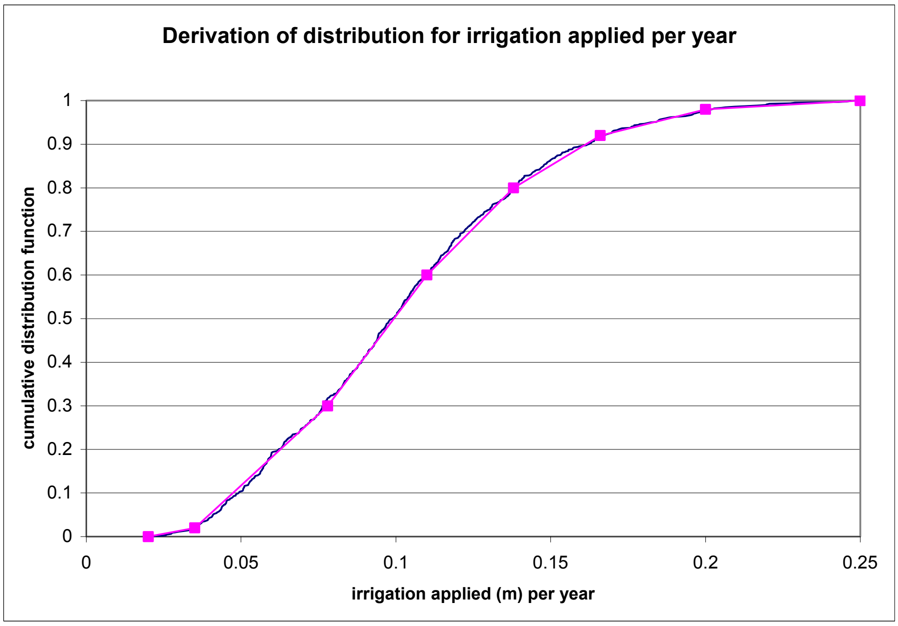


FIG. II-2.4.2. Distribution for irrigation applied per year derived from the distribution specified for irrigation time and irrigation rate.

— *Outputs*

The probabilistic sampling part of the code produced a set of 1000 inputs to conform to the stipulated distributions and correlations. The fate, transport, accumulation, exposure part of the code then automatically processed each of the 1000 sets of input and produced 1000 predictions of each of the desired outputs (dose and concentrations in this case.). The probabilistic post processor of the code then computed a number of statistics for the peak dose due to the initially present nuclides (^{226}Ra in this case) and also a number of correlation and regression coefficients between peak dose and the probabilistic inputs. The most sensitive parameters were identified using the correlation and regression coefficients. Some of the end results requested in the scenario were not standard outputs in the version of RESRAD-OFFSITE used and had to be extracted from the data saved in the aforementioned ASCII file. The standard output and the information in the ASCII file attribute dose and risk due to a nuclide that is initially present in the contamination and due to its progeny produced over time to the nuclides that are initially present in the contamination. The dose and risk attributed to the (parent or progeny) nuclides present at the time of exposure is in the binary file and these results were not provided as the code to extract the desired information from the binary file has not yet been developed. The outputs are available for the major exposure pathways, but not for the sub pathways. Hence some of the results requested in this scenario (leafy vegetables and potatoes, indoor and outdoor components of inhalation and indoor and outdoor components of external radiation) have been combined.

II-2.4.1.7. Assumptions concerning parameter values, exposure pathways, etc.

1. The scenario stipulated that the vegetable garden was located next to the house on equally contaminated soil. It was assumed that the pasture was also located on land with the same level of contamination.
2. A dry to fresh weight ratio of 0.1 was assumed for pasture.
3. The specified water soil distribution coefficient was assumed to apply to all layers of soil.
4. The diffusion coefficients used (for groundwater transport) in RESRAD-OFFSITE are nuclide independent; the values specified for Pb was ignored and the value specified for Ra was used for both nuclides.
5. RESRAD-OFFSITE uses a single dust concentration for inhalation and an indoor dust filtration factor to model the reduction of dust concentration indoors. The distribution specified for “Outdoors + Agricultural activities” was used, the distributions specified for “Outdoors” and for “Indoors” were ignored.
6. Table I-XXVI (Appendix I) states that the distribution for daily uptake of pasture by cattle is triangular with parameters 10, 12.5, 15 in kg (dw)/d. Application of the assumed value of the dry to fresh weight ratio of 0.1 would have produced excessively high values of kg (fw)/d pasture intakes. Hence the values in table I-XXVI (Appendix I) were used as kg (fw)/d inputs.
7. The soil intake by livestock is an input in RESRAD-OFFSITE, and not the fractional uptake of soil by cattle [kg (dw)/kg (dw) pasture]. It was not possible to use the specified value in the version of RESRAD-OFFSITE used.
8. Infiltration rate is not an input in RESRAD-OFFSITE; it is computed using a number of inputs (precipitation rate, runoff coefficient, evapotranspiration coefficient, irrigation rate). Hence it was not possible to use the distribution specified for infiltration rate.

II-2.4.2. Results of model predictions

Deterministic model calculations

Concentrations in the different compartments - Situation I (maximum values = optional)

To analyse the results also the soil concentrations used for each pathway are required;
(1) soil concentration used to calculate the radionuclide concentration of dust indoors
(2) soil concentration used to calculate the radionuclide concentration of dust outdoors
(3) soil concentration used to calculate external irradiation indoors
(4) soil concentration used to calculate the external irradiation outdoors
(5) soil concentration used to calculate radionuclide concentration in grass
(6) soil concentration used to calculate radionuclide concentration in potatoes
(7) soil concentration used to calculate radionuclide concentration in leafy vegetables
(8) soil concentration used to calculate radionuclide concentration in ground water
(9) soil concentration used to calculate the radon concentration indoors
(10) soil concentration used to calculate the radon concentration outdoors

1. Without remedial action

Ra-226 concentration

	Soil (Bq/kg)										Ground Water (Bq/m3)
Years	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	
1	2,8E+03	2,8E+03	2,8E+03	2,8E+03	2,4E+03	1,9E+03	1,9E+03	2,8E+03	2,8E+03	2,8E+03	2,6E-02
50	2,6E+03	2,6E+03	2,6E+03	2,6E+03	2,2E+03	1,8E+03	1,8E+03	2,6E+03	2,6E+03	2,6E+03	1,3E+00
100	2,5E+03	2,5E+03	2,5E+03	2,5E+03	2,1E+03	1,7E+03	1,7E+03	2,5E+03	2,5E+03	2,5E+03	2,7E+00
200	2,3E+03	2,3E+03	2,3E+03	2,3E+03	2,0E+03	1,6E+03	1,6E+03	2,3E+03	2,3E+03	2,3E+03	5,2E+00
500	1,7E+03	1,7E+03	1,7E+03	1,7E+03	1,5E+03	1,2E+03	1,2E+03	1,7E+03	1,7E+03	1,7E+03	1,1E+01
Maximum											

Pb-210 concentration

	Soil (Bq/kg)								Ground Water (Bq/m3)
Years	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	
1	8,4E+01	8,4E+01	8,4E+01	8,4E+01	7,2E+01	5,7E+01	5,7E+01	8,4E+01	2,8E-03
50	2,1E+03	2,1E+03	2,1E+03	2,1E+03	1,8E+03	1,4E+03	1,4E+03	2,1E+03	3,6E+00
100	2,4E+03	2,4E+03	2,4E+03	2,4E+03	2,0E+03	1,6E+03	1,6E+03	2,4E+03	8,6E+00
200	2,3E+03	2,3E+03	2,3E+03	2,3E+03	1,9E+03	1,6E+03	1,6E+03	2,3E+03	1,7E+01
500	1,7E+03	1,7E+03	1,7E+03	1,7E+03	1,5E+03	1,2E+03	1,2E+03	1,7E+03	3,4E+01
Maximum									

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Ra-226 concentration

Years	Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	Ground Water (Bq/m3)
1	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	6,0E+01	5,6E-04
50	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	5,7E+01	2,9E-02
100	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,5E+01	5,8E-02
200	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	1,1E-01
500	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	2,5E-01
Maximum											

Pb-210 concentration

Years	Soil (Bq/kg) (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	Ground Water (Bq/m3)
1	1,8E+00	1,8E+00	1,8E+00	1,8E+00	1,8E+00	1,8E+00	1,8E+00	1,8E+00	6,1E-05
50	4,5E+01	4,5E+01	4,5E+01	4,5E+01	4,5E+01	4,5E+01	4,5E+01	4,5E+01	7,9E-02
100	5,2E+01	5,2E+01	5,2E+01	5,2E+01	5,2E+01	5,2E+01	5,2E+01	5,2E+01	1,9E-01
200	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	5,0E+01	3,7E-01
500	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	3,8E+01	7,5E-01
Maximum									

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

Ra-226 concentration

Years	Soil (Bq/kg)										Ground Water (Bq/m3)
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	
1	0,0E+00	0,0E+00	2,8E+03	2,8E+03	0,0E+00	4,8E-06	4,8E-06	2,8E+03	2,8E+03	2,8E+03	2,6E-02
50	0,0E+00	0,0E+00	2,6E+03	2,6E+03	0,0E+00	1,2E-02	1,2E-02	2,6E+03	2,6E+03	2,6E+03	1,3E+00
100	0,0E+00	0,0E+00	2,5E+03	2,5E+03	0,0E+00	4,8E-02	4,8E-02	2,5E+03	2,5E+03	2,5E+03	2,7E+00
200	0,0E+00	0,0E+00	2,3E+03	2,3E+03	0,0E+00	1,8E-01	1,8E-01	2,3E+03	2,3E+03	2,3E+03	5,2E+00
500	0,0E+00	0,0E+00	1,7E+03	1,7E+03	0,0E+00	9,2E-01	9,2E-01	1,7E+03	1,7E+03	1,7E+03	1,1E+01
Maximum											

Pb-210 concentration

Years	Soil (Bq/kg)								Ground Water (Bq/m3)
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	
1	0,0E+00	0,0E+00	8,4E+01	8,4E+01	0,0E+00	5,6E-07	5,6E-07	8,4E+01	2,8E-03
50	0,0E+00	0,0E+00	2,1E+03	2,1E+03	0,0E+00	2,3E-02	2,3E-02	2,1E+03	3,6E+00
100	0,0E+00	0,0E+00	2,4E+03	2,4E+03	0,0E+00	9,1E-02	9,1E-02	2,4E+03	8,6E+00
200	0,0E+00	0,0E+00	2,3E+03	2,3E+03	0,0E+00	2,9E-01	2,9E-01	2,3E+03	1,7E+01
500	0,0E+00	0,0E+00	1,7E+03	1,7E+03	0,0E+00	1,2E+00	1,2E+00	1,7E+03	3,4E+01
Maximum									

Deterministic model calculations
Individual doses for adult for Olen site (mSv/y) - Situation I (maximum values = optional)

1. Without remedial action

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water				
1	2,1E-03	5,5E-03	1,5E+00	1,5E+00	3,8E+00	4,5E-02	3,0E-01	2,4E-06	9,6E-02	4,8E-07	2,9E-06	1,0E-02	1,1E-02	1,4E-02	7,3E+00
50	2,0E-03	5,3E-03	1,4E+00	1,4E+00	3,7E+00	4,3E-02	2,8E-01	1,1E-04	9,2E-02	2,5E-05	1,5E-04	1,0E-02	1,0E-02	1,3E-02	7,0E+00
100	1,9E-03	5,0E-03	1,4E+00	1,4E+00	3,5E+00	4,1E-02	2,7E-01	2,2E-04	8,8E-02	4,9E-05	3,0E-04	9,5E-03	9,8E-03	1,3E-02	6,7E+00
200	1,7E-03	4,6E-03	1,3E+00	1,3E+00	3,2E+00	3,7E-02	2,5E-01	4,4E-04	8,0E-02	9,5E-05	5,8E-04	8,7E-03	8,9E-03	1,2E-02	6,1E+00
500	1,3E-03	3,5E-03	9,5E-01	9,5E-01	2,4E+00	2,8E-02	1,9E-01	9,5E-04	6,1E-02	2,1E-04	1,3E-03	6,6E-03	6,8E-03	8,9E-03	4,6E+00
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water				
1	3,7E-05	9,9E-05	2,7E-05	2,7E-05	0,0E+00	0,0E+00	2,2E-02	6,5E-07	4,8E-03	1,3E-07	7,7E-07	5,5E-04	6,0E-04	1,1E-03	2,9E-02
50	9,1E-04	2,4E-03	6,7E-04	6,7E-04	0,0E+00	0,0E+00	5,5E-01	7,5E-04	1,2E-01	1,6E-04	1,0E-03	1,4E-02	1,5E-02	2,6E-02	7,3E-01
100	1,1E-03	2,8E-03	7,8E-04	7,8E-04	0,0E+00	0,0E+00	6,3E-01	1,8E-03	1,4E-01	3,9E-04	2,4E-03	1,6E-02	1,7E-02	3,0E-02	8,4E-01
200	1,0E-03	2,7E-03	7,4E-04	7,4E-04	0,0E+00	0,0E+00	6,0E-01	3,5E-03	1,3E-01	7,6E-04	4,6E-03	1,5E-02	1,6E-02	2,9E-02	8,1E-01
500	7,6E-04	2,0E-03	5,6E-04	5,6E-04	0,0E+00	0,0E+00	4,6E-01	7,1E-03	1,0E-01	1,6E-03	9,5E-03	1,1E-02	1,2E-02	2,2E-02	6,2E-01
Maximum															

2. After implementing remedial action 1 (removal of contaminated soil)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking water	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar					
1	4,5E-05	1,2E-04	3,3E-02	3,3E-02	8,3E-02	9,8E-04	9,4E-03	5,8E-08	3,1E-03	1,0E-08	6,3E-08	2,7E-04	2,7E-04	3,1E-04	1,6E-01
50	4,3E-05	1,1E-04	3,2E-02	3,2E-02	8,0E-02	9,4E-04	9,0E-03	2,5E-06	2,9E-03	5,4E-07	3,3E-06	2,5E-04	2,6E-04	2,9E-04	1,6E-01
100	4,1E-05	1,1E-04	3,0E-02	3,0E-02	7,6E-02	8,9E-04	8,6E-03	4,9E-06	2,8E-03	1,1E-06	6,5E-06	2,4E-04	2,5E-04	2,8E-04	1,5E-01
200	3,7E-05	1,0E-04	2,7E-02	2,7E-02	6,9E-02	8,2E-04	7,8E-03	9,5E-06	2,6E-03	2,1E-06	1,3E-05	2,2E-04	2,3E-04	2,6E-04	1,4E-01
500	2,8E-05	7,5E-05	2,1E-02	2,1E-02	5,2E-02	6,2E-04	5,9E-03	2,1E-05	1,9E-03	4,5E-06	2,8E-05	1,7E-04	1,7E-04	1,9E-04	1,0E-01
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking water	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar					
1	8,1E-07	2,2E-06	5,9E-07	5,9E-07	0,0E+00	0,0E+00	7,1E-04	1,4E-08	1,5E-04	2,8E-09	1,7E-08	1,4E-05	1,5E-05	2,3E-05	9,2E-04
50	2,0E-05	5,3E-05	1,5E-05	1,5E-05	0,0E+00	0,0E+00	1,7E-02	1,6E-05	3,8E-03	3,6E-06	2,2E-05	3,4E-04	3,8E-04	5,7E-04	2,3E-02
100	2,3E-05	6,1E-05	1,7E-05	1,7E-05	0,0E+00	0,0E+00	2,0E-02	3,9E-05	4,4E-03	8,5E-06	5,2E-05	4,0E-04	4,4E-04	6,6E-04	2,6E-02
200	2,2E-05	5,8E-05	1,6E-05	1,6E-05	0,0E+00	0,0E+00	1,9E-02	7,6E-05	4,2E-03	1,7E-05	1,0E-04	3,8E-04	4,2E-04	6,3E-04	2,5E-02
500	1,7E-05	4,4E-05	1,2E-05	1,2E-05	0,0E+00	0,0E+00	1,5E-02	1,6E-04	3,2E-03	3,4E-05	2,1E-04	2,9E-04	3,2E-04	4,8E-04	1,9E-02
Maximum															

3. After implementing remedial action 2 (capping with clean soil layer of 50 cm)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water				
1	0,0E+00	0,0E+00	2,9E-03	2,9E-03	2,8E+00	3,3E-02	8,5E-10	2,2E-06	2,8E-10	4,8E-07	2,9E-06	1,1E-08	1,2E-08	7,4E-13	2,8E+00
50	0,0E+00	0,0E+00	2,8E-03	2,8E-03	2,6E+00	3,1E-02	2,2E-06	1,1E-04	7,1E-07	2,5E-05	1,5E-04	5,9E-07	6,1E-07	1,9E-09	2,7E+00
100	0,0E+00	0,0E+00	2,7E-03	2,7E-03	2,5E+00	3,0E-02	8,4E-06	2,3E-04	2,7E-06	4,9E-05	3,0E-04	1,2E-06	1,2E-06	7,3E-09	2,6E+00
200	0,0E+00	0,0E+00	2,4E-03	2,5E-03	2,3E+00	2,7E-02	3,2E-05	4,4E-04	1,0E-05	9,5E-05	5,8E-04	2,3E-06	2,4E-06	2,8E-08	2,3E+00
500	0,0E+00	0,0E+00	1,8E-03	1,9E-03	1,7E+00	2,0E-02	1,6E-04	9,5E-04	5,3E-05	2,1E-04	1,3E-03	5,0E-06	5,2E-06	1,4E-07	1,8E+00
Maximum															

Pb-210 calculations

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		potatoes		drinking	milk	meat	soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root	foliar	root	foliar	water				
1	0,0E+00	0,0E+00	4,2E-11	4,2E-11	0,0E+00	0,0E+00	2,4E-10	5,9E-07	5,3E-11	1,3E-07	7,7E-07	2,3E-09	2,5E-09	2,1E-13	1,5E-06
50	0,0E+00	0,0E+00	1,0E-09	2,0E-09	0,0E+00	0,0E+00	9,8E-06	7,6E-04	2,1E-06	1,6E-04	1,0E-03	2,9E-06	3,2E-06	8,5E-09	1,9E-03
100	0,0E+00	0,0E+00	1,2E-09	5,3E-09	0,0E+00	0,0E+00	4,0E-05	1,8E-03	8,7E-06	3,9E-04	2,4E-03	7,0E-06	7,7E-06	3,5E-08	4,6E-03
200	0,0E+00	0,0E+00	1,1E-09	1,4E-08	0,0E+00	0,0E+00	1,3E-04	3,5E-03	2,8E-05	7,6E-04	4,6E-03	1,4E-05	1,5E-05	1,1E-07	9,1E-03
500	0,0E+00	0,0E+00	8,5E-10	5,4E-08	0,0E+00	0,0E+00	5,1E-04	7,1E-03	1,1E-04	1,6E-03	9,5E-03	2,8E-05	3,1E-05	4,4E-07	1,9E-02
Maximum															

