IAEA TECDOC SERIES

User Manual for NORMALYSA v.2.3

Description of Program Module Libraries, Mathematical Models and Parameters

Modelling and Data for Radiological Impact Assessments (MODARIA) Programme

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USER MANUAL FOR NORMALYSA V.2.3

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USER MANUAL FOR NORMALYSA V.2.3

DESCRIPTION OF PROGRAM MODULE LIBRARIES, MATHEMATICAL MODELS AND PARAMETERS

MODELLING AND DATA FOR RADIOLOGICAL IMPACT ASSESSMENTS (MODARIA) PROGRAMME

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2023

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FOREWORD

Models are essential tools for evaluating radiological impacts within the safety assessment process and for regulatory control of nuclear facilities and activities in planned, existing and emergency exposure situations. Modelling the fate of radionuclides in the environment and assessing the resulting radiation doses to people and the environment is needed, for example, for evaluating the radiological relevance of routine and accidental releases of radionuclides, as part of decision making during remediation activities, within the framework of long term safety assessments for nuclear waste disposal facilities, and for clearance and exemption of material with low levels of radioactivity from the need for regulatory control.

The IAEA has been organizing programmes of international model testing since the 1980s. These programmes have contributed to a general improvement in models, in the transfer of data and in the capabilities of modellers in Member States. IAEA publications on this subject over the past three decades demonstrate the comprehensive nature of the programmes and record the associated advances made.

From 2012 to 2015 the IAEA organized a programme entitled Modelling and Data for Radiological Impact Assessments (MODARIA), which concentrated on testing the performance of models, developing and improving models for particular environments, reaching consensus on data sets that are generally applicable in environmental transfer models and providing an international forum for the exchange of experience, ideas and research information.

Different aspects were addressed by ten working groups within the MODARIA programme, covering four thematic areas: remediation of contaminated areas; uncertainties and variability; exposures and effects on biota; and marine modelling.

This publication is a user manual for the NORMALYSA v.2.3 software and was prepared as part of the activities of Working Group 3, Application of models for assessing radiological impacts arising from NORM and radioactively contaminated legacy sites to support the management of remediation.

CONTENTS

SUMMARY

This publication describes the work undertaken by the Working Group 3 'Application of models for assessing radiological impacts arising from NORM and radioactively contaminated legacy sites to support the management of remediation' of the IAEA's MODARIA programme. The activities of Working Group 3 covered three tasks:

— Task 1: Methodology for risk and safety assessment in support of remediation;
— Task 2: Development of the Normalysa modelling platform;
— Task 3: Model–model and model–data comparison studies.

Within Task 2, a software tool, NORMALYSA (NORM And LegacY Site Assessment), was designed to simulate radionuclide transport in the environment from the source term (e.g. radioactively contaminated land) to the relevant receptors (e.g. residential areas, agricultural areas, water bodies) and to estimate resulting radiation exposure and corresponding doses to humans. The NORMALYSA software tool consists of a Simulator program engine, which is integrated with a set of program modules organized into five libraries: Sources, Cover Layers, Transport, Receptors, and Doses. NORMALYSA utilizes a number of models that have been used beforehand in the safety assessment of radioactive waste disposal facilities; for some of the radionuclide migration and transfer processes, it uses models recommended by the IAEA.

The NORMALYSA software was developed by Facilia AB (Bromma, Sweden) with the support of the IAEA. It is based on the Ecolego 6 software package, which has been developed for implementing deterministic and stochastic dynamics models. It was further tested and benchmarked with other similar software tools (e.g. RESRAD) between 2013–2016 within the IAEA's MODARIA programme under the activities within Working Group 3.

This publication presents the User Manual for the NORMALYSA v.2.3 software tool.

1. INTRODUCTION

The International Atomic Energy Agency (IAEA) organized a programme from 2012 to 2015 entitled Modelling and Data for Radiological Impact Assessments (MODARIA), which had the general aim of improving capabilities in the field of environmental radiation dose assessment by means of acquisition of improved data for model testing, model testing and comparison, reaching consensus on modelling philosophies, approaches and parameter values, development of improved methods and exchange of information.

The following topics were addressed in ten working groups:

Remediation of Contaminated Areas

— Working Group 1: Remediation strategies and decision-aiding techniques;
— Working Group 2: Exposures in contaminated urban environments and effect of remedial measures;
— Working Group 3: Application of models for assessing radiological impacts arising from naturally occurring radioactive material (NORM) and radioactively contaminated legacy sites to support the management of remediation.

Uncertainties and Variability

— Working Group 4: Analysis of radioecological data in IAEA Technical Reports Series publications to identify key radionuclides and associated parameter values for human and wildlife exposure assessment;
— Working Group 5: Uncertainty and variability analysis for assessments of radiological impacts arising from routine discharges of radionuclides;
— Working Group 6: Common framework for addressing environmental change in long term safety assessments of radioactive waste disposal facilities;
— Working Group 7: Harmonization and intercomparison of models for accidental tritium releases.

Exposures and Effects on Biota

— Working Group 8: Biota modelling: Further development of transfer and exposure models and application to scenarios;
— Working Group 9: Models for assessing radiation effects on populations of wildlife species.

Marine Modelling

— Working Group 10: Modelling of marine dispersion and transfer of radionuclides accidentally released from land-based facilities.

The activities and results achieved by the Working Groups will be described in individual IAEA Technical Documents (IAEA-TECDOCs) where appropriate. This publication describes the work of the Application of models for assessing radiological impacts arising from NORM and radioactively contaminated legacy sites to support the management of remediation Working Group 3 to develop the software tool NORMALYSA (NORM And LegacY Site Assessment).

The NORMALYSA software tool is designed to simulate radionuclide transport in the environment from the source term (e.g. radioactively contaminated land) to the relevant receptors (e.g. residential areas, agricultural areas, water bodies) and to estimate resulting radiation exposure and corresponding doses to humans.

The NORMALYSA software[1] was developed by Facilia AB (Bromma, Sweden) with the support of the International Atomic Energy Agency (IAEA). The NORMALYSA software tool was further tested and benchmarked with other similar software tools (e.g. RESRAD) between 2013–2016 within the frame of IAEA's MODARIA programme (Modelling and Data for Radiological Impact Assessments) under activities within Working Group 3.

The NORMALYSA software tool is based on the Ecolego 6[2] software [1]. Ecolego is a software package developed by Facilia AB for implementing deterministic and stochastic dynamic models described by first order ordinary differential equations (i.e. compartmental models).

This publication represents the user manual for NORMALYSA v.2.3 software, beginning with a description of the overall software architecture and functionality of NORMALYSA.

Next, the following sections focus on main module libraries and provide detailed descriptions of the specific module library and individual modules included as part of this library.

The following information is provided for each program module:

— General description;
— Details on how this module can be connected to other modules;
— Underlying conceptual model of radioecological transport/transfer process;
— Detailed description of mathematical model used;
— Input and output parameters;
— Information on default values of radioecological and dose assessment parameters with reference to relevant sources.

The Appendix provides a compilation of radioecological and dose assessment parameters used by various NORMALYSA modules.

Annexes I–III provide three NORMALYSA tutorial exercises which may be performed using the NORMALYSA software. Each of the exercises may be used for familiarization with the NORMALYSA software and for training purposes. The exercises included are:

— Exercise 1 on Calculation of outdoor exposure of the reference individual[3] using radiation monitoring data (Annex I);
— Exercise 2 on Radionuclide transport to groundwater from the uranium tailing (Annex II);
— Exercise 3 on Calculation of radon transport in the atmosphere from the uranium tailing site and resulting inhalation doses to the reference persons (Annex III).

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[1] The software is available for free download from http://project.facilia.se/normalysa/software.html
[2] https://www.ecolego.se/ecolego/
[3] The 'reference individual' in the NORMALYSA tool is equivalent to the 'representative person'.

4

2. SOFTWARE OVERVIEW

2.1. GENERAL DESCRIPTION

The NORMALYSA tool consists of a Simulator module, which is integrated with a set of program modules organized into the following main libraries: 'Sources' and 'Cover Layers', 'Transports', 'Receptors', 'Doses' (see Fig. 1).

The software architecture of NORMALYSA allows easy configuration of a variety of 'source → transport pathway → receptor environment → exposed reference individual' combinations, providing essential flexibility in accounting for site specific conditions and exposure situations (see Section 2.2 for more detail on the specifics of the user interface).

The NORMALYSA tool is currently based on relatively simple environmental transport and exposure assessment models. In particular, NORMALYSA utilizes a number of models that have been used in the safety assessment of radioactive waste disposal facilities which were performed by the Swedish Nuclear Fuel and Waste Management Company (SKB) [2, 3]. For some of the radionuclide migration and transfer processes NORMALYSA uses models recommended by the IAEA [4–8]. Moreover, the models discussed may be especially useful in the early stages of safety assessment, as well as for conservative radionuclide transport and dose assessment analyses (e.g. for obtaining upper bound estimates of radiological impacts from contaminated land).

NORMALYSA module libraries are supplied with the default values for most parameters, which are needed to run the environmental transport and radioecological transfer models. These default parameters are usually taken from reputable parameter compilations (e.g. [7–11]).

2.2. USER INTERFACE AND FUNCTIONALITY

In this section, detailed description of the user interface is provided.

2.2.1. Software user interface

As previously mentioned, NORMALYSA consists of the Simulator module as well as a set of module libraries.
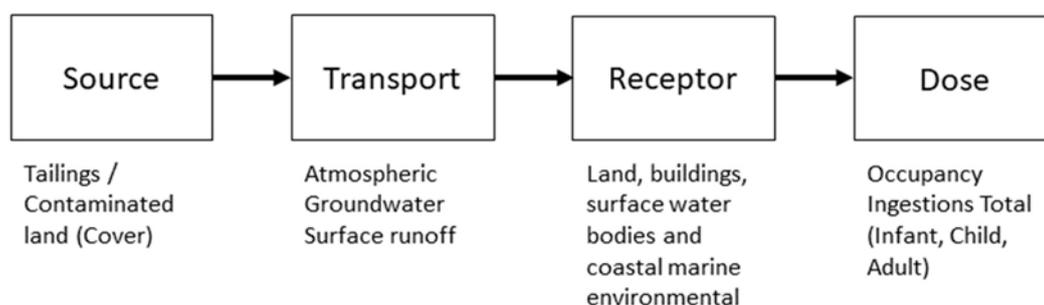
FIG. 1. Conceptual schematization of 'source → dose' analysis in NORMALYSA software tool.

The Simulator module provides the Graphical User Interface capabilities where site specific models can be created using blocks from the module libraries. This Graphical User Interface is generally similar to the interface of the Ecolego 6 software[4].

Furthermore, the Simulator module supports a classic 'Interaction Matrix' interface and graphical 'Block Scheme' interface. An example of the 'Interaction Matrix' interface is shown in Fig. 2.

This interface easily allows:

—— The selection of the required program modules from libraries;
—— 'Connecting models', i.e. the setting of data exchanges between these modules;
—— The specification of input parameters;
—— The running of the assembled model;
—— The examination of outputs and the analysis of simulation results (in table and/or graph formats).

The interface of the Simulator module also allows for the selection of either English, Spanish or Russian languages.

2.2.2. Functionality

The NORMALYSA Simulator includes the simulation capabilities and functionality inherent to the Ecolego 6 modelling platform, which includes:

—— A built-in radionuclide database (see Section 2.2.3 for the list of radionuclides);
—— Powerful numerical solvers for ordinary differential equations, which are used to mathematically describe radionuclide transport and transfer processes;
—— Capabilities for probabilistic simulation and sensitivity analyses;
—— Output data processing capabilities, including graphical presentation of modelling results;
—— Report generation options.

2.2.3. List of radionuclides

By default, NORMALYSA includes the following decay chains and individual radionuclides that may (or may not) be incorporated into the model:

—— ^{238}U decay series (^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{210}Po);
—— ^{232}Th decay series (^{232}Th $\rightarrow$ ^{228}Ra $\rightarrow$ ^{228}Th);
—— ^{235}U decay series (^{235}U $\rightarrow$ ^{231}Pa $\rightarrow$ ^{227}Ac);
—— ^{222}Rn;
—— ^{137}Cs and ^{90}Sr.

For all of these radionuclides NORMALYSA modules are supplied with the default values for all relevant radionuclide specific radioecological parameters (e.g. *Kd* values, transfer coefficients).

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[4] Available for free download from https://www.ecolego.se/
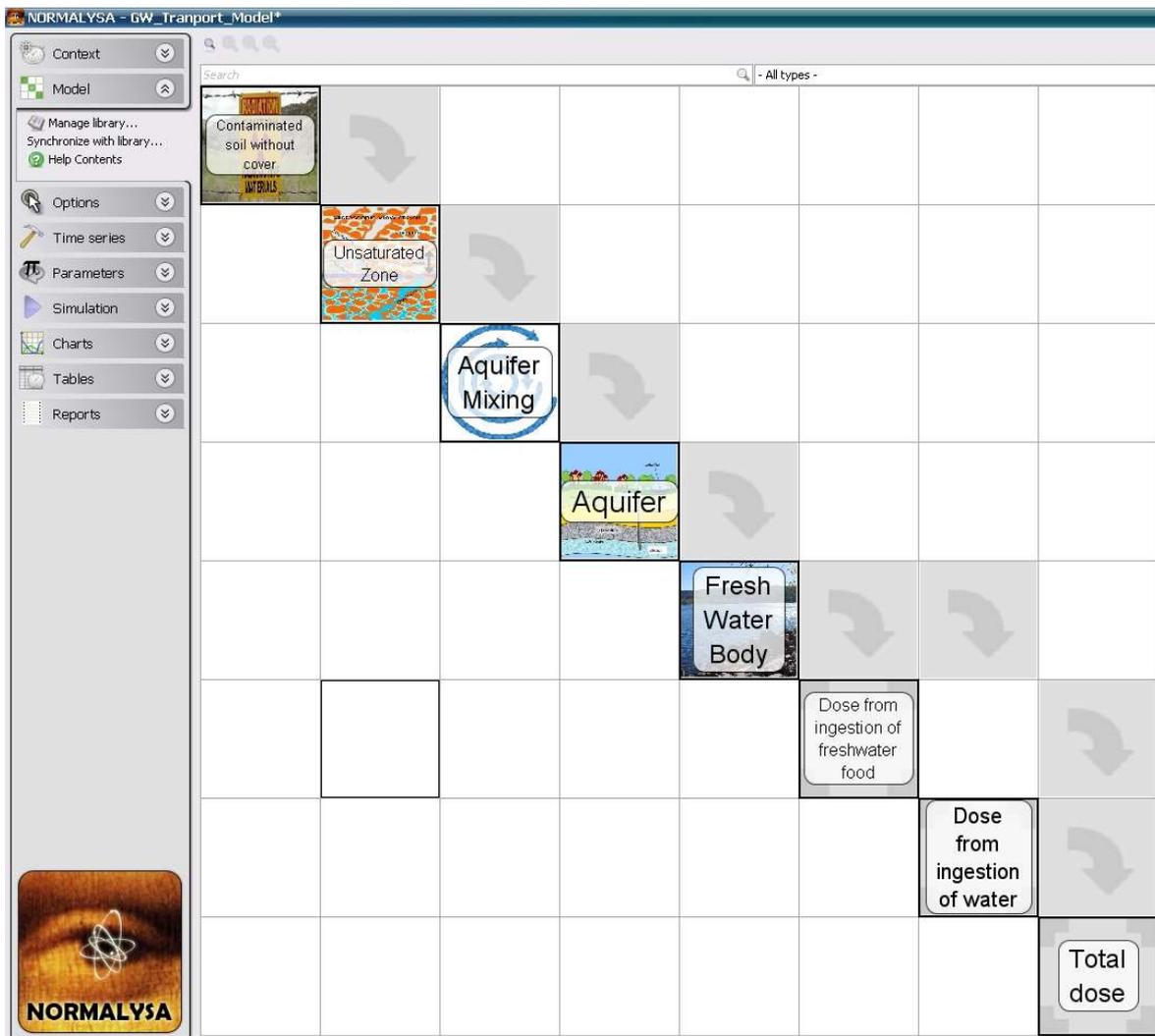
FIG. 2. Interface of NORMALYSA software tool in 'Interaction Matrix' format for an example describing radionuclide transport in 'Contaminated Site – Groundwater – Surface Water' system.

The user has an option to also add additional radionuclides to the model if so desired. However, in this case the user will need to specify values of all relevant radionuclide specific radioecological parameters for the NORMALYSA modules used.

2.3. MODULE LIBRARIES (OVERVIEW)

NORMALYSA includes five module libraries, describing different components (elements) of the modelled system in accordance with the 'source → dose' analysis schematization shown in Fig. 1. A brief overview of these module libraries is presented below, and detailed descriptions of various libraries and individual modules (and respective radioecological models) included in these libraries are presented in the subsequent sections of this publication.

2.3.1. Sources

The 'Sources' library includes modules for calculation of radionuclide releases to air, surface waters and groundwater from the contaminated object (source term), such as uranium mill tailings or radioactively contaminated land.

The source term modules included in the 'Sources' library are described in Table 1, and a detailed description of this library and individual modules is provided in Section 3 of this publication.

2.3.2. Cover layers

The 'Cover Layers' library includes modules for simulating soil covers over the source to calculate resulting radon exhalation rate and concentration in air, as well as the external dose rate above the cover. The respective modules are summarized in Table 2, and a detailed description of this library and individual modules is provided in Section 4 of this publication.

2.3.3. Transports

The 'Transports' library includes modules for calculation of the atmospheric, groundwater or surface runoff transport of radionuclides from the contamination source to different receptors. The respective source term modules are described in Table 3, and a detailed description of this library and individual modules is provided in Section 5 of this publication.

2.3.4. Receptors

The 'Receptors' library includes modules for calculation of radionuclide transfer and the redistribution process in different types of receptor environments, such as different types of land (e.g. crop lands, pasture lands, forests, uncultivated lands), buildings, surface water bodies (lakes and rivers), and near shore (coastal) marine environments. These modules are essentially based on radioecological models that have been developed and used by SKB in the safety assessment of radioactive waste disposal facilities [2, 3]. The respective receptor modules are described in Table 4, and a detailed description of this library and individual modules is provided in Section 6 of this publication.

2.3.5. Doses

A set of modules included in the 'Doses' library calculates the doses to humans (reference persons) based on the radionuclide concentrations in different environmental media simulated using the receptor modules described above (see Section 2.3.4). The modeller also has an option to directly specify radionuclide concentrations in environmental media and/or foodstuffs (e.g. based on monitoring data). The doses are calculated for various relevant exposure pathways (e.g. external irradiation, inhalation, ingestion), and can be summed into a total annual effective dose (Sv/year).

The reference persons may belong to different age groups, i.e. adults, children (10 year olds) and infants (1 year olds) according to the ICRP approach [12]. For practical implementation of the recommendations listed in [12] the age group 'adults' represent ages in the range of 16–70 years, children (10 year olds) represent the age range 6–15 years and infants (1 year olds) represent the age range 0–5 years.

Exposure pathways considered for different receptor environments are summarized in Table 5.

Dose coefficients for effective doses from external irradiation from surface deposition and immersion into cloud are based on Ref. [13]. Dose coefficients for internal exposure through inhalation and ingestion pathways are based on Ref. [14]. A detailed description of this library and individual modules is provided in Section 7 of this publication.

TABLE 1. DESCRIPTION OF MODULES IN 'SOURCES' LIBRARY

Module	Description
Tailings without cover	This module is designed to describe radionuclide fluxes to subsurface environments and/or radon exhalation to the atmosphere from the uranium mill tailings site. The source term is modelled as a single compartment. The radionuclide leaching from soil is described using model described in Ref. [15]. Radon exhalation to the atmosphere is modelled using the diffusion model described in Ref. [16] (see Section 3.2 for more detail).
Contaminated Land Without Cover	This module describes radionuclide fluxes to subsurface environments and/or radon exhalation to the atmosphere from the radioactively contaminated topsoil layer. It implements the same mathematical models as the 'Tailings without cover' module described above (see Section 3.2 for more detail).
Chronic release	This simple model describes chronic (constant in time) release of a radioactive contaminant to the atmosphere and/or groundwater or surface water body (see Section 3.3 for more detail).

TABLE 2. DESCRIPTION OF MODULES IN 'COVER LAYERS' LIBRARY

Module	Description
Cover Layer	This module allows the simulation of soil covers over the source in order to calculate the resulting radon exhalation rate and concentration in air above the cover, as well as the external dose rate. Radon exhalation to the atmosphere is modelled using the diffusion model described in Ref. [16]. External dose calculations are based on the methodology described in Ref. [17] (see Section 4.2 for more detail).
House Slab	This module allows the simulation of the effect of the house slab residing on a contaminated soil layer on radon diffusive flux to house and external dose rate above the slab. It implements models similar to the 'Cover layer' module described above (see Section 4.2 for more detail).

TABLE 3. DESCRIPTION OF MODULES IN 'TRANSPORTS' LIBRARY

Module	Description
Aquifer, Aquifer mixing	These modules simulate radionuclide transport in the aquifer. The model employs 1D flow tube schematization of the radionuclide transport process in the subsurface. The modelled radionuclide transport mechanisms include advection, dispersion and retardation due to sorption (Kd model). Radionuclide transfers due to the advection and dispersion process in groundwater are modelled using the approach described in Appendix C of Ref. [17] (see Section 5.2 and 5.3 for more detail).
Unsaturated zone	This module simulates 1D vertical radionuclide transport in the unsaturated zone. The modelled radionuclide transport mechanisms include advection, dispersion and retardation due to sorption (Kd model). Radionuclide transfers due to the advection and dispersion process are modelled using the approach described in Appendix C of Ref. [17] (see Section 5.4 for more detail).
Surface Runoff	This module simulates radionuclide mobilization and transport in surface runoff from the soil of a contaminated watershed. The model operates total radionuclide inventory in the so called 'exchangeable soil layer', which represents the upper soil layer interacting with surface runoff [18]. Radionuclide concentrations in runoff water and those adsorbed on suspended particles are calculated using the equilibrium Kd based sorption models, while the soil erosion process is described using empirical coefficients (see Section 5.5 for more detail).
Atmosphere SR-19	This module simulates atmospheric dispersion of a contaminant from the point of source using the Gaussian plume atmospheric dispersion model described in Ref. [4] (see Section 5.6 for more detail).
Atmosphere chronic	This module calculates the atmospheric dispersion of contaminant from the chronic (steady state) source of atmospheric contamination to the receptor point. It employs normalized radionuclide concentrations in the atmospheric air and deposition rates for a unit release rate from the source (which will be evaluated using an external model). These values are scaled with the actual release rate from the source (see Section 5.7 for more detail).