Stochastic model calculations

Individual doses for adult (mSv/y) for Olen site - Situation I (maximum values = optional)

1. Without remediation

Ra-226 & Pb-210 calculations

	Inhalation of dust (optional)			External irradiation		
	indoors+outdoors	95% confidence interval		indoors+outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	1,6E-02	3,9E-03	3,3E-02	3,0E+00	2,6E+00	3,1E+00
100	2,1E-02	5,0E-03	4,5E-02	2,6E+00	1,7E+00	3,0E+00
500	1,3E-02	1,1E-03	3,5E-02	1,6E+00	1,8E-01	2,4E+00
Maximum	2,2E-02	5,2E-03	4,6E-02	3,0E+00	2,6E+00	3,1E+00

Ra-226 & Pb-210 calculations

	Inhalation of radon			Leafy vegetables + Potatoes			Drinking water			
	indoors+outdoors	confidence interval		95% confidence interval			95% confidence interval			
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	
1	4,5E+00	1,4E+00	8,9E+00	6,4E-01	1,4E-01	2,0E+00	3,6E-05	1,2E-07	2,3E-04	
100	3,9E+00	1,1E+00	8,1E+00	1,4E+00	6,6E-01	2,6E+00	1,8E-02	8,6E-05	1,0E-01	
500	2,5E+00	2,0E-01	6,3E+00	9,1E-01	1,7E-01	2,0E+00	4,3E-02	3,7E-04	2,4E-01	
Maximum	4,5E+00	1,4E+00	8,9E+00	1,4E+00	7,3E-01	2,7E+00	**4,8E-02**	**5,9E-04**	**2,5E-01**	**Within 1000 years**

Ra-226 & Pb-210 calculations

	Milk			Meat			Soil ingestion (optional)		
	95% confidence interval			95% confidence interval			95% confidence interval		
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,3E-02	6,9E-03	4,7E-02	1,3E-02	3,7E-03	3,2E-02	1,5E-02	1,5E-02	1,5E-02
100	6,1E-02	2,1E-02	1,2E-01	3,2E-02	1,4E-02	5,7E-02	4,0E-02	2,8E-02	4,5E-02
500	4,0E-02	4,4E-03	9,2E-02	2,1E-02	2,5E-03	4,5E-02	2,6E-02	3,0E-03	3,9E-02
Maximum	6,2E-02	2,2E-02	1,2E-01	3,3E-02	1,4E-02	5,7E-02	4,1E-02	3,1E-02	4,6E-02

Total dose:

Ra-226 & Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval			95% confid. interval			95% confid. interval			95% confid. interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
8,2E+00	4,8E+00	1,3E+01	8,1E+00	4,4E+00	1,3E+01	5,2E+00	7,3E-01	1,0E+01	8,6E+00	5,3E+00	1,3E+01

2. Covering with 0,5 m clean soil layer

Ra-226 & Pb-210 calculations

	Inhalation of dust (optional)			External irradiation		
	indoors+outdoors	confidence interval		indoors+outdoors	confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	0,0E+00	0,0E+00	0,0E+00	5,8E-03	5,1E-03	6,1E-03
100	0,0E+00	0,0E+00	0,0E+00	5,1E-03	3,4E-03	5,8E-03
500	0,0E+00	0,0E+00	0,0E+00	3,5E-03	1,3E-03	4,7E-03
Maximum	0,0E+00	0,0E+00	0,0E+00	6,3E-03	5,3E-03	8,0E-03

Ra-226 & Pb-210 calculations

	Inhalation of radon			Leafy vegetables + Potatoes			Drinking water			
	indoors+outdoors	confidence interval		95% confidence interval			95% confidence interval			
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	
1	3,2E+00	1,0E+00	6,4E+00	3,2E-05	5,4E-08	2,2E-04	3,6E-05	1,2E-07	2,3E-04	
100	2,8E+00	8,2E-01	5,8E+00	1,6E-02	4,1E-05	1,0E-01	1,8E-02	8,6E-05	1,0E-01	
500	1,8E+00	1,5E-01	4,6E+00	4,1E-02	2,1E-04	2,4E-01	4,3E-02	3,7E-04	2,4E-01	
Maximum	3,3E+00	1,0E+00	6,4E+00	**4,7E-02**	**3,5E-04**	**2,5E-01**	**4,8E-02**	**5,9E-04**	**2,5E-01**	**Within 1000 years**

Ra-226 & Pb-210 calculations

	Milk			Meat			Soil ingestion (optional)		
	95% confidence interval			95% confidence interval			95% confidence interval		
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,8E-07	6,7E-10	1,6E-06	1,6E-07	3,4E-10	1,1E-06	1,1E-11	1,8E-14	7,8E-11
100	1,4E-04	5,3E-07	8,7E-04	7,6E-05	3,1E-07	4,7E-04	3,4E-07	9,5E-10	1,9E-06
500	3,3E-04	2,2E-06	1,9E-03	1,8E-04	1,3E-06	1,0E-03	2,5E-06	1,0E-08	1,2E-05
Maximum	**3,7E-04**	**3,5E-06**	**2,2E-03**	**2,0E-04**	**2,0E-06**	**1,1E-03**	**3,8E-06**	**2,7E-08**	**1,5E-05**

Total dose:

Ra-226 & Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confid. interval		95% confid. interval			95% confid. interval			95% confid. interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
3,3E+00	1,0E+00	6,4E+00	2,9E+00	8,6E-01	5,8E+00	2,5E+00	6,9E-01	5,5E+00	3,3E+00	1,0E+00	6,4E+00

II-2.4.3. Sensitivity analyses

Tables: Ranking of the three most sensitive parameters for the total dose (Ra and Pb)

1. Without remedial action

From most to less sensitive	Parameter
1	Emanation fraction
2	Soil density
3	TF(Ra&Pb) soil to leafy vegetables

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer – option 2a)

From most to less sensitive	Parameter
1	Emanation fraction
2	Soil density
3	House ventilation rate

References

[1] YU, C., "RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities," Chapter 11, pp. 207–231, Health Physics Society 1999 Summer School Textbook, M.J. Slobodien (Ed.), Medical Physics Publishing, Madison, Wis. (1999).

[2] YU, C., ET AL., "Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil" Argonne, Ill.: Argonne National Laboratory. ANL/EAIS-8 (1993a).

[3] YU, C., ET AL., "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0: Working Draft for Comment" Argonne, Ill.: Argonne National Laboratory, ANL/EAD/LD-2 (1993b).

[4] YU, C., ET AL., Unpublished information, Argonne, Ill.: Argonne National Laboratory (2000).

II-2.5. RESRAD (ONSITE)

II-2.5.1. General model description

II-2.5.1.1. Name of model, model developer(s) and model user(s)

Model name:	RESRAD 5.91 – a computer code for evaluating radioactively contaminated sites
Model developer(s):	Charley Yu, Environmental Assessment Division Argonne National Laboratory, Argonne, Illinois, United States of America
Name of model user:	Peter Lietava, Nuclear Research Institute, Waste Management Department, Rez, Czech Republic

II-2.5.1.2. Intended purpose of the model in radiation assessment

RESRAD is a computer code developed at Argonne National Laboratory for the U.S. Department of Energy to calculate site-specific RESidual RADioactive material guidelines as well as radiation dose and excess lifetime cancer risk to a chronically exposed on-site resident.

II-2.5.1.3. Model type (equilibrium, dynamical, numerical, analytical,...)

RESRAD uses a pathway analysis method in which the relation between radionuclide concentrations in soil and the dose to a member of a critical population group is expressed as a pathway sum, which is the sum of products of “pathway factors”. Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or radiation emitted. Radiation doses, health risks, soil guidelines and media concentrations are calculated over user-specified time intervals. The source is adjusted over time to account for radioactive decay and ingrowth, leaching, erosion, and mixing. RESRAD uses a one-dimensional groundwater model that accounts for differential transport of parent and daughter radionuclides with different distribution coefficients.

II-2.5.1.4. Description of model and assumptions concerning parameter values used in different components of the model: (procedures, parameters, main equations)

Following environmental pathways are considered:

- direct exposure to external radiation from contaminated soil material;
- internal dose from inhalation of airborne radionuclides, including radon progeny;
- internal dose from ingestion of:
  - plant foods grown in the contaminated soil and irrigated with contaminated water,
  - meat from livestock fed with contaminated fodder and water,
  - milk from livestock fed with contaminated fodder and water,
  - fish from a contaminated pond,
  - drinking water from contaminated well or pond,
  - contaminated soil.

II-2.5.1.5. Contaminated zone parameters

Area of contaminated zone: 200 000 m^2 for the whole field between Kleine Nete and Roerdompstraat and 1500 m^2 for Farm (Scenario description, Appendix I of this report).

Thickness of contaminated zone: 1/1.5 m (no remediation and rem. action 1/ rem. action 2) (Appendix I).

Length parallel to aquifer flow (radius of drawdown cone): 53,3 / 58,7 / 50,4 m; calculated from the total amount of water extracted from the farm's well, which covers the annual consumption of drinking water for 5 persons living in the farm (each 400 l/y), 60 cows (21 900 l/y) and is used for the irrigation of the garden placed near by the farm (0,1 m/y). The groundwater and infiltrated water contributes to the total amount of extracted water as:

$$V_{tot} = V_{aq} + V_{inf} = 2.r.h_{aq}.v_{Darcy} + (\pi.r^2-1500).I_1 + 1500.I_2 \qquad (1)$$

where:

V_{tot}	is the total amount of water extracted from the well (1466 m^3/y);
V_{aq}	is the contribution of groundwater to the total amount of water extracted from the well [m^3/y];
V_{inf}	is the contribution of infiltrated water to the total amount of water extracted from the well [m^3/y];
r	is the radius of drawdown cone [m];
h_{aq}	is the thickness of the aquifer for no remedial action and remedial action 1 and 2 (1 m / 0.5 m / 1.5 m);
v_{Darcy}	is the Darcy velocity (3,5 m/y);
I_1	is the infiltration rate without irrigation [m/y];
I_2	is the infiltration rate with irrigation [m/y]:

$$I_1 = (1-EVP)[(1-R_{off}).PREC] \qquad (2)$$

$$I_2 = (1-EVP)[(1-R_{off}).PREC+IRR] \qquad (3)$$

where:

EVP	is the evapotranspiration coefficient [-];
R_{off}	is the runoff coefficient [-];
PREC	is the precipitation rate [m/y];
IRR	is the irrigation rate [m/y].

Due to the high retardation of Ra (about 0.004 m/y) and Pb (about 0.008 m/y) in soil it is not assumed, that other parts of contaminated area exceeding the radius of 53 m from the well contribute to the groundwater contamination (Appendix I, Olen Type A scenario)

II-2.5.1.6. Initial concentration of principle radionuclide (Ra-226)

No remedial action: 0,766 Bq/g for the 0.15 m thick root zone in the whole field, calculated from the results of soil profile measurement performed in 1998. If possible each sampling point was linked to one of 6 soil contamination levels defined before the deep ploughing remedial action. This approach is based on the assumption, that the deep ploughing does not affect the horizontal contaminant distribution. Only for the highest Ra-226 contamination in the soil, corresponding to the contamination level 6 and without any sampling points, was Ra-226 contamination estimated according to the ratio of Ra-226 concentration contaminated to the level 6 and 5 before deep ploughing.

TABLE II-2.5.I. RESULTS OF SOIL PROFILE MEASUREMENTS OF Ra-226 CONCENTRATION FROM 1998 (TABLE I-XVIII, APPENDIX I)

Sample	Depth [cm]	[Ra] [Bq/kg dw]	[Ra]-root zone [Bq/kg dw] Pasture/food crops	Moisture [%]
A1	0-15	65	65	27
A2	15-30	23	43.84222589	25
A3	30-50	16	32.50705917	18
B1	0-15	734	734	35
B2	15-30	1285	1009.333276	38
B3	30-50	3549		51
B4	50-75	33		49
B5	75-100	17		19
C1	0-15	1827	1827	32
C2	15-30	1710	1768.286251	32
C3	30-50	1243		46
C4	50-75	35		51
C5	75-100	40		76
D1	0-15	2356	2356	33
D2	15-30	1399	1877.156676	28
D3	30-50	4069		54
D4	50-75	60		76
D5	75-100	26		69
E1	0-15	590	590	29
E2	15-30	590	590	29
E3	30-50	11800		73
E4	50-75	25		45
E5	75-100	27		48
F1	0-15	267	267	27
F2	15-30	141	203.7092663	21
F3	30-50	35		23
F4	50-75	68		35
F5	75-100	3223		69

— 0.628 Bq/g for the whole profile of the contaminated zone in the whole field used for the radon and external irradiation exposure pathway. The weighted average value of Ra-226 concentration was calculated in the same way as for the root zone.

— 1.614 Bq/g for the area contributing to the groundwater contamination. The size of the area, exceeding the dimensions of field, was calculated from the scenario description (Chapter I-5, Appendix I)

— 1.88/1.40 Bq/g for Farm outdoor/indoor exposure pathways, derived from the measured soil profile D placed in the middle of the farm garden.

Remedial action 1 (removal of sources): A minimum dose rate for soil removal – 200 nSv/h, has been used as a limit value for the soil removal according to the scenario description (Appendix I). From the Tables I-XV and I-XVI (Appendix I) it is clear, that 410 nodal points, corresponding to the volume of 28 360 m^3 , have to be removed (depth – 1m). This volume is significantly lower than the value of 100 000 m^3 published in (Appendix I), but the radiological survey performed in 1991–95 did not cover the whole field area. The studied area is not only larger than the area monitored by radiological survey, but contains zones contaminated up to the level 5 (before deep ploughing) (Appendix I). Therefore the volume of 100 000 m^3 of removed soil, recommended by authors of the scenario, was used in this calculation. Because the thickness of ‘clean’, 0.5 m thick, soil layer replacing the contaminated soil, exceeds the thickness of root zone layers for food crops (0.3 m), the first value of soil contamination for Farm is equal the contamination of ‘clean’ soil layer – 0.06 Bq/g and is used for selected exposure pathways, related to the whole field area (meat and milk pathway, dust inhalation, soil ingestion) and all exposure pathways at the farm garden.

— 0.316 Bq/g for the area contributing to the Rn-222 exposure and external irradiation pathways during the time spent on the field, calculated as average value from non removed elements, contaminated up to the level 3 and other elements (contaminated to the level 4-6), replaced by ‘clean’, 0.5 m thick, soil layer.

Remedial action 2 (capping with clean soil layer): it was assumed that the whole field is capped with 0,5 m thick clean soil layer. Therefore the average field contamination, used as the pasture and for the food crops production in Farm, is 0.02 Bq/g (background level).

The contribution from deeper, more contaminated, soil layers was included only by the calculations of external irradiation and Rn-222 pathway doses. The value of 0.425 Bq/g was used for outdoors external pathway doses - the weighted average of 0,02 Bq/g background level in 0.5 m thick clean soil cap and 0.628 Bq/g in 1 m thick soil under the cap calculated from the soil profile measurements as described in the case of no remedial action.

— 1.072 Bq/g for the area contributing to the groundwater contamination (calculated as for no remedial action).

— 0.93 Bq/g was used as the initial soil concentration for indoors and outdoors external irradiation and Rn-222 pathway calculation. It is a weighted average of Ra-226 concentration in 0.5 m thick soil cap and underlying 1 m thick contaminated soil layer.

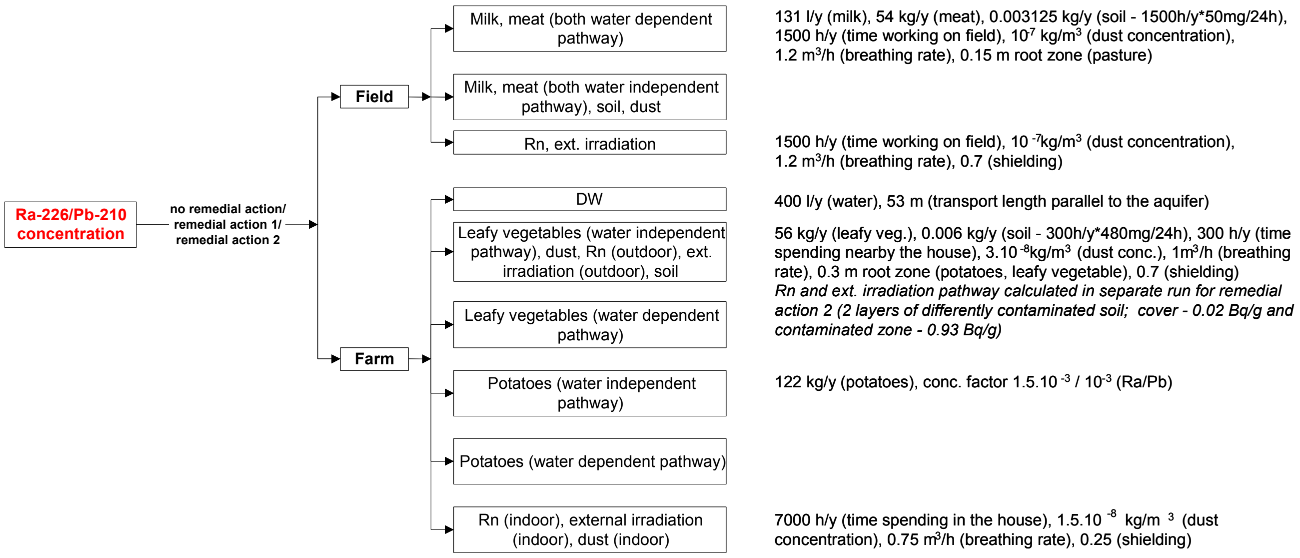


FIG. II-2.5.1. Calculation scheme for Olen B Scenario.

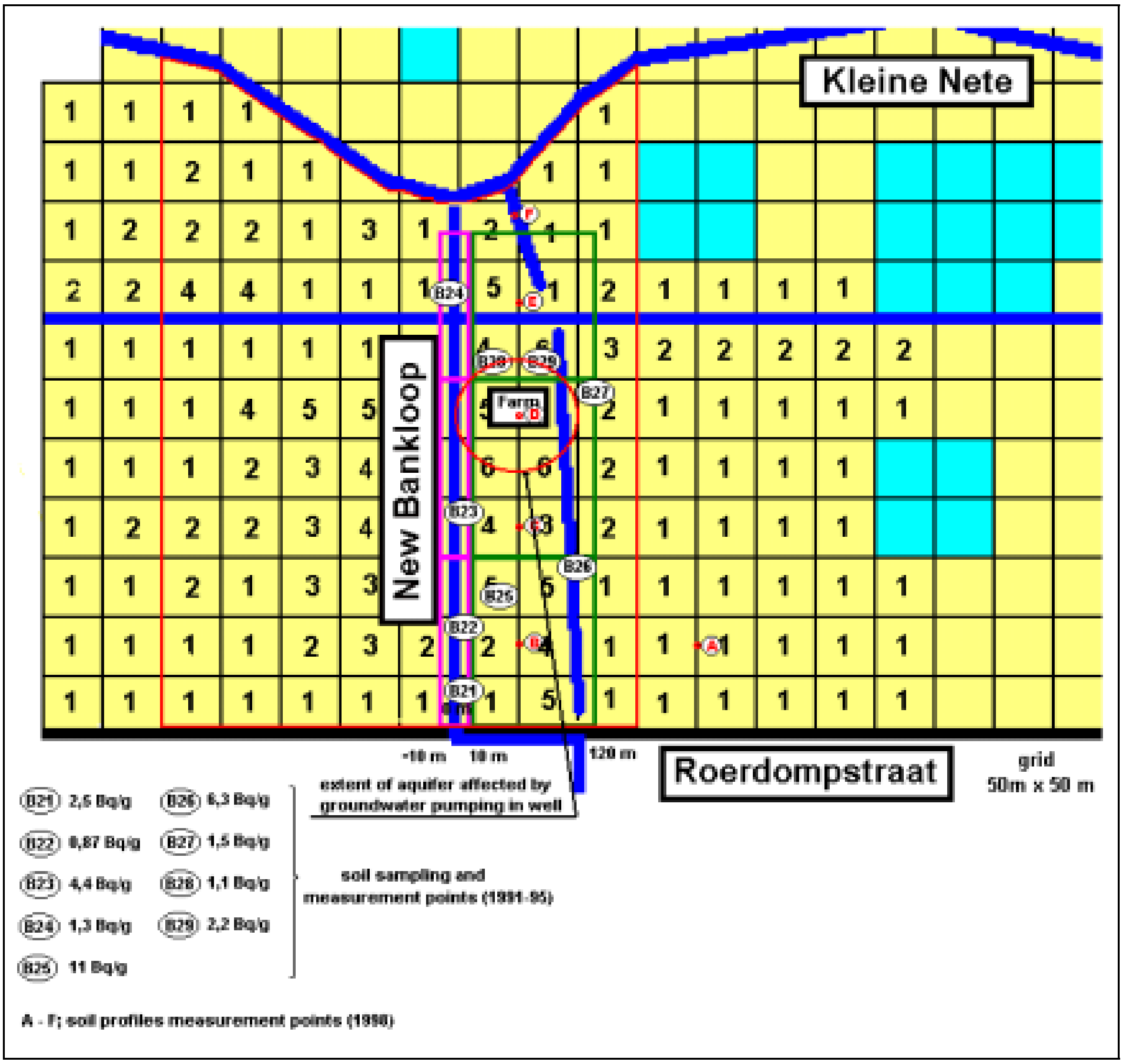


FIG. II-2.5.2. *Soil sampling places and aquifer area affected by groundwater pumping.*

II-2.5.1.7. Cover and contaminated zone hydrological data

Density of contaminated zone (sandy loam): 1,44 g/cm^3 (Appendix I, [1])

Density of contaminated zone: 800 kg/m^3 (Appendix I)

Contaminated zone erosion rate: 0,001 m/y [2]

Contaminated zone effective porosity: 0,5 (Appendix I)

Contaminated zone Hydraulic conductivity: 1,7.10^{-4} m/s (Appendix I)

Evapotranspiration coefficient: 0,5 [2]

Precipitation: 0,757 m/y (Appendix I)

Irrigation: 0,1 m/y (Appendix I)

Runoff coefficient: 0,3 [1]

II-2.5.1.8. Saturated zone hydrological data

Density of saturated zone (sandy clay loam): 1,42 g/cm^3 (Appendix I, [1])

Saturated zone total porosity: 0,4

Saturated zone effective porosity: 0,2

Saturated zone Hydraulic conductivity: 199 m/y (Appendix I)

Saturated zone Hydraulic gradient: 0,0176; calculated from the value of Darcy velocity 3,5 m/y (Appendix I) and Darcy equation:

$$v = K.dh/dx \tag{4}$$

where:

v	is the Darcy velocity [m/s];
K	is the hydraulic conductivity [m/s];
dh/dx	is the hydraulic gradient [-].

Well pump intake depth: 1/1,5 m (Appendix I)

Well pumping rate: 1466 m^3/y; calculated from expected number of farm inhabitants (5), number of cattle (60), groundwater intake by man and cattle (400 l/y and 21 900 l/y), irrigation rate (0,1 m/y) and the area of farm (1500 m^2).

II-2.5.1.9. Distribution coefficients

Ra - 500 cm^3/g and Pb - 270 cm^3/g (Appendix I)

II-2.5.1.10. Dust inhalation and external gamma irradiation exposure pathway

$$D_{dust}\text{ (no cover)} = ASR.AF.OF.DF_{air}.S(0).SOF(t).\ DCF_{inh} \tag{5}$$

$$D_{dust}\text{(cover)} = D_{dust}\text{ (no cover)}.TH_{cont}(t)/TH_{mix}\ ;\ TH_{mix}>TH_{cover}(t)+TH_{cont}(t) \tag{6}$$

$$\begin{gathered} D_{dust}\text{(cover)} = D_{dust}\text{ (no cover)}.(1-TH_{cover}(t)/TH_{mix}); \\ TH_{mix}>TH_{cover}(t),\ TH_{mix}<TH_{cover}(t)+TH_{cont}(t) \end{gathered}$$

$$\begin{gathered} D_{ext}\text{ (no cover)} = \rho_{cont}.OSF.AF.SF.\{1-\exp[-k.\ \rho_{cont}.(TH_{cont}(0)-ER_{cont}.t)]\}. \\ S(0).SOF(t).\ DCF_{ing} \end{gathered} \tag{7}$$

$$D_{ext}\text{ (cover)} = D_{ext}\text{ (no cover)}.\ \exp[-k.\ \rho_{cover}.TH_{cover}(0)-ER_{cover}.t)];\ 0 \le t \le t_{cover} \tag{8}$$

$$\begin{gathered} D_{ext}\text{ (cover)} = \rho_{cont}.OSF.AF.SF.\{1-\exp[-k.\ \rho_{cont}.(TH_{cont}(0)-ER_{cont}.(t-t_{cover}))]\}. \\ S(0).SOF(t).\ DCF_{ing};\ t > t_{cover} \end{gathered}$$

where:

ASR	is the air/soil concentration ratio [kg/m^3];
AF	is the area factor [-];
OF	is the occupancy factor [-];
DF_{air}	is the annual intake of air [m^3/y];
S(0)	is the initial concentration of radionuclide in soil [kg/m^3];
SOF(t)	is the correction factor for source term (decay, ingrowth, leaching)[-]

DCF	is the dose conversion factor (inh - inhalation, ing - ingestion) [Sv/Bq];
$TH_{cont}(t)$	is the time dependent thickness of contaminated zone [m];
TH_{mix}	is the depth of soil mixing layer [m];
$TH_{cover}(t)$	is the time dependent thickness of cover [m];
ρ_{cont}	is the density of contaminated soil material [kg/m^3];
ρ_{cover}	is the density of cover material [kg/m^3];
k	is the empirical constant for the calculation of the depth factor [m^2/kg];
ER_{cont}	is the erosion rate of the contaminated zone [m/y];
ER_{cover}	is the erosion rate of the cover material [m/y];
t_{cover}	is the time for the cover removal by erosion [y];
t	is the time [y].

Inhalation rate: 5250/300/1800 m^3/y for adults indoor/outdoor/agricultural activity (Appendix I)

Mass loading for inhalation: $1.10^{-4}/1{,}5.10^{-5}/3.10^{-5}$ g/m^3 for agricultural activity/indoor /outdoor (Appendix I)

Shielding factor for inhalation: 0,4/1 for adults indoor/outdoor (Appendix I)

Shielding factor for external gamma: 0,25/0,25/0,75 for agricultural activity/indoor/ outdoor (Appendix I)

II-2.5.1.11. Ingestion exposure pathway

$$D_{water} = DF_{water}.WSR.\ S(0).SOF(t).DCF_{ing} \tag{9}$$

$$D_{soil} = DF_{soil}.FCD.OCF.\ S(0).SOF(t).\ DCF_{ing} \tag{10}$$

Water independent pathway = root uptake + foliar dust deposition

Water dependent pathway = overhead irrigation pathway

$$D_{plants}(\text{water ind.}) = \{\overbrace{FCD.DF_{plant}.B}^{\text{root uptake}}+\overbrace{FCD.DF_{plant}.AF.ASR.3{,}16.10^{4}.(v_{dep}.f_r.TRANS_{plant}).}^{\text{foliar dust deposition}}$$

$$.[1-\exp(-\lambda_{weath}.\ t_{exp})]/(Y.\ \lambda_{weath})\}.\ S(0).SOF(t).DCF \tag{11}$$

$$D_{plants}(\text{water dep.}) = FCD.DF_{plant}.FWR.\ WSR.\ S(0).SOF(t).DCF \tag{12}$$

$$FWR=IRR.f_r.TRANS_{plant}.[1-\exp(-\lambda_{weath}.t_{exp})]/(Y.\ \lambda_{weath})+(1-f_r).IRR.B.$$
$$.[1-\exp(-L.\ t_{exp})]/(\ \rho_{cover}\ .L)$$

Water independent pathway = root uptake + soil uptake + foliar dust deposition

Water dependent pathway = overhead irrigation pathway + water intake by livestock

$$D_{milk/meat}(\text{water ind.}) = \{\overbrace{FCD.\ DF_{fodder}.B}^{\text{root uptake}}+\overbrace{FCD.\ DF_{fodder}.AF.ASR.3{,}16.10^{4}.(v_{dep}-f_r.0{,}1).}^{\text{foliar dust deposition}}$$

$$[1-\exp(-\lambda_{\ weath}.\ t_{exp})]/(Y.\ \lambda_{\ weath})\}\ TRANS_{milk/meat}.\ DF_{milk/meat}.\ S(0).SOF(t).DCF \tag{13}$$

$$D_{milk/meat}(\text{water dep.})) = DF_{milk/meat}.(\overbrace{FWR.WSR.DF_{fodder}}^{\text{overhear irrigation}}\overbrace{+DFA_{water}.WSR+}^{\text{water intake}}$$

$$\overbrace{+DFA_{soil}.FCD.}^{\text{soil intake}}OCF).\ S(0).SOF(t).DCF.\ TRANS_{milk/meat} \qquad (14)$$

where:

DF_{water}	is the drinking water consumption rate [m^3/y];
DF_{soil}	is the soil consumption rate [kg/y];
DF_{plant}	is the leafy vegetable/potatoes consumption rate [kg/y];
$DF_{milk/meat}$	is the milk/meat consumption rate [kg/y];
DF_{fodder}	is the fodder consumption rate [kg/y];
DFA_{water}	is the drinking water consumption rate (animals) [m^3/y];
DFA_{soil}	is the soil consumption rate (animals) [kg/y];
WSR	is the well water contaminant concentration to soil contaminant concentration ratio [-];
FCD	is the cover and depth factor; for root uptake:

$$\begin{array}{ll} FCD=0; & TH_{root}=0 \text{ or } TH_{cover}(t) \geq TH_{root} \\ \quad 1; & TH_{over}(t)=0,\ TH_{cont}(t) \geq TH_{root} \\ \quad TH_{cont}(t)\ /TH_{root}\ ; & TH_{cover}(t)+ TH_{cont}(t) < TH_{root} \\ \quad 1- TH_{cover}(t)/TH_{root}\ ; & TH_{cover}(t) < TH_{root}\ ,TH_{cover}(t)+ \\ & \quad + TH_{cont}(t) \geq TH_{root} \end{array}$$

for foliar deposition and livestock soil intake:

$$\begin{array}{ll} FCD=1; & TH_{cover}=0 \text{ or } TH_{cont}(t) \geq TH_{mix} \\ \quad TH_{cont}(t)\ /Th_{mix}; & TH_{cover}(t)+ TH_{cont}(t) < TH_{mix} \\ \quad 0; & TH_{cover}(t) \geq TH_{mix} \\ \quad 1- TH_{cover}(t)/TH_{root}; & TH_{cover}(t) < TH_{mix}\ ,TH_{cover}(t)+ \\ & \quad + TH_{cont}(t) \geq TH_{mix} \end{array}$$

OCF	is the occupancy factor [-];
B	is the food/soil concentration ratio;
v_{dep}	is the dust deposition velocity [m/y];
f_r	is the fraction of deposited radionuclides retained on the vegetation (0,25);
λ_{weath}	is the weathering removal constant [1/y];
t_{exp}	is the time of exposure during the growing season (0,17 y potatoes, 0,25 y leafy vegetables, 0,08 y fodder);
Y	is the yield [kg/m^2];
FWR	is the food/water concentration ratio for overhead irrigation [m^3/kg];
L	is the leach rate [1/y] calculated as:

$$L=(1-EVP)[(1-R_{off}).PREC+IRR]/[TH_{cont}(0).R_d.\ \theta]$$

R_d	is the retardation factor [-];
θ	is the volumetric water content of the contaminated cover [-];
IRR	is the irrigation rate [m/y];
$TRANS_{plant}$	is the foliage to food transfer coefficient [-];
$TRANS_{milk/meat}$	radionuclide transfer factor [y/m^3; y/kg].

The following values of consumption rates were given in the scenario description (Appendix I):

Fruits, vegetables and grain consumption: 122 kg/y (potatoes)
Leafy vegetable consumption: 56 kg/y
Milk consumption: 131 kg/y
Meat and poultry consumption: 62,2 kg (meat + poultry)
Soil ingestion: 50 mg/d / 480 mg/d
Drinking water intake: 400 l/d
Livestock fodder intake for milk and meat: 12,5 kg/d
Livestock water intake for milk and meat: 60 kg/d
Livestock intake of soil: 0,5 kg/d

Mass loading for foliar deposition: 10^{-4} g/m^2 [2]
Depth of soil mixing layer: 0,5–1 m (Appendix I)
Depth of roots: 0,15 / 0,3 m (pasture / food crops) (Appendix I)

II-2.5.1.12. Radon exposure pathway

Dose calculations are based on the transformation of working levels (WL) for atmosphere containing a mixture of radon progeny from workers to general population (K factor of 0,76). The concentration of radon progenies are calculated from indoors and outdoors radon concentrations:

$$\mathrm{WL}=1{,}03.10^{-6}.C_{\mathrm{Po\text{-}218}}+5{,}05.10^{-6}.C_{\mathrm{Pb\text{-}214}}+3{,}73.10^{-6}.C_{\mathrm{Bi\text{-}214}} \tag{15}$$

$$C_{out}=(n.d_{diff}.dC/dz)/(\ \lambda_{Rn}.H_{mix}\underline{)}\ .\ [1-\exp(-\lambda_{Rn}.A^{0.5}/(2.v_{wind}))] \tag{16}$$

$$C_{in}=\{[n.d_{diff}.dC/dz\ .(1+4.d_{foun}/\ A_{house}^{\ 0.5})].\ A_{house}/\ V_{house}+\mathrm{VENT}.C_{out}\}/\underline{(}\lambda_{Rn}.\mathrm{VENT})+$$

$$+C_w.f_{wa}.V_{water}/[\underline{(}\lambda_{Rn}.\mathrm{VENT}).\ V_{house}] \tag{17}$$

where:

$C_{\mathrm{Po\text{-}218}}$	is the Po-218 concentration in the air [Bq/m^3];
$C_{\mathrm{Pb\text{-}214}}$	is the Pb-214 concentration in the air [Bq/m^3];
$C_{\mathrm{Bi\text{-}214}}$	is the Bi-214 concentration in the air [Bq/m^3];
d_{diff}	is the diffusion coefficient of Rn-222 in soil [m^2/y] calculated as:

$$d_{diff}=d_{diff}(\mathrm{air}).n.\exp(-6R_s.n-6R_s^{\ 14n})$$

n	is the total porosity [-];
R_s	is the saturation ratio [-];
λ_{Rn}	is the Rn-222 decay constant [1/y];
H_{mix}	is the height into which Rn-222 plume is uniformly mixed [m];
A	is the area of the contaminated zone [m^2];
v_{wind}	is the annual average wind speed [m/s];
d_{foun}	is the depth of the foundation below and within the contaminated zone [m];
A_{house}	is the area of the house floor [m^2];
V_{house}	is the volume of the house [m^3];
VENT	is the ventilation rate [1/y];
C_w	is the Rn-222 concentration in water [Bq/m^3];
f_{wa}	is the transfer efficiency of radon from water to air [-];
V_{water}	is the household water use [m^3/y].

Cover material thickness: 0,5 m
Cover material density: 1,44 g/cm^3 (sandy loam) [1]
Cover material total porosity: 0,42 (sandy loam) [1]
Cover material effective radon diffusion coefficient: 8.10^{-7} m^2/s [1]
Building foundation thickness: 0,3 m [2]
Building foundation density: 2,4 g/cm^3 [2]
Building foundation total porosity: 0,2 [2]
Building foundation effective radon diffusion coefficient: 2.10^{-7} m^2/s [2]
Contaminated zone radon diffusion coefficient: 2.10^{-6} m^2/s [2]
Radon vertical dimension of mixing: 2 m [2]
Average annual wind speed: 4 m/s (Appendix I)
Height of the building: 2,5 m [2]
Building air exchange rate: 0,5 h^{-1} [2]
Building indoor area factor: 1 for indoor calculation
Building depth below ground surface: 3,5 m (Appendix I)
Radon emanation coefficient: 0,25 [2]

II-2.5.1.13. Dose conversion factors (Appendix I) and food transfer factors [(Appendix I), 2, 3]

	Concentration factor / Food transfer factor			DCF for inhalation [Sv/Bq]	DCF for ingestion [Sv/Bq]
	Plants	Milk	Meat		
Ra-226	$10^{-2}/1{,}5.10^{-3}$	2.10^{-4} d/l	5.10^{-4} d/kg	$9{,}5.10^{-6}$	$2{,}8.10^{-7}$
Pb-210	$10^{-2}/10^{-3}$	$1{,}5.10^{-4}$ d/l	4.10^{-4} d/kg	$5{,}6.10^{-6}$	$6{,}9.10^{-7}$

II-2.5.1.14. Stochastic data input set (Appendix I)

Parameters	Mean	Range/pdf
Density of soil, after deep ploughing (kg/m^3)	800	320–1300 triangular
Moisture of soil (-)	0.3	0.15–0.5 triangular
Thickness of root zone layer:		
Pasture	0.15	0.1–0.3
Potatoes, leafy vegetables	0.3	0.2–0.5 triangular
Ventilation of house (h^{-1})	0.5	0.2–1 triangular
Pore diffusion coefficient radon in concrete (m^2/y)	6.3	1–15 triangular
Thickness of basement (m)	0.3	0.1–0.5 triangular
Daily uptake of pasture by cattle (kg dw/d)	12.5	10–15 triangular
Daily uptake water by cow (m^3/d)	0.06	0.04–0.08 uniform
Fractional uptake of soil by cattle (kg dw/kg dw pasture)	0.04	0.01–0.1 triangular
Yield of vegetation (kg/m^2/y):		
Leafy vegetables (fresh)	2	0.8–4.0
Potatoes (fresh)	2	0.8–4.0 triangular
Interception factor food crops (-)	0.2	0.1–0.5 triangular

(Continued)

Parameters	Mean	Range/pdf
Infiltration velocity (mm/y)	100	40–150 uniform
Irrigation time (d)	100	30–150 triangular
Irrigation rate (m/d)	1.0E-03	(0.3–2)E-03 triangular

II-2.5.2. Evaluation of results

For the time dependent total dose for no remediation scenario the indoors Rn inhalation, outdoors external irradiation and leafy vegetable pathways are dominant contributors to the total dose. Due to the different soil-plant concentration factor for potatoes and for leafy vegetable and different times of exposure during the growing season (0,17 y potatoes, 0,25 y leafy vegetables – default RESRAD values) is the contribution of this pathway about 3 times lower than leafy vegetables pathway. The importance of drinking water increases in time, but due to high retardation in soil and aquifer does not reach the maximal value in selected time horizon (max. value is reached after about 800-900 years). The total Pb dose is build mostly by water and potatoes intake. RESRAD code calculates the Pb concentration in soil from Ra concentration and does not automatically take into account the equilibrium between Ra-226 and its decay products. The equilibrium between Pb and Ra concentration in soil is reached after about 200 years from the initial deposition, what corresponds to the assumption, that the equilibrium status is reached after T = 225 years calculated as:

$$T > 10.T_1.T_2/(T_1-T_2) \qquad (18)$$

where:

T_1 is the half-live of Ra-226 (1600 y);
T_2 is the half-life of Pb-210 (22.26 y).