TABLE 4. DESCRIPTION OF MODULES IN 'RECEPTORS' LIBRARY

Module	Description
Land	This module simulates the contaminated land where exposure of an individual may occur by external irradiation from radionuclides deposited on the soil, inhalation of radionuclides in the air and due to inadvertent ingestion of contaminated soil. The implemented radioecological model dynamically simulates vertical distribution of radionuclides in the soil profile (consisting of 'top' and 'deep' zone compartments), and it accounts for losses from the soil through erosion, bioturbation (using diffusion type transfer models) and leaching processes [2]. The model calculates the concentration of radionuclides in soil, as well as the concentration of radionuclides in outdoor air due to resuspension from soil (see Section 6.4 for more detail).
Cropland	This module considers exposure pathways associated with cultivation of agricultural plants in a cropland. The model simulates dynamically vertical distribution of radionuclides in the soil profile (consisting of 'top' and 'deep' zones), and it estimates radionuclide concentrations in crops using the transfer factor approach [8]. The model takes into account input of radionuclides through deposition from the atmosphere and irrigation with contaminated water, and losses of radionuclides from the system through erosion, bioturbation and leaching processes [2] (see Section 6.2 for more detail).
Garden Plot	This module is designed for assessing exposures by ingestion of fruits, vegetables, potatoes and other foods produced in a garden plot. The garden plot may be contaminated via deposition of radionuclides from the atmosphere and/or by irrigation with contaminated water. The mathematical approach for this model is generally similar to the 'cropland' model described above, while the foodstuff types and radioecological parameters are model-specific (see Section 6.5 for more detail).
Pasture Land	This module considers exposure pathways associated with ingestion of meat and milk obtained from livestock grazing on a pastureland. The model accounts for inputs of radionuclides to the pastureland by deposition from the atmosphere and by irrigation with contaminated water. The mathematical approach for this model is generally similar to the 'cropland' model described above, while it also accounts for radionuclide transfers to livestock due to ingestion of contaminated forage and water using the transfer factor approach (see Section 6.3 for more detail).
Forest	This module covers exposure pathways related to utilizing a forest as a source of food. The model dynamically simulates the vertical distribution of radionuclides in the soil profile (consisting of 'top' and 'deep' zone compartments) and radionuclide concentrations in trees (leaves, tree wood, understorey, litter compartments) and forest food species (berries, mushrooms and game animals) [3]. The model takes into account input of radionuclides through deposition from the atmosphere, and it accounts for losses from the soil by leaching processes (see Section 6.6 for more detail).
Freshwater body	The module covers exposure pathways associated with the utilization of the water body (lakes, rivers and streams) as a source of drinking water and aquatic foods, as well as for recreational activities such as swimming and boating. The water body may receive radionuclides from the atmosphere through deposition, through runoff from the adjacent catchment area, as well as by direct discharges from a source of aquatic releases of radioactivity (e.g. from industrial source such as a nuclear power plant (NPP)). The model dynamically simulates distribution of radionuclides in abiotic media such as water, suspended particulate matter and sediments (consisting of 'top' and 'deep' compartments) and biotic media such as fish and other edible freshwater organisms (using the transfer factor approach). The implemented model is based on the 'LAKE' model described in Ref. [2] (see Section 6.9 for more detail).
Marine	This module is applicable for sea coastal areas that might receive radionuclides deposited from the atmosphere on the sea water surface, as well as direct radionuclide discharges to water from a source of aquatic releases. The model covers exposure pathways associated with the use of a sea coastal area ('inner' water compartment) as a source of food, as well as for recreational activities such as swimming and boating. The 'Marine' module dynamically simulates the distribution of radionuclide in abiotic media (i.e. sea water, suspended particulate matter, bottom and beach sediments) and biotic media (fish and other edible sea organisms). The mathematical model for sea water compartment implemented in 'Marine' module is based on 'POSEIDON' model described in Ref. [19]. The model for radionuclide accumulation in the beach sediment is based on Ref. [4]. (See Section 6.10 for more detail).
House	This module is used for assessment of indoor air concentrations of radionuclides (including radon). Radionuclides enter houses due to exchange with outdoor air. Radon enters houses due to diffusion through the basement slab, and its concentration is calculated using mathematical expressions accounting for inflow from the basement (by diffusive flux) and ventilation by outdoor air (see Section 6.7 for more detail).
Well	This module calculates radionuclide concentrations in the groundwater extracted by well. It employs a simple mixing model for contaminated groundwater migrating from the source (e.g. output of an 'Aquifer' transport module) and non-contaminated groundwater with a 'background' concentration (see Section 6.8 for more detail).

TABLE 5. MAIN EXPOSURE PATHWAYS CONSIDERED FOR THE DIFFERENT RECEPTOR ENVIRONMENTS (SHOWN IN BLUE)

Pathway/ Receptor	Forest	Garden plot	Cropland	Pasture land	Land	House	Fresh water body	Marine environment	Well
Outdoor occupancy*	■	■	■	■	■				
Indoor occupancy**						■			
Marine activities***								■	
Ingestion of water							■		■
Ingestion of garden plot foodstuff		■							
Ingestion of crops			■						
Ingestion of forest food	■								
Ingestion of livestock products				■					
Ingestion of freshwater food							■		
Ingestion of marine food								■	

Notes: * The 'Outdoor occupancy' includes effective doses from external irradiation (from deposited radioactivity, cloud immersion), dose from inhalation of airborne radionuclides, and dose from occasional ingestion of soil
** The 'Indoor occupancy' includes doses from external irradiation and from inhalation of airborne radionuclides.
*** The 'Marine activities' includes doses from external irradiation (from beach sediments and from immersion in water).

TABLE 6. DESCRIPTION OF MODULES AND SUBLIBRARIES IN 'DOSES' LIBRARY

Module/ Sub-library	Description
Doses from occupancy	This sub-library includes modules for calculating doses from outdoor occupancy, indoor occupancy and marine activities (see the Notes from Table 5).
Doses from ingestion	This sub-library includes a set of modules for estimation of internal doses from ingestion of various foodstuffs and products such as water, garden products, forest products, livestock, agricultural foodstuffs and aquatic edible species (the list of foodstuffs is specific for the respective receptor environment).
Total dose	This module sums the total effective dose received by reference persons over various radionuclides and exposure pathways.

2.4. CREATING AND RUNNING A MODEL IN NORMALYSA

Setting up and running a model in NORMALYSA includes seven main steps which are shown in Fig. 3. To take these steps, NORMALYSA the 'Simulator' module uses simple and intuitive Graphical User Interface which is generally similar to the interface of Ecolego 6[5] software. The main steps which need to be undertaken to run a simulation in NORMALYSA are briefly explained below.

2.4.1. Setting of the assessment context

In this step, the Ecolego project file is created defining the simulation case. In particular, the user specifies the name of the project file and selects the radionuclides to be included to the simulation case. The user may also input further radionuclides in addition to those listed in Section 2.2.3.

The modeller also has the possibility to activate or deactivate specific index lists relevant to the modelled case such as, e.g. 'Reference persons', 'Age groups' or specific food types included in the simulation.

The user may also manage specific interface options here, such as language of the software interface, as well as various other options.

2.4.2. Defining the model

This is the key step in setting up the modelling case, where the user sets up the radioecological model. For composing the model, the Simulator module supports the classic Ecolego 'Interaction Matrix' interface and the graphical 'Block Scheme' interface (see Fig. 2).

The radioecological model can be composed from modules included into libraries as described in Section 2.3. The user selects particular modules needed for his/her modelling case and sets up data exchanges between modules. The procedures are similar to those employed in Ecolego 6 when working with libraries.

2.4.3. Specifying modelling options

In this step, the user specifies particular modelling options available in relevant modules used to setup the radioecological model.

For example, the modeller may specify whether dose calculations will employ predetermined radionuclide concentrations in soil (e.g. based on monitoring data), or these will be modelled dynamically using a relevant radionuclide transport model.

2.4.4. Entering model parameters

The NORMALYSA modules are supplied with the default values of all model parameters. These default values are described, and relevant references included, in this publication which is split into sections summarizing the particular module libraries.

The user has the possibility of modifying all model parameters. Some of these do not necessarily need to be changed (e.g. radionuclide *Kd* values for soil, or dose coefficients for dose assessment simulations). However, only some models include site-specific and/or modelling case specific parameters that will need to be specified by the user.

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[5] https://www.ecolego.se/ecolego/
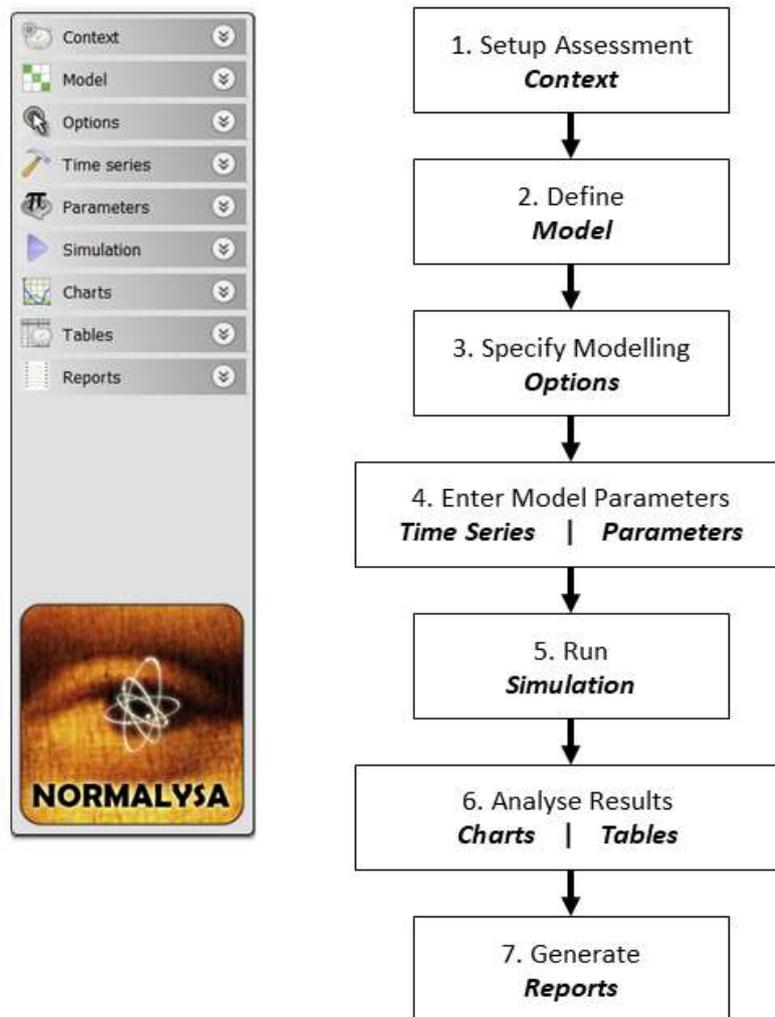
FIG. 3. Seven steps for performing assessment using NORMALYSA software tool.

The Simulator menu includes two menu items for input of model parameter values, i.e. 'Time series' and 'Parameters'.

The 'Time series' menu allows the entry, in table format, of those input parameters of the model that are time dependent (if any).

The 'Parameters' menu allows the entry of parameters representing individual values as well as parameters which are dependent on index lists (e.g. radionuclides, or age categories of reference persons).

The user has the possibility of carrying out parameter export/import operations using the Excel file format (similar to Ecolego 6 functionality).

2.4.5.   Running the simulation

This menu allows the user to set up simulation options (e.g. start and end times), and to eventually run the model. Moreover, the user can activate the index list related to 'Scenarios'.

The simulation can be performed in either deterministic or probabilistic contexts. The relevant simulation options for the deterministic case include output times, the list of output parameters etc. The simulation options for the probabilistic case include a number of iterations, parameters to be treated probabilistically, etc. More details can be found in the context sensitive 'Help Contents' menu of NORMALYSA.

2.4.6. Analyzing results

The Simulator menu includes two menu items for analyzing simulation results, i.e. 'Charts' and 'Tables'. These menu items allow the modeller to view data either in chart or table format. Various table/chart options are available by means of the respective menus and are generally similar to those provided by the Ecolego 6 user interface. Furthermore, simulation data can be exported into Excel format.

2.4.7. Generating reports

This menu allows the automatic generation of a modelling report describing the simulation case, model used, input parameters and simulation results. The report can be printed or exported to PDF format.

Additional information on the user interface of NORMALYSA Simulator can be obtained from the context sensitive 'Help Content' menu.

3. 'SOURCES' MODULE LIBRARY

3.1. GENERAL DESCRIPTION OF THE LIBRARY

The 'Sources' library includes modules for calculation of radionuclide releases to the atmosphere and groundwater from a contaminated object (source term) such as uranium mill tailings and contaminated land.

The library includes three modules, i.e. 'Tailings Without Cover', 'Contaminated Land Without Cover' and 'Chronic Release' (see Table 1).

The first two modules are designed to simulate the radionuclide fluxes with infiltration moisture flow to a subsurface environment and/or radon exhalation to the atmosphere from the uranium mill tailings site or contaminated soil layer. These modules may be further combined with modules from the 'Cover Layers' library to simulate influence of a cover layer on radon diffusive flux to the atmosphere. The combined use of the 'source term' modules with other transport and receptor modules of NORMALYSA as discussed below is shown in Fig. 4.

The 'Chronic release' module allows the simulation of a simple steady state (constant in time) release of radioactive contaminant to the atmosphere and/or groundwater or surface water body. Detailed descriptions of individual modules are provided in Sections 3.2 and 3.3.

3.2. 'TAILINGS WITHOUT COVER' AND 'CONTAMINATED LAND WITHOUT COVER' MODULES

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules.

3.2.1. Module description

In this section, detailed descriptions of the 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules are provided.

3.2.1.1. General description

Both the 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules implement similar mathematical models for radionuclide source terms for groundwater transport (due to radionuclide leaching by infiltration water) and for atmospheric transport of radon from radium contaminated waste/soil material (due to ^{222}Rn diffusion in waste material and exhalation to the atmosphere) (see Fig. 4). These modules are similarly organized and have the same notation of main model variables and parameters.

The goal of the source term modules discussed is to dynamically simulate radionuclide concentrations in waste (or soil) material and fluxes of radioactive contaminants to the subsurface (for all radionuclides) and to the atmosphere (for radon). Modules also estimate radon concentrations in the air above the contaminated site using a simple atmospheric mixing model.

The output radon fluxes obtained from the modules can be used directly as inputs to the atmosphere (e.g. for the case of bare tailings) or as inputs to complementary modules such as 'Cover Layer' and 'House Slab' that simulates the presence of a cover (or covers, several modules can be linked sequentially) over the tailings or contaminated soil.
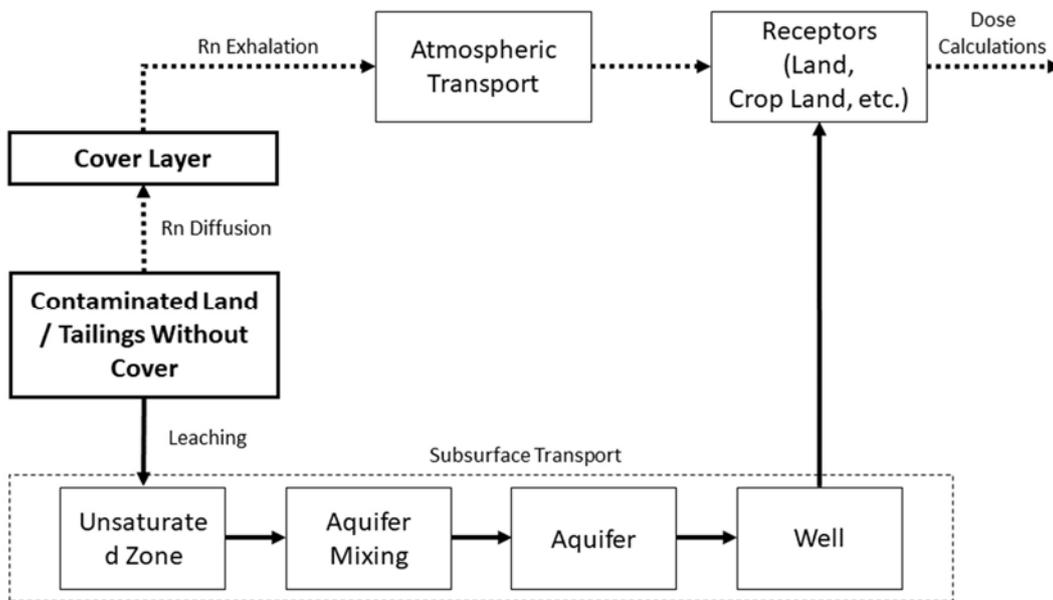
FIG. 4. Combined used of Source Term modules along with transport and receptor modules of the NORMALYSA library.

The calculated output flux of radionuclides leached to the subsurface can be used as an input to the 'Unsaturated Zone' transport module for simulation of radionuclide transport in the soil profile towards the aquifer (see Fig. 4).

Estimated ^{222}Rn concentrations in soil and atmosphere above the contaminated site can be used to estimate doses for person exposed to radioactivity immediately at the modelled site.

3.2.1.2. Conceptual model

The 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules assume that the source of radiation is a layer of contaminated soil (waste) of a given thickness, and that soil/waste material is homogeneous with respect to contaminant concentrations, as well as its hydraulic, geochemical properties and other transport parameters (see Fig. 5).

Hydraulic leaching process

For radionuclide leaching from contaminated soil by infiltrating atmospheric water, modules use the model described in Ref. [15]. This model assumes that all radionuclide inventory in contaminated material is present in mobile (exchangeable) form. For radionuclide sorption the assumptions are used of instantaneous and reversible sorption described by a linear isotherm, also known as a '*Kd* model' (*Kd* is the sorption distribution coefficient). Mathematical equations of the model are described in Section 3.2.2.

The source term modules discussed simulate radionuclide leaching processes from soil dynamically. However, it is assumed that radionuclide leaching from contaminated soil occurs under the steady state infiltration flux conditions (i.e. that infiltration rate through contaminated material is constant in time).
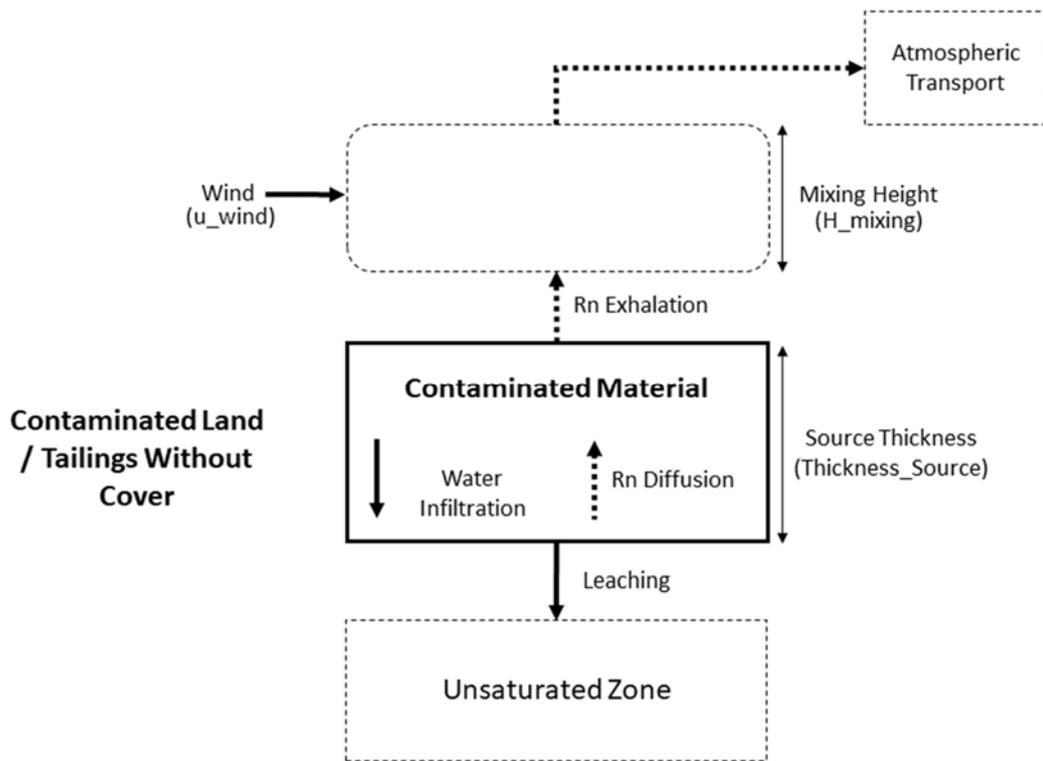
FIG. 5. Conceptual model of 'Contaminated Land/Tailing Without Cover' Modules.

Radon diffusion and exhalation from waste material

For radon (^{222}Rn) exhalation from waste material, the diffusion model described in Ref. [16] is used. This model assumes that the contaminated soil/waste layer thickness is much greater than the radon diffusion length.

The modules considered assume 'a point source' release model for the contaminated site. Therefore, the modules use a single release rate value (for each involved radionuclide) as representative of the whole source term system.

The radon concentration in air above the contaminated soil layer is calculated using the atmospheric mixing model described in Ref. [20].

For the calculation of radon concentrations in the air, the following assumptions hold:

— The annual average radon concentrations in the air are evaluated;
— The wind speed conservatively represents the annual average value;
— The wind direction flow is uniform around the compass;
— The location of the point where the calculations are made is the geometric centre of the contaminated area;
— The vertical dimension of the plume is conservatively bounded by 2 m, and a uniform concentration exists along the vertical plane for the downwind distance evaluated;
— The ^{222}Rn concentration to flux ratio is limited by a value of 500 s/m for a very large area of contamination — a value corresponding to the ratio of the radon concentration to the flux level generally observed in the natural environment;
— All emissions from ground surfaces are uniform.

Radon produced by decay in the contaminated soil layer migrates through this layer and emanates to the open atmosphere. Once in the open atmosphere, emanated radon is influenced by the dynamics of the wind, which remove part of the radon. Radon emanation from soil and radon removal by the wind in the near soil atmosphere interact in such a way that a steady state (equilibrium radon concentration in air) is reached.

3.2.1.3. Potential coupled modules

Initially, the 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules all provide release rates of radioactive contaminants from the source to transport modules (groundwater transport, atmospheric transport) of the NORMALYSA library.

Module simulation results can also be used to calculate exposure of a person present immediately at the contaminated site (see Table 7).

3.2.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Tailings Without Cover' and 'Contaminated Land Without Cover' modules are provided.

3.2.2.1. Mass balance equation for the source term compartment

The mass balance equation for the 'Source' compartment (Bq) (representing the soil waste layer containing the contaminated material; see Fig. 5) is given by the following equation:

$$\frac{dSource}{dt} = Infiltration - Source \times Leaching - \lambda \times Source + \qquad (1)$$
$$\sum_{p \in P} Br_p \times \lambda \times Source$$

where:

Infiltration is the mass transfer by infiltration (inflow) to the contaminated source (soil) layer (Bq/year);

λ is the decay constant (1/s);

Br_p is the branching ratio (Branching ratios indicate the fractions of decays of a nuclide to a daughter nuclide) of parent nuclide (unitless);

$\quad p \in P$ is one of parent nuclides from the set of parent nuclides;

Leaching is the mass transfer coefficient by radionuclide leaching from the source by infiltration water (1/year).

The terms $\lambda \times Source$ and $\sum_{p \in P} Br_p \times \lambda \times Source$ in Eq. (1) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Mass transfer by infiltration to the source term (Infiltration, Bq/year)

$$Infiltration = C_{infiltration} \times Rate_{infiltration} \times Area_{source} \qquad (2)$$

where:

$C_{infiltration}$ is the radionuclide concentration in water infiltrating to the contaminated material (soil) layer (Bq/m³);

$Rate_{infiltration}$ is the infiltration rate to contaminated site (m/year); and

$Area_{source}$ is the area of contaminated site (m²).

TABLE 7. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'TAILINGS WITHOUT COVER' AND 'CONTAMINATED LAND WITHOUT COVER' MODULES

Coupled module	Description of parameters used as loadings/inputs or outputs
Outputs from considered modules can be used by the following modules:	
'Unsaturated Zone', 'Aquifer Mixing', 'Aquifer'	Radioactive contaminant concentration (Bq/m^3) or activity flux to subsurface (Bq/year) in infiltrating water
'Atmosphere SR-19'	Radon (^{222}Rn) flux to the atmosphere (Bq/s) from contaminated site
'Dose from Occupancy Outdoors'	Volumetric concentration of radionuclides in soil/waste (Bq/m^3), concentration of radon in outdoor air (Bq/m^3)

Mass transfer coefficient by leaching (Leaching, 1/year)

The radionuclide mass transfer coefficient from contaminated source (soil) layer due to leaching is given by Refs [6, 15]:

$$Leaching = \frac{Rate_{infiltration}}{Moisture_{source} \times Thickness_{source} \times Ret_{source}} \quad (3)$$

where:

$Moisture_{source}$ is the moisture content in source (soil) material (unitless);
$Thickness_{source}$ is the thickness of the contaminated material (soil) layer (see Fig. 5) (m); and
Ret_{source} is the retardation coefficient due to radionuclide sorption on source (soil) materials (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{source} = 1 + \frac{Rho_{source}}{Moisture_{source}} \times Kd_{source} \quad (4)$$

where:

Rho_{source} is the density of source (soil) material (kg·DW/m^3); and
Kd_{source} is the sorption distribution coefficient for the source (soil) with respect to radionuclides (radionuclide-specific) (m^3/kg·DW).

3.2.2.2.   Radionuclide concentration in source material (soil) (C$_{source}$, Bq/kg)

The radionuclide concentration in source (soil) material (*C$_{source}$*, Bq/kg) is calculated dynamically as:

$$C_{source} = Source / (Area_{source} \cdot Thickness_{source} \cdot Rho_{source}) \quad (5)$$

3.2.2.3.   Radionuclide concentration in outflowing pore water (C$_{water,pore,out}$, Bq/m^3)

$$C_{water,pore,out} = \frac{C_{waste} \times Rho_{source}}{Moisture_{source} \times Ret_{source}} \quad (6)$$

3.2.2.4.   Radionuclide flux in outflowing pore water (Flux$_{out,gw}$, Bq/year)

$$Flux_{out,gw} = C_{water,pore,out} \times Rate_{infiltration} \times Area_{source} \quad (7)$$

3.2.2.5.   Radon release rate from the source (Rate$_{release,atm}$, Bq/s)

$$Rate_{release,atm} = Radon_{flux,out} \times Area_{source} \quad (8)$$

where:

$Radon_{flux,out}$ is the radon emission rate from the source per unit area (Bq/(m²·s)).

Radon emission rate from the source (Radon_flux,out, Bq/m²·s)

The radon emission (exhalation) from the source is given by the following formula which is taken from Ref. [16]:

$$Radon_{flux,out} = Rho_{source} \times C_{source}[Ra - 226] \times Coeff_{eman} \times \quad (9)$$
$$\sqrt{\lambda_{Rn} \times D_{radon,source}} \times \tanh\left(Thickness_{source} \Big/ \sqrt{D_{radon,source}/\lambda_{Rn}}\right)$$

where:

$Coeff_{eman}$ is the radon emanation coefficient from the source (soil) layer (unitless);
$D_{radon,source}$ is the diffusion coefficient of radon in the source (soil) layer (m²/s); and
λ_{Rn} is the radon decay constant (1/s).

3.2.2.6.   Radon concentration in outdoor air above the source (Radon_conc,air, Bq/m³)

The Radon concentration in outdoor air above the source is given by the formula taken from Ref. [20]:

$$Radon_{conc,air} = Rn_{flux,out} \times F_{a0} \times \left(1 - \exp\left(-\lambda_{Rn} \times \frac{0.5 \times Length_{eff}}{U_{wind}}\right)\right) \quad (10)$$
$$\times \frac{1}{\lambda_{Rn} \times H_{mixing}}$$

where:

F_{a0} is the outdoor area factor (unitless);
$Length_{eff}$ is the 'effective length' of contaminated site (m);
U_{wind} is the average wind speed (annual)(m/s); and
H_{mixing} is the mixing height for radionuclides above the source (m).

The 'effective length' of the contaminated site is calculated as:

$$Length_{eff} = \sqrt{Area_{source}} \quad (11)$$

The outdoor area factor (F_{a0}) is calculated as:

$$F_{a0} = \begin{cases} \frac{Area_{source}}{100}, for\ Area_{source} < 100\ m^2, \\ 1.0\ for\ Area_{source} > 100\ m^2 \end{cases} \quad (12)$$

It is also taken into account in calculations that the ratio:

$$CF_{ratio} = Radon_{conc,air}/Radon_{flux,out} \quad (13)$$

is bounded by the value 500 s/m [20]. Therefore, if calculations using the Eq. (10) yield value $CF_{ratio} > 500$ s/m, then the following corrected value is used for outdoor radon concentration:

$$Radon_{conc,air} = Rn_{flux,out} \times 500 \quad (14)$$

3.2.3. Input parameters

TABLE 8. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS FOR SOURCE TERM MODULES

Abbreviation and unit	Full name	Default value	Reference
C0_soil_t0 (Bq/kg·DW)	Initial contamination of soil in the source soil (waste)	0	Site specific parameter
C_infiltration (Bq/m^3)	Concentration of the radioactive contaminant in pore water infiltrating to the source	0	Site specific parameter

TABLE 9. INPUT PARAMETERS OF SOURCE TERM MODULES RELATED TO SITE GEOMETRY, HYDRAULIC PARAMETERS AND PHYSICAL AND CHEMICAL PROPERTIES OF SOURCE MATERIAL

Abbreviation and unit	Full name	Default value	Reference
Area_source (m^2)	Surface area of the modelled contaminated site	4000	Site specific parameter
Thickness_source (m)	Thickness of the contaminated source (soil) layer	8	Site specific parameter
Rho_source (kg·DW/m^3)	Source material (soil) bulk density	1500	Site specific parameter
Moisture_source (unitless)	Soil moisture content in the source material (soil)	0.15	Site specific parameter
Rate_infiltration (m/year)	Infiltration recharge rate to the source material (soil)	0.05	Site specific parameter
Kd_source (m^3/kg·DW)	Sorption distribution coefficient (radionuclide specific) of source material (soil)	Table 141 (Appendix)	See Table 14 of Ref. [8]

TABLE 10. INPUT PARAMETERS OF SOURCE TERM MODULES RELATED TO ATMOSPHERIC RELEASE RATE OF RADON FROM THE SOURCE MATERIAL

Abbreviation and unit	Full name	Default value	Reference
Coeff_eman (unitless)	Radon emanation coefficient from source (soil) material	0.2	[16]
D_radon_source (m^2/s)	Radon diffusion coefficient in source (soil) material	1.3E-6	[16]
H_mixing (m)	Mixing height of radionuclides above the source	2	[20]
U_wind (m/s)	Average wind speed	2	Site specific parameter

3.2.4. Output parameters

The output parameters of the source term module described above are radionuclide concentrations and fluxes in outflowing pore water from the modelled system, radon flux to the atmosphere from the source, as well as radionuclide concentrations in soil and the radon concentration in the air above the contaminated site.

TABLE 11. OUTPUT PARAMETERS OF SOURCE TERM MODULES

Abbreviation and unit	Full name	Purpose
Hydraulic releases		
C_water_pore_out (Bq/m^3)	Radioactive contaminant concentration in the pore water outflowing from the source term modules	Used to calculate further radionuclide transport in the underlying unsaturated zone and/or aquifer (see Table 7)
Flux_out _gw (Bq/year)	Radioactive contaminant flux from the source term modules	Used to calculate further radionuclide transport in the underlying unsaturated zone and/or aquifer (see Table 7)
Atmospheric releases		
Release_rate_radon (Bq/s)	Release rate of radon from the contaminated site to the atmosphere (cumulative over the site)	Used to calculate further radon dispersion in the atmosphere (see Table 7)
Radon_conc_air (Bq/m^3)	Radon concentration in the air above the site	Used to estimate the dose from inhalation of radon for a person exposed to radioactivity at the site
Radionuclide concentration in source material (soil)		
C_source (Bq/kg)	Radionuclide concentrations in the source material (soil) layer	Used to estimate doses from the external irradiation for a person exposed to radioactivity at the site

3.3. 'CHRONIC RELEASE' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Chronic release' module.

3.3.1. Module description

In this section, detailed descriptions of the 'Chronic release' module are provided.

3.3.1.1. *General description*

This module represents a simple model for chronic (constant in time) release of a radioactive contaminant to the atmosphere and/or aquatic object (unsaturated zone/aquifer or surface water body) (see Fig. 6). The release rates of radionuclides are directly specified by the modeller as module 'input–output' parameters.

3.3.1.2. *Potential coupled modules*

TABLE 12. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'CHRONIC RELEASE' MODULES

Coupled module	Description of parameters used as loadings/inputs or outputs
Output from module can be used by the following modules:	
'Atmosphere SR-19'	Radionuclide flux to the atmosphere (Bq/s) from the contaminated site
'Unsaturated Zone', 'Aquifer Mixing', 'Aquifer'	Radioactive contaminant activity flux to subsurface (Bq/year) in infiltrating water
'Fresh Water Body', 'Marine'	Radioactive contaminant activity flux (Bq/year) to surface water body
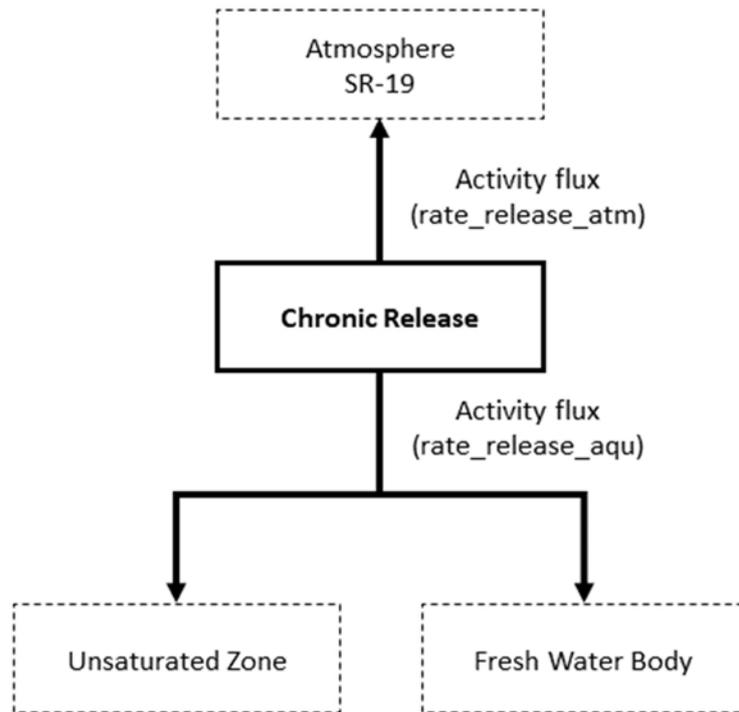
FIG. 6. Conceptual model of the 'Chronic Release' module.

3.3.2. Mathematical model

As mentioned previously, the modeller directly specifies release rates of radionuclides from the source of 'Chronic Release' to the relevant environmental media.

3.3.3. Input–output parameters

TABLE 13. INPUT–OUTPUT PARAMETERS OF 'CHRONIC RELEASE' MODULE

Abbreviation and unit	Full name	Default value	Purpose
Aquatic releases			
Rate_release_aqu (Bq/year)	Radioactive contaminant flux from the source term to the aquatic environment	0	Used to calculate further radionuclide transport in the underlying unsaturated zone, or aquifer or surface water body (see Table 12)
Atmospheric releases			
Rate_release_atm (Bq/s)	Release rate of radionuclides from the contaminated site to the atmosphere (cumulative over the site)	0	Used to calculate further radon dispersion in the atmosphere (see Table 12)

4. 'COVER LAYERS' MODULE LIBRARY

4.1. GENERAL DESCRIPTION OF THE LIBRARY

The 'Cover Layers' library includes modules for simulating soil covers over the source to calculate resulting radon exhalation rate and concentration in air above the cover, as well as the external dose rate.

The library includes two modules, i.e. 'Cover Layer' and 'House Slab'. The 'Cover Layer' module allows the simulation of a soil cover on top of the uranium mill tailings, and it calculates the resulting radon exhalation rate and concentration in the air above the cover, as well as the external dose rate. The 'House Slab' module simulates the effect of the house slab residing on the contaminated soil layer on the radon diffusive flux to house and external dose rate above the slab. Detailed descriptions of these modules are provided in Section 4.2.

4.2. 'COVER LAYER' AND 'HOUSE SLAB' MODULES

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Cover Layer' and 'House Slab' modules.

4.2.1. Module description

In this section, detailed descriptions of the 'Cover Layer' and 'House slab' modules are provided.

4.2.1.1. General description

The objectives of the 'Cover Layer' and 'House Slab' modules are to model, respectively, the cover layer of soil (i.e. engineered barrier) or house slab (basement) on top of the source term of radioactivity (such as the 'Tailings Without Cover' or 'Contaminated Land Without Cover' modules discussed in the previous section of this publication) (see Fig. 7).

These modules allow the estimation of the influence of the cover layer on the following radiological impacts from the contaminated site:

—— Radon (^{222}Rn) release rate to the atmosphere and concentration in the atmosphere above the contaminated site;
—— Dose rate on the surface of the contaminated site covered by a layer.

In the approach applied for modelling, the 'Cover Layer' compartment functions as an interphase between the previous compartment (contaminated source or another cover layer) and the next one (another contaminated layer or the open atmosphere) (see Fig. 7).

Several modules can be used to model a multilayer soil cover with varying physical properties.

Moreover, the modules 'Cover Layer' and 'House Slab' employ the same mathematical models and use same notation of input data and output parameters. The only difference is that the 'House Slab' module does not calculate the radon concentration in the air above the house basement. Only radon flux from the basement is calculated. In the case of the 'House Slab' module, radon concentration inside the house may be calculated using the 'House' receptor module.

In the following sections, the conceptual model (see Fig. 8), the mathematical model and input/output parameters are presented for the 'Cover Layer' module. These models and parameter descriptions are fully applicable to the 'House Slab' module (taking into account the remarks given above).
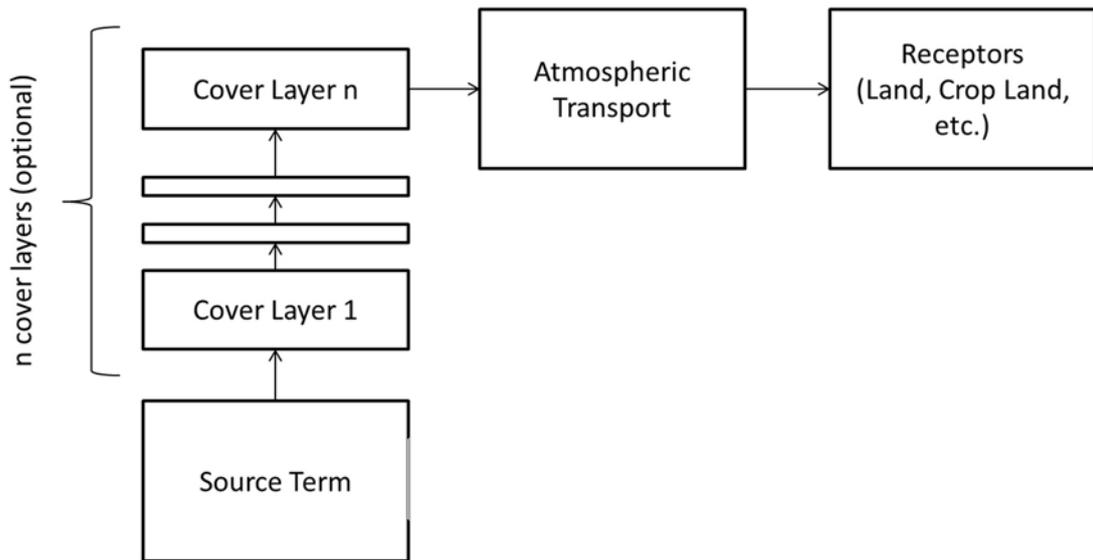
FIG. 7. Scheme illustrating application of 'Cover Layer' module for modelling atmospheric releases from the source term of radioactivity.
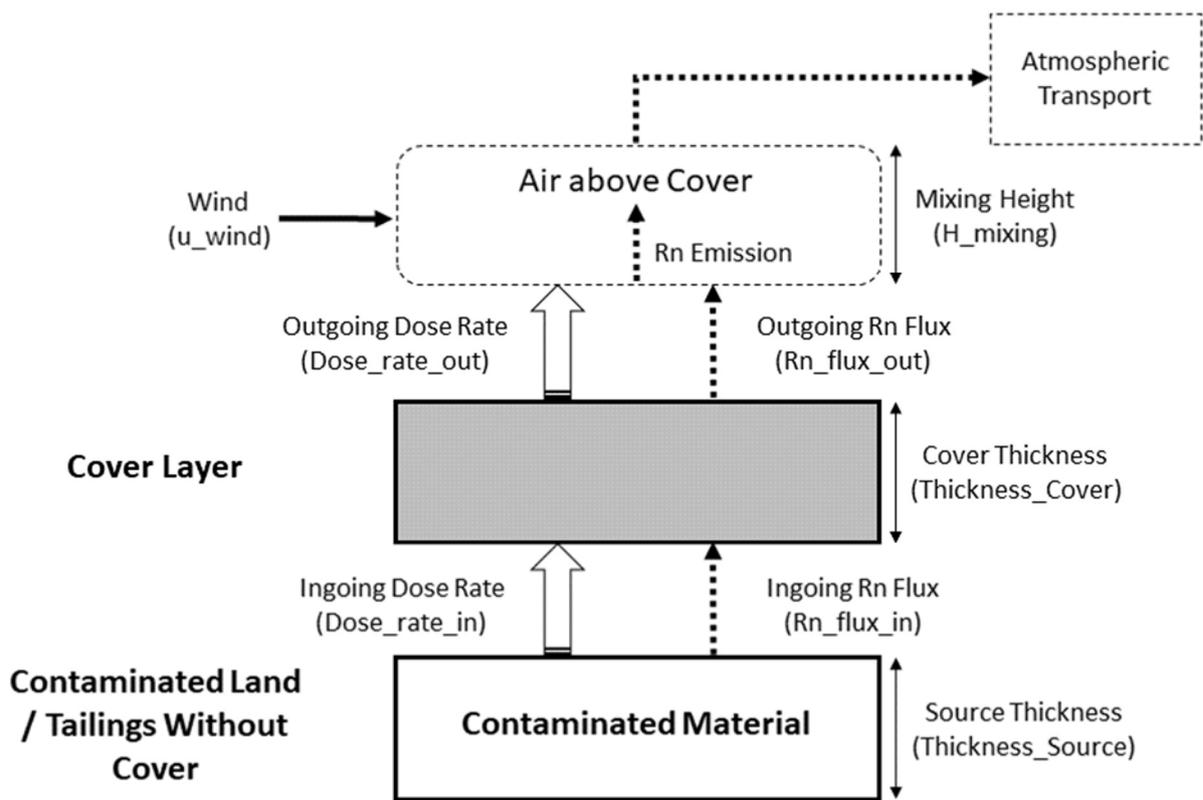
FIG. 8. Conceptual model of 'Cover Layer' module.

TABLE 14. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'COVER LAYER' MODULES

Coupled module	Description of parameters used as loadings/inputs or outputs
Modules providing inputs (loads) to 'Cover Layer' module	
'Contaminated Land Without Cover', 'Tailings Without Cover'; previous 'Cover Layer' module	Radon (^{222}Rn) flux to the atmosphere (Bq/year) from contaminated site; effective dose rate from contaminated material per radionuclide (Sv/h)
Outputs from combined 'Cover Layer' and source term modules can be used by following modules	
'Atmosphere SR-19'	Radon (^{222}Rn) flux to the atmosphere (Bq/s) from contaminated site
'Dose from Occupancy Outdoors'	Effective dose rate outdoors (Sv/h), concentration of ^{222}Rn in outdoor air (Bq/m^3)
'Cover Layer' (next module)	Radon (^{222}Rn) flux to the atmosphere (Bq/s) from contaminated site; effective dose rate from contaminated material per radionuclide (Sv/h)

4.2.1.2. Conceptual model

It is assumed that the soil cover layer has a uniform thickness and that this layer is homogenous with respect to its physical properties and parameters.

Fig. 8 above illustrates the conceptual model for a contaminated site with a cover layer. The source of radioactivity (contaminated layer containing ^{226}Ra, which is the parent radionuclide for ^{222}Rn) is covered by one (or several) radiologically inert layer(s).

For modelling the impact of soil cover on the radon release rate to the atmosphere, the model described in Ref. [16] is used.

Radon concentration in air above the soil cover is calculated using the atmospheric mixing model described in Ref. [20] and the underlying assumptions are discussed in Section 3.2.1.2 of this publication.

In order to calculate the dose rate from a contaminated site covered by one or several cover layers, the approach described in Ref. [17] is used.

4.2.1.3. Potential coupled modules

The 'Cover Layer' module can be coupled with the source term modules from the NORMALYSA library (for inputs/loads) and atmospheric transport modules and dose modules (for outputs) (see Table 14). The 'Cover Layer' can also exchange input/output parameters with other similar consecutive modules simulating a multilayer cover screen on top of the contaminated site.

4.2.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Cover Layer' and 'House slab' modules are provided.

4.2.2.1. Radon release rate from the cover layer ($Rate_{release\_atm}$, Bq/s)

$$Rate_{release\_atm} = Radon_{flux\_out} \times Area_{source} \tag{15}$$

where:

$Radon_{flux\_out}$ is the radon emission rate from the cover layer per unit area (Bq/(m²·s)).

Radon emission rate from the cover layer ($Radon_{flux\_out}$, Bq/(m²·s))

The radon emission (exhalation) from the cover layer ($Radon_{flux,out}$, Bq/(m²·s)) is given by the following formula [16]:

$$Radon_{flux\_out} = Radon_{flux\_in} \times exp\left(-Thickness_{cover} \times \sqrt{\frac{\lambda_{Rn}}{D_{cover}}}\right) \qquad (16)$$

where:

$Radon_{flux\_in}$ is the radon emission rate to cover layer from the source of radioactivity or previous cover layer (Bq/(m²·s));
$Thickness_{cover}$ is the thickness of the cover layer (m);
D_{cover} is the diffusion coefficient of radon in the cover layer (m²/s); and
λ_{Rn} is the radon decay constant (1/s).

4.2.2.2. Radon concentration in outdoor air above the cover layer ($Radon_{conc\_air}$, Bq/m³)

The radon concentration in outdoor air above the cover layer is given by the following formula [20]:

$$Radon_{conc\_air} = Rn_{flux\_out} \times F_{a0} \times \left(1 - \exp\left(-\lambda_{Rn} \times \frac{0.5 \times Length_{eff}}{U_{wind}}\right)\right) \qquad (17)$$
$$\times \frac{1}{\lambda_{Rn} \times H_{mixing}}$$

where:

F_{a0} is the outdoor area factor (unitless);
$Length_{eff}$ is the 'effective length' of contaminated site (m);
U_{wind} is the average wind speed (annual)(m/sec); and
H_{mixing} is the mixing height for radionuclides above the source (m).

The 'effective length' of contaminated site is calculated as:

$$Length_{eff} = \sqrt{Area_{source}} \qquad (18)$$

The outdoor area factor (F_{a0}) is calculated as:

$$F_{a0} = \begin{cases} \frac{Area_{source}}{100}, for\ Area_{source} < 100\ m^2, \\ 1.0\ for\ Area_{source} > 100\ m^2 \end{cases} \qquad (19)$$

It is also taken into account in calculations that the ratio:

$$CF_{ratio} = Radon_{conc\_air}/Radon_{flux\_out} \qquad (20)$$

is bounded by the value 500 s/m [20]. Therefore, if calculations using Eq. (17) above, yield the value $CF_{ratio} > 500$ s/m, then the following corrected value is used for outdoor radon concentration:

$$Radon_{conc\_air} = Rn_{flux\_out} \times 500 \qquad (21)$$

4.2.2.3.   Effective dose rate on top of the cover layer (DoseRate$_{eff\_out}$, Sv/h)

Effective dose rate on top of cover layer is calculated as:

$$DoseRate_{eff\_out} = \sum_i DoseRate_{eff\_out\_RNi} \tag{22}$$

where:

$DoseRate_{eff\_out\_RNi}$ is the dose rate formed by radionuclide *'i'* (Sv/h).