The concentration of Pb-210 in soil increases in time until the equilibrium state is reached and so the water independent contamination pathways for potatoes and leafy vegetables.

Remedial action 1 limits the importance of leafy vegetable pathway due to the reduced Ra-226 concentration in the root zone and only the outdoors external irradiation and indoors Rn inhalation contribute significantly to the whole Ra-226 dose. The total dose for Pb-210 is made mostly by drinking water pathway, milk and meat ingestion and leafy vegetables ingestion. The RESRAD code takes into account the erosion of contaminated zone (1 mm/y), which causes a steep decrease of total dose after 500 years after deposition, when the entire contaminated zone is removed.

The remedial action 2 does not change significantly importance of exposure pathways as calculated in the ‘no remediation’ scenario. The calculated average contamination of cover and contaminated soil at the site of the farm is 1.5 times lower than for ‘no remediation’ scenario and this is also the ratio of indoors Rn exposure pathways for both scenarios.

TABLE II-2.5.II. RELATIVE EFFICIENCY OF PROPOSED REMEDIAL ACTIONS

	Remedial action 1 [%]	Remedial action 2 [%]
Ra	82–95	21–39
Pb	97–98	76–87

TABLE II-2.5.III. MEASURED VERSUS CALCULATED Ra-226 CONCENTRATIONS

Ra-226 concentration in:	Measured value	Calculated value
Groundwater [Bq/m^3]	2–18	11.4
Milk [Bq/l]	0.0084–0.0359[a]	0.73
Leafy vegetable [Bq/kg]	17[b]	35 / 16.2[c]
Root vegetable [Bq/kg]	4.3–11	5.3
Grass [Bq/kg]	89–254	191.2

[a] Only small fraction of grazing fields placed on the contaminated area.

[b] Garden located on the non-contaminated ground.

[c] Only water dependent exposition.

The efficiency of remedial action 1 is for Ra-226 about 3–4 as high as for remedial action 2. The efficiency of remedial actions for Pb are about 87–98% for both actions. Because the total Pb dose is only very little affected by external irradiation dose, the efficiency of remedial actions does not vary in such extent as in the case of Ra-226.

The Olen B scenario description contain values of measured Ra-226 concentrations in selected components of biosphere. The comparison of measured values with calculated Ra-226 concentrations (for time 0 y without remedial action) is presented in Table II-2.5.III. For most dietary product is the agreement between calculated and measured values very good. Only for milk and leafy vegetables are the differences significant and are caused by using clean areas for cow grazing and leafy vegetable production. By taking into account only the water dependent exposure pathway for leafy vegetable is the difference between measured and calculated value negligible.

Except the uncertainties associated with the input data set used for calculation, there is an additional main source of uncertainties of the output results. The RESRAD code is developed for conceptual model which does not exactly correspond to the proposed conceptual model for Olen B scenario. Therefore for each scenarios it was necessary to run the code 9–10 times, derive the results from 18–20 output files (separate files for concentrations and doses) and retype them to the output forms. This procedure, together with the transformation of units (RESRAD uses pCi as the standard unit for radioactivity and mrem for effective dose) could introduce some errors to the output data set.

The input data set for stochastic calculation (see Chapter II-2.5.1.14) was taken from Chapter I-5 (Appendix I). RESRAD code is not able to describe stochastically all of the contaminant dependent parameters presented in Table I-XXV of Appendix I except K_d values in soil and some of contaminant independent parameters presented in Table I-XXVI of Appendix I– dust concentration in air and weathering decay constant.

The computer code RESRAD 5.91 does not present separately in the output files the concentrations and doses for root and foliar uptake for leafy vegetation and potatoes exposure pathways, but only water dependent and independent contamination pathways. Water dependent pathways include ditch irrigation, overhead irrigation (considered as the only irrigation method for leafy vegetation and potatoes) and livestock water. Water independent pathways consist of root uptake, foliar deposition and livestock intake of soil. Unfortunately the output file for stochastic calculations presents only the sum of doses for Ra and Pb and it is not possible to extract these two sets of values. RESRAD also evaluates the stochastic results in form of minimal and maximal calculated values and average value and standard deviation of dose. The 95% confidence interval, required in the Olen B scenario output forms can be obtained only for the total dose, but due to the used calculation scheme, which consisted of 9 independent runs to evaluate one scenario (see Figure II-2.5.1), it was not possible to use this code’s capability. Due to these limitation it was not possible to perform stochastic calculations in a form required in the scenario description.

II-2.5.3. Results of model predictions

Deterministic calculations

1. Without remedial action

Ra-226 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	farm	indoors	outdoors	outdoors agricult(*)							indoors	outdoors
0	7,66E+02	1,88E+03	3,52E-06	7,85E-06		6,13E+01			0,00E+00	7,14E-01	1,78E+00		
1	7,65E+02	1,88E+03	3,50E-06	7,83E-06		6,12E+01			2,86E+00	7,13E-01	1,78E+00		
50	7,21E+02	1,77E+03	3,14E-06	7,01E-06		5,77E+01			1,34E+02	6,71E-01	1,68E+00		
100	6,78E+02	1,66E+03	2,80E-06	6,25E-06		5,43E+01			2,50E+02	6,30E-01	1,58E+00		
200	6,00E+02	1,47E+03	2,20E-06	4,92E-06		4,81E+01			4,38E+02	5,56E-01	1,02E+00		
500	4,16E+02	1,02E+03	9,53E-07	2,13E-06		3,35E+01			7,30E+02	3,84E-01	9,61E-01		
Maximum													

Pb-210 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	farm	indoors	outdoors	outdoors agricult(*)						
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00		0,00E+00			0,00E+00	0,00E+00	0,00E+00
1	2,34E+01	5,75E+01	1,07E-07	2,40E-07		1,20E+00			2,30E-01	1,29E-02	3,53E-02
50	5,66E+02	1,39E+03	2,46E-06	5,51E-06		2,84E+01			2,58E+02	2,99E-01	7,98E-01
100	6,43E+02	1,58E+03	2,65E-06	5,92E-06		3,24E+01			5,45E+02	3,41E-01	9,12E-01
200	6,18E+02	1,46E+03	2,18E-06	4,87E-06		3,00E+01			9,14E+02	3,18E-01	8,48E-01
500	4,13E+02	1,01E+03	9,53E-07	2,12E-06		2,11E+01			1,41E+03	2,27E-01	6,05E-01
Maximum											

Ra-226 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.					
0	1,75E-04	3,20E-04	7,94E-01	4,97E-01	8,88E+00	3,06E-03	2,95E-01	0,00E+00	9,64E-02	0,00E+00	0,00E+00	8,46E-03	9,01E-03	6,73E-04	1,06E+01
1	1,75E-04	3,20E-04	7,94E-01	4,97E-01	8,88E+00	3,04E-03	2,95E-01	1,86E-05	9,63E-02	1,54E-06	3,20E-04	8,45E-03	9,03E-03	6,71E-04	1,06E+01
50	1,57E-04	2,87E-04	7,47E-01	4,68E-01	8,32E+00	2,87E-03	2,78E-01	8,76E-04	9,07E-02	7,53E-05	1,50E-02	7,90E-03	8,44E-03	6,01E-04	9,94E+00
100	1,40E-04	2,56E-04	7,02E-01	4,39E-01	7,76E+00	2,70E-03	2,61E-01	1,64E-03	8,54E-02	1,41E-04	2,82E-02	7,37E-03	7,88E-03	5,36E-04	9,30E+00
200	1,10E-04	2,01E-04	6,21E-01	3,89E-01	6,76E+00	2,39E-03	2,31E-01	2,87E-03	7,56E-02	2,47E-04	4,93E-02	6,43E-03	6,87E-03	4,22E-04	8,14E+00
500	4,76E-05	8,72E-05	4,18E-01	2,66E-01	4,29E+00	1,66E-03	1,60E-01	4,87E-03	5,24E-02	4,11E-04	8,20E-02	4,30E-03	4,59E-03	1,83E-04	5,28E+00
Maximum															

Pb-210 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking	Milk	Meat	Soil	**Total**
	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.	water			ingestion	
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
1	4,58E-06	3,04E-06	1,38E-05	8,49E-06	1,65E-02	6,42E-06	8,62E-03	5,21E-07	4,71E-05	2,77E-04	3,27E-04	3,75E-05	2,58E-02
50	1,05E-04	6,96E-05	3,34E-04	2,05E-04	3,99E-01	7,24E-03	2,04E-01	6,22E-04	5,29E-02	6,47E-03	7,38E-03	8,62E-04	6,79E-01
100	1,13E-04	7,51E-05	3,80E-04	2,33E-04	4,54E-01	1,53E-02	2,32E-01	1,32E-03	1,12E-01	7,38E-03	8,33E-03	9,29E-04	8,32E-01
200	1,10E-04	6,08E-05	3,51E-04	2,16E-04	4,20E-01	2,57E-02	2,15E-01	2,21E-03	1,88E-01	6,85E-03	7,82E-03	7,63E-04	8,67E-01
500	4,04E-05	2,68E-05	2,44E-04	1,41E-04	2,92E-01	3,97E-02	1,49E-01	3,41E-03	2,90E-01	4,12E-03	5,60E-03	3,31E-04	7,85E-01
Maximum													

Ra-226 calculations (mSv/y)

(sensitivity analysis of indoors Rn dose to vent. rate)

Years	Inhalation eman. Rn		**Total**
	0.5 1/h	1 1/h	
0	8,88E+00	3,54E+00	5,24E+00
1	8,88E+00	3,53E+00	5,23E+00
50	8,32E+00	3,30E+00	4,92E+00
100	7,76E+00	3,08E+00	4,62E+00
200	6,76E+00	2,68E+00	4,06E+00
500	4,29E+00	1,69E+00	2,68E+00

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Ra-226 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	farm	indoors	outdoors	outdoors agricult(*)							indoors	outdoors
0	5,99E+01	5,99E+01	4,07E-07	3,07E-07					0,00E+00				
1	5,99E+01	5,99E+01	4,03E-07	3,07E-07					4,66E-02				
50	5,64E+01	5,64E+01	3,29E-07	2,74E-07					2,09E+00				
100	5,31E+01	5,31E+01	2,65E-07	2,44E-07					3,70E+00				
200	4,70E+01	4,70E+01	1,63E-07	1,92E-07					5,96E+00				
500	2,99E+01	2,99E+01	0,00E+00	8,51E-08					7,33E+00				
Maximum													

Pb-210 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	farm	indoors	outdoors	outdoors agricult(*)						
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00					0,00E+00		
1	1,83E+00	1,83E+00	1,23E-08	9,37E-09					3,74E-03		
50	4,43E+01	4,43E+01	2,55E-07	2,15E-07					4,00E+00		
100	5,04E+01	5,04E+01	2,47E-07	2,32E-07					8,14E+00		
200	4,65E+01	4,65E+01	1,58E-07	1,91E-07					1,22E+01		
500	3,23E+01	3,23E+01	0,00E+00	8,29E-08					1,37E+01		
Maximum											

Ra-226 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.					
0	2,02E-05	2,42E-05	1,74E-01	1,66E-01	1,78E+00	1,53E-03	9,41E-03	0,00E+00	3,07E-03	0,00E+00	0,00E+00	6,62E-04	7,08E-04	5,27E-05	2,14E+00
1	2,01E-05	2,42E-05	1,74E-01	1,66E-01	1,78E+00	1,53E-03	9,40E-03	3,03E-07	3,07E-03	6,34E-08	5,22E-06	6,61E-04	7,07E-04	5,25E-05	2,14E+00
50	1,64E-05	2,17E-05	1,56E-01	1,56E-01	1,58E+00	1,40E-03	8,85E-03	1,37E-05	2,78E-03	2,96E-06	2,35E-04	6,18E-04	6,60E-04	4,71E-05	1,90E+00
100	1,32E-05	1,93E-05	1,39E-01	1,47E-01	1,38E+00	1,28E-03	8,33E-03	2,45E-05	2,52E-03	5,30E-06	4,20E-04	5,75E-04	6,15E-04	4,19E-05	1,68E+00
200	8,11E-06	1,52E-05	1,08E-01	1,29E-01	1,03E+00	1,05E-03	7,37E-03	3,90E-05	2,06E-03	8,45E-06	6,69E-04	4,97E-04	5,32E-04	3,30E-05	1,28E+00
500	0,00E+00	6,58E-06	0,00E+00	8,71E-02	0,00E+00	5,09E-04	5,11E-03	4,81E-05	1,44E-07	1,04E-05	8,27E-04	3,17E-04	3,38E-04	1,43E-05	9,43E-02
Maximum															

Pb-210 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.					
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
1	5,26E-07	2,14E-07	3,13E-06	2,82E-06	5,27E-04	1,05E-07	2,74E-04	2,14E-08	7,68E-07	2,17E-05	2,56E-05	2,94E-06	8,59E-04
50	1,09E-05	4,93E-06	7,18E-05	6,81E-05	1,27E-02	1,20E-04	6,19E-03	2,42E-05	8,18E-04	5,04E-04	5,76E-04	6,75E-05	2,12E-02
100	1,05E-05	5,31E-06	7,79E-05	7,75E-05	1,45E-02	2,25E-04	6,73E-03	4,88E-05	1,65E-03	5,72E-04	6,52E-04	7,27E-05	2,46E-02
200	6,73E-06	4,36E-06	6,58E-05	7,15E-05	1,34E-02	3,42E-04	5,73E-03	7,42E-05	2,50E-03	5,19E-04	5,93E-04	5,97E-05	2,34E-02
500	0,00E+00	1,89E-06	0,00E+00	4,96E-05	9,30E-03	3,85E-04	4,00E-07	8,34E-05	2,81E-03	3,28E-04	3,74E-04	2,59E-05	1,34E-02
Maximum													

Ra-226 calculations (mSv/y)
(sensitivity analysis of indoors Rn dose to vent. rate)

Years	Inhalation eman. Rn 0.5 1/h	Inhalation eman. Rn 1 1/h	**Total**
0	1,78E+00	7,05E-01	1,06E+00
1	1,78E+00	7,02E-01	1,06E+00
50	1,58E+00	6,20E-01	9,47E-01
100	1,38E+00	5,42E-01	8,42E-01
200	1,03E+00	4,03E-01	6,53E-01
500	0,00E+00	0,00E+00	9,43E-02

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

Ra-226 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	Rn-222 concentration (Bq/m3)	
	pasture	farm	indoors	outdoors	outdoors agricult(*)							indoors	outdoors
0	2,00E+01	2,00E+01	1,94E-06	5,11E-08					0,00E+00				
1	1,99E+01	1,99E+01	1,94E-06	5,09E-08					7,20E-01				
50	1,88E+01	1,81E+01	1,85E-06	4,16E-08					3,42E+01				
100	1,77E+01	1,63E+01	1,76E-06	3,35E-08					6,50E+01				
200	1,57E+01	1,34E+01	1,60E-06	2,05E-08					1,17E+02				
500	1,09E+01	7,33E+00	1,20E-06	0,00E+00					2,14E+02				
Maximum													

Pb-210 concentration

Years	Soil (Bq/kg)		Inhalable dust (Bq/m3)			Grass (Bq/kg)	Potatoes (Bq/kg)	Leafy vegetables (Bq/kg)	Ground water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
	pasture	farm	indoors	outdoors	outdoors agricult(*)						
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00					0,00E+00		
1	6,11E-01	6,11E-01	5,93E-08	1,56E-09					5,80E-02		
50	1,48E+01	1,40E+01	1,46E-06	3,23E-08					6,61E+01		
100	1,68E+01	1,52E+01	1,68E-06	3,12E-08					1,42E+02		
200	1,55E+01	1,30E+01	1,60E-06	1,99E-08					2,46E+02		
500	1,08E+01	7,12E+00	1,20E-06	0,00E+00					4,18E+02		
Maximum											

Ra-226 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Inhalation eman. Rn		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.					
0	9,70E-05	7,98E-06	6,36E-01	3,08E-01	5,96E+00	2,48E-03	3,14E-03	0,00E+00	1,02E-03	0,00E+00	0,00E+00	2,12E-04	2,36E-04	1,76E-05	6,91E+00
1	9,69E-05	7,96E-06	6,35E-01	3,07E-01	5,95E+00	2,48E-03	3,13E-03	4,69E-06	1,02E-03	9,79E-07	8,07E-05	2,21E-04	2,37E-04	1,75E-05	6,90E+00
50	9,24E-05	7,12E-06	6,06E-01	2,94E-01	5,67E+00	4,53E-02	2,84E-03	2,24E-04	9,27E-04	4,85E-05	3,85E-03	2,32E-04	2,48E-04	1,57E-05	6,63E+00
100	8,81E-05	6,34E-06	5,77E-01	2,80E-01	5,40E+00	2,20E-03	2,57E-03	4,26E-04	8,39E-04	9,22E-05	7,31E-03	2,43E-04	2,59E-04	1,40E-05	6,27E+00
200	8,00E-05	4,97E-06	5,25E-01	2,55E-01	4,88E+00	1,94E-03	2,10E-03	7,68E-04	6,86E-04	1,66E-04	1,32E-02	2,58E-04	2,76E-04	1,10E-05	5,68E+00
500	6,01E-05	2,13E-06	3,93E-01	1,90E-01	3,58E+00	1,30E-03	1,05E-08	1,40E-03	4,80E-08	3,04E-04	2,41E-02	2,77E-04	2,96E-04	4,77E-06	4,19E+00
Maximum															

Pb-210 calculations (mSv/y)

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	**Total**
	indoors	outdoors	indoors	outdoors	water indep.	water dep.	water indep.	water dep.					
0	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
1	2,53E-06	2,08E-07	1,10E-05	5,26E-06	1,75E-04	1,62E-06	9,15E-05	3,31E-07	1,19E-05	1,71E-05	2,01E-05	2,30E-06	3,39E-04
50	6,23E-05	4,78E-06	2,69E-04	1,35E-04	4,03E-03	1,86E-03	2,06E-03	4,02E-04	1,36E-02	4,60E-04	5,25E-04	5,28E-05	2,35E-02
100	7,19E-05	5,14E-06	3,11E-04	1,49E-04	4,38E-03	4,00E-03	2,24E-03	8,67E-04	2,92E-02	5,89E-04	6,72E-04	5,69E-05	4,25E-02
200	6,83E-05	4,21E-06	2,95E-04	1,41E-04	3,73E-03	6,92E-03	1,91E-03	1,50E-03	5,06E-02	6,56E-04	7,47E-04	4,67E-05	6,66E-02
500	5,13E-05	1,80E-06	2,22E-04	1,07E-04	1,87E-08	1,18E-02	1,34E-07	2,55E-03	8,59E-02	6,97E-04	7,94E-04	2,03E-05	1,02E-01
Maximum													

Ra-226 calculations (mSv/y)
(sensitivity analysis of indoors Rn dose to vent. rate)

Years	Inhalation eman. Rn		**Total**
	0.5 1/h	1 1/h	
0	5,96E+00	2,33E+00	3,28E+00
1	5,95E+00	2,33E+00	3,28E+00
50	5,67E+00	2,22E+00	3,17E+00
100	5,40E+00	2,11E+00	2,98E+00
200	4,88E+00	1,91E+00	2,71E+00
500	3,58E+00	1,40E+00	2,01E+00

References

[1] YU, C., ET AL., Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil, ANL/EAIS-8, April (1993).