Dose rate formed by radionuclide *'i'* (DoseRate$_{eff\_out\_RNi}$, Sv/h)

$$DoseRate_{eff\_out\_RNi} = DoseRate_{eff\_out\_RN\_in_i} \times Factor\_Cover_{depth} \tag{23}$$

where:

$DoseRate_{eff\_out\_RN\_in_i}$ is the dose rate formed by radionuclide *'i'* before attenuation by cover (Sv/h); and

$Factor\_Cover_{depth}$ is the correction factor (coefficient) accounting for attenuation by cover of dose rate from radionuclide (unitless).

Correction factor (coefficient) accounting for dose rate attenuation (Factor_cover$_{depth,i}$)

The correction factor accounting for dose rate attenuation, depending on the thickness and density of the cover material, is given by the following formula [17]:

$$\begin{aligned}
Factor_{cover\,depth,i} = &\left(A_i \times \exp\left(-0.1 \times K_{A,i} \times Rho_{cover_{eff}} \times Thickness_{cove\,out}\right)\right) \times \\
&\left(1.0 - \exp(-0.1 \times K_{A,i} \times Rho_{sourc} \times Thickness_{source})\right) + \\
&\left(B_i \times \exp\left(-0.1 \times K_{B,i} \times Rho_{cover_{eff}} \times Thickness_{cover_{out}}\right)\right) \times \\
&(1.0 - \exp(-0.1 \times K_{B,i} \times Rho_{source} \times Thickness_{source}))
\end{aligned} \tag{24}$$

where:

Rho_source is the density of source term layer (Bq/kg·DW);

Rho_cover_eff is the effective cover density, calculate as the sum of cover densities weighted by cover thicknesses (kg·DW/m³);

Thickness_source is the thickness of source term layer (m);

Thickness_cover_out is the total thickness of covers (m);

A_i, B_i, is the tabulated fitted radionuclide-specific parameters for calculating cover correction factors (unitless) (provided in Ref. [17]); and

$K_{A,i}$, $K_{B,i}$ is the tabulated fitted radionuclide-specific parameters for calculating cover correction factors (g/cm²) (provided in ref. [17]).

Here:

$$Rho_{cove\,eff} = RhoXthickness_{out}/Thickness_{cove\,out} \tag{25}$$

where:

RhoXthickness_out is the cumulative sum of products of density cover times cover thickness for all cover layers (kg·DW/m²).

The last parameter is defined as:

$$RhoXthickness_{out} = RhoXthickness_{in} + Rho_{cover} \times Thickness_{cover} \tag{26}$$

where:

$Thickness_{cover}$ is the thickness of the cover layer (input parameter to be provided by the modeller) (m);

Rho_{cover} is the cover layer material (soil) bulk density (kg·DW/m^3);

$RhoXthickness\_in$ is the product of density cover times cover thickness for previous layer(s) (input parameter to be provided by the modeller) (kg·DW/m^2).

4.2.3.   Input parameters

TABLE 15. INPUT PARAMETERS RELATED TO RADIOLOGICAL LOADS FOR 'COVER LAYER' MODULE

Abbreviation and unit	Full name	Default value	Reference
Radon_flux_In (Bq/(m^2·s))	Radon flux incoming from the source or previous cover layer	0	Site specific parameter
DoseRate_eff_out_RN_in (Sv/h)	Effective dose rate before attenuation by the cover	0	Site specific parameter

TABLE 16. INPUT PARAMETERS OF 'COVER LAYER' MODULE RELATED TO SITE GEOMETRY AND PHYSICAL PROPERTIES OF COVER LAYER(S) AND SOURCE MATERIAL

Abbreviation and unit	Full name	Default value	Reference
Area_source (m^2)	Surface area of the modelled contaminated site	4000	Site specific parameter
Thickness_source (m)	Thickness of the contaminated source (soil) layer	8	Site specific parameter
Rho_source (kg·DW/m^3)	Source material (soil) bulk density	1500	Site specific parameter
Thickness_cover (m)	Thickness of the cover layer	0.5	Site specific parameter
Rho_cover (kg·DW/m^3)	Cover layer material (soil) bulk density	1300	Site specific parameter
Thickness_cover_in (m)	Previous cumulative thickness of all covers (m)	0	Site specific parameter
RhoXthickness_in (kg·DW/m^2)	Product of density cover times cover thickness for previous layer(s)	0	Site specific parameter

TABLE 17. INPUT PARAMETERS OF 'COVER LAYER' MODULE RELATED TO ATMOSPHERIC RELEASE RATE OF RADON FROM COVER LAYER

Abbreviation and unit	Full name	Default value	Reference
D_cover (m^2/s)	Radon diffusion coefficient in cover layer	7.8E-7	[16]
H_mixing (m)	Mixing height of radionuclides above the cover layer	2	[20]
U_wind (m/s)	Average wind speed	2	Site specific parameter

4.2.4. Output parameters

TABLE 18. OUTPUT PARAMETERS OF 'COVER LAYER' MODULE

Abbreviation and unit	Full name	Purpose
Atmospheric releases		
Release_rate_radon (Bq/s)	Release rate of radon from the contaminated site to the atmosphere (cumulative over the site)	Used to calculate further radon dispersion in the atmosphere (see Table 14)
Radon_conc_air (Bq/m^3)	Radon concentration in the air above the site	Used to estimate the dose from inhalation of radon for a person exposed to radioactivity at the site
Dose rate from the site		
Dose_rate_eff_out (Sv/h)	Effective dose rate outdoors taking into account attenuation in the cover layer	Used to estimate the dose from external irradiation for a person exposed to radioactivity at the site

5. 'TRANSPORTS' MODULE LIBRARY

5.1. GENERAL DESCRIPTION OF THE LIBRARY

The 'Transports' library includes modules for calculation of radionuclide transport in the atmosphere, groundwater or surface runoff from the contamination source to different receptor environments (see Table 3).

Modules 'Aquifer Mixing', 'Aquifer', and 'Unsaturated Zone' are designed for modelling groundwater transport. Modules 'Atmosphere SR-19' and 'Atmosphere Chronic' simulate radionuclide transport in the atmosphere. The 'Surface runoff' module simulates radionuclide transport from the contaminated watershed in overland flow.

Before discussing individual modules, some additional explanations are presented below on typical combined use of groundwater transport modules for simulating the radionuclide migration process in subsurface environment.

The generic schematization of the groundwater transport process in NORMALYSA for assessment purposes is shown in Fig. 9.

The subsurface environment is schematized into the following compartments:

— 'Unsaturated Zone', where vertical radionuclide migration is assumed to occur from the source of migration towards the saturated groundwater aquifer;
— 'Aquifer Mixing' zone below the contaminated site, where vertical infiltration from the unsaturated zone mixes with the horizontal groundwater flux in the aquifer;
— 'Aquifer' zone, where radionuclide transport occurs sub-horizontally in groundwater flow towards the relevant receptor point (e.g. a well or surface water body).

The respective representation of the transport process by compartmental model is presented in Fig. 10.

Detailed descriptions of the individual modules from the 'Transports' library are provided in Sections 5.2–5.7.
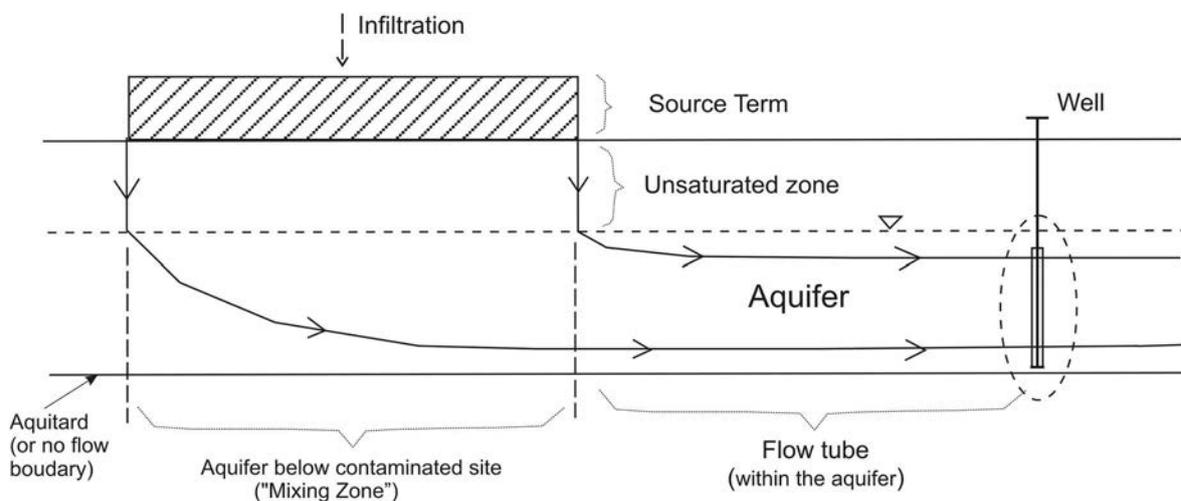
FIG. 9. Schematization of groundwater transport calculations in NORMALYSA.
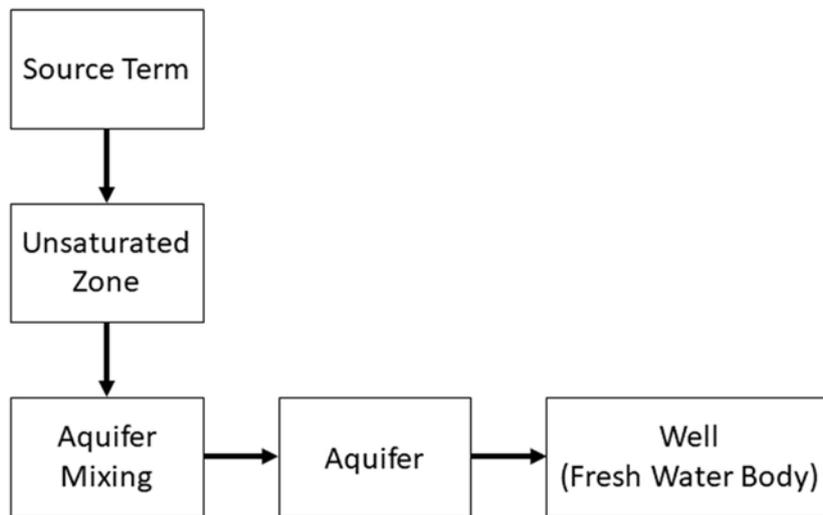
FIG. 10. Compartmental model for groundwater transport from contaminated site using NORMALYSA modules (arrows show data exchanges between modules).

5.2. 'AQUIFER MIXING' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Aquifer mixing' module.

5.2.1. Module description

In this section, detailed descriptions of the 'Aquifer mixing' module are provided.

5.2.1.1. General description

The 'Aquifer Mixing' module simulates the section of groundwater aquifer situated immediately below the contaminated site (see Fig. 9). This module usually receives contaminant input from the source of the radioactivity (e.g. 'Tailings Without Cover', 'Contaminated Land' modules), which may be further coupled with the 'Unsaturated Zone' module, simulating intermediate contaminant transfer in unsaturated soil between the source of the radionuclide migration and the saturated zone of geological deposits (i.e. aquifer) (see Fig. 10).

The inputs of radioactive contaminant(s) into the 'Aquifer Mixing' compartment can have the following physical origins:

— Contaminants leached from the waste disposal facilities (such as uranium mill tailings facilities);
— Contaminants originating from a contaminated topsoil layer due to leaching by atmospheric precipitations;
— Contaminants originating from the direct application of liquid effluents on topsoil (e.g. direct application of sludge originating from sewage treatment plants or fertilizers).

The output of the 'Aquifer Mixing' module usually serves as an input to the 'Aquifer' module simulating radionuclide transport in groundwater horizontally towards receptor points of interest (e.g. 'Well' or 'Fresh Water Body' module(s)) (see Fig. 10).
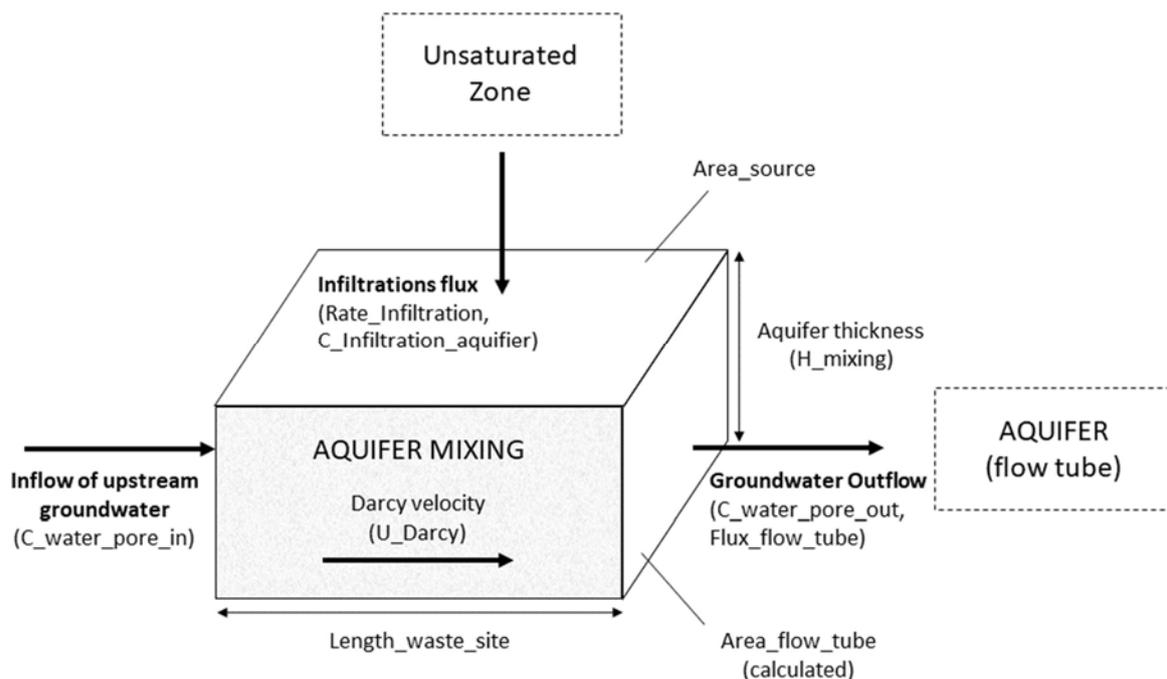
FIG. 11. Conceptual model of the 'Aquifer Mixing' compartment.

5.2.1.2. Conceptual model

The 'Aquifer Mixing' module schematizes the groundwater aquifer immediately below the contaminated site as a single compartment with homogeneous hydraulic and geochemical properties. The physical dimensions of the 'Aquifer Mixing' module (i.e. its length, width and height) are usually determined by the geometry of the source zone and features of the hydrogeological system under investigation (see Fig. 11).

The 'Aquifer Mixing' module simulates radionuclide transfer processes within the hydrogeological environment dynamically. However, it is assumed that radionuclide transport in the aquifer occurs under the steady state groundwater flow conditions (i.e. that the infiltration rate from the source and horizontal groundwater flow velocity in the aquifer are constant in time).

The exchanges of radioactive contaminants between pore water and soil matrix are assumed to be at sorption equilibrium. Radioactive contaminant concentrations in pore water and soil matrix are calculated for this compartment based on a known layer inventory and equilibrium *Kd* sorption model using the corresponding partitioning equation.

The inputs of radioactive contaminant(s) into the 'Aquifer Mixing' system may occur through the following mechanisms:

—— Vertical infiltration from the contaminant source situate above the aquifer; or
—— Horizontal contaminant inflow from the upstream (contaminated) aquifer zone.

Contaminant inputs by the infiltration mechanism need to be defined by the user in the coupled external source model (possibly coupled with modules simulating intermediate transfers such as the 'Unsaturated Zone' module).

Losses of radioactive contaminant(s) from the 'Aquifer Mixing' compartment include:

— Contaminant leaving the 'Aquifer Mixing' system towards adjacent downstream zones of the hydrogeological system (e.g. consecutive 'Aquifer' module) by outflow (i.e. contaminant movement by advective outflow);

— Radioactive decay of the contaminant in the aquifer media.

5.2.1.3. *Potential coupled models*

TABLE 19. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'AQUIFER MIXING' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by the following modules:	
Source Term models ('Tailings without cover', 'Contaminated Land'), 'Unsaturated Zone'	Radioactive contaminant concentration (Bq/m^3) or activity flux (Bq/year) in infiltrating water
Outputs from module can be used by the following modules:	
'Aquifer', 'Well', 'Fresh Water Body'	Radioactive contaminant concentration (Bq/m^3) or activity fluxes (Bq/year) in outflow water

5.2.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Aquifer mixing' module are provided.

5.2.2.1. *Mass balance equation for aquifer compartment*

The mass balance for the activity of radionuclides in the 'Aquifer Mixing' compartment (*AM, Bq*) is given by the following differential equation:

$$\frac{dAM}{dt} = Inflow + Infiltration - Advection_{gw_{out}} \times AM - \lambda \times AM + \sum_{P \in Pi} Br_p \times \lambda \times AM \tag{27}$$

where:

Infiltration is the mass transfer by vertical infiltration to the 'Aquifer Mixing' cell (Bq/year); *Inflow* is the mass transfer by horizontal inflow to the 'Aquifer Mixing' cell (Bq/year); and *Advection$_{gw\_out}$* is the mass transfer coefficient by advective transport from the cell (1/year).

The terms $\lambda \times AM$ and $\sum_{p \in P} Br_p \times \lambda \times AM$ in Eq. (27) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Mass transfer by infiltration (Infiltration, Bq/year)

$$Infiltration = Area_{source} \times C_{infiltration} \times Rate_{infiltration} \tag{28}$$

where:

Area$_{source}$ is the area of 'Aquifer Mixing' cell (same as the area source of contamination to the aquifer) (m^2);
C$_{infiltration}$ is the radionuclide concentration in water infiltrating to the aquifer (Bq/m^3); and
Rate$_{infiltration}$ is the infiltration rate to the aquifer (m/year).

Mass transfer by horizontal inflow (Inflow, Bq/year)

$$Inflow = C_{waterporein}(u_{Darcy} \times Area_{flow\_tube} - Area_{source} \times Rate_{infiltration}) \quad (29)$$

where:

u_{Darcy} is the groundwater Darcy velocity in the aquifer (m/year);
$Area_{flow\_tube}$ is the cross sectional area of the flow tube (m^2); and
$C_{water\ pore\ in}$ is the radionuclide concentration in groundwater entering the aquifer compartment from an upstream direction (Bq/m^3).

The parameter $Area_{flow\_tube}$ is calculated as follows:

$$Area_{flow\_tube} = H_{mixing} \times Width_{waste\_site} \quad (30)$$

where:

H_{mixing} is the aquifer mixing zone (flow tube) thickness (see Fig. 11) (m); and
$Width_{waste\_site}$ is the width of the waste site (m).

The parameter $Width_{waste\_site}$ is calculated as follows:

$$Width_{waste\_site} = \frac{Area_{source}}{Length_{waste\_site}} \quad (31)$$

where:

$Length_{waste\_site}$ is the length of the contaminated site along the groundwater flow direction (see Fig. 11) (m).

Mass transfer coefficient by advective transport (Advection$_{gw\_out}$, 1/year)

The mass transfer coefficient by advection in the aquifer is calculated as follows (taken from Appendix C of Ref. [6]:

$$Advection_{gw\_out} = \frac{u_{Darcy}}{Porosity_{aquifer} \times Length_{waste\_site} \times Ret_{aquifer}} \quad (32)$$

where:

$Porosity_{aquifer}$ is the aquifer porosity (unitless); and
$Ret_{aquifer}$ is the radionuclide retardation coefficient due to radionuclide sorption on the aquifer materials (unitless).

Retardation coefficient in the aquifer (Ret$_{aquifer}$, unitless)

$$Ret_{aquifer} = 1 + \frac{Rho_{aquifer}}{Porosity_{aquifer}} \times Kd_{aquifer} \quad (33)$$

where:

$Rho_{aquifer}$ is the density of soil in the aquifer (kg/m^3); and
$Kd_{aquifer}$ is the sorption distribution coefficient for the aquifer sediments with respect to radionuclides (radionuclide dependent) (m^3/kg).

5.2.2.2. Radionuclide concentration in groundwater

The radionuclide concentration in the groundwater ($C_{\_water\_pore\_out}$, Bq/m^3) is dynamically calculated from the radionuclide inventory in the 'Aquifer Mixing' compartment (*AM*):

$$C_{water\_pore\_out} = \frac{AM}{Are_{source} \times H_{mixing}} \times \frac{1}{Porosity_{aquifer} \times Ret_{aquifer}} \qquad (34)$$

5.2.2.3. Activity flux in water from the compartment

The activity flux in the groundwater ($Flux_{flow\_tube}$, Bq/year) is calculated using the formula:

$$Flux_{flow\_tube} = u_{Darcy} \times Area_{flow\_tube} \times C_{water\_pore\_out} \qquad (35)$$

5.2.3. Input parameters

TABLE 20. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS FOR 'AQUIFER MIXING' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_infiltration_aquifer (Bq/m^3)	Concentration of the radioactive contaminant in water infiltrating to the aquifer	0	Site specific parameter
Rate_infiltration (m/year)	Infiltration rate to the aquifer	0.3	Site specific parameter
C_water_pore_in (Bq/m^3)	Concentration of radionuclides in groundwater inflowing to the aquifer from upstream direction	0	Site specific parameter
C0_gw_aquifer (Bq/m^3)	Initial contamination of groundwater in the aquifer by radionuclides	0	Site specific parameter

TABLE 21. INPUT PARAMETERS OF 'AQUIFER MIXING' MODULE RELATED TO SITE GEOMETRY, HYDRAULIC PARAMETERS AND PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

Abbreviation and unit	Full name	Default value	Reference
Area_source (m^2)	Waste site area	4000	Site specific parameter
Length_waste_site (m)	Length of the waste site	200	Site specific parameter
H_mixing (m)	Aquifer mixing thickness	10	Site specific parameter
Rho_aquifer (kg·DW/m^3)	Aquifer material bulk density	1600	Value for sandy deposits
Porosity_aquifer (unitless)	Aquifer porosity	0.3	Value for sandy deposits
u_Darcy (m/year)	Darcy velocity in the aquifer	10	Site specific parameter
Kd_aquifer (m^3/kg·DW)	Sorption distribution coefficient (radionuclide specific)	Table 141 (Appendix)	See Table 14* of Ref. [8]

Note: * mean *Kd* value for 'all soils'

5.2.4. Output parameters

The main output parameter of the 'Aquifer Mixing' module is the radionuclide concentration in outflowing groundwater from the compartment (see Eq. (34)). The module also calculates the activity flux from the compartment (see Eq. (35)).

TABLE 22. OUTPUT PARAMETERS OF 'AQUIFER MIXING' MODULE

Abbreviation and unit	Full name	Purpose
C_water_pore_out (Bq/m³)	Radioactive contaminant concentration in the porous solutions outflowing from the 'Aquifer Mixing' cell	To calculate doses from contaminated groundwater. Can also be used to calculate further radionuclide transport in the 'Aquifer', 'Well' or 'Fresh Water Body' modules (see Table 19)
Flux_flow_tube (Bq/year)	Radioactive contaminant flux from the 'Aquifer Mixing' cell (integral over aquifer cross section)	To calculate activity inputs to the 'Aquifer', 'Well' or 'Fresh Water Body' modules (see Table 19)

5.3. 'AQUIFER' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Aquifer' module.

5.3.1. Module description

In this section, detailed descriptions of the 'Aquifer' module are provided.

5.3.1.1. General description

The goal of the 'Aquifer' module is to dynamically simulate transport of radioactive contaminants within the groundwater aquifer towards receptor environment(s).

This module usually receives contaminant input from the upstream 'Aquifer Mixing' module (see the block scheme shown in Fig. 10). Alternatively, this module can receive inputs from the upstream 'Aquifer' module. (Several consecutive 'Aquifer' modules can be used for aquifers with spatially varying physical or geochemical properties or varying initial contamination conditions.)

The output of the 'Aquifer' module usually serves as an input to the receptor module(s) (e.g. 'Well', or 'Fresh Water Body').

5.3.1.2. Conceptual model

The 'Aquifer' module assumes that the aquifer system is homogeneous with respect to its hydraulic and geochemical properties and parameters (see Fig. 12).

For aquifer environments showing laterally (horizontally) significant variations in their properties, it is recommended to subdivide these latter in a sequence of homogeneous and independent flow zones that can be modelled by several consecutive 'Aquifer' modules.

The transport process taken into account by the module includes advection, hydrodynamic dispersion, radioactive decay and ingrowth of daughter radionuclides from parent radionuclides, and radionuclide sorption by soil matrix. For radionuclide sorption, the assumptions are used of instantaneous and reversible sorption described by a linear isotherm, also known as a 'Kd model' (Kd is the sorption distribution coefficient).
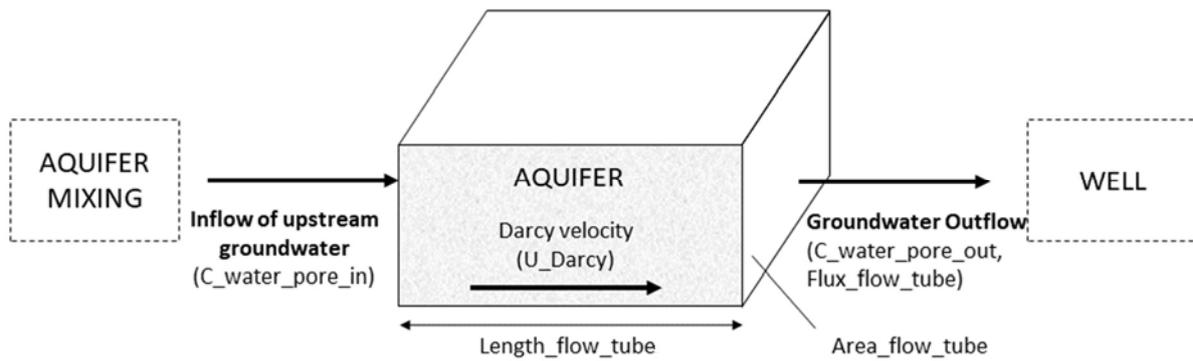
FIG. 12. Conceptual model of the 'Aquifer' module.
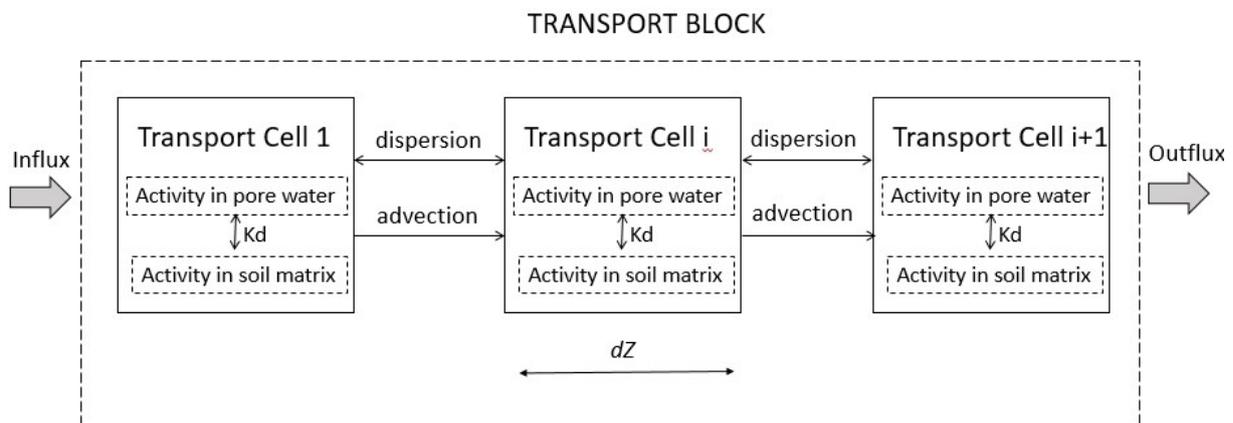
FIG. 13. Representation of the modelled aquifer system by a sequence of individual transport cells using Ecolego 'Transport' block.

The 'Aquifer' module simulates radionuclide transfer processes within the hydrogeological environment dynamically. However, it is assumed that radionuclide transport in the aquifer occurs under the steady state groundwater flow conditions (i.e. that groundwater flow velocity in the aquifer is constant in time).

For numerical analysis, the 'Aquifer' module represents the groundwater aquifer (flow tube) system as a sequence of individual transport cells with a constant length. Exchanges between individual cells include transfers due to the advection and dispersion process following the approach described in Appendix C of Ref. [6]. The respective schematization is represented in Fig. 13. The model expressions operate total radionuclide inventories in each transport cell. Subsequently radioactive contaminant concentrations in pore water and the soil matrix can be calculated for each transport cell based on the known cell inventory and the equilibrium Kd based sorption model describing radionuclide partitioning between the liquid and solid phases (see Section 5.3.2 for model formulas).

The number and horizontal size of cells is determined automatically based on specified accuracy requirements (see Section 5.3.2.5). The program generates the necessary number of cell compartments using the Ecolego 6 'Transport' block.

5.3.1.3.   Potential coupled models

TABLE 23. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'AQUIFER' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by following modules:	
'Unsaturated Zone', 'Aquifer Mixing', 'Aquifer' (upstream module)	Radioactive contaminant concentration (Bq/m^3) or activity flux (Bq/year) in infiltrating water
Outputs from module can be used by following modules:	
'Well', 'Fresh Water Body', 'Aquifer' (downstream module)	Radioactive contaminant concentration (Bq/m^3) or activity fluxes (Bq/year) in outflow water

5.3.2.   Mathematical model

This section provides a detailed description of the mathematical model of the 'Aquifer' module.

5.3.2.1.   Mass balance equation for aquifer transport cells

The mass balance equation for the *'Transp_Cell_i'* (Bq) compartment (see Fig. 13) is given by:

$$
\begin{aligned}
dTransp\_Cell_i &= Advection_{aquifer} \times Transp\_Cell_{i-1} - Advection_{aquifer} \times Transp_{Cell_i} \\
&- Disperson_{aq_{forward}} \times Transp_{Cell_i} - Dispersion_{aq_{back}} \times Transp_{Cell_i} \\
&+ Dispersion_{aq_{back}} \times Transp_{Cell_{i+1}} \\
&+ Dispersion_{aq_{forwa}} \times Transp_{Cell_{i-1}} - \lambda \times Transp_{Cell_i} \\
&+ \sum_{p \in P} Br_p \times \lambda \times Transp_{Cell_i}
\end{aligned}
$$

(36)

where:

Advection$_{aquifer}$ is the mass transfer coefficient by advective transport (1/year);
Dispersion$_{aq\_forward}$ is the mass transfer coefficient by forward dispersive transport (1/year); and
Dispersion$_{aq\_back}$ is the mass transfer coefficient by backward dispersive transport (1/year).

The terms $\lambda \times Transp_{Cell_i}$ and $\sum_{p \in P} Br_p \times \lambda \times Transp_{Cell_i}$ in Eq. (36) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Here mass transfer coefficients are calculated as follows (taken from Appendix C of Ref. [6]):

Mass transfer coefficient by advective transport (advection$_{aquifer}$, 1/year)

$$
Advection_{aquifer} = \frac{u_{Darcy}}{Porosity_{aquifer} \times dz \times Ret_{aquifer}}
$$

(37)

where:

u$_{Darcy}$ is the groundwater Darcy velocity in the aquifer (m/year);
Porosity$_{aquifer}$ is the aquifer porosity (unitless);
dZ is the horizontal size of transport cell in the aquifer (m); and
Ret$_{aquifer}$ is the retardation coefficient due to radionuclide sorption on aquifer materials (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{aquifer} = 1 + \frac{Rho_{aquifer}}{Porosity_{aquifer}} \times Kd_{aquifer} \qquad (38)$$

where:

$Rho_{aquifer}$ is the density of soil in the aquifer (kg/m^3); and
$Kd_{aquifer}$ is the sorption distribution coefficient for the aquifer sediments with respect to radionuclides (radionuclide-specific) (m^3/kg).

Mass transfer coefficient by dispersive transport (Dispersion$_{aq\_forward}$, 1/year)

$$Dispersion_{aq\_forward} = \frac{Dispersivity_{aq} \times u_{Darcy}}{Porosity_{aquifer} \times dz^2 \times Ret_{aquifer}} \qquad (39)$$

where:

$Dispersivity_{aq}$ is the dispersivity parameter for solute transport in the aquifer (m).

The expression for mass transfer coefficient $dispersion_{aq\_back}$ is the same as for $dispersion_{aq\_forward}$.

5.3.2.2.   Mass balance equation for the first Transport Cell in the aquifer

The mass balance equation for the 'Transp_Cell_1' (1st Transport Cell) is given by:

$$\frac{dTransp\_Cell_1}{dt} = Infiltration - Dispersion_{aq\_forward} \times Transp\_Cell_1 +$$
$$Dispersion_{aq\_back} \times Transp\_Cell_2 - Advection_{aquifer} \times Transp\_Cell_1$$
$$-\lambda \times Transp\_Cell_1 + \sum_{p \in P} Br_p \times \lambda \times Transp\_Cell_1 \qquad (40)$$

where:

Infiltration is the mass transfer by infiltration (inflow) to the first 'Aquifer' cell (Bq/year).

Mass transfer by infiltration to the first Aquifer cell (Infiltration, Bq/year)

$$Infiltration = C_{water\_pore\_in} \times u_{Darcy} \times Area_{flow\_tube} \qquad (41)$$

where:

$C_{water\_pore\_in}$ is the radionuclide concentration in water infiltrating (inflowing) to the aquifer (Bq/m^3); and
$Area_{flow\_tube}$ is the cross sectional area of the flow tube (m^2).

5.3.2.3.   Mass balance equation for the last Transport Cell in the aquifer

The mass balance equation for the 'Transp_Cell_N' (last Transport Cell) is given by:

$$\frac{dTransp\_Cell_N}{dt}$$
$$= Advection_{aquifer} \times Transp\_Cell_{N-1}$$
$$- Advection_{aquifer} \times Transp\_Cell_N$$
$$-Dispersion_{aq\_forward} \times Transp\_Cell_N - Dispersion_{aq\_back} \times Transp\_Cell_N +$$
$$+Dispersion_{aq\_forward} \times Transp\_Cell_{N-1} - \lambda \times Transp\_Cell_N$$
$$+ \sum_{p \in P} Br_p \times \lambda \times Transp\_Cell_N$$

<div align="right">(42)</div>

5.3.2.4. Calculation of dispersivity parameter for aquifer transport

Following the recommendations given in Refs [6, 21], the dispersivity parameter for aquifer transport ($dispersivity_{aq}$) is calculated as 10% of the linear scale of transport problem, i.e.:

$$Dispersivity_{aq} = 0.1 \times Length_{flow\_tube} \tag{43}$$

where:

$Length_{flow\_tube}$ is the length of the modelled aquifer system (see Fig. 12) (m).

5.3.2.5. Accuracy criteria for advective–dispersive transfers calculations

It can be shown that using the advective transfer coefficients (see Eq. (37)) to represent advection fluxes between adjacent compartments is equivalent to using upstream finite difference approximations of advection terms in the solute transport equation.

Using upstream finite differences in the transport equation is known to result in 'numerical dispersion', where the numerical dispersion coefficient is given by the following formula [22]:

$$D_{num} = \frac{u_{Darcy} \times dZ}{2} \tag{44}$$

The formula above shows that numerical dispersion is proportional to the size of compartment dZ. The true dispersion coefficient in the transport equation is given by the formula:

$$D_{true} = Dispersivity_{aq} \times u_{Darcy} \tag{45}$$

To ensure accurate approximation of advective-dispersive transport, the following condition needs to hold:

$$D_{num} << D_{true} \tag{46}$$

or, substituting into Eq. (46) expressions Eq. (44) and Eq. (45):

$$dZ << 2 \times Dispersivity_{aq} \tag{47}$$

In particular, numerical experiments have shown that reasonable accuracy can be achieved if numerical dispersion makes a fraction of no more than 0.1–0.2 of true dispersion.

This leads to the following rule to calculate the required number of transport compartments (N):

$$dZ = Dispersion_{accuracy} \times 2 \times Dispersivity_{aq} \tag{48}$$

where:

$Dispersion_{accuracy}$ is the module parameter controlling accuracy of calculation of advection-dispersion transfers (with the recommended value of 0.1–0.2).

If the value of the $dispersion_{accuracy}$ parameter is too small, this may result in the dZ being too small, and, respectively, the number of transport cells being too large and the calculation times being long.

Formula for number (N_{Transp}) and size (dZ) of Transport Cells

The respective number of Transport Cells N_{Transp} and dZ parameters are calculated as:

$$N_{transp} = \left[\frac{Length_{flow\_tube}}{Dispersion_{accuracy} \times 2 \times Dispersvity_{aq}} \right] + 1$$

$$dZ = \frac{Length_{flow\_tube}}{N_{Transp}} \qquad (49)$$

The number between the brackets is rounded to the nearest real integer number towards zero.

5.3.2.6.   Radionuclide concentration in outflowing groundwater for the 'Aquifer' module

The radionuclide concentration in the groundwater ($C_{water\_pore\_out}$, Bq/m³) is dynamically calculated from the radionuclide inventory in '*Transport_Cell$_N$*' compartment:

$$C_{water\_pore\_out} = \frac{Transp\_Cell_N}{Area_{flow\_tube} \times dZ} \times \frac{1}{Porosity_{aquifer} \times Ret_{aquifer}} \qquad (50)$$

5.3.2.7.   Activity flux in water from the 'Aquifer' module

The activity flux in the groundwater ($Flux_{flow\_tube}$, Bq/year) is calculated using formula:

$$Flux_{flow\_tube} = u_{Darcy} \times Area_{flow\_tube} \times C_{water\_pore\_out} \qquad (51)$$

5.3.3.   Input parameters

TABLE 24. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS FOR THE 'AQUIFER' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_water_pore_in (Bq/m³)	Concentration of the radioactive contaminant in groundwater inflowing to the aquifer	0	Site specific parameter
C0_gw_aquifer (Bq/m³)	Initial contamination of groundwater in the aquifer by radionuclides	0	Site specific parameter

TABLE 25. INPUT PARAMETERS OF THE 'AQUIFER' MODULE RELATED TO SITE GEOMETRY, HYDRAULIC PARAMETERS AND PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

Abbreviation and unit	Full name	Default value	Reference
Area_flow_tube (m^2)	Aquifer (flow tube) cross section area	4000	Site specific parameter
Length_flow_tube (m)	Length of the modelled aquifer system	100	Site specific parameter
Rho_aquifer (kg·DW/m^3)	Aquifer material bulk density	1600	Value for sandy deposits
Porosity_aquifer (unitless)	Aquifer porosity	0.3	Value for sandy deposits
u_Darcy (m/year)	Darcy velocity in the aquifer	10	Site specific parameter
Kd_aquifer (m^3/kg·DW)	Sorption distribution coefficient (radionuclide specific)	Table141 (Appendix)	See Table 14 of Ref. [8]

5.3.4. Output parameters

The main output parameter of the 'Aquifer' module is radionuclide concentration in outflowing groundwater from the compartment (see Eq. (50)). The module also calculates the activity flux from the system (see Eq. (51)).

TABLE 26. OUTPUT PARAMETERS OF THE 'AQUIFER' MODULE

Abbreviation and unit	Full name	Purpose
C_water_pore_out (Bq/m^3)	Radioactive contaminant concentration in the groundwater outflowing from the 'Aquifer' module	Used to calculate doses from contaminated groundwater. Also used to calculate further radionuclide transport in the 'Well', 'Fresh Water Body' and other modules (see Table 23)
Flux_flow_tube (Bq/year)	Radioactive contaminant flux from the 'Aquifer' module	Used to calculate activity inputs to the 'Fresh Water Body' and other modules (see Table 23)

5.4. 'UNSATURATED ZONE' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Unsaturated zone' module.

5.4.1. Module description

In this section, detailed descriptions of the 'Unsaturated zone' module are provided.

5.4.1.1. General description

The goal of the 'Unsaturated Zone' module is to dynamically simulate the transport of radioactive contaminants, within the unsaturated zone of soil underlying the contaminated site, towards the aquifer (see Fig. 10).

This module usually receives contaminant input from the groundwater source term modules (such as 'Tailings Without Cover' or 'Contaminated Land Without Cover' modules; see block scheme in Fig. 10).

The output of the 'Unsaturated Zone' module (radionuclide concentration and/or flux in outflowing pore water) usually serves as an input to the 'Aquifer Mixing' module. Coupled Source, 'Unsaturated Zone' and aquifer transport modules can be used for evaluating

radioactive contaminant concentrations in relevant receptor compartments (e.g. 'Well' or 'Fresh Water Body') (see Fig. 10).

5.4.1.2. *Conceptual model*

The 'Unsaturated Zone' module assumes that the unsaturated soil zone is homogeneous with respect to its hydraulic and geochemical properties and parameters (see Fig. 14).

For the unsaturated zone systems showing significant variations in their properties in a vertical direction, it is recommended to subdivide these latter into a sequence of homogeneous layers that can be modelled by several consecutive 'Unsaturated Zone' modules.

It is assumed that pore water flow and associated transport of radionuclides in dissolved form in the unsaturated zone occurs in a vertical (downward) direction (see Fig. 14). The transport process taken into account by the module includes advection, hydrodynamic dispersion, radioactive decay and ingrowth of daughter radionuclides from parent radionuclides, and radionuclide sorption by soil matrix. For radionuclide sorption, the assumptions used are of instantaneous and reversible sorption as described by a linear isotherm, also known as a '*Kd* model' (*Kd* is the sorption distribution coefficient).

The 'Unsaturated Zone' module simulates radionuclide transfer processes in the soil profile dynamically. However, it is assumed that the radionuclide transport in soil occurs under steady state infiltration flow conditions (i.e. that the infiltration flow velocity in the soil profile is constant in time).

For numerical analysis, the 'Unsaturated Zone' module represents the unsaturated zone system as a sequence of individual soil layers with a constant length (Fig. 15). Exchanges between individual layers include transfers due to the advection and dispersion process following the approach described in Appendix C of Ref. [6].

The number and size of layers (cells) is determined automatically based on specified accuracy requirements. The program generates the required number of cell compartments using the Ecolego 6 'Transport' block. This approach is similar to the radionuclide transport modelling methodology used for the 'Aquifer' module (see Section 5.3.1.2).

The input of radioactive contaminant(s) to the 'Unsaturated Zone' module is usually defined by the user in the coupled Source module. The contaminant input is defined by specifying two parameters, i.e. radioactive contaminant activity concentration in the infiltrating water and pore water flow rate. Alternatively, input can be defined in the form of contaminant flux.

Losses of radioactive contaminant(s) from the 'Unsaturated Zone' module include:

— Contaminant leaving the 'Unsaturated Zone' module towards underlying hydrogeological system (e.g. 'Aquifer Mixing' module) or subsequent layer of the unsaturated zone (in case several consecutive unsaturated soil layers are modelled) by outflow (i.e. contaminant movement by advective outflow);
— Radioactive decay of contaminant in the unsaturated zone media.
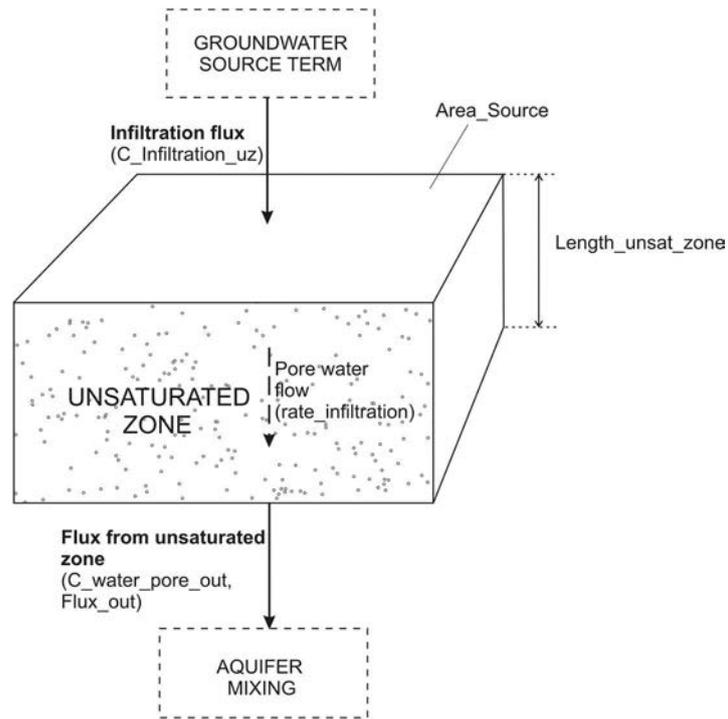
FIG. 14. Conceptual model of the 'Unsaturated Zone' Module.
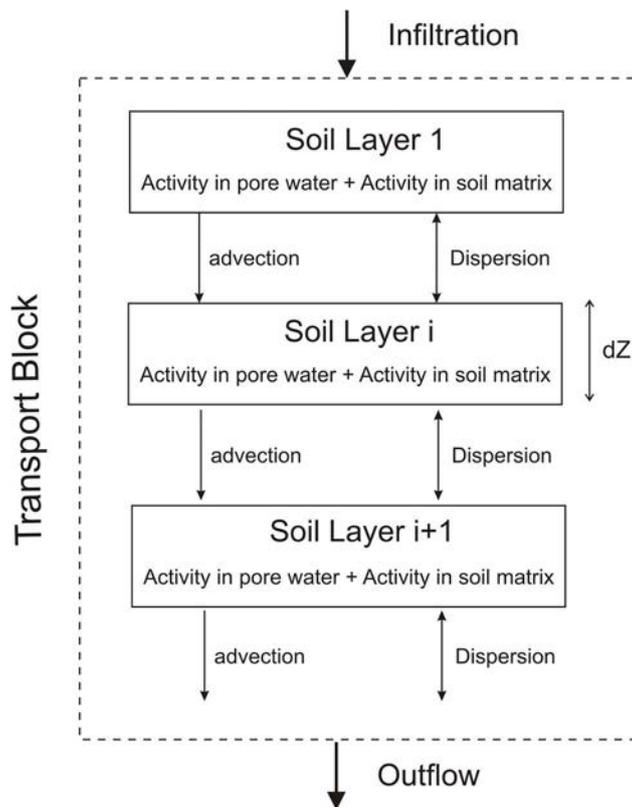
FIG. 15. Representation of the modelled unsaturated zone by a sequence of individual soil layers using Ecolego 'Transport' block.