[2] YU, C., ET AL., Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0, ANL/EAD/LD-2, September (1993).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environment, Technical Report No. 364, IAEA, Vienna (1994).

II-2.6. TAMDYN-UV

II-2.6.1. General model description

II-2.6.1.1. Name of model, model developer(s) and model user(s)

Model name:	TAMDYN-UV
Model developer(s):	Bela Kanyár and Árpad Nényei University of Veszprém, Department of Radiochemistry, Veszprém, Hungary
Name of model user:	Bela Kanyár

II-2.6.1.2. Intended purpose of the model in radiation assessment

Taking part in the BIOMASS exercise theme 2 Scenario Olen-B.

II-2.6.1.3. Model type (equilibrium, dynamic, numerical, analytical,...)

Equilibrium, analytical + dynamic, numerical (mixed). The migration (decay, diffusion, leaching, exhalation) in soil is described by dynamic and the processes of root uptake, resuspension, foliar deposition, consumption and dose components by steady state forms, mainly by concentration factors.

II-2.6.1.4. Method used for deriving uncertainty estimates

Monte Carlo and analytical.

II-2.6.1.5. Description of model (procedures, parameters, main equations, scheme)

— *Ra-226 and Pb-210 concentration profiles with depth of the soil*

The concentration profiles of radionuclides have been simulated by a layered soil system, given in Figure II-2.6.1. The model is built in the software ModelMaker4 [3].

According to the figure the Ra concentrations (Ra1, Ra2, Ra3…) have been calculated by the following partial differential equation system:

$$\frac{\partial c(x,t)_{Ra}}{\partial t} = -D_{Ra}\frac{\partial^2 c(x,t)_{Ra}}{\partial x^2} + \left(\lambda_l - \lambda_{Ra}\right)\cdot c(x,t)_{Ra} + \lambda_U \cdot c_U \qquad (1)$$

where:

$c(x,t)_{Ra}$	is the concentration of the Ra-226 nuclide in depth x, at time t ($Bq\cdot kg^{-1}$);
D_{Ra}	is the diffusion coefficient of Ra-226 in the soil ($m^2\cdot y^{-1}$);
c_u	is the background concentration of the U-238 nuclide, it was 20 $Bq\cdot kg^{-1}$;
λ_{Ra}	is the decay constant of Ra-226 (y^{-1});
λ_U	is the decay constant of U-238 (y^{-1});
λ_l	is the leaching coefficient (m/y), according to:

$$\lambda_l = \frac{I \cdot p}{m \cdot (1+\rho) \cdot K_d} \tag{2}$$

where:

I	is the infiltration velocity ($m \cdot y^{-1}$);
p	is the porosity (-);
m	is the moisture (-);
ρ	is the density of the soil ($kg \cdot m^{-3}$);
K_d	is the equilibrium factor of Ra ($m^3 \cdot kg^{-1}$).

The not emanated part of Rn (not_em_Rn1, not_em_Rn2, not_em_Rn3 …) is closed into the solid phase and its whole part is decayed to lead at the place of origin. The emanated part of radon (em_Rn1, em_Rn2, em_Rn3 …) moves to the pore space followed by diffusion and exhalation. During the diffusion it's decaying and in addition increasing from Ra-decay in the proper layer. These processes are written by similar equations as (1).

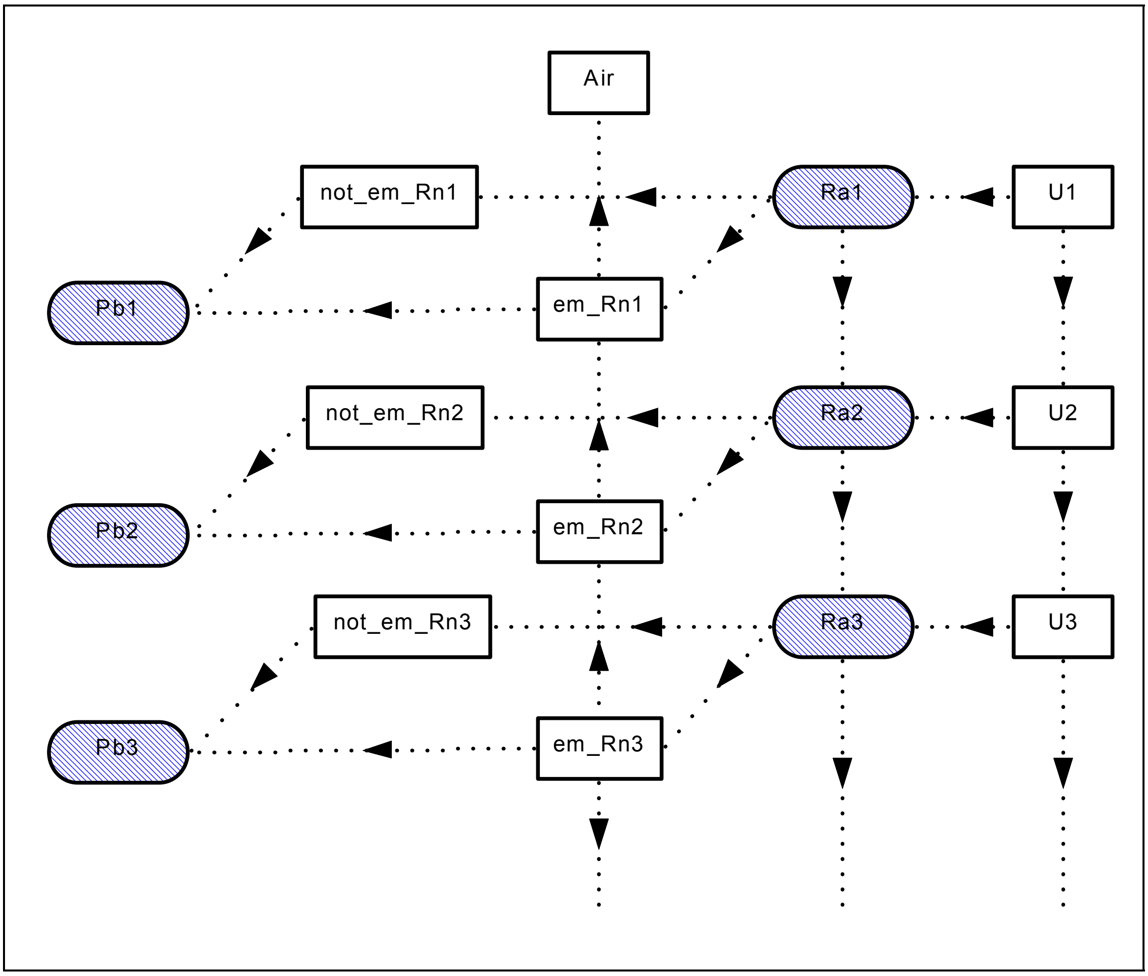


FIG. II-2.6.1. Model of the migration in soil of the radionuclides Ra, Rn and Pb (the Rn is shared into emanated and non-emanated parts).

The distribution of Pb-210 concentration (as a daughter of Rn-222) in soil is derived from the concentration profiles of total Rn-222 in the following way:

$$c_{Pb}(x,t) = \int_{\tau=0}^{t} \left\{ \left[1 - e^{-\lambda_{Pb}\cdot(t-\tau)}\right] \cdot \left[c_{Rn}(x,t-\tau) + c_{Ra}(x,t-\tau)\cdot(1-\varepsilon)\right] \right\} dt \qquad (3)$$

where:

$c(x,t)_{Pb}$	is the concentration of the Pb-210 nuclide in depth x, at the t time ($Bq\cdot kg^{-1}$);
$c(x,t)_{Ra}$	is the concentration of the Ra-226 nuclide in depth x, at the t time ($Bq\cdot kg^{-1}$);
$c(x,t)_{Rn}$	is the concentration of the Rn-222 nuclide in depth x, at the t time ($Bq\cdot kg^{-1}$);
ε	is the emanation coefficient of Rn-222 (-); and
λ_{Pb}	is the decay constant of Pb-210 (y^{-1}).

Practically it means the Pb profile is nearly the same as the Rn one, expect the first years (it needs some time to build up the lead profile). A complete equilibrium between Ra-226 to Pb-210 provides an overestimation of Pb-210, especially at the beginning (1-50) years. In case of remediation (capping by 0.5 m soil) for condition of equilibrium the concentration of Pb should be underestimated in the upper layer. Namely in real situation the lead is provided from the transported radon meanwhile only very small Ra might be observed near the surface.

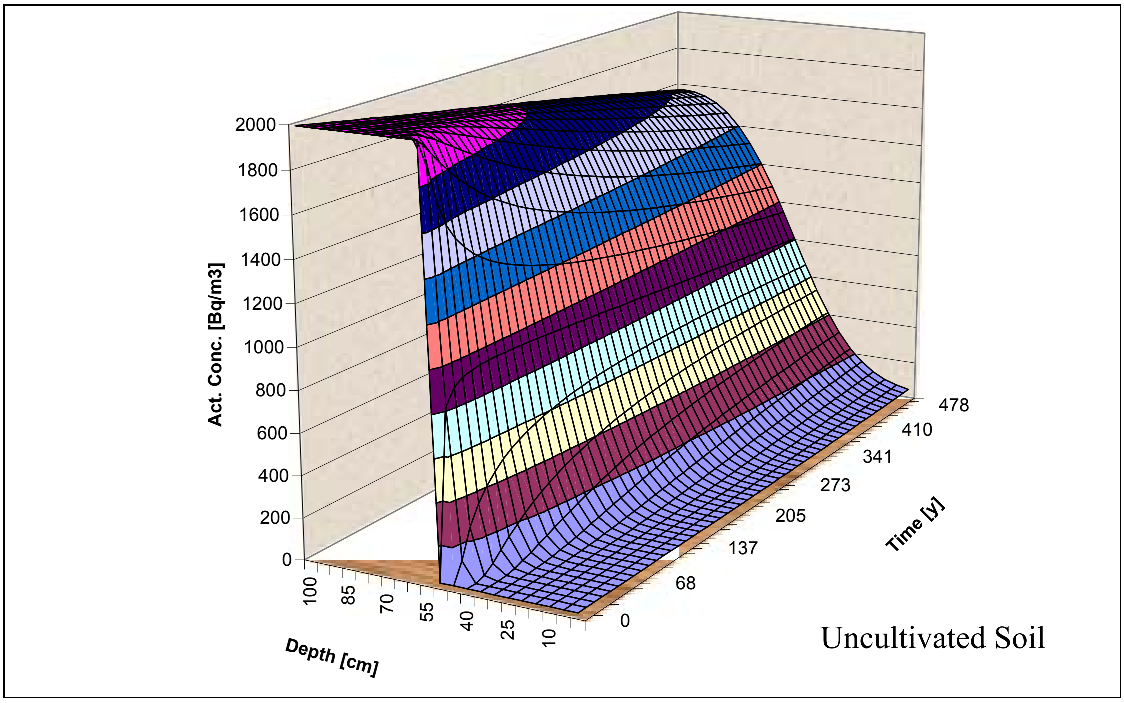
The expression of (3) used in the last simulations takes into consideration the slowly growing of the Pb-210 from Rn-222 and Ra-226 (by the coefficient of $(1-\exp[-\lambda_{Pb}\cdot(t-\tau)])$ and the decay of the Pb-210. The integration with respect to the τ was provided numerically by time step of 1 year.

The partial differential equations are solved numerically by taking 10 cm thick soil layers. The total soil depth simulated was 2.5 m. The source term, namely the initial concentrations of the Ra-226 in the soil layers with different depth were taken from scenario description, as averages from the measured soil samples. The initial values both of Rn-222 and Pb-210 were zero. The action of ploughing has been taking into consideration by averaging the concentrations of the radionuclides in the cultivated layers. The small amount (background) of U-238 – as mother of a small part of Ra - was taken into consideration, too.

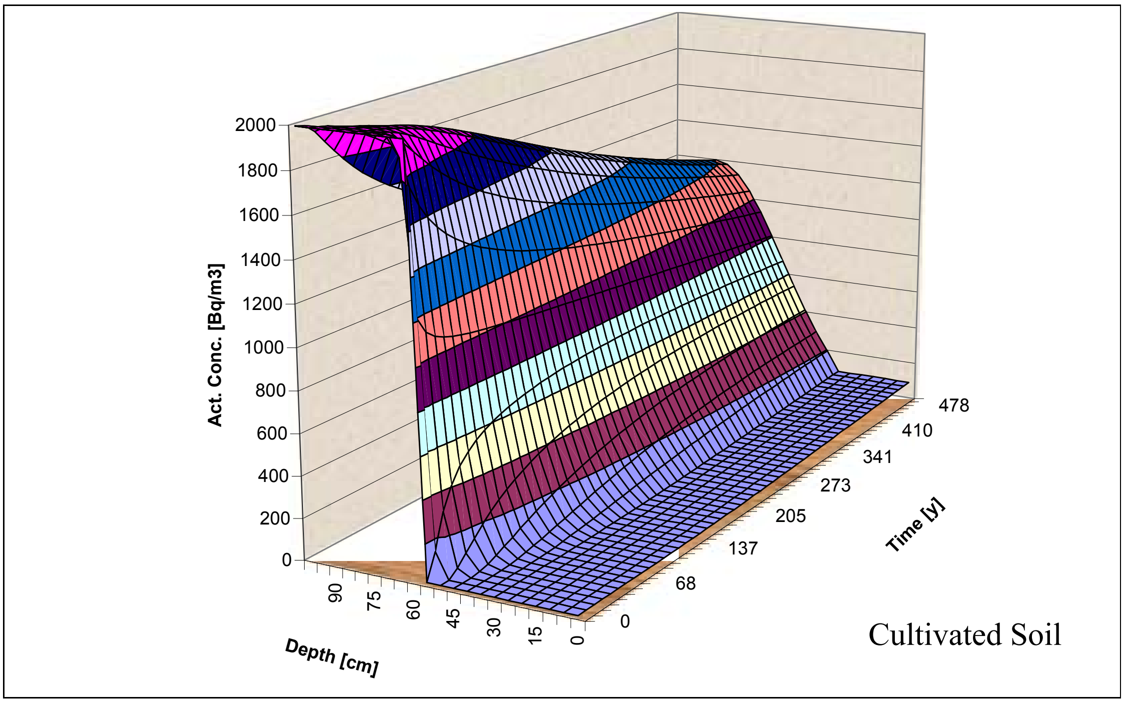
Figure II-2.6.2 shows examples of simulated concentrations of Ra-226 in the soil layers, without and with ploughing.

There are two sources of the Pb-210, first from the emanated and diffused Rn and the second one the not emanated Rn, the last is in equilibrium with Ra-226.

Figure II-2.6.3 gives examples of Ra-226, Rn-222 and Pb-210 concentrations in the soil layers in different conditions.



Uncultivated Soil



Cultivated Soil

FIG. II-2.6.2. Distribution of Ra Concentration Profiles.