5.4.1.3. Potential coupled modules

TABLE 27. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'UNSATURATED ZONE' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by the following modules:	
'Contaminated Land Without Cover', 'Tailings Without Cover'	Radioactive contaminant concentration (Bq/m^3) or activity flux (Bq/year) in infiltrating water
Outputs from module can be used by the following modules:	
'Aquifer Mixing', 'Aquifer'	Radioactive contaminant concentration (Bq/m^3) or activity fluxes (Bq/year) in outflow water

5.4.2. Mathetmatical model

In this section, detailed descriptions of the mathematical model of the 'Unsaturated zone' module are provided.

5.4.2.1. Mass balance equation for unsaturated soil system

The mass balance equation for the *'Soil_Layer_i'* (Bq) compartment generated by the Ecolego *'Transport'* block (see Fig. 15) is given by:

$$
\frac{dSoil\_Layer_i}{dt} = Advection_{uz} \times Soil\_Layer_{i-1} - Advection_{uz} \times Soil\_Layer_i
$$
$$
- Dispersion_{uz\_back} \times Soil\_Layer_i - Dispersion_{uz\_forward} \times Soil\_Layer_i +
$$
$$
Dispersion_{uz\_back} \times Soil\_Layer_{i+1} + Dispersion_{uz\_forward} \times Soil\_Layer_{i-1}
$$
$$
- \lambda \times Soil\_Layer_i + \sum_{p \in P} Br_p \times \lambda \times Soil\_Layer_i \qquad (52)
$$

where:

Advection$_{uz}$ is the mass transfer coefficient by advective transport (1/year);
Dispersion$_{uz\_forward}$ is the mass transfer coefficient by forward dispersive transport (1/year); and
Dispersion$_{uz\_back}$ is the mass transfer coefficient by backward dispersive transport (1/year).

The terms $\lambda \times Soil\_Layer_i$ and $\sum_{p \in P} Br_p \times \lambda \times Soil\_Layer_i$ in Eq. (52) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Here mass transfer coefficients are calculated as follows (taken from Appendix C of Ref. [6]):

Mass transfer coefficient by advective transport (Advection$_{uz}$, 1/year)

$$
Advection_{uz} = \frac{Rate_{infiltration}}{Moisture_{uns\_zone} \times dZ \times Ret_{uns\_zone}} \qquad (53)
$$

where:

rate$_{infiltration}$ is the soil moisture infiltration rate to the unsaturated zone (m/year);
Moisture$_{uns\_zone}$ is the moisture content in the unsaturated zone (unitless);
dZ is the vertical size of the transport layer in the unsaturated zone generated by the Ecolego 'Transport' block (see Fig. 15) (m); and
Ret$_{uns\_zone}$ is the retardation coefficient due to radionuclide sorption on soil (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{aquifer} = 1 + \frac{Rho_{uns\_zone}}{Moisture_{uns\_zone}} \times Kd_{unsa\_zone} \qquad (54)$$

where:

Rho_{uns_zone} is the density of soil in the unsaturated zone (kg/m^3); and
Kd_{unsat_zone} is the sorption distribution coefficient of soil in the unsaturated zone with respect to radionuclides (radionuclide-specific) (m^3/kg).

Mass transfer coefficient by dispersive transport (Dispersion$_{uz\_forward}$, 1/year)

$$Dispersion_{uz\_forward} = \frac{Dispersivit_{uz} \times Rate_{infiltration}}{Moisture_{uns\_zon} \times dZ^2 \times Ret_{uns\_zone}} \qquad (55)$$

where:

Dispersivity$_{uz}$ is the dispersivity parameter for solute transport in the unsaturated zone (m).

The expression for mass transfer coefficient *dispersion$_{uz\_back}$* is the same as for *Dispersion$_{uz\_forward}$*.

5.4.2.2.   Mass balance equation for the first Soil Layer in the unsaturated zone

The mass balance equation for the 'Soil_Layer_1' (1st Transport Cell) is given by:

$$\frac{dSoil\_Layer_1}{dt} = Infiltration - Dispersion_{uz\_forward} \times Soil\_Layer_1 +$$
$$Dispersion_{uz\_back} \times Soil\_Layer_2 - Advection_{uz} \times Soil\_Layer_1$$
$$-\lambda \times Soil\_Layer_1 + \sum_{p \in P} Br_p \times \lambda \times Soil\_Layer_1 \qquad (56)$$

where:

Infiltration is the mass transfer by infiltration to the first soil layer of the 'Unsaturated Zone' module from the external source term (Bq/year).

Mass transfer by infiltration to the 1st soil layer (Infiltration, Bq/year)

$$Infiltration = C_{infiltration} \times Rate_{infiltration} \times Area_{source} \qquad (57)$$

where:

$C_{infiltration}$ is the radionuclide concentration in water infiltrating to the unsaturated zone system (Bq/m^3),
$Area_{source}$ is the surface area of the modelled unsaturated zone system (underlying contaminant source) (m^2).

5.4.2.3.   Mass balance equation for the last Soil Layer in the unsaturated zone

The mass balance equation for the last *Soil_Layer_N* (last Transport Cell) is given by:

$$\frac{dSoil\_Layer_N}{dt} = Advection_{uz} \times Soil\_Layer_{N-1} - Advection_{uz} \times Soil\_Layer_N$$
$$-Dispersion_{uz\_for} \times Soil\_Layer_N - Dispersion_{uz\_back} \times Soil\_Layer_N +$$
$$+Dispersion_{uz\_forward} \times Soil\_Layer_{N-1} - \lambda \times Soil\_Layer_N$$
$$+ \sum_{p \in P} Br_p \times \lambda \times Soil\_Layer_N$$

$$(58)$$

5.4.2.4. Calculation of dispersivity parameter for the unsaturated zone

Following the recommendation given in Refs [6, 21], the dispersivity parameter for unsaturated zone transport (*dispersivity_{uz}*) is calculated as 10% of the linear scale of the transport problem:

$$Dispersivity_{uz} = 0.1 \times Length_{unsat\_zone} \qquad (59)$$

where:

$Length_{unsat\_zone}$ is the length (depth) of the modelled unsaturated zone system (see Fig. 14) (m).

5.4.2.5. Accuracy criteria for advective–dispersive transfers calculations

The theoretical background for accuracy criteria for advective-dispersion transfer calculations in the unsaturated zone are the same as for aquifer transport calculations (see Section 5.3.2.5).

Formula for number (N_{Transp}) and size (dZ) of Soil Layers

The respective number of Soil Layers N_{Transp} and dZ parameters in the Ecolego 'Transport' block is calculated as:

$$N_{transp} = \left[\frac{Length_{unsat\_zone}}{Dispersion_{accuracy} \times 2 \times Dispersivity_{uz}} \right] + 1$$

$$dZ = \frac{Length_{unsat\_zone}}{N_{Transp}} \qquad (60)$$

5.4.2.6. Radionuclide concentration in outflowing pore water for the 'Unsaturated Zone' module

The radionuclide concentration in the groundwater ($C_{water\_pore\_out}$, Bq/m^3) is dynamically calculated from the radionuclide inventory in '*Soil_Layer_N*' compartment:

$$C_{water\_pore\_out} = \frac{Soil\_Layer_N}{Area_{source} \times dZ} \times \frac{1}{Moisture_{uns\_zone} \times Re_{uns\_zone}} \qquad (61)$$

5.4.2.7. Activity flux in water from the 'Unsaturated Zone' module

The activity flux in the groundwater ($Flux_{flow\_tube}$, Bq/year) is calculated using the formula:

$$Flux_{out} = Rate_{infiltration} \times Area_{source} \times C_{water\_pore\_out} \qquad (62)$$

5.4.3. Input parameters

TABLE 28. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS FOR 'UNSATURATED ZONE' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_infiltration (Bq/m^3)	Concentration of the radioactive contaminant in pore water infiltration to the unsaturated zone	0	Site specific parameter
C0_soil_uz (Bq/kg·DW)	Initial contamination of soil in the unsaturated zone by radionuclides	0	Site specific parameter

TABLE 29. INPUT PARAMETERS OF 'UNSATURATED ZONE' MODULE RELATED TO SITE GEOMETRY, HYDRAULIC PARAMETERS AND PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

Abbreviation and unit	Full name	Default value	Reference
Area_source (m^2)	Surface area of the modelled unsaturated zone system (contaminated site)	42 000	Site specific parameter
Length_unsat_zone (m)	Length (depth) of the modelled unsaturated zone system	8	Site specific parameter
Rho_uns_zone (kg·DW/m^3)	Soil bulk density	2000	Site specific parameter
Moisture_uns_zone (unitless)	Soil moisture content in the unsaturated zone	0.15	Site specific parameter
Rate_infiltration (m/year)	Infiltration recharge rate to the unsaturated zone	0.05	Site specific parameter
Kd_unsat_zone (m^3/kg·DW)	Sorption distribution coefficient (radionuclide specific)	Table 141 (Appendix)	See Table 14 of Ref. [8]
Dispersion_accuracy	Parameter controlling accuracy of dispersive–advective transport calculations	0.2	See Section 5.3.2.5

5.4.4. Output parameters

The main output parameter of the 'Unsaturated Zone' module is the radionuclide concentration in outflowing pore water from the modelled system (see Eq. (61)). The module also calculates activity flux from the system (see Eq. (62)).

TABLE 30. OUTPUT PARAMETERS OF 'UNSATURATED ZONE' MODULE

Abbreviation and unit	Full name	Purpose
C_water_pore_out (Bq/m^3)	Radioactive contaminant concentration in the pore water outflowing from the 'Unsaturated Zone' module	Used to calculate further radionuclide transport in the underlying unsaturated zone or aquifer (see Table 27)
Flux_out (Bq/year)	Radioactive contaminant flux from the 'Unsaturated Zone' module	Used to calculate further radionuclide transport in the underlying unsaturated zone or aquifer (see Table 27)

5.5. 'SURFACE RUNOFF' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Surface runoff' module.

5.5.1. Module description

In this section, detailed descriptions of the 'Surface runoff' module are provided.

5.5.1.1. General description

The goal of the 'Surface Runoff' module is to dynamically simulate the transport of radioactive contaminants from the contaminated watershed soils via the surface runoff mechanism to the 'Fresh Water Body' receptor. The contamination of the watershed may be formed, for example, by the atmospheric deposition of radionuclides (see Fig. 16).

The mathematical model for radionuclide leaching from contaminated watershed soil is based on the 'exchangeable soil layer' concept described in Refs [18, 23]. It is assumed that radionuclide interaction between runoff water and soil in the contaminated watershed occurs in the top 'exchangeable soil layer' of a relatively small (e.g. centimeter scale) thickness.

The model for radionuclide redistribution in the watershed soil profile takes into account the input of radionuclides to the watershed soil through deposition from the atmosphere and losses of radionuclides from the system caused by surface runoff and vertical leaching processes. It accounts for radionuclide transport in surface runoff both in dissolved form and adsorbed on suspended particles (see Fig. 16).

Both the water runoff and radionuclide transport processes are described in a simplified way using empirical coefficients and parameters, such as runoff coefficient (fraction of atmospheric precipitation that goes to surface runoff), infiltration coefficient (fraction of atmospheric precipitation that infiltrates to soil profile), and *Kd* values (sorption distribution coefficients).

The output of the 'Surface Runoff' module (radionuclide concentrations and fluxes in surface runoff) usually serves an input to the receptor module such as the 'Fresh Water Body' receptor (e.g. lake or river) (see Fig. 17).

5.5.1.2. Conceptual model

The 'Surface Runoff' module assumes that the modelled contaminated watershed is homogeneous (laterally and longitudinally) with respect to its hydrologic and geochemical properties and parameters.

The model formulas operate radionuclide inventory in the so called 'exchangeable soil layer', which represents the upper soil layer of the watershed soil presumably interacting with surface runoff. Then radioactive contaminant concentrations in runoff water, and contaminant concentrations adsorbed on suspended particles in the surface runoff water, are calculated based on a known inventory of the 'exchangeable soil layer' compartment and equilibrium *Kd* based sorption models describing radionuclide partitioning between the liquid and solid phases (see Fig. 18).
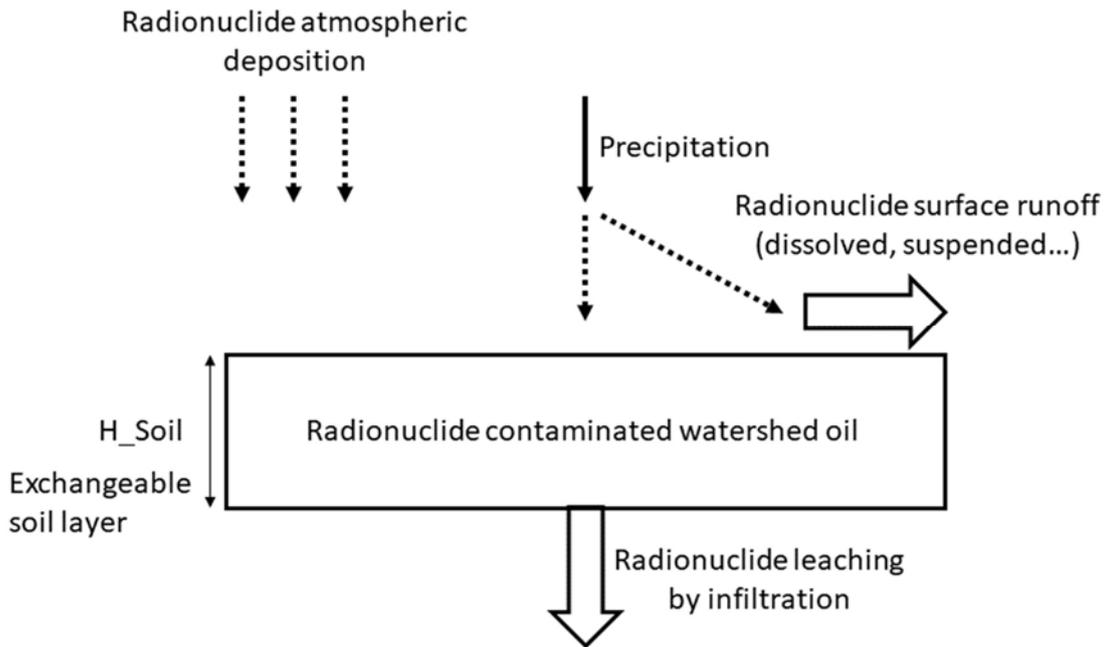
FIG. 16. Illustrative scheme for the 'Surface Runoff' module.
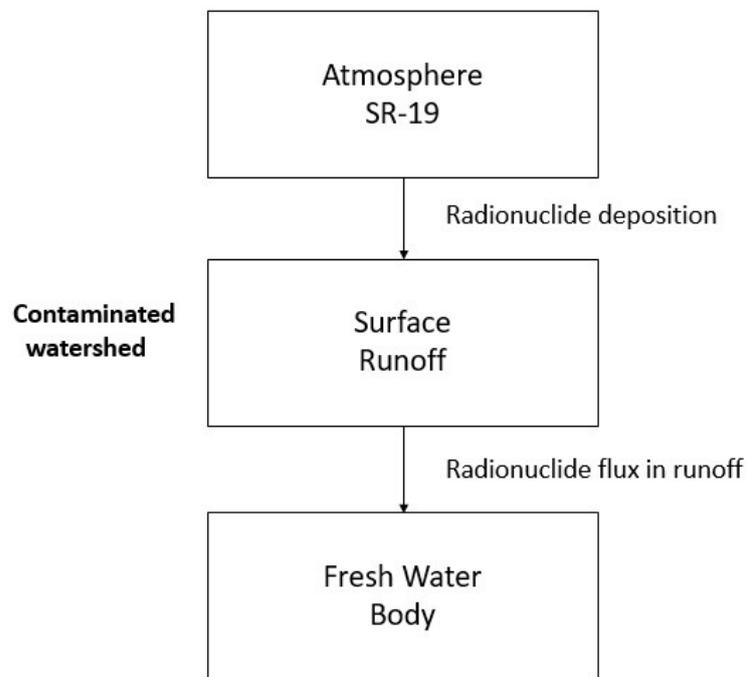
FIG. 17. Data exchanges of the 'Surface Runoff' module with other NORMALYSA modules.
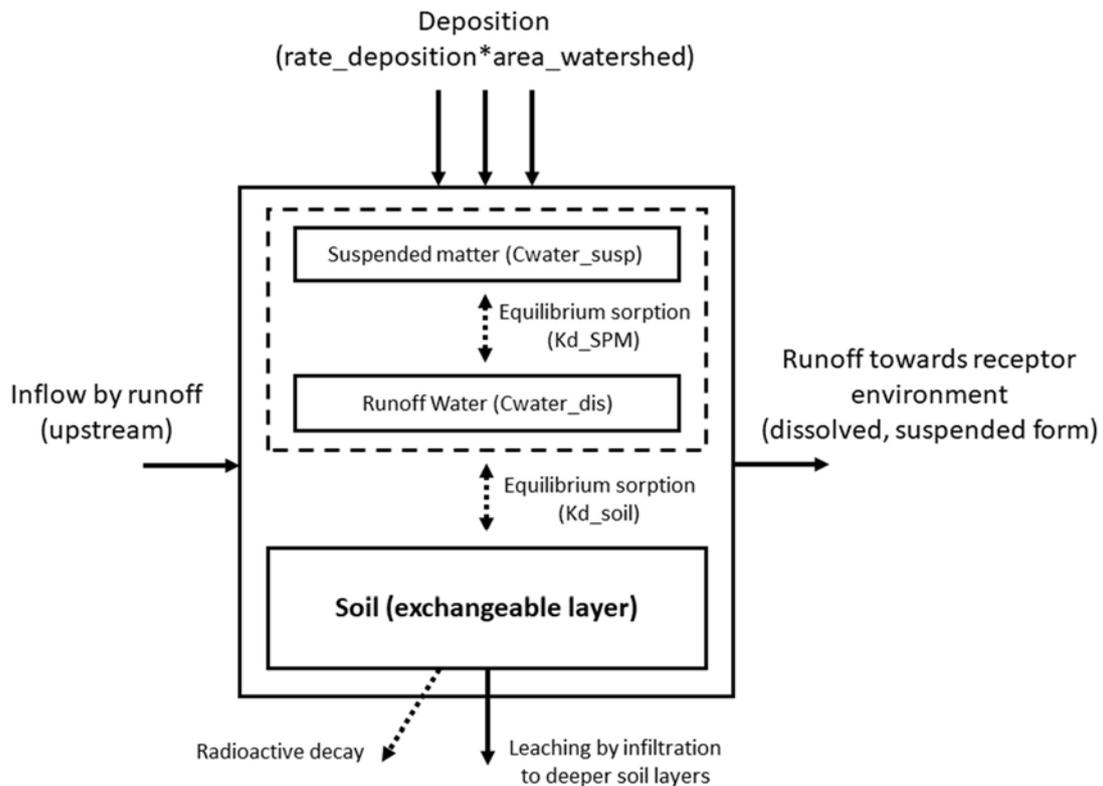
FIG. 18. Conceptual model of the 'Surface Runoff' module.

The 'Surface Runoff' module simulates radionuclide transfer processes within the hydrological environment dynamically, however:

— It is assumed that the hydrological process at watershed scale are characterized by transport parameters (e.g. precipitation rate, runoff coefficient, deposition rate etc.) which are constant during the simulated time period;

— The exchanges of radioactive contaminants between water and soil matrix are assumed to be at sorption equilibrium (i.e. sorption process is represented by a distribution coefficient *Kd*).

The inputs of radioactive contaminant(s) to the 'Surface Runoff' (i.e. contaminated watershed soil) compartment may have the following origins:

— Contaminants deposited from the atmosphere;

— Contaminants entering the modelled watershed compartment by lateral inflow (e.g. surface runoff) from the upstream watershed zone.

The modeller may also specify initial contamination of watershed soil.

Losses of radioactive contaminant(s) from the 'Surface Runoff' compartment include:

— The contaminant leaving the watershed soil compartment by surface runoff (both in dissolved and suspended form);

— Vertical radionuclide leaching to deeper soil layers;

— Radioactive decay of contaminants.

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5.5.1.3. Potential coupled modules

TABLE 31. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'SURFACE RUNOFF' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to 'Surface Runoff' module:	
Atmospheric transport models ('Atmosphere Chronic', 'Atmosphere SR-19')	Radioactive contaminant deposition rate (Bq/(m^2·year)) to watershed soil
Outputs from 'Surface Runoff' can be used by following modules:	
'Fresh Water Body'	Radioactive contaminant concentration in runoff water (Bq/m^3) and/or activity flux (Bq/year) from contaminated watershed entering surface water body

5.5.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Surface runoff' module are provided.

5.5.2.1. Mass balance equation for watershed soil – 'exchangeable soil layer'

The mass balance equation for the watershed 'Soil' (exchangeable soil layer) (Bq) compartment is given by:

$$\frac{dSoil}{dt} = Runoff_{upstream} + Deposition - TC_{Runoff} \times Soil - TC_{Infiltration} \times Soil - \lambda \times Soil + \sum_{p \in P} Br_p \times \lambda \times Soil$$

(63)

where:

Deposition is the mass transfer by deposition from atmosphere to watershed soil (Bq/year);
Runoff$_{upstream}$ is the mass transfer by runoff from the upstream watershed compartment (Bq/year);
TC$_{Runoff}$ is the mass transfer coefficient by surface runoff water (1/year); and
TC$_{Infiltration}$ is the mass transfer coefficient due to infiltration of water to soil profile (1/year).

The terms $\lambda \times Soil$ and $\sum_{p \in P} Br_p \times \lambda \times Soil$ in Eq. (63) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Here mass transfers and transfer coefficients are calculated as follows:

Mass transfer by deposition from atmosphere to watershed soil (Deposition, Bq/year)

$$Deposition = Rate_{dep} \times Area_{watershed}$$

(64)

where:

Rate$_{dep}$ is the radionuclide deposition rate from the atmosphere (Bq/(m^2·year));
Area$_{watershed}$ is the area of watershed (m^2).

Mass transfer by runoff from the upstream watershed compartment (Runoff_{upstream}, Bq/year)

$$Runoff_{upstream} = Flux_{runoff\_upstream} \qquad (65)$$

where:

Flux_{runoff_upstream} is the flux of the radioactive contaminant in surface runoff from upstream watershed areas (specified by the modeller) (Bq/year).

Mass transfer coefficient by surface runoff water (TC_runoff, 1/year)

$$TC_{runoff} = \frac{Flux\_water_{runoff} \times (1 + 0.001 \times Kd_{SPM} \times C_{SPM})}{Kd_{soil} \times Rho_{soil} \times V_{soil}} \qquad (66)$$

where:

Flux_water_{runoff} is the rate of surface water runoff from the watershed (m^3/year);
Kd_{soil} is the sorption distribution coefficient for watershed soil (m^3 /kg·DW);
Rho_{soil} is the dry density of watershed soil (kg·DW/m^3);
V_{soil} is the soil volume in the exchangeable layer for the whole watershed (m^3);
Kd_{SPM} is the sorption distribution coefficient for suspended particles in runoff water (m^3/kg); and
C_{SPM} is the concentration of suspended soil particles in runoff water (kg·DW/m^3). The rate of surface water runoff from the watershed soil is calculated as follows:

$$Flux_{water\_runoff} = Rate_{prec} \times Coeff_{runoff} \times Area_{watershed} \qquad (67)$$

where:

Rate_{prec} is the meteoric water precipitation rate (m/year); and
Coeff_{runoff} is the surface runoff coefficient (unitless).

The soil volume in the exchangeable layer for the whole watershed is calculated as follows:

$$V_{soil} = Area_{watershed} \times H_{soil} \qquad (68)$$

where:

H_{soil} is the thickness of the exchangeable layer of watershed soil (m).

Mass transfer coefficient by infiltration water flow (TC_{Infiltration}, 1/year)

$$TC_{infiltratio} = \frac{Rate_{prec} \times Coeff_{infiltration}}{Soil\_moisture \times H_{soil} \times Re_{soil}} \qquad (69)$$

where:

Coeff_{infiltration} is the infiltration coefficient–fraction of precipitation that infiltrates to soil profile (unitless);
Soil_moisture is the soil moisture content (unitless); and
Ret_{soil} is the radionuclide retardation factor for soil (unitless).

Here the soil radionuclide retardation coefficient is calculated as follows:

$$Ret_{soil} = 1 + \frac{Rho_{soil}}{Soil\_moisture} \times Kd_{soil}. \qquad (70)$$

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5.5.2.2. Radionuclide concentration in the watershed soil (C_{soil}, Bq/kg)

$$C_{soil} = \frac{Soil}{Rho_{soil} \times V_{soil}} \tag{71}$$

5.5.2.3. Radionuclide concentration in surface runoff

Radioactive contaminant concentration in the surface runoff in dissolved form (C_{water_dis}, Bq/m³)

$$C_{water\_dis} = \frac{C_{Soil}}{Kd_{soil}} \tag{72}$$

Radioactive contaminant concentration in the surface runoff in suspended form (C_{water_susp}, Bq/m³)

$$C_{water\_susp} = c_{water\_dis} \times 0.001 \times Kd_{SPM} \times C_{SPM} \tag{73}$$

5.5.2.4. Radioactive contaminant flux from the watershed by surface runoff

Total radioactive contaminant flux from the watershed by surface runoff (Flux_runoff_total, Bq/year)

$$Flux_{runoff\_total} = Flux_{runoff\_diss} + Flux_{runoff\_susp} \tag{74}$$

where:

$Flux_{ruoff\_diss}$ is the radioactive contaminant flux in dissolved form (Bq/year); and
$Flux_{ruoff\_susp}$ is the radioactive contaminant flux in suspended form (Bq/year).

Radioactive contaminant flux from watershed by surface runoff in dissolved phase ($Flux_{runoff\_dis}$, Bq/year)

$$Flux_{runoff\_dis} = C_{water\_dis} \times Flux_{water\_runoff} \tag{75}$$

Radioactive contaminant flux from watershed by surface runoff in suspended phase ($Flux_{runoff\_susp}$, Bq/year)

$$Flux_{runoff\_susp} = C_{water\_susp} \times Flux_{water\_runooff} \tag{76}$$

5.5.3. Input parameters

TABLE 32. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS FOR 'SURFACE RUNOFF' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_soil_0 (Bq/kg·DW)	Radionuclide concentration in watershed soil in the exchangeable layer (initial value)	0	Site specific parameter
Rate_dep (Bq/(m²·year))	Radionuclide deposition rate from the atmosphere	0	Site specific parameter
Flux_runoff_upstream (Bq/year)	Flux of the radioactive contaminant in surface runoff from upstream watershed areas	0	Site specific parameter

TABLE 33. INPUT PARAMETERS OF 'SURFACE RUNOFF' MODULE RELATED TO WATERSHED GEOMETRY, HYDRAULIC PARAMETERS AND PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

Abbreviation and unit	Full name	Default value	Reference
Area_watershed (m^2)	Watershed area	10 000	Site specific parameter
H_soil (m)	Thickness of exchangeable soil layer	0.01	Ref. [23]
Rho_soil (kg·DW/m^3)	Watershed soil density	1600	Value for sandy deposits
Soil_moisture (unitless)	Moisture content in watershed soil	0.15	Value for sandy deposits
Rate_prec (m/year)	Precipitation rate	0.6	Site specific parameter
Coeff_runoff (unitless)	Runoff coefficient (fraction of precipitation that goes to surface runoff)	0.1	Site specific parameter
Coeff_infiltration (unitless)	Infiltration coefficient (fraction of precipitation that infiltrates the soil profile)	0.3	Site specific parameter
C_SPM (g/m^3)	Concentration of suspended particles in runoff water	20	Site specific parameter
Kd_soil (m^3/kg·DW)	Sorption distribution coefficient of watershed soil (radionuclide specific)	Table 141 (Appendix)	See Table 14* of Ref. [8]
Kd_SPM (m^3/kg·DW)	Sorption distribution coefficient of suspended particles in surface runoff (radionuclide specific)	Table 34	See Table 14** of Ref. [8]

Notes: * Value for 'All soils'.
    ** Value for 'Loam + clay' (if available, otherwise 'All soils' value).

TABLE 34. DEFAULT RADIONUCLIDE *Kd* VALUES FOR SUSPENDED PARTICLES IN SURFACE RUNOFF (Table 14* Ref. [8])

Radionuclide	*Kd*, m^3/kg·DW
Ac	1.7E+00
Cs	3.7E-01
Pa	2.0E+00
Pb	1.3E+01
Po	2.1E-01
Ra	3.8E+01
Sr	6.9E-02
Th	1.9E+00
U	2.0E-01

Note: * Value for 'Loam + clay' (if available, otherwise 'All soils' value).

5.5.4. Output parameters

The main output parameters of the 'Surface Runoff' module are radionuclide concentrations in surface runoff in dissolved and suspended form (see Section 5.5.2.3) and related activity fluxes (see Section 5.5.2.4).

TABLE 35. OUTPUT PARAMETERS OF 'SURFACE RUNOFF' MODULE

Abbreviation and unit	Full name	Purpose
C_water_dis (Bq/m³)	Radioactive contaminant concentration in the surface runoff (dissolved phase)	Calculation of contaminant inputs (loads) to 'Fresh Water Body' receptor
C_water_susp (Bq/m³)	Radioactive contaminant concentration in the surface runoff (in suspended phase)	Same as above
Flux_runoff_diss (Bq/year)	Radioactive contaminant flux from watershed by surface runoff in the dissolved phase	Same as above
Flux_runoff_susp (Bq/year)	Radioactive contaminant flux from watershed by surface runoff in the suspended phase	Same as above
Flux_runoff_total (Bq/year)	Total radioactive contaminant flux from the watershed by surface runoff	Same as above

5.6. 'ATMOSPHERE SR-19' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Atmosphere SR-19' module.

5.6.1. Module description

In this section, detailed descriptions of the 'Atmosphere SR-19' module are provided.

5.6.1.1. General description

The 'Atmosphere SR-19' module has the purpose of simulating radionuclide transport in the atmosphere in aerosol form from a relevant source of release (see Section 3 for a description of source term modules). It allows calculation of the air concentrations and deposition rates for the receptor modules (e.g. 'Land', 'Cropland' modules) to be used for calculations of radionuclide concentrations in other environmental media and objects. Integration of the atmospheric transport module with the source term module and with the receptor modules is illustrated in Fig. 4 above.

5.6.1.2. Conceptual model

After release to the atmosphere, radionuclides undergo downwind transport by wind (advection) and mixing processes (turbulent diffusion). Radioactive material will also be removed from the atmosphere by both wet and dry deposition on to the ground, and by radioactive decay [4].

The 'Atmosphere SR-19' module implements the Gaussian plume model to simulate the atmospheric dispersion of long term atmospheric releases and is described in Ref. [4]. This model is widely accepted for use in radiological assessment activities and is considered to be the most appropriate for representing the dispersion of either continuous or long term intermittent releases within a distance of a few kilometers of the source (see Fig. 19).
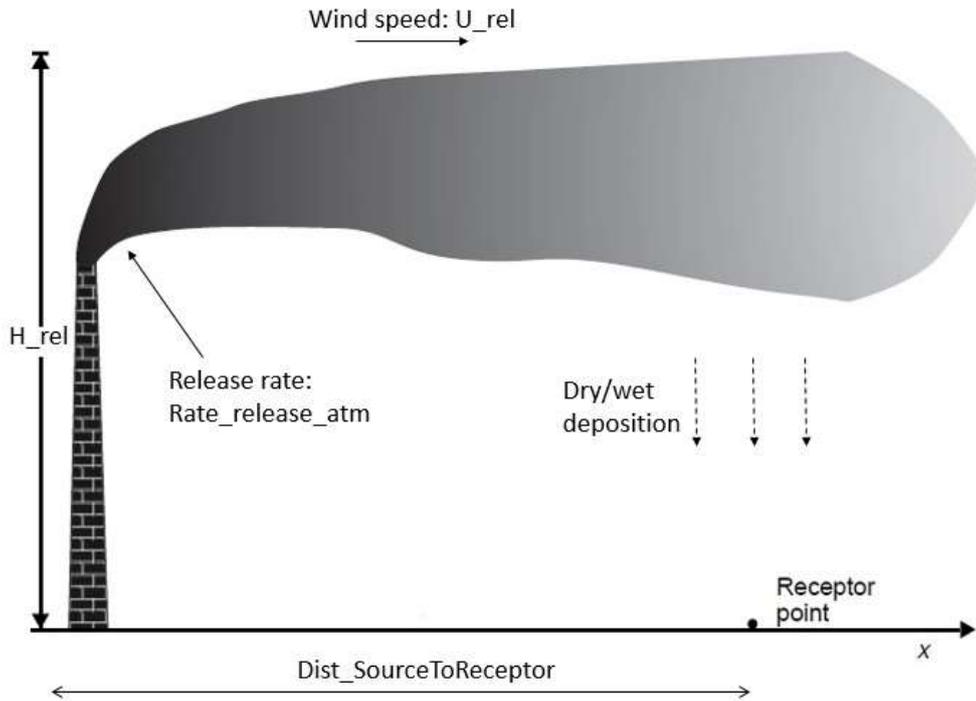
FIG. 19. Conceptual model of radioactive contaminant atmospheric dispersion from the point source.

The Gaussian plume model implemented in the 'Atmosphere SR-19' module assumes atmospheric dispersion of radioactive contaminants in the lee of an isolated point source when building wake effects are insignificant. In this case, the sector averaged form of the Gaussian plume model can be used with the following simplifying assumptions (see Annex V of Ref. [4] for more detail):

(a)   A single wind direction for each air concentration calculation;
(b)   A single long term average wind speed;
(c)   A neutral atmospheric stability class (Pasquill–Gifford stability class D).

Thus, the 'Atmosphere SR-19' module treats the atmospheric release from the contaminated site as a point source.

The model expressions presented below are appropriate for dispersion over relatively flat terrain without pronounced hills or valleys. The terrain is assumed to be covered with pastures, forests and small villages.

5.6.1.3.   Potential coupled modules

The inputs (release rates) of radioactive contaminant(s) for the 'Atmosphere SR-19' module need to be defined by the user in the coupled external Source module (possibly coupled with modules simulating intermediate transfers, such as 'Cover Layer' module).

The outputs of the 'Atmosphere SR-19' can be used to define loadings (atmospheric deposition rates) for various receptor modules. The calculated ground level air concentrations of radionuclides at receptor locations can be directly used for calculations of dose by inhalation pathway by respective module from the 'Doses' library (see Table 36).

TABLE 36. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'ATMOSPHERE SR-19' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by following modules:	
Atmospheric source modules ('Tailings Without Cover', 'Contaminated Land Without Cover', 'Chronic Release')	Radionuclide release rates to the atmosphere (Bq/s)
Outputs from module can be used by following modules:	
'Land', 'Cropland', 'Pasture land', 'Garden', 'Forest', 'Fresh Water Body', 'Marine', 'Surface Runoff'	Radioactive contaminant deposition rates (Bq/(m^2·year)) to the receptor
'Dose from Occupancy Outdoors'	Radioactive contaminant concentrations in the air (Bq/m^3)

5.6.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Atmosphere SR-19' module are provided.

5.6.2.1. Ground level radionuclide concentration in the air

Ground level radionuclide concentration in the air at receptor (C_air_atm, Bq/m^3) is calculated as follows [4]:

$$C\_air\_atm = \frac{Freq\_wind \times Diff\_factor \times Rate\_release\_atm}{U\_rel} \tag{77}$$

where:

Rate_release_atm is the annual average release rate for radionuclide from the source (Bq/s);
Diff_factor is the Gaussian diffusion factor appropriate for the height of release and the downwind distance being considered (1/m^2);
U_rel is the geometric mean of the wind speed at the height of release representative of one year (m/s); and
Freq_wind is the fraction of the time during the year that the wind blows towards the receptor of interest (unitless).

Gaussian diffusion factor (Diff_factor, 1/m^2)

$$Diff\_factor = \frac{12}{\sqrt{2 \times \pi^3}} \times \frac{exp[-(H_{rel}{}^2/(2 \times Sigma_Z^2))]}{Dist_{ourceToReceptor}s \times Sigma_Z} \tag{78}$$

where:

H_{rel} is the height of release (see Fig. 19) (m);
$Dist_{sourceToReceptor}$ is the distance from the source of release to the receptor (m); and
$Sigma_Z$ is the vertical diffusion parameter (m).

Vertical diffusion parameter (Sigma_Z, m)

$$Sigma\_Z = \begin{cases} 0.06 \times Dist_{SourceToReceptor}/\sqrt{1 + 0.0015 \times Dist_{SourceToReceptor}} \; ; for \; H_{rel} < 46m \\[2mm] (0.215 \times Dist_{SourceToReceptor})^{0.885} \; ; for \; 46m \leq H_{rel} < 80m \\[2mm] (0.265 \times Dist_{SourceToReceptor})^{0.818}; for \; H_{rel}l \geq 80m \end{cases} \tag{79}$$

5.6.2.2.   Radionuclide deposition rate at the receptor location (rate_dep, Bq/(m²·year))

$$Rate\_dep = C\_air\_atm \times u\_tot\_dep \times Days\_per\_Year \qquad (80)$$

where:

u_tot_dep is the total deposition velocity (m/d); and
Days_per_Year is the number of days per year (days/year).

here:

$$u\_tot\_dep = u\_wet\_dep + u\_dry \qquad (81)$$

where:

u_wet_dep is the wet deposition velocity (m/day); and
u_dry is the dry deposition velocity (m/day).

5.6.3.   Input parameters

TABLE 37. INPUT PARAMETERS RELATED TO RADIOLOGICAL LOADS FOR 'ATMOSPHERE SR-19' MODULE

Abbreviation and unit	Full name	Default value	Reference
Rate_release_atm (Bq/s)	The annual average release rate for radionuclide from the source	0	Site specific parameter

TABLE 38. INPUT PARAMETERS OF 'ATMOSPHERE SR-19' MODULE RELATED TO SYSTEM GEOMETRY AND ATMOSPHERIC TRANSPORT PARAMETERS

Abbreviation and unit	Full name	Default value	Reference
H_rel (m)	Height of release	0	Site specific parameter
Dist_sourceToReceptor (m)	Distance from the source of release to the receptor point	1000	Site specific parameter
U_rel (m/s)	The geometric mean of the wind speed at the height of release (yearly average)	2	Site specific parameter
Freq_wind (unitless)	The fraction of the time during the year that the wind blows towards the receptor	0.25	Site specific parameter
u_wet_dep (m/day)	Wet deposition velocity	500	Site specific parameter
u_dry (m/day)	Dry deposition velocity	500	Site specific parameter

5.6.4.   Output parameters

TABLE 39. OUTPUT PARAMETERS OF 'ATMOSPHERE SR-19' MODULE

Abbreviation and unit	Full name	Purpose
C_air_atm (Bq/m³)	Radioactive contaminant concentrations in the air	Calculation of doses by inhalation pathway at the receptor point
Rate_dep (Bq/(m²·year))	Radioactive contaminant deposition rates to ground surface	Calculation of contaminant inputs (loads) to receptor modules (see Table 36)

5.7. 'ATMOSPHERE CHRONIC' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Atmosphere chronic' module.

5.7.1. Module description

In this section, detailed descriptions of the 'Atmosphere chronic' module are provided.

5.7.1.1. General description

The 'Atmosphere Chronic' module is designed to calculate atmospheric dispersion of a radioactive contaminant from the chronic (steady state) source of atmospheric contamination to the receptor point and is based on calculations and results produced by external atmospheric dispersion model.

In fact, this module employs normalized radionuclide concentrations in the atmospheric air and deposition rates for a unit release rate from the source, that needs to be evaluated using an external model. These values are scaled with the actual release rate from the source, which is specified by the modeller as an input information for the module. Results are corrected to account for radioactive decay and ingrowth of daughter nuclides during atmospheric transport.

5.7.1.2. Potential coupled modules

Similarly to the atmospheric transport module discussed in Section 5.6, the inputs (release rates) of radioactive contaminant(s) for the 'Atmosphere Chronic' module need to be defined by the user in the coupled external Source module. The outputs of the 'Atmosphere Chronic' module may be used to specify atmospheric deposition rates for various receptor modules. The calculated ground level air concentrations of radionuclides at receptor locations can be directly used for calculations of dose by inhalation pathway by respective module from the 'Doses' library (see Table 36).

5.7.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Atmosphere chronic' module are provided.

5.7.2.1. Radionuclide concentrations in the outdoor atmospheric air at the receptor point (C_air_atm, Bq/m³)

$$C\_air\_atm = Rate\_release\_atm \times C\_air\_atm\_norm \times CorrFactor\_decay \qquad (82)$$

where:

$Rate\_release\_atm$ is the radionuclide release rate at source (Bq/year);
$C\_air\_atm\_norm$ is the normalized radionuclide concentration in the atmospheric air obtained from simulations with an external atmospheric dispersion model for continuous unit releases (1 Bq/year) of radionuclides (year/m³); and
$CorrFactor\_decay$ is the correction factor for decay and ingrowth during the atmospheric transport from the source to the receptor (unitless), obtained by:

$$CorrFactor\_decay = \exp(-\lambda \times (Dist_{SourceToReceptor}/u\_wind)) \qquad (83)$$

where:

$Dist_{SourceToReceptor}$ is the distance from the source of atmospheric release to the receptor (m);
u_wind is the average yearly wind speed in the direction from release source to receptor (m/s); and
λ is the radionuclide-specific radioactive decay constant (1/s).

5.7.2.2.   Radionuclide deposition rates at the receptor point (Rate_dep, Bq/(m²·year))

$$Rate\_dep = Rate\_release\_atm \times Rate\_dep\_norm \times CorrFactor\_decay \qquad (84)$$

where:

$Rate\_dep\_norm$ is the normalized rate of deposition obtained from simulations with an external atmospheric dispersion model assuming continuous unit (1 Bq/year) release rates (1/m²).

5.7.3.   Input parameters

TABLE 40. INPUT PARAMETERS RELATED TO RADIOLOGICAL LOADS FOR 'ATMOSPHERE CHRONIC' MODULE

Abbreviation and unit	Full name	Default value	Reference
Rate_release_atm (Bq/year)	The annual average release rate for radionuclide from the source	0	Site specific parameter
C_air_atm_norm (m³/year)	Normalized radionuclide concentration in the atmospheric air obtained from simulations with an external atmospheric dispersion model for continuous unit releases (1 Bq/year) of radionuclides	0	Site specific parameter
Rate_dep_norm (1/m²)	Normalized rate of deposition obtained from simulations with an external atmospheric dispersion model assuming continuous unit (1 Bq/year) release rates	0	Site specific parameter

TABLE 41. INPUT PARAMETERS OF 'ATMOSPHERE CHRONIC' MODULE RELATED TO SYSTEM GEOMETRY AND ATMOSPHERIC TRANSPORT PARAMETERS

Abbreviation and unit	Full name	Default value	Reference
Dist_sourceToReceptor (m)	Distance from the source of release to the receptor point	1000	Site specific parameter
U_wind (m/s)	Average wind speed towards receptor point (yearly average)	2	Site specific parameter

5.7.4.   Output parameters

TABLE 42. OUTPUT PARAMETERS OF 'ATMOSPHERE CHRONIC' MODULE

Abbreviation and unit	Full name	Purpose
C_air_atm (Bq/m³)	Radioactive contaminant concentrations in the air	Calculation of doses by inhalation pathway at the receptor point
Rate_dep (Bq/(m²·year))	Radioactive contaminant deposition rates to ground surface	Providing contaminant inputs (loads) to receptor modules

6. 'RECEPTORS' MODULE LIBRARY

6.1. GENERAL DESCRIPTION OF THE LIBRARY

The 'Receptors' library includes modules for calculation of radionuclide transfers and redistribution in different types of receptor environments, such as different types of lands (e.g. crop lands, pasture lands, forests, uncultivated lands), buildings, surface water (lakes and rivers), and near shore marine environments (see Table 4).

The inputs to these modules (e.g. radionuclide deposition rates from atmosphere, radionuclide inputs on cropland with irrigation water extracted by groundwater well) are usually calculated using the modules from the 'Transports' library described in Section 5.

The receptor modules presented below are essentially based on dynamic radioecological models that have been developed and used by SKB in the safety assessment of radioactive waste disposal facilities (see e.g. Refs [2, 3]).

The modules discussed usually provide both radionuclide concentrations in the abiotic media (e.g. soil, water, air) and in various foodstuffs associated with respective receptor environments (e.g. agricultural plants for 'Cropland', mushrooms, berries and game for the 'Forest module'). Detailed descriptions of individual modules are presented in Sections 6.2–6.10.

6.2. 'CROPLAND' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Cropland' module.

6.2.1. Module description

In this section, detailed descriptions of the 'Cropland' module are provided.

6.2.1.1. General description

The 'Cropland' module is designed to assess exposure pathways associated with the cultivation of agricultural plants in a cropland.

The 'Cropland' module simulates dynamically vertical distribution of radionuclides in the soil and radionuclide transfer to cultivated crops. The mathematical model of radionuclide transfers in soil is based on the crop irrigation model described in Ref. [2]. The model takes into account input of radionuclides through deposition from the atmosphere and irrigation with contaminated water and losses of radionuclides from the system through erosion and leaching processes (see Fig. 20). The same mathematical model for radionuclide transfers in the soil profile is used in the 'Pasture land', 'Garden' and 'Land' modules.