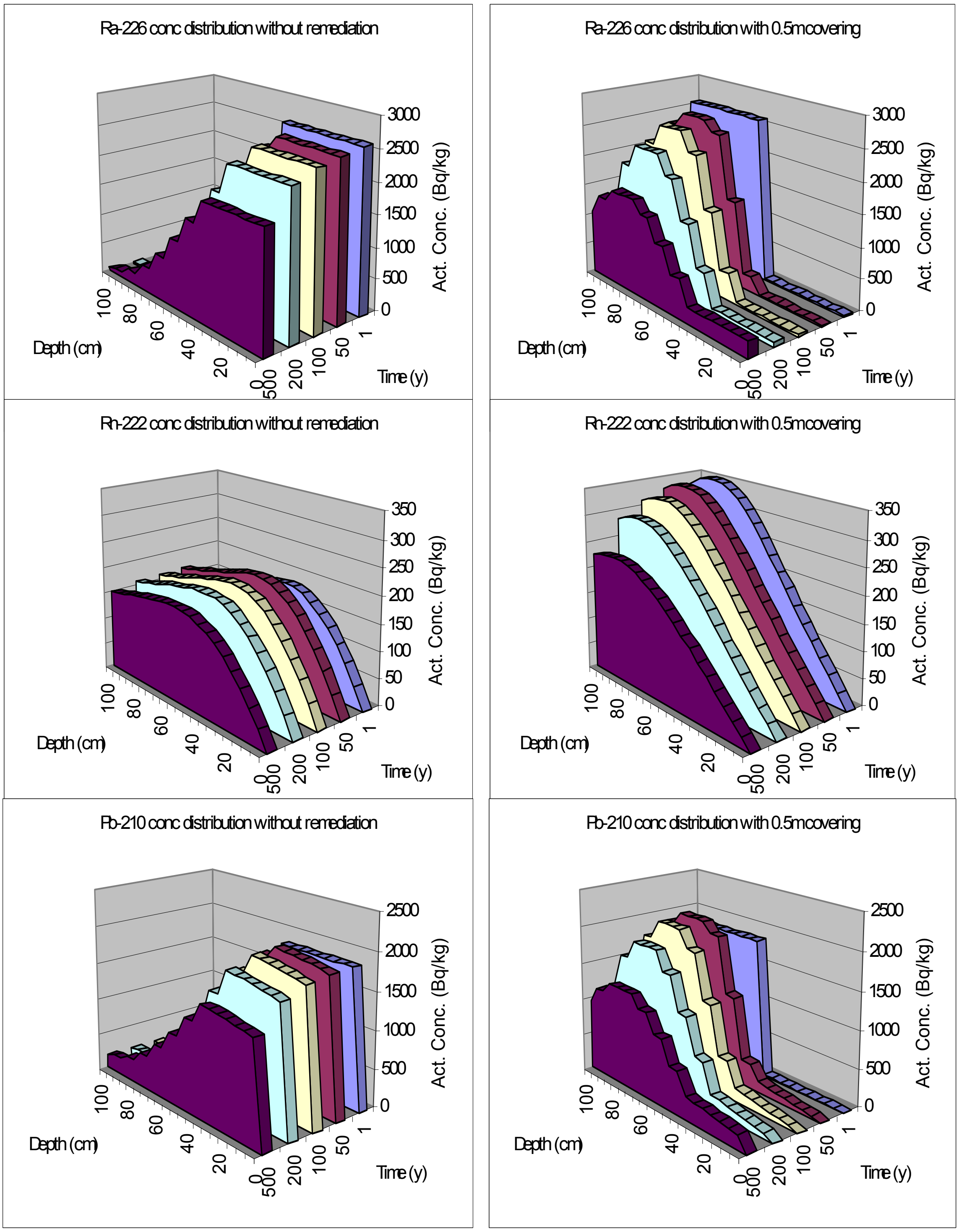


FIG. II-2.6.3. Distribution of Ra, Rn and Pb Concentration Profiles.

— *Rn exhalation*

The steady-state Rn-exhalation was calculated from the Ra-226 concentration in soil. According to the calculations [IAEA TR No. 333, 1992] the Rn-222 exhalation from Ra-226 contaminated soil has been assessed as:

$$F_t = c_{Ra,soil} \cdot \rho \cdot \varepsilon \cdot \sqrt{\lambda_{Rn} \cdot D_{Rn}} \cdot \tanh\left(\sqrt{\frac{\lambda_{Rn}}{D_{Rn}}} \cdot x_t\right) \tag{4}$$

where:

$c_{Ra,soil}$	is the Ra-226 activity concentration in soil (homogenous);
ε	is the emanation (-);
x_t	is the thickness of Ra-226 contaminated soil layer (m);
λ_{Rn}	is the decay constant of Rn-222 (y^{-1});
D_{Rn}	is the diffusion constant of radon in soil ($m^2 \cdot y^{-1}$).

The Rn-flux (exhalation) from the multiple layered soil can be derived as following [1]:

$$F_{t,i} = c_i \cdot \rho_i \cdot \varepsilon_i \cdot \sqrt{\lambda_{Rn} \cdot D_{Rn,i}} \cdot \tanh\left(\sqrt{\frac{\lambda_{Rn}}{D_{Rn,i}}} \cdot x_t\right) \cdot \exp\left[-\sum_{k=1}^{i-1}\left(\sqrt{\frac{\lambda_{Rn}}{D_{Rn,k}}} \cdot x_k\right)\right] \tag{5}$$

and i= 1,2,…N,

where:

x_i	is the thickness of the layer i (m);
N	is the total number of layers.

— *Rn concentration in the room*

Figure II-2.6.4 gives the main pathway of Rn flux into the house (room).

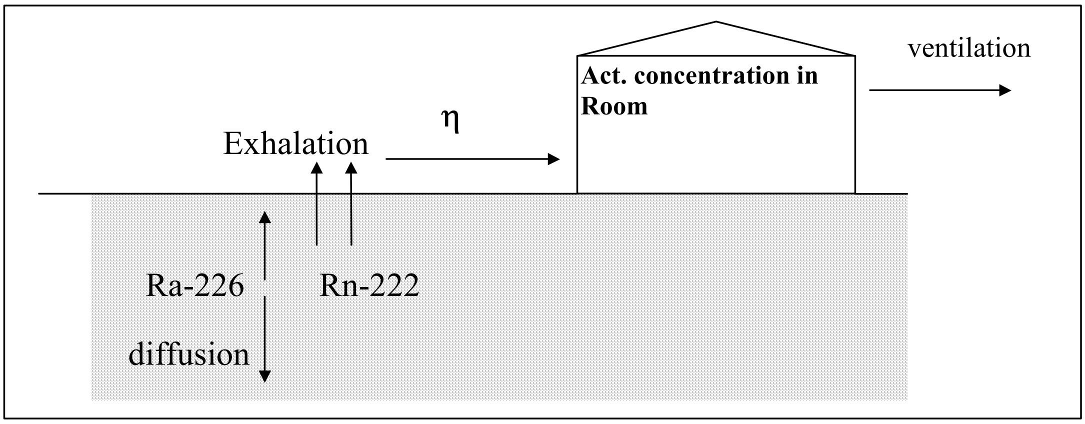


FIG. II-2.6.4. Rn-activity concentration in the room.

The Rn concentration has been derived directly from the soil exhalation by the relation:

$$c_{Rn,in} = \eta . F_t \tag{6}$$

where:

$c_{Rn,in}$ is the Rn-222 concentration in the room ($Bq.m^{-3}$);

η is the factor of exhalation to activity concentration, radon concentration in room due to unit exhalation of Rn-222 ($Bq.m^{-3}$ / $Bq.m^{-2}.y^{-1}$);

F_t is the exhalation from the surface soil ($Bq.m^{-2}.y^{-1}$).

To take into consideration a concrete foundation of the house with thickness of building material x_c the reduced Rn-flux into the room can be estimated as:

$$F_r = F_t. \exp(-(\lambda_{Rn}/D_{Rn-c})^{0.5}.x_c) , \tag{7}$$

where:

D_{Rn-c} means the Rn-diffusion constant in the building material.

According to the scenario description the 1 $kBq.kg^{-1}$ Ra-226 in the soil results radon concentrations:

outdoor: 20 $Bq\cdot m^{-3}$ and
indoor (room): 330 $Bq\cdot m^{-3}$.

These values have been used to estimate the η-factor indoors and outdoors.

From the exhalation expression (form 5) and the indoor/outdoor concentrations of Rn the factors of exhalation to the activity concentration are the following:

$$\eta_{outdoor} = 1.6\cdot 10^{-6} (Bq\cdot m^{-3}) / (Bq\cdot m^{-2}\cdot y^{-1}),$$
$$\eta_{indoor} = 2.6\cdot 10^{-5} (Bq\cdot m^{-3}) / (Bq\cdot m^{-2}\cdot y^{-1}). \tag{8}$$

These values refer to the soil type given in the scenario used on, to annual averages meanwhile no seasonality was taken into consideration. Both η-values are estimated from the condition of 1 m total thick soil layer with 800 $kg\cdot m^3$ density.

— *Ra-226 and Pb-210 concentration in air due to dust*

$$c_{j, air} (Bq\cdot m^{-3}) = \rho_{dust, out air} (kg\cdot m^{-3}) \cdot c_{j,soil} (Bq\cdot kg^{-1}). \tag{9}$$

where:

$c_{j,soil}$ is the activity concentration of j-th radionuclide (Ra or Pb) in soil;

$\rho_{dust, air}$ is the density of dust (soil) in the air outdoor, indoor and agricultivated field.

— *Annual dose due to inhalation of Rn-222/Ra-226/Pb-210 (last two ones due to dust)*

$$E_{inh, in}= I_{inh} \cdot O_{in} \cdot \Sigma_j K_{inh,j} \cdot c_{in,j} , \tag{10}$$

$$E_{inh, out}= I_{inh} \cdot (1-O_{in}) \cdot \Sigma_j K_{inh,j}c_{out,j} . \tag{11}$$

where:

$K_{inh,j}$. is the dose conversion coefficient of radionuclide j, for inhalation, age group dependency (Sv.Bq^{-1});
I_{inh}. is the inhalation rate, age group dependency (m^3·s^{-1});
O_{in}. is the occupancy (-);
$c_{in,j}$, $c_{out,j}$ is the radionuclide concentration indoor and outdoor air (Bq·m^{-3}).

— *Annual dose due to external radiation of Ra-226/Pb-210 in soil*

$$E_{ext}= \sum_j K_{ext,j} \cdot (O_{in}.\Sigma_l S_{in,j,l} \cdot c_{j,l} +(1-O_{in})\cdot \Sigma_l S_{out,j,l} \cdot c_{j,}) , \quad (12)$$

where:

$K_{ext,j}$ is the external dose factor of the jth nuclide (Ra-226 and daughter product: ^{210}Bi; ^{214}Bi; ^{210}Pb; ^{214}Pb; ^{210}Po; ^{214}Po; ^{218}Po; ^{222}Rn), in units Sv·s^{-1}/Bq·kg^{-1});
$S_{in,j,l}$, $S_{out,j,l}$ shielding factors used for external dose from the soil layer, outdoors:

Depth	^{226}Ra	^{210}Pb
0–10 cm	1.0	0.5
10–20 cm	0.5	0.1

and for every additional 0.1 m thick layer 0.25 and 0.05 respectively. Assessed by
the MicroShield software [2].
The indoor has additional shieldings, for ^{226}Ra: 0.25 and ^{210}Pb: 0.05.

$c_{j,l}$ is the concentration of the jth radionuclide (Ra-226 and Pb-210) in the soil layer l (Bq·kg^{-1}).

For the situation no remedial action, the inital values of ^{226}Ra were taken from the soil samples D1-D5, in the scenario description.

For pasture soil (0-100 cm) c = 250 Bq/kg was assessed as an initial average value over the whole pasture area, except for actions when in both cases the initial averages were 150 Bq/kg.

In case of option removal of upper 1 m of the most contaminated soil and refilling by a near one the concentration in the upper 1 m takes 60 Bq·kg^{-1} during the whole period, because ^{226}Ra arising from ^{238}U.

— *Concentration of feed- and foodstuff*

Pasture, leafy vegetables, potatoes

The contamination were provided by simple concentration factors between soil and vegetation in the following way:

$$c_{j,r,veg} = B_{j,r} \cdot c_{j,r,soil} , \quad (13)$$

where:

$c_{j,r,veg}$ is the concentration of the j-th radiocuclide, in r-th vegetation (pasture, leafy vegetation, potatoes), in units of Bq·kg^{-1} (dry weight for pasture, others wet);
$B_{j,r}$ is the bioaccumulation coefficient (-);
$c_{j,r,soil}$ is the activity concentration in soil, for the proper (rth) root zone (Bq·kg^{-1}, dry).

Resuspension and foliar contamination were provided. The air concentration due to resuspension is:

$$c_{air} = c_{soil1} \cdot RF\ ,$$

where c_{soil1} is the activity concentration in the upper soil layer (Bq.kg^{-1}) and RF the resuspension factor (1.10^{-6} kg.m^{-3}). The total deposition rate is the sum of dry (v_{dry},) and wet ones and it has been assessed to 570 m/d, same as for aerosol particles got partly from [4, 5] and scenario description.

Ground- and drinking water

The contamination of the ground water ($c_{gr.w.,j}$, in Bq·m^{-3}), has been derived from the free form of the radionuclide j (for both of Ra-226 and Pb-210) in the deep (at 1 m) soil by:

$$c_{gr.w.,j} = c_{soil,j} / K_d, \tag{14}$$

The concentration of the drinking water is assessed as:

$$c_{dr.w.,j} = \varphi .\ c_{gr.w,j}\ , \tag{15}$$

where φ is less ≤ 1, here was used as 1.

Leafy vegetables and potatoes due to irrigation by groundwater and soil uptake

$$c_{j,veg} = B_j \cdot c_{j,soil} + I_{irr} \cdot c_{gr.w,j} \cdot \omega / (\lambda_{weath} \cdot Y) \tag{16}$$

where:

I_{irr}	is the irrigation rate, ω is the foliar interception (≈0.2) (m/d);
Y	is the yield (kg/m^2);
λ_{wealth}	is the weathering loss constant (1/d).

In garden there has been taken into consideration the atmospheric resuspension and deposition similarly as for pasture.

Milk, beef, eggs etc.

Steady state situation was taken into consideration and the activity concentrations are:

$$c_{j,f} = \Sigma_s F_{j,f} \cdot c_{j,s}\ , \tag{17}$$

where:

$c_{j,f}$	is the the activity concentration of nuclide j, in edible part of foodstuff f (Bq·kg^{-1} or Bq·l^{-1});
$F_{j,f}$:	is the transfer factor of radionuclide j, foodstuff f (d·kg^{-1});
$c_{j,s}$:	is the activity concentration in feeds s (Bq·kg^{-1}, dry).

Annual dose due to ingestion of Ra-226/Pb-210 (soil ingestion, etc)

$$E_{ing} = \Sigma_j K_{ing,j} \cdot \Sigma_k \cdot (I_{ing,k} \cdot c_{k,j}), \tag{18}$$

where:

E_{ing}	is the total ingestion dose due to the all the j-th nuclides ($Sv \cdot y^{-1}$);
$K_{ing,j}$	is the ingestion dose conversion factor for nuclide j ($Sv \cdot Bq^{-1}$);
$I_{ing,k}$	is the ingestion rate of food k (including drinking water and soil) ($kg.y^{-1}$);
$c_{k,j}$	is the activity concentration of the j-th radionuclide in food k, including drinking water and soil ($Bq.kg^{-1}$);
k	is the food types, including drinking water and soil.

II-2.6.2. Stochastic assessments

The stochastic assessment were not performed for the solution of the partial d.e.s. only for assessments defined by the equations 4-17. (from beginning with Rn exhalation, Rn-concentrations indoor, outdoor, concentrations of vegetables, milk, ground water etc.) including radiation doses.

Monte Carlo method has been used to provide uncertainties. Determination coefficients (square of correlations in %) were calculated to assess the contributions of the different parameters to the concentrations, doses etc. Figure II-2.6.5 shows examples on the coefficients in time duration. It is shown that the uncertainty of emanation has the greatest contribution to the uncertainties of the total dose.

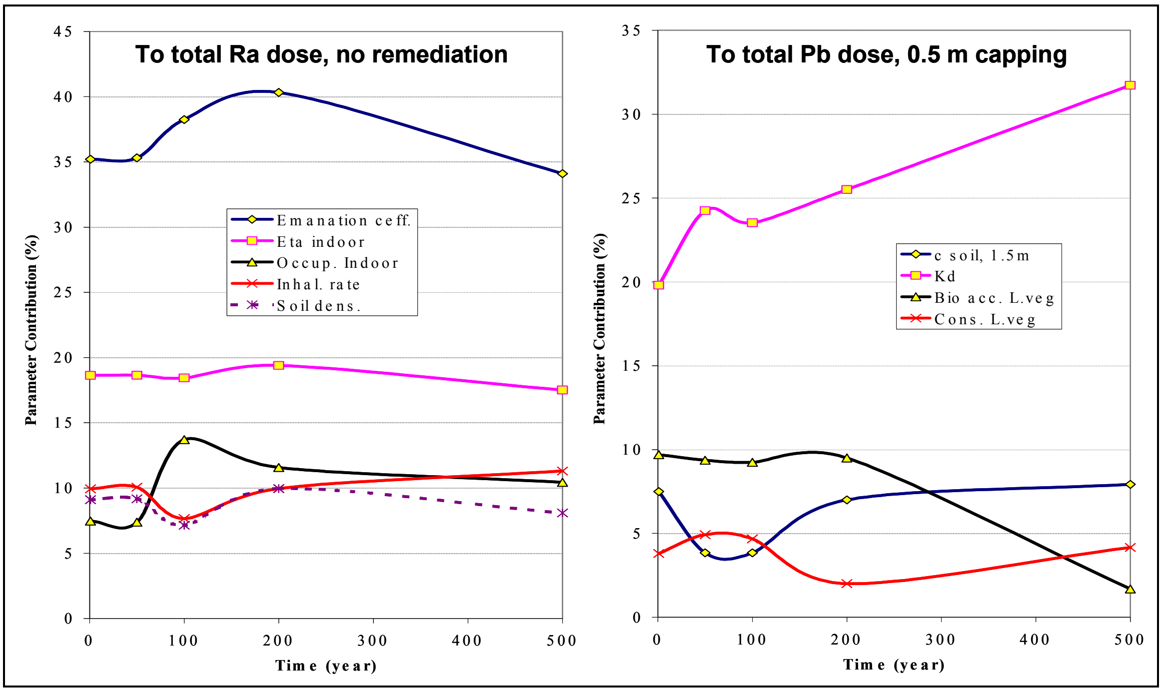


FIG. II-2.6.5. Determination coefficients (contributions) of the uncertainties of parameters to the uncertainties of the total Ra and Pb doses, in %.

II-2.6.3. Remarks

In most of the cases the pathway of Rn inhalation has the largest contribution to the total dose. Therefore the sensitivity of the dose with respect to the parameters emanation and η provide high values.

Mainly due to the many different values to be used both for inputs and got as outputs – and less time for controlling them - we have had many problems with repackaging the results of our outputs to the forms demanded by the scenario descriptions.

Mostly to the having less time for planning the simulations and for need to use 3-4 different soft wares for the work the first results provided were poor with relation to the demanded ones. Later on the calculations and so the results have been extended.

II-2.6.4. Parameter values used in different components of the model

From the description Olen-B scenario, and some additional ones (resuspension, shielding factors etc.) are given in Tables II-2.6.I to II-2.6.V.

TABLE II-2.6.I. RADIONUCLIDE DEPENDENT PARAMETERS

Parameters	Ra-226	Rn-222	Pb-210
λ_r (y^{-1})	4.33e-4	65.6	0.0311
D in soil ($m^2.y^{-1}$)	5.0e-5	63.1	5e-5
K_d in soil ($dm^3.kg^{-1}$)	500	–	270
Emanation in soil, ε (-)	–	0.25	–
$K_{inh,j}$ (Sv/Bq) 2-7 ages	1.9e-5	4.0E-9	1.1e-5
$K_{inh,j}$ (Sv/Bq) adult	9.5e-6	2.5E-9	5.6e-6
$K_{ing,j}$ (Sv/Bq) 2-7 ages	6.2e-7	–	2.2e-6
$K_{ing,j}$ (Sv/Bq) adult	2.8e-7	–	6.9e-7
$B_{j,r}$ (soil-plant) Pasture	0.08	–	0.05
Leafy veg.	0.01	–	0.01
Potatoes	1.5e-3	–	1.0e-3
$F_{j,r}$ (cow tr.) Milk (d/l)	2.0e-4	–	1.5e-4
Beef (d/kg)	5.0e-4	–	4.0e-4
(chicken) eggs (d/kg)	5.0e-4	–	4.0e-4
S, ext. shielding, Outdoor	0.70	–	0.7
Indoor	0.35	–	0.35

TABLE II-2.6.II. RADIONUCLIDE INDEPENDENT PARAMETERS

Parameters		Value
ρ (density) of soil (kg.m^{-3}), after deep plough.		800
Site I		"
Site II		"
Moisture of soil (-)		0.3
Porosity (-)		0.5
ρ (density) of dust in air (kg.m^{-3}) outside		1.0e-7
ζ (dust indoor / outdoor)		0.2
Thickness of root zone layer (m),	Pasture	0.15
	Potatoes, Leafy veg.	0.3
Ventilation of the house (1/h)		0.5
Height of the room, inner (m)		3.0
Pore diffusion coeff. in concrete (m^2/y)		6.3
Porosity of concrete		0.2
Thickness of basement (m)		0.03
Cattle consumption, pasture (kg/d)		12.5
Water (m^3/d)		0.06
θ (soil intake / consumpt., kg/kg dry)		0.04
Poltry consumption (kg/d)		12.5
Water (m^3/d)		0.06
θ (soil intake / consumpt., kg/kg dry)		0.04
Yield of vegetation (kg/m^2 /y)	Pasture (dry)	2.5
	Leafy veg. (fresh)	2
	Potatoes (fresh)	2
Interception of pasture, other veget.,ω (-)		0.2
Irrigation time (d)		100
Irrigation rate, I_{irr} (m/d)		1.0e-3
φ (concentr. of drinking w. / ground water)		0.5
λ_{weath}(1/d)		0.023
RF Resuspension Factor of soil average (Bq·kg^{-3} / kg)		1.0e-6
η C_{Rn} from exhalation (Bq.m^{-3} / Bq.m^{-2}.y^{-1}),	indoor	2.6 e-6
	outdoor	1.6e-6

TABLE II-2.6.III. AGE-DEPENDENT PARAMETERS

Parameters		2–7 ages	Adult
I_{inh} (m^3.h^{-1}) outdoor		0.82	1.2 (1.05e4 m^3/y)
I_{inh} (m^3.h^{-1}) indoor		0.62	0.9 (0.79e4 m^3/y)
Occupation factor		0.91	0.80
Soil intake (kg/d)		2.5e-4	7.0e-5 (0.26 kg/y)
Consumpt. r.,	Milk(kg/y)	145	137
	Meat	21	54
	Leafy veg.	34	56
	Potatoes	49	122
	Poultry	2.5	8.2
	Cereals (flour)	40	81
	Eggs	18	18

TABLE II-2.6.IV. RADIONUCLIDE DEPENDENT PARAMETER VALUES USED FOR UNCERTAINTY ANALYSIS

Parameter	Ra-226		Rn-222		Pb-210	
	Mean	Range/pfd	Mean	Range	Mean	Range
Diffusion coeff. in soil (m^2/y)	1.0E-05	(0.2–5)E-05 triangular	63.1	20–200 triangular	5E-06	(0.1–2)E-05 triangular
K_d in soil (m^3/kg)	0.5	0.05–5 loguniform	/	/	0.27	0.025–2.5 loguniform
Soil-to-plant TF						
pasture (dw/dw)	0.08	(1–30)E-02	/	/	0.05	0.02–0.2
leafy veg. (dw/fw)	0.01	(0.1–10)E-02	/	/	0.01	(3–20)E-03
potatoes (dw/fw)	1.5E-03	(0.2–15)E-03 logtriangular	/	/	1E-03	(0.3–3)E-03 triangular
Grass-to-milk TF (d/l)	2.0E-04	(0.5–10)E-04 triangular	/	/	1.5E-04	(0.5–10)E-04 triangular
Grass-to-beef TF (d/kg)	5.0E-04	(0.1–2)E-03 logtriangular	/	/	4.0E-04	(1–10)E-04 triangular
Translocation factor potatoes	0.1	0.001–0.15 logtriangular	/	/	0.1	0.001–0.15 logtriangular

TABLE II-2.6.V. RADIONUCLIDE INDEPENDENT PARAMETER VALUES USED FOR UNCERTAINTY ANALYSIS

Parameters	Mean	Range/pdf
Daily uptake of pasture by cattle (kg dw/d)	12.5	10–15 triangular
Daily uptake water by cow (m^3/d)	0.06	0.04–0.08 uniform
Fractional uptake of soil by cattle (kg dw/kg dw pasture)	0.04	0.01–0.1 triangular
Yield of vegetation ($kg/m^2/y$)		
Leafy vegetables (fresh)	2	0.8–4.0
Potatoes (fresh)	2	0.8–4.0 triangular
Consumption rate of drinking water (l/y)	400	180-890 triangular
Intake rate of soil (mg/y)	50	20-110

II-2.6.5. Results of model predictions

Deterministic calculations (Univ. Veszprem, H)

1. Concentrations in the different compartments (Situation I)

1. Without remedial action

	Ra-226 concentration															Rn-222 concentration	
	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)	(Bq/m3)	
Years	pasture	garden	farm	indoors	outdoors	outdoors agric	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake				indoors	outdoors
1	2,50E+02	2,59E+03	2,59E+03	3,88E-05	7,77E-05	2,50E-05	2,00E+01	1,17E-02	3,88E+00	4,06E-02	2,59E+01	3,25E-01	6,00E+01	7,57E-02	1,89E-01	3,68E+02	2,26E+01
50	2,35E+02	2,44E+03	2,44E+03	3,65E-05	7,31E-05	2,35E-05	1,88E+01	1,10E-02	3,65E+00	4,02E-02	2,44E+01	3,21E-01	6,00E+01	7,12E-02	1,78E-01	3,62E+02	2,23E+01
100	2,20E+02	2,28E+03	2,28E+03	3,42E-05	6,84E-05	2,20E-05	1,76E+01	1,03E-02	3,42E+00	3,97E-02	2,28E+01	3,17E-01	6,00E+01	6,67E-02	1,67E-01	3,57E+02	2,19E+01
200	2,00E+02	2,00E+03	2,00E+03	3,00E-05	5,99E-05	2,00E-05	1,60E+01	9,36E-03	3,00E+00	4,97E-02	2,00E+01	3,97E-01	8,00E+01	6,10E-02	1,52E-01	3,45E+02	2,12E+01
500	1,50E+02	1,36E+03	1,36E+03	2,04E-05	4,08E-05	1,50E-05	1,20E+01	7,02E-03	2,04E+00	2,76E-01	1,36E+01	2,21E+00	5,00E+02	5,10E-02	1,28E-01	3,10E+02	1,91E+01
Maxim	2,50E+02	2,59E+03	2,59E+03	3,88E-05	7,77E-05	2,50E-05	2,00E+01	1,17E-02	3,88E+00	2,76E-01	2,59E+01	2,21E+00	5,00E+02	7,57E-02	1,89E-01	3,68E+02	2,26E+01

Maximum = optional

	Pb-210 concentration														
	Soil (Bq/kg)			Inhalable dust (Bq/m3)			Grass (Bq/kg)		Potatoes (Bq/kg)		Leafy vegetables (Bq/kg)		Ground Water (Bq/m3)	Milk (Bq/l)	Meat (Bq/kg)
Years	pasture	garden	farm	indoors	outdoors	outdoors agricult	root uptake	foliar uptake	root uptake	foliar uptake	root uptake	foliar uptake			
1	2,00E+02	1,98E+03	1,99E+03	2,97E-05	5,93E-05	2,00E-05	1,00E+01	9,36E-03	1,98E+00	1,37E-01	1,98E+01	1,10E+00	2,41E+02	3,59E-02	9,58E-02
50	1,90E+02	1,86E+03	1,87E+03	2,79E-05	5,59E-05	1,90E-05	9,50E+00	8,89E-03	1,86E+00	1,43E-01	1,86E+01	1,14E+00	2,52E+02	3,43E-02	9,15E-02
100	1,80E+02	1,74E+03	1,75E+03	2,62E-05	5,23E-05	1,80E-05	9,00E+00	8,42E-03	1,74E+00	1,46E-01	1,74E+01	1,17E+00	2,59E+02	3,27E-02	8,72E-02
200	1,60E+02	1,53E+03	1,54E+03	2,30E-05	4,60E-05	1,60E-05	8,00E+00	7,49E-03	1,53E+00	1,70E-01	1,53E+01	1,36E+00	3,04E+02	2,97E-02	7,93E-02
500	1,40E+02	1,05E+03	1,06E+03	1,58E-05	3,15E-05	1,40E-05	7,00E+00	6,55E-03	1,05E+00	5,21E-01	1,05E+01	4,16E+00	9,52E+02	3,22E-02	8,58E-02
Maxim	2,00E+02	1,98E+03	1,99E+03	2,97E-05	5,93E-05	2,00E-05	1,00E+01	9,36E-03	1,98E+00	5,21E-01	1,98E+01	4,16E+00	9,52E+02	3,59E-02	9,58E-02

Maximum = optional

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

	Ra-226 concentration				Pb-226 concentration			
	Soil (Bq/kg)			Ground Water (Bq/m3)	Soil (Bq/kg)			Ground Water (Bq/m3)
Years	pasture	garden	farm		pasture	garden	farm	
1	1,50E+02	6,00E+01	6,00E+01	6,00E+01	1,10E+02	4,60E+01	4,60E+01	1,85E+02
50	1,40E+02	5,60E+01	5,60E+01	6,00E+01	1,03E+02	4,35E+01	4,40E+01	1,81E+02
100	1,35E+02	5,20E+01	5,40E+01	7,00E+01	9,50E+01	4,05E+01	4,10E+01	1,81E+02
200	1,20E+02	4,60E+01	4,60E+01	8,00E+01	8,50E+01	3,60E+01	3,63E+01	1,81E+02
500	9,00E+01	3,10E+01	3,10E+01	1,00E+02	6,50E+01	2,45E+01	2,50E+01	1,81E+02
Maxim	1,50E+02	6,00E+01	6,00E+01	1,00E+02	1,10E+02	4,60E+01	4,60E+01	1,85E+02

Maximum = optional

3. After implementing of remedial action 2 (covering with 0.5 m clean soil layer - option 2a)
Soil type (% clay content): loam (20 % (range 15 - 30%) clay)
Ra-226 co Pb-210 concentration

	Ra-226 concentration				Pb-226 concentration			
	Soil (Bq/kg)			Ground Water (Bq/m3)	Soil (Bq/kg)			Ground Water (Bq/m3)
Years	pasture	garden	farm		pasture	garden	farm	
1	1,50E+02	2,00E+01	2,00E+01	3,00E+01	1,10E+02	3,90E+01	4,70E+01	1,92E+02
50	1,35E+02	1,90E+01	1,90E+01	3,00E+01	1,03E+02	3,80E+01	4,60E+01	1,96E+02
100	1,20E+02	1,90E+01	1,90E+01	3,00E+01	9,50E+01	3,70E+01	4,47E+01	2,02E+02
200	1,10E+02	1,80E+01	1,80E+01	4,00E+01	8,50E+01	3,55E+01	4,30E+01	2,24E+02
500	9,00E+01	1,80E+01	1,80E+01	2,53E+02	6,50E+01	3,35E+01	4,00E+01	5,74E+02
Maxim	1,50E+02	2,00E+01	2,00E+01	2,53E+02	1,10E+02	3,90E+01	4,70E+01	5,74E+02

Maximum = optional

2. Individual doses for an adult (mSv/y) for Olen site (Situation I)

1. Without remedial action

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation exhal. Rn		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	Total Dose
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake					
1	1,94E-03	2,21E-04	1,67E+00	1,72E+00	6,95E+00	1,71E-01	4,06E-01	5,10E-03	1,33E-01	1,39E-03	6,72E-03	2,78E-03	2,86E-03	1,31E-02	1,11E+01
50	1,82E-03	2,08E-04	1,58E+00	1,62E+00	6,85E+00	1,69E-01	3,82E-01	5,04E-03	1,25E-01	1,37E-03	6,72E-03	2,61E-03	2,69E-03	1,23E-02	1,08E+01
100	1,70E-03	1,95E-04	1,48E+00	1,52E+00	6,74E+00	1,66E-01	3,57E-01	4,98E-03	1,17E-01	1,36E-03	6,72E-03	2,45E-03	2,52E-03	1,15E-02	1,04E+01
200	1,49E-03	1,71E-04	1,31E+00	1,35E+00	6,52E+00	1,60E-01	3,13E-01	6,23E-03	1,02E-01	1,70E-03	8,96E-03	2,24E-03	2,30E-03	1,01E-02	9,78E+00
500	1,02E-03	1,16E-04	9,07E-01	9,33E-01	5,86E+00	1,44E-01	2,13E-01	3,46E-02	6,97E-02	9,43E-03	5,60E-02	1,87E-03	1,93E-03	6,85E-03	8,24E+00
Maxim	1,94E-03	2,21E-04	1,67E+00	1,72E+00	6,95E+00	1,71E-01	4,06E-01	3,46E-02	1,33E-01	9,43E-03	5,60E-02	2,78E-03	2,86E-03	1,31E-02	1,11E+01

Maximum = optional

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	Total Dose
	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake					
1	8,72E-04	9,97E-05	4,60E-05	2,36E-04	7,64E-01	4,23E-02	1,67E-01	1,15E-02	6,64E-02	3,25E-03	3,57E-03	2,44E-02	1,08E+00
50	8,22E-04	9,39E-05	4,33E-05	2,23E-04	7,20E-01	4,41E-02	1,57E-01	1,20E-02	6,95E-02	3,10E-03	3,41E-03	2,30E-02	1,03E+00
100	7,69E-04	8,79E-05	4,05E-05	2,08E-04	6,74E-01	4,52E-02	1,47E-01	1,23E-02	7,16E-02	2,96E-03	3,25E-03	2,15E-02	9,79E-01
200	6,76E-04	7,72E-05	3,56E-05	1,83E-04	5,92E-01	5,25E-02	1,29E-01	1,43E-02	8,38E-02	2,69E-03	2,95E-03	1,89E-02	8,97E-01
500	4,64E-04	5,30E-05	2,44E-05	1,25E-04	4,06E-01	1,61E-01	8,85E-02	4,38E-02	2,63E-01	2,91E-03	3,20E-03	1,29E-02	9,82E-01
Maxim	8,72E-04	9,97E-05	4,60E-05	2,36E-04	7,64E-01	1,61E-01	1,67E-01	4,38E-02	2,63E-01	3,25E-03	3,57E-03	2,44E-02	1,08E+00

Maximum = optional

2. After implementing of remedial action 1 (removal of most contaminated soil - option 1a)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation exhal. Rn		Leafy vegetables		Potatoes		Drinking water	Milk	Meat	Soil ingestion	Total Dose
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake					
1	4,49E-05	5,13E-06	3,87E-02	3,98E-02	2,47E-01	6,07E-03	9,41E-03	4,11E-03	3,07E-03	1,12E-03	6,72E-03	1,68E-03	1,73E-03	3,02E-04	3,59E-01
50	4,19E-05	4,79E-06	3,63E-02	3,74E-02	2,40E-01	5,90E-03	8,78E-03	4,11E-03	2,87E-03	1,12E-03	6,72E-03	1,57E-03	1,61E-03	2,82E-04	3,46E-01
100	3,89E-05	4,45E-06	3,45E-02	3,55E-02	2,37E-01	5,83E-03	8,15E-03	4,79E-03	2,66E-03	1,31E-03	7,84E-03	1,52E-03	1,56E-03	2,62E-04	3,41E-01
200	3,44E-05	3,93E-06	3,03E-02	3,11E-02	2,22E-01	5,46E-03	7,21E-03	5,47E-03	2,36E-03	1,49E-03	8,96E-03	1,36E-03	1,40E-03	2,32E-04	3,17E-01
500	2,32E-05	2,65E-06	2,08E-02	2,14E-02	1,84E-01	4,53E-03	4,86E-03	6,83E-03	1,59E-03	1,86E-03	1,12E-02	1,03E-03	1,07E-03	1,56E-04	2,60E-01
Maxim	4,49E-05	5,13E-06	3,87E-02	3,98E-02	2,47E-01	6,07E-03	9,41E-03	6,83E-03	3,07E-03	1,86E-03	1,12E-02	1,68E-03	1,73E-03	3,02E-04	3,59E-01

Maximum = optional

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking	Milk	Meat	Soil	Total
	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake	water			ingestion	Dose
1	2,03E-05	2,32E-06	1,07E-06	5,52E-06	1,78E-02	3,12E-02	3,87E-03	8,48E-03	5,11E-02	1,83E-03	2,01E-03	5,71E-04	1,17E-01
50	1,92E-05	2,19E-06	1,01E-06	5,17E-06	1,68E-02	3,05E-02	3,66E-03	8,31E-03	5,01E-02	1,72E-03	1,89E-03	5,34E-04	1,14E-01
100	1,79E-05	2,04E-06	9,36E-07	4,81E-06	1,56E-02	3,05E-02	3,41E-03	8,31E-03	5,01E-02	1,60E-03	1,76E-03	4,97E-04	1,12E-01
200	1,59E-05	1,81E-06	8,40E-07	4,32E-06	1,39E-02	3,05E-02	3,03E-03	8,31E-03	5,01E-02	1,44E-03	1,59E-03	4,47E-04	1,09E-01
500	1,08E-05	1,23E-06	5,63E-07	2,89E-06	9,47E-03	3,05E-02	2,06E-03	8,31E-03	5,01E-02	1,14E-03	1,25E-03	2,98E-04	1,03E-01
Maxim	2,03E-05	2,32E-06	1,07E-06	5,52E-06	1,78E-02	3,12E-02	3,87E-03	8,48E-03	5,11E-02	1,83E-03	2,01E-03	5,71E-04	1,17E-01

Maximum = optional

3. After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)
Soil type (% clay content): loam (20 % (range 15 - 30%) clay)