The module provides an option for the user to specify radionuclide concentration in soil (e.g. based on monitoring data). In this case, soil concentration values specified and fixed in time by the modeller are used to calculate radionuclide concentrations in crops.
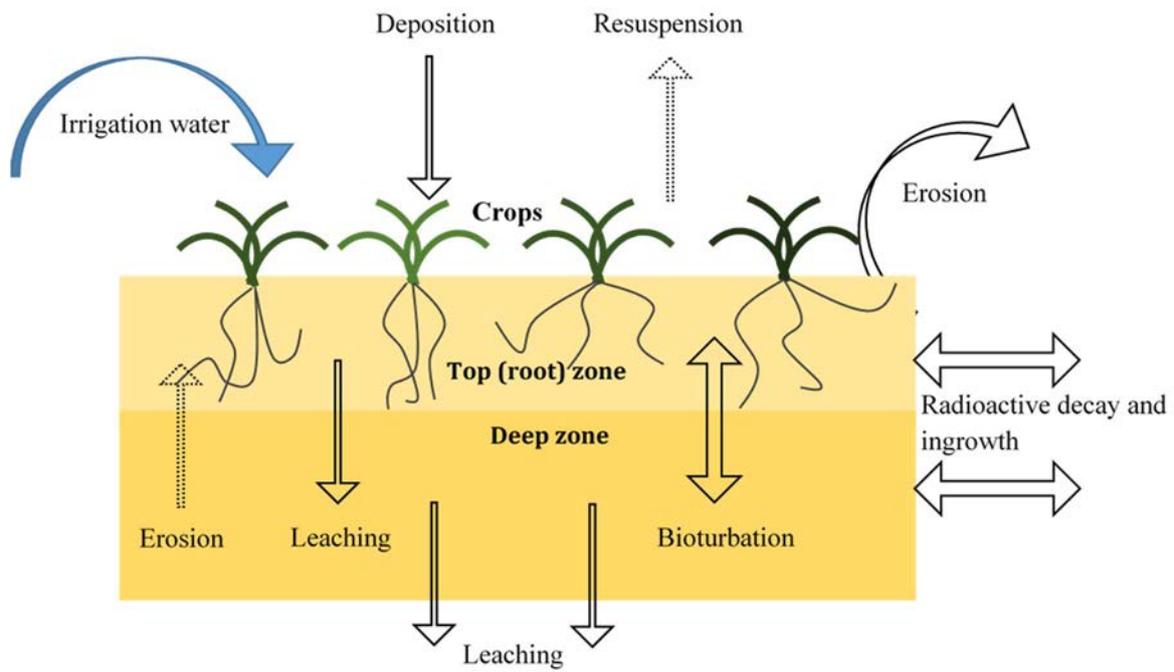
FIG. 20. Illustrative scheme of the 'Cropland' module. Exchanges between media, loadings and losses are shown by arrows.
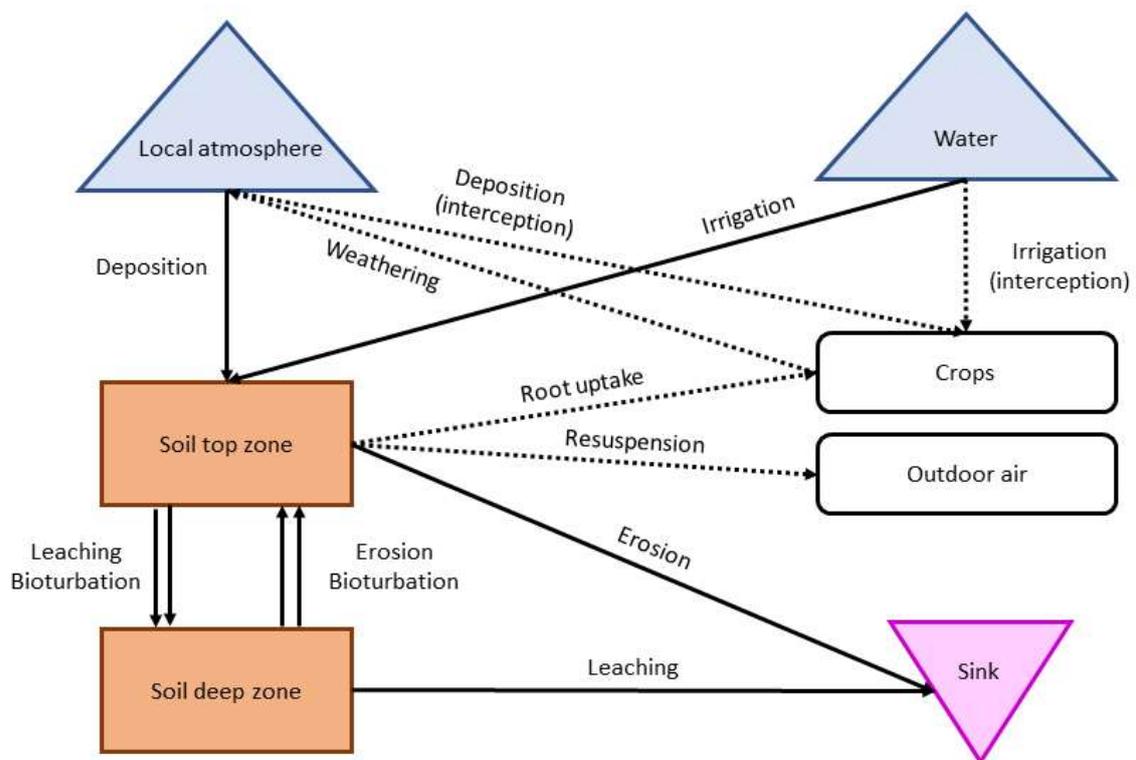
FIG. 21. Conceptual model of the 'Cropland' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

6.2.1.2.   Conceptual model

The conceptual model of 'Cropland' is illustrated in Fig. 21, and it includes the following media:

— Soil is subdivided into two compartments:
  • Soil top (root) zone: This media is defined as the top soil layer hosting most of the active roots of the crops. In this zone, transfer of radionuclides from soil to plants by root uptake takes place;
  • Soil deep zone: This media is defined as the deeper layer of the 'Cropland' soil, i.e. the soil layer which extends from below the root zone to the ground water table;
— Crops: This media is defined as the crops cultivated on the 'Cropland' being considered and are part of the human diet;
— Air: This media is defined as the outdoor air in the 'Cropland' area.

The inputs of radionuclides into the modelled 'Cropland' system may occur through the following mechanisms:

— Irrigation by contaminated water coming from another receptor (e.g. a river or a lake);
— Deposition of radionuclides (dry and/or wet) from atmosphere in aerosol form and/or dissolved in rainwater;
— Ingrowth of daughter radionuclides due to radioactive decay of their parent nuclides.

The potential losses of contaminants from the 'Cropland' system may occur through the following mechanisms:

— Leaching that involves the movement of dissolved radionuclides down through the soil profile due to water infiltration;
— Erosion caused by wind and/or water action;
— Radioactive decay.

The exchanges of contaminants between the Soil Top (Root) Zone and Deep Zone of the model may occur through the following mechanisms, which are modelled as a first order rate process:

— Bioturbation (which is modelled as a diffusive process);
— Leaching (i.e. vertical transport of radionuclides dissolved in pore water by moisture flow);
— Erosion (removal of soil by wind resuspension and/or water runoff processes).

Exchanges of radionuclides in the soil solid and liquid phases are modelled using the instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

Radionuclide accumulation in plants is calculated based on radionuclide concentration in topsoil (root zone) layer, and it accounts for root transfer from contaminated soil and interception by plant leaves. Radionuclide transfer to plants by root uptake is modelled using the Concentration Ratio (or Transfer Coefficients) approach [4]. Detailed model equations are given in Section 6.2.2.

The model takes into account four different crop types:

—— Legumes;

—— Leafy vegetables;

—— Cereals;

—— Roots.

These crop types have specific values of relevant radioecological parameters such as concentration ratio values describing radionuclide transfer to agricultural plants from soil, biomass per area values, irrigation rates, mass interception factors by plant surfaces, irrigation rates and evapotranspiration rates.

Radionuclide concentration in air is calculated based on radionuclide concentration in soil and assuming resuspension of the radioactivity to the atmosphere that is determined by the 'dust load' model parameter.

6.2.1.3. *Potential coupled modules*

TABLE 43. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'CROPLAND' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by following modules:	
'Atmosphere SR-19', 'Atmosphere chronic'	Deposition rates of radionuclides (Bq/m²·year)
'Fresh Water Body', 'Well'	Radionuclide concentration in irrigation water (Bq/m³)
Outputs from the module can be used by following modules:	
'Dose from ingestion of crops'	Radionuclide concentration in crops (Bq/kg·FW)
	Volumetric concentration of radionuclides in the soil root zone (Bq/m³)
'Dose from occupancy outdoors'	Mass radionuclide concentration in soil root zone (Bq/kg·DW)
	Concentration of radionuclides in outdoor air (Bq/m³)

6.2.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Cropland' module are provided.

Below, the main dynamic mathematical equations and formulas for calculating radionuclide redistributions and transfers in the 'soil–plant–atmosphere' media for the modelled 'Cropland' system are presented.

6.2.2.1. *Mass balance equation for soil media*

Radionuclide inventory in the root zone (Soil$_{RZ}$, Bq)

The mass balance for the activity of radionuclides in the soil root zone *(Soil$_{RZ}$, Bq)* is given by the following differential equation:

$$\frac{dSoil_{RZ}}{dt} = Dep + Irr + Soil_{DZ} \times Erosion_{DZ} + Soil_{DZ} \times BioT_{DZ} - Soil_{RZ} \times Leach_{RZ} - Soil_{RZ} \times Erosion_{RZ} - Soil_{RZ} \times BioT_{RZ} - \lambda \times Soil_{RZ} + \sum_{p \in P} Br_p \times \lambda \times Soil_{RZ}^p \qquad (85)$$

where:

Dep is the total deposition rate of radionuclides from atmosphere on the receptor area (Bq/year);
Irr is the transfer of radionuclide to the receptor area with irrigation water (Bq/year);
$Soil_{DZ}$ is the radionuclide inventory in deep zone of soil (Bq);
$Erosion_{DZ}$ is the transfer coefficient of radionuclide from deep soil zone to rooting zone to compensate erosion losses from the rooting zone (1/year);
$BioT_{DZ}$ is the transfer coefficient of radionuclide from the deep soil to rooting zone due to bioturbation (1/year);
$Leach_{RZ}$ is the transfer coefficient of radionuclides from the root zone to deep zone by leaching (1/year);
$Erosion_{RZ}$ is the transfer coefficient of radionuclides from the rooting zone due to erosion process (1/year);
$BioT_{RZ}$ is the transfer coefficient of radionuclide from the rooting soil to deep zone due to bioturbation (1/year).

The terms $\lambda \times Soil_{RZ}$ and $\sum_{p \in P} Br_p \times \lambda \times Soil_{RZ}^p$ in Eq. (85) describe, respectively, the radioactive decay and ingrowth of radionuclides.

Deposition rate of radionuclides (Dep, Bq/year)

$$Dep = Rate_{dep} \times A \tag{86}$$

where:

$Rate_{dep}$ is the radionuclide deposition per unit area of receptor (Bq/(m²·year)); and
A is the area of the receptor (m²).

Transfer of radionuclides by irrigation (Irr, Bq/year)

$$Irr = C_{water,irr} \times Rate_{irr,crops} \times A \tag{87}$$

where:

$C_{water,irr}$ is the radionuclide concentration in irrigation water (Bq/m³); and
$Rate_{irr,crops}$ is the irrigation rate for crops (m/year).

Mass transfer coefficient from the deep soil zone to compensate for erosion (Erosion$_{DZ}$, 1/year)

$$Erosion_{DZ} = Rate_{erosion} / (H_{soil,DZ} \times Rho_{soil,DZ}) \tag{88}$$

where:

$Rate_{erosion}$ is the erosion rate of soils in the considered receptor (kg·DW/(m²·year));
$Hh_{soil,DZ}$ is the height of the deep soil zone (m); and
$Rho_{soil,DZ}$ is the density of the deep zone soil (kg·DW/m³).

Mass transfer coefficient due to erosion from the soil root zone (Erosion$_{RZ}$, 1/year)

$$Erosion_{RZ} = Rate_{erosion} / (H_{soil,RZ} \times Rho_{soil,RZ}) \tag{89}$$

where:

$Rate_{erosion}$ is the erosion rate of soils in the considered receptor (kg·DW/(m²·year));
$H_{soil,RZ}$ is the height of the rooting soil zone (m); and
$Rho_{soil,RZ}$ is the density of the rooting zone soil (kg·DW/m³).

Mass transfer coefficient due to bioturbation in the soil deep zone (BioT$_{DZ}$, 1/year)

$$BioT_{DZ} = BioT/\left(H_{soil,DZ} \times Rho_{soil,DZ}\right) \tag{90}$$

where:

$BioT$ is the bioturbation coefficient in the soil (kg·DW/(m^2·year)).

Mass transfer coefficient due to bioturbation in the soil root zone (BioT$_{RZ}$, 1/year)

$$BioT_{RZ} = BioT/\left(H_{soil,RZ} \times Rho_{soil,RZ}\right) \tag{91}$$

Mass transfer coefficient due to leaching from the soil deep zone (Leach$_{DZ}$, 1/year)

$$Leach_{DZ} = \frac{max\left((Rate_{prec}+Ra_{\ irr,crops}-E_{\ crops}),0.0\right)}{\left(H_{soil,DZ} \times Porosity_{soil,DZ} \times Ret_{DZ}\right)} \tag{92}$$

where:

$Rate_{prec}$ is the precipitation rate (m^3/(m^2·year));
ET_{crops} is the evapotranspiration rate (m^3/(m^2·year));
$Porosity_{soil,DZ}$ is the porosity of the soil deep zone (m^3/m^3); and
Ret_{DZ} is the retardation factor for the soil deep zone (unitless).

Mass transfer coefficient due to leaching from the soil root zone (Leach$_{RZ}$, 1/year)

$$Leach_{RZ} = \frac{max\left((Rate_{prec}+Rate_{irr,crops}-E_{\ crops}),0.0\right)}{\left(H_{soil,RZ} \times Porosity_{soil,RZ} \times Ret_{RZ}\right)} \tag{93}$$

where:

Ret_{RZ} is the retardation factor for the soil root zone (unitless).

The equation for calculating the retardation factor in the soil root zone is:

$$Ret_{RZ} = 1.0 + Kd_{soil,RZ} \times Rho_{soil,RZ}/Porosity_{soil,RZ} \tag{94}$$

where:

$Kd_{soil,RZ}$ is the distribution coefficient for the soil root zone (m^3/kg·DW).

Radionuclide inventory in the deep zone (Soil$_{DZ}$, Bq)

The mass balance for the activity of radionuclides in the soil deep zone is given by the differential equation:

$$\frac{dSoil_{DZ}}{dt} = Soil_{RZ} \times Leach_{RZ} + Soil_{RZ} \times BioT_{RZ} - Soil_{DZ} \times Leach_{DZ} - Soil_{DZ} \times Erosion_{DZ} - Soil_{DZ} \times BioT_{DZ} - \lambda \times Soil_{DZ} + \sum_{p \in P_i} Br_p \times \lambda \times Soil_{DZ}^p \tag{95}$$

where:

$Soil_{RZ}$ is the radionuclide inventory in root zone of soil (Bq);
$Erosion_{DZ}$ is the transfer coefficient of radionuclide from deep soil zone to rooting zone to compensate for the erosion process (1/year);

$BioT_{DZ}$ is the transfer coefficient of radionuclide from the deep soil to rooting zone due to bioturbation (1/year);

$Leach_{DZ}$ is the transfer coefficient of radionuclides from the root zone to deep zone by leaching (1/year);

$Erosion_{RZ}$ is the transfer coefficient of radionuclides from the rooting zone due to the erosion process (1/year); and

$BioT_{RZ}$ is the transfer coefficient of radionuclide from the rooting soil to deep zone due to bioturbation (1/year).

The terms $\lambda \times Soil_{DZ}$ and $\sum_{p \in P} Br_p \times \lambda \times Soil_{DZ}^p$ in Eq. (95) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the root zone.

The equation for calculating the retardation factor in the soil deep zone in the 'Cropland' area is as follows:

$$Ret_{DZ} = 1.0 + Kd_{soil,DZ} \times Rho_{soil,DZ}/Porosity_{soil,DZ} \qquad (96)$$

where:

$Kd_{soil,DZ}$ is the distribution coefficient for the soil deep zone (m³/kg·DW).

6.2.2.2. Radionuclide concentration in soil media

Radionuclide mass concentration in the soil root zone (C_{soil}, Bq/kg_{DW})

$$C_{soil} = Soil_{RZ}/(A \times H_{soil,RZ} \times Rho_{soil,RZ}) \qquad (97)$$

where:

$Soil_{RZ}$ is the radionuclide inventory in the soil rooting zone (Bq);
A is the area of the receptor (m²);
$H_{soil,RZ}$ is the height of the soil rooting zone (m);
$Rho_{soil,RZ}$ is the density of the soil rooting zone (kg·DW/m³).

Radionuclide volumetric concentration in soil ($C_{soil,vol}$, Bq/m³)

$$C_{soil,vol} = C_{soil} \times Rho_{soil,RZ} \qquad (98)$$

6.2.2.3. Radionuclide concentration in outdoor air

The radionuclide concentration in the outdoor air is calculated as:

$$C_{air,outdoor} = C_{air,res} + C_{air,atm} \qquad (99)$$

where:

$C_{air,res}$ is the radionuclide concentration in outdoor air from resuspension (Bq/m³); and
$C_{air,atm}$ is the radionuclide concentration in atmospheric air (Bq/m³) resulting from the radionuclide atmospheric transport from the source to the receptor.

Radionuclide concentration in outdoor air due to resuspension ($C_{air,resusp}$, Bq/m³)

The radionuclide concentration in outdoor air from resuspension is calculated by:

$$C_{air,resusp} = C_{soil} \times C_{dust} \qquad (100)$$

where:

$C_{soil,byCrop}$ is the radionuclide concentration in the receptor top soil (Bq/kg·DW); and
C_{dust} is the concentration of dust in atmospheric air (dust load) (kg·DW/m³).

6.2.2.4. Radionuclide concentration in crops

The radionuclide concentration in crops *(C_{crops}, Bq/kg·FW)* is calculated by:

$$C_{crops} = C_{root\ uptake} \times \left(1.0 - WC_{crops}\right) \times UnitCorr_{DW,FW} + C_{crops,interc} \qquad (101)$$

where:

$C_{root\ uptake}$ is the radionuclide concentration in the specific crop type due to root uptake (Bq/kg·DW);
WC_{crops} is the fractional water content of the crops (unitless);
$UnitCorr_{DW,FW}$ is the unit correction factor from dry weight to fresh weight (kg·DW/kg·FW); and
$C_{crops,interc}$ is the radionuclide concentration in the crop type due to interception from air and irrigation water (Bq/kg·FW).

Radionuclide concentration in crops from root uptake (C_{root_uptake}, Bq/kg·DW)

Radionuclide concentration in crops from root uptake is calculated by taking the minimum value of two expressions, i.e. the first giving the maximum possible concentration based on the amount of radionuclides present in the soil, and the second modelling the concentration based on the concentration ratio (CR) [4]:

The equation for calculating the radionuclide concentration in a specific crop types due to root uptake is:

$$C_{root\ uptake} = min\left(C_{soil} \times H_{soil,RZ} \times \frac{Rho_{soil,RZ}}{Biomass_{crops}}, C_{soil} \times CR_{crops}\right) \qquad (102)$$

where:

$biomass_{crops}$ is the biomass of crops (kg·DW/m²); and
CR_{crops} is the activity concentration ratio for crops ((Bq/kg·DW)/(Bq/kg·DW)).

Radionuclide concentration in crops due to interception ($C_{crops,interc}$, Bq/kg·FW)

The equation for calculating the radionuclide concentration in crops due to interception of atmospheric deposition and irrigation water is:

$$C_{crops,interc} = \frac{C_{water,irr} \times Rate_{irr,crops} \times Factor_{interc,crops} \times \left(1.0 - exp\left(-\left(\frac{\ln(2)}{T_{weath}} + \lambda_{decay,days}\right) \times T_{irr,crops}\right)\right)}{\left(\frac{\ln(2.0)}{T_{weath}} + \lambda_{decay,days}\right) \times daysPerYear} +$$
$$\frac{Rate_{dep} \times Factor_{interc,crops} \times \left(1.0 - exp\left(-\left(\frac{\ln(2)}{T_{weath}} + \lambda_{decay,days}\right) \times T_{exp,crops}\right)\right)}{\left(\frac{\ln(2.0)}{T_{weath}} + \lambda_{decay,days}\right) \times daysPerYear} \qquad (103)$$

where:

$Factor_{interc,crops}$ is the mass interception factor for crops (m²/kg·FW);
T_{weath} is the weathering half time (days);
$\lambda_{decay,days}$ is the radionuclide decay constant (1/days);
$T_{irr,crops}$ is the time period that crops are irrigated (days);
$T_{exp,crops}$ is the crops exposure period i.e. the number of days that crops have above ground
      parts and as a result are exposed to radionuclide deposition (days); and
$daysPerYear$ is the number of days in a year (days/year).

6.2.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial conditions for soil compartments are zero (see Table 44), however modellers need to adapt these values according to their specific modelling case.

TABLE 44. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON 'CROPLAND'

Abbreviation and unit	Full name	Default value	Reference
C_air_atm (Bq/m³)	Concentration of radionuclide in atmospheric air	0	Site specific parameter
Dep_init (Bq)	Initial deposition on the 'Cropland's	0	Site specific parameter
C_soil_meas* (Bq/kg·DW)	Measured radionuclide concentration in soil	0	Site specific parameter
Rate_dep (Bq/(m²·year)	Deposition rate	0	Site specific parameter
C_water_irr (Bq/m³)	Concentration of radionuclides in irrigation water	0	Site specific parameter

Note: * The *c_soil_meas* value is needed in case radionuclide concentrations in crop are calculated based on user-specified soil concentration values. Dynamic calculations of radionuclide concentrations in soil profile are not performed (see Section 6.2.1.1).

Input parameters related to contaminated land geometry and physicochemical properties of soils are provided in Table 142 in the Appendix.

TABLE 45. INPUT PARAMETERS RELATED TO AGRICULTURAL CROPS

Abbreviation and Unit	Name	Default value	Reference
ET_crops (m³/(m²·year))	Evapotranspiration rate	0	
Biomass_crops (kg·DW/m²)	Biomass of crops	See Table 46	See Table 17–9 of Ref. [24]
CR_crops (kg·DW/kg·DW)	Concentration ratio for crops	See Table 47	[8, 11]
Factor_interc_crops (m²/kg·FW)	Mass interception factor	See Table 46	See Table VII of Ref. [4]
Rate_irr_crops (m³/(m²·year))	Irrigation rate for crops	See Table 46	[10, 25]
T_exp_crops (d)	Crop exposure period	See Table 46	[26]
T_irr_crops (d)	Time period of irrigation of crops	See Table 46	See Table VIII of Ref. [4]
T_weath (d)	Weathering half time	22.4	[8]
WC_crops (unitless)	Fractional water content of the crops	See Table 46	[7]

TABLE 46. DEFAULT VALUES OF PARAMETERS RELATED TO CROPS*

Abbreviation and Unit	Cereals	Leafy vegetables	Legumes	Roots
ET_crops (m^3/(m^2·year))	0	0	0	0
Biomass_crops (kg·DW/m^2)	0.39	0.54	1.11	1.02
Factor_interc_crops (m^2/kg·FW)	0.3	0.3	0.3	0.3
Rate_irr_crops (m^3/(m^2·year))	0.122	0.049	0.122	0.122
T_exp_crops (d)	75	90	75	75
T_irr_crops (d)	18.75	22.5	18.75	18.75
WC_crops (unitless)	1.2E-1	1.03E-1	1.2E-1	1.1E-1

Note: * See Table 45 for literature sources for parameter values.

TABLE 47. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO CROPS, kg/kg [8, 11]

Radionuclide	Cereals	Leafy vegetables	Legumes	Roots
Ac	5.3E–03	2.44E-03	3.90E-04	5.70E-03
Cs	2.90E-02	6.00E-02	4.00E-02	4.20E-02
Pa	5.30E-03	2.44E-03	3.90E-04	5.70E-03
Pb	1.10E-02	8.00E-02	1.50E-03	1.50E-02
Po	2.40E-04	7.40E-03	2.70E-04	5.80E-03
Ra	1.70E-02	9.10E-02	1.40E-02	7.00E-02
Sr	1.10E-01	7.60E-01	1.40E+00	7.20E-01
Th	2.10E-03	1.20E-03	5.30E-04	8.00E-04
U	6.20E-03	2.00E-02	2.20E-03	8.40E-03

6.2.4. Output parameters

The main output parameter of the 'Cropland' module is radionuclide concentration in agricultural crops, which are used for calculating doses from ingestion of crops.

Other calculated parameters are radionuclide concentrations in soil and air, that are used for calculating doses to persons exposed to radioactivity at the contaminated cropland area (e.g. agricultural workers).

TABLE 48. OUTPUT PARAMETERS OF 'CROPLAND' MODULE

Abbreviation (unit)	Name