Ra-226 calculations

Years	Inhalation dust		External irradiation		Inhalation exhal. Rn		Leafy vegetables		Potatoes		Drinking	Milk	Meat	Soil	Total
	indoors	outdoors	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake	water			ingestion	Dose
1	1,50E-05	1,71E-06	1,31E-02	1,35E-02	4,84E+00	1,19E-01	3,14E-03	2,05E-03	1,02E-03	5,59E-04	3,36E-03	1,66E-03	1,71E-03	1,01E-04	5,00E+00
50	1,42E-05	1,62E-06	1,44E-02	1,48E-02	4,59E+00	1,13E-01	2,98E-03	2,05E-03	9,74E-04	5,59E-04	3,36E-03	1,50E-03	1,54E-03	9,58E-05	4,74E+00
100	1,42E-05	1,62E-06	1,57E-02	1,62E-02	4,32E+00	1,06E-01	2,98E-03	2,05E-03	9,74E-04	5,59E-04	3,36E-03	1,33E-03	1,37E-03	9,58E-05	4,47E+00
200	1,35E-05	1,54E-06	1,62E-02	1,67E-02	3,80E+00	9,35E-02	2,82E-03	2,73E-03	9,22E-04	7,45E-04	4,48E-03	1,23E-03	1,27E-03	9,07E-05	3,94E+00
500	1,35E-05	1,54E-06	1,56E-02	1,60E-02	2,53E+00	6,23E-02	2,82E-03	1,73E-02	9,22E-04	4,70E-03	2,83E-02	1,10E-03	1,14E-03	9,07E-05	2,68E+00
Maxim	1,50E-05	1,71E-06	1,62E-02	1,67E-02	4,84E+00	1,19E-01	3,14E-03	1,73E-02	1,02E-03	4,70E-03	2,83E-02	1,66E-03	1,71E-03	1,01E-04	5,00E+00

Maximum = optional

Pb-210 calculations

Years	Inhalation dust		External irradiation		Leafy vegetables		Potatoes		Drinking	Milk	Meat	Soil	Total
	indoors	outdoors	indoors	outdoors	root uptake	foliar uptake	root uptake	foliar uptake	water			ingestion	Dose
1	1,72E-05	1,97E-06	7,65E-07	3,93E-06	1,51E-02	3,23E-02	3,28E-03	8,79E-03	5,30E-02	1,83E-03	2,02E-03	3,85E-04	1,17E-01
50	1,68E-05	1,92E-06	7,42E-07	3,81E-06	1,47E-02	3,30E-02	3,20E-03	8,97E-03	5,41E-02	1,73E-03	1,90E-03	3,73E-04	1,18E-01
100	1,63E-05	1,86E-06	7,18E-07	3,69E-06	1,43E-02	3,40E-02	3,11E-03	9,25E-03	5,58E-02	1,61E-03	1,77E-03	3,60E-04	1,20E-01
200	1,57E-05	1,79E-06	6,93E-07	3,56E-06	1,37E-02	3,77E-02	2,99E-03	1,03E-02	6,18E-02	1,48E-03	1,63E-03	3,48E-04	1,30E-01
500	1,48E-05	1,69E-06	6,64E-07	3,42E-06	1,29E-02	9,65E-02	2,82E-03	2,63E-02	1,58E-01	1,46E-03	1,60E-03	3,35E-04	3,00E-01
Maxim	1,72E-05	1,97E-06	7,65E-07	3,93E-06	1,51E-02	9,65E-02	3,28E-03	2,63E-02	1,58E-01	1,83E-03	2,02E-03	3,85E-04	3,00E-01

Maximum = optional

Characters Kd: 1,0 dm3,kg-1 (local soil: 0,5)
Pb Kd: 0,5 dm3,kg-1 (local soil: 0,27)
Density of soil: 1,1 kg,dm-3 (local: 0,8),

Stochastic model calculations

Individual doses for adult (mSv/y) for Olen site (Situation I)

1. Without remedial action

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	3,17E-03	7,69E-04	7,32E-03	3,82E-04	8,21E-05	9,47E-04	1,70E+00	1,08E+00	2,42E+00	1,99E+00	9,83E-01	3,21E+00
100	3,07E-03	6,99E-04	6,98E-03	3,53E-04	7,85E-05	9,97E-04	1,64E+00	1,03E+00	2,33E+00	1,96E+00	9,56E-01	3,14E+00
500	1,86E-03	4,31E-04	4,39E-03	2,20E-04	4,53E-05	5,78E-04	9,96E-01	6,24E-01	1,44E+00	1,18E+00	5,94E-01	1,88E+00
Maxim	3,17E-03	7,69E-04	7,32E-03	3,82E-04	8,21E-05	9,97E-04	1,70E+00	1,08E+00	2,42E+00	1,99E+00	9,83E-01	3,21E+00

Maximum = optional

Pb-210 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	1,66E-03	3,61E-04	4,09E-03	1,96E-04	4,31E-05	4,80E-04	5,28E-05	2,79E-05	8,79E-05	3,16E-04	1,37E-04	5,63E-04
100	1,43E-03	3,05E-04	3,26E-03	1,64E-04	3,43E-05	4,65E-04	4,69E-05	2,40E-05	7,86E-05	2,81E-04	1,23E-04	5,11E-04
500	9,00E-04	2,09E-04	2,10E-03	1,07E-04	2,20E-05	2,81E-04	3,00E-05	1,83E-05	4,54E-05	1,77E-04	8,95E-05	2,98E-04
Maxim	1,66E-03	3,61E-04	4,09E-03	1,96E-04	4,31E-05	4,80E-04	5,28E-05	2,79E-05	8,79E-05	3,16E-04	1,37E-04	5,63E-04

Maximum = optional

Ra-226 calculations (Without remedial action)

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limi	Upper limit
1	9,26E+00	2,57E+00	2,17E+01	2,45E-01	6,18E-02	6,36E-01	7,56E-01	7,70E-02	3,22E+00	1,81E-02	8,38E-04	9,02E-02	1,63E-02	6,98E-04	7,24E-02
100	9,95E+00	2,61E+00	2,52E+01	2,63E-01	6,14E-02	6,43E-01	7,61E-01	7,31E-02	3,03E+00	1,82E-02	1,07E-03	9,81E-02	1,74E-02	7,18E-04	7,75E-02
500	8,59E+00	2,41E+00	2,05E+01	2,25E-01	5,04E-02	5,59E-01	4,32E-01	4,01E-02	1,76E+00	1,18E-01	2,85E-03	6,38E-01	1,23E-01	5,14E-03	5,70E-01
Maxim	9,95E+00	2,61E+00	2,52E+01	2,63E-01	6,18E-02	6,43E-01	7,61E-01	7,70E-02	3,22E+00	1,18E-01	2,85E-03	6,38E-01	1,23E-01	5,14E-03	5,70E-01

Maximum = optional

Pb-210 calculations

	Leafy vegetables						Drinking water		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	7,82E+00	7,50E-01	2,26E+01	1,79E-01	5,18E-03	9,72E-01	1,82E-01	8,08E-03	8,29E-01
100	6,87E+00	7,27E-01	2,09E+01	2,00E-01	5,63E-03	1,13E+00	2,04E-01	7,85E-03	9,22E-01
500	4,12E+00	4,37E-01	1,20E+01	6,60E-01	1,45E-02	3,61E+00	6,89E-01	2,78E-02	3,27E+00
Maxim	7,82E+00	7,50E-01	2,26E+01	6,60E-01	1,45E-02	3,61E+00	6,89E-01	2,78E-02	3,27E+00

Maximum = optional

Ra-226 calculations (Without remedial action)

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,30E-01	2,55E-02	8,45E-01	1,44E-03	1,24E-05	1,05E-02	7,48E-03	1,08E-03	2,55E-02	4,38E-03	5,94E-04	1,46E-02	2,56E-02	6,98E-03	5,59E-02
100	2,26E-01	2,54E-02	8,77E-01	1,44E-03	1,44E-05	1,08E-02	6,58E-03	1,01E-03	2,17E-02	3,98E-03	5,47E-04	1,31E-02	2,52E-02	6,83E-03	5,59E-02
500	1,34E-01	1,54E-02	5,29E-01	1,01E-02	5,81E-05	7,72E-02	6,34E-03	8,95E-04	2,06E-02	3,76E-03	4,95E-04	1,25E-02	1,49E-02	4,06E-03	3,60E-02
Maxim	2,30E-01	2,55E-02	8,77E-01	1,01E-02	5,81E-05	7,72E-02	7,48E-03	1,08E-03	2,55E-02	4,38E-03	5,94E-04	1,46E-02	2,56E-02	6,98E-03	5,59E-02

Maximum = optional

Pb-210 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,93E-01	8,92E-02	6,81E-01	1,39E-02	1,13E-04	9,81E-02	1,73E-02	2,35E-03	5,60E-02	9,66E-03	2,01E-03	2,67E-02	5,49E-02	1,26E-02	1,23E-01
100	2,59E-01	7,31E-02	6,03E-01	1,58E-02	9,77E-05	1,21E-01	1,62E-02	2,66E-03	5,00E-02	9,21E-03	1,90E-03	2,50E-02	4,91E-02	1,24E-02	1,15E-01
500	1,59E-01	4,97E-02	3,50E-01	5,63E-02	3,21E-04	4,22E-01	1,93E-02	2,44E-03	6,81E-02	1,07E-02	1,99E-03	3,00E-02	3,15E-02	8,95E-03	7,16E-02
Maxim	2,93E-01	8,92E-02	6,81E-01	5,63E-02	3,21E-04	4,22E-01	1,93E-02	2,66E-03	6,81E-02	1,07E-02	2,01E-03	3,00E-02	5,49E-02	1,26E-02	1,23E-01

Maximum = optional

Total dose: (Without remedial action)

Ra-226 calculations

1 y			100 y			500 y			Maximum (optional)		
	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1,43E+01	6,91E+00	2,75E+01	1,49E+01	6,58E+00	3,02E+01	1,18E+01	4,91E+00	2,38E+01	1,43E+01	6,91E+00	2,75E+01

Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
8,58E+00	1,27E+00	2,33E+01	7,62E+00	1,16E+00	2,21E+01	5,75E+00	1,06E+00	1,47E+01	8,58E+00	1,27E+00	2,33E+01

Ra-226 & Pb-210 calculations

1 y			100 y			500 y			Maximum (optional)		
95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
2,28E+01	7,03E+00	3,60E+01	2,25E+01	6,68E+00	3,74E+01	1,76E+01	5,02E+00	2,80E+01	2,28E+01	7,03E+00	3,60E+01

2, After implementing of remedial action 2 (covering with 0,5 m clean soil layer - option 2a)

Soil type (% clay content): loam (20 % (range 15 - 30%) clay)

Ra-226 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	3,24E-05	6,81E-06	8,04E-05	3,81E-06	8,23E-07	9,61E-06	1,68E-02	9,72E-03	2,59E-02	2,01E-02	9,54E-03	3,41E-02
100	3,09E-05	7,49E-06	7,58E-05	3,67E-06	7,73E-07	1,04E-05	2,00E-02	1,16E-02	2,99E-02	2,36E-02	1,13E-02	3,89E-02
500	3,16E-05	7,35E-06	7,73E-05	3,59E-06	6,82E-07	9,81E-06	2,06E-02	1,26E-02	3,09E-02	2,43E-02	1,16E-02	4,06E-02
Maxim	3,24E-05	7,49E-06	8,04E-05	3,81E-06	8,23E-07	1,04E-05	2,06E-02	1,26E-02	3,09E-02	2,43E-02	1,16E-02	4,06E-02

Maximum = optional

Pb-210 calculations

	Inhalation of dust (optional)						External irradiation					
	indoors	95% confidence interval		outdoors	95% confidence interval		indoors	95% confidence interval		outdoors	95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	4,78E-05	1,07E-05	1,28E-04	5,70E-06	1,07E-06	1,65E-05	1,77E-06	4,90E-07	3,84E-06	1,05E-05	2,48E-06	2,50E-05
100	3,88E-05	8,51E-06	9,62E-05	4,39E-06	8,31E-07	1,24E-05	1,11E-06	4,37E-07	2,10E-06	6,53E-06	2,28E-06	1,40E-05
500	3,77E-05	8,50E-06	9,15E-05	4,26E-06	7,19E-07	1,11E-05	1,06E-06	4,00E-07	2,04E-06	6,30E-06	2,22E-06	1,28E-05
Maxim	4,78E-05	1,07E-05	1,28E-04	5,70E-06	1,07E-06	1,65E-05	1,77E-06	4,90E-07	3,84E-06	1,05E-05	2,48E-06	2,50E-05

Maximum = optional

Ra-226 calculations (covering with 0,5 m clean soil layer - option 2a)

	Inhalation of radon						Leafy vegetables						Drinking water		
	indoors	95% confidence interval		outdoors	95% confidence interval		Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	6,33E+00	1,64E+00	1,67E+01	1,66E-01	3,81E-02	4,31E-01	7,81E-03	6,25E-04	3,29E-02	9,14E-03	2,04E-04	4,97E-02	9,42E-03	4,03E-04	4,36E-02
100	6,00E+00	1,52E+00	1,46E+01	1,61E-01	3,79E-02	4,02E-01	7,78E-03	6,60E-04	3,18E-02	1,03E-02	1,94E-04	5,74E-02	1,04E-02	4,07E-04	4,97E-02
500	3,70E+00	1,06E+00	9,28E+00	9,88E-02	2,11E-02	2,50E-01	8,08E-03	6,52E-04	3,56E-02	6,66E-02	1,45E-03	4,09E-01	6,42E-02	2,85E-03	2,93E-01
Maxim	6,33E+00	1,64E+00	1,67E+01	1,66E-01	3,81E-02	4,31E-01	8,08E-03	6,60E-04	3,56E-02	6,66E-02	1,45E-03	4,09E-01	6,42E-02	2,85E-03	2,93E-01

Maximum = optional

Pb-210 calculations

	Leafy vegetables						Drinking water		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,32E-01	2,10E-02	7,04E-01	1,57E-01	2,84E-03	8,78E-01	1,59E-01	5,98E-03	7,65E-01
100	1,87E-01	1,65E-02	6,12E-01	1,46E-01	3,06E-03	8,80E-01	1,41E-01	5,58E-03	6,92E-01
500	1,75E-01	1,94E-02	5,27E-01	3,81E-01	8,68E-03	2,18E+00	3,95E-01	1,55E-02	2,14E+00
Maxim	2,32E-01	2,10E-02	7,04E-01	3,81E-01	8,68E-03	2,18E+00	3,95E-01	1,55E-02	2,14E+00

Maximum = optional

Ra-226 calculations (covering with 0,5 m clean soil layer - option 2a)

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	2,30E-03	2,58E-04	9,91E-03	7,09E-04	4,12E-06	5,05E-03	4,94E-03	6,78E-04	1,68E-02	2,96E-03	4,01E-04	1,09E-02	2,56E-04	5,61E-05	6,00E-04
100	2,27E-03	2,53E-04	9,13E-03	7,60E-04	3,47E-06	5,28E-03	4,64E-03	5,79E-04	1,50E-02	2,97E-03	3,38E-04	1,06E-02	2,52E-04	5,83E-05	6,31E-04
500	2,21E-03	2,29E-04	9,17E-03	5,25E-03	2,98E-05	3,92E-02	4,04E-03	5,02E-04	1,31E-02	2,51E-03	2,98E-04	9,91E-03	2,48E-04	5,76E-05	5,91E-04
Maxim	2,30E-03	2,58E-04	9,91E-03	5,25E-03	2,98E-05	3,92E-02	4,94E-03	6,78E-04	1,68E-02	2,97E-03	4,01E-04	1,09E-02	2,56E-04	5,83E-05	6,31E-04

Maximum = optional

Pb-210 calculations

	Potatoes						Milk			Meat			Soil ingestion (optional)		
	Root uptake	95% confidence interval		Foliar uptake	95% confidence interval			95% confidence interval			95% confidence interval			95% confidence interval	
Years	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
1	8,65E-03	2,17E-03	2,21E-02	1,16E-02	5,07E-05	8,05E-02	1,26E-02	1,61E-03	4,04E-02	7,44E-03	1,24E-03	2,18E-02	1,89E-03	2,53E-04	5,72E-03
100	6,78E-03	1,72E-03	1,69E-02	1,16E-02	6,40E-05	8,80E-02	1,24E-02	1,55E-03	3,88E-02	7,17E-03	1,15E-03	2,31E-02	1,09E-03	2,05E-04	2,81E-03
500	6,63E-03	1,59E-03	1,57E-02	2,86E-02	1,69E-04	1,89E-01	1,18E-02	1,46E-03	3,90E-02	6,63E-03	1,16E-03	1,92E-02	1,09E-03	1,95E-04	2,90E-03
Maxim	8,65E-03	2,17E-03	2,21E-02	2,86E-02	1,69E-04	1,89E-01	1,26E-02	1,61E-03	4,04E-02	7,44E-03	1,24E-03	2,31E-02	1,89E-03	2,53E-04	5,72E-03

Maximum = optional

Total dose:

Ra-226 calculations (covering with 0,5 m clean soil layer - option 2a)

1 y 95% confidence interval			100 y 95% confidence interval			500 y 95% confidence interval			Maximum (optional) 95% confidence interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
6,57E+00	1,81E+00	1,71E+01	6,25E+00	1,64E+00	1,52E+01	3,99E+00	1,28E+00	9,71E+00	6,57E+00	1,81E+00	1,71E+01

Pb-210 calculations

1 y 95% confidence interval			100 y 95% confidence interval			500 y 95% confidence interval			Maximum (optional) 95% confidence interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
5,90E-01	8,50E-02	1,88E+00	5,13E-01	8,36E-02	1,85E+00	1,01E+00	1,11E-01	4,18E+00	1,01E+00	1,11E-01	4,18E+00

Ra-226 & Pb-210 calculations

1 y 95% confidence interval			100 y 95% confidence interval			500 y 95% confidence interval			Maximum (optional) 95% confidence interval		
Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
7,16E+00	1,81E+00	1,72E+01	6,76E+00	1,64E+00	1,53E+01	5,00E+00	1,28E+00	1,06E+01	7,16E+00	1,81E+00	1,72E+01

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Meetings

BIOMASS Theme 2 Planning Meeting, Vienna, Austria: 24–28 June 1996

BIOMASS Remediation Assessment WG Planning Meeting, Mol, Belgium: 9–11 June 1997

BIOMASS Plenary and Working Group Meetings, Vienna, Austria: 20–24 October 1997

BIOMASS Remediation Assessment WG Meeting, Veszprém, Hungary: 8–12 June 1998

BIOMASS Research Co-ordination, Plenary and Working Group Meetings,
Vienna, Austria: 5–9 October 1998

BIOMASS Remediation Assessment WG Meeting, Vienna, Austria: 31 May – 1 June 1999

BIOMASS Research Co-ordination, Plenary and Working Group Meetings,
Vienna, Austria: 4–8 October 1999

BIOMASS Remediation Assessment WG Meeting, Kjeller, Norway: 22–23 May 2000

BIOMASS Research Co-ordination, Plenary and Working Group Meetings,
Vienna, Austria: 6–10 November 2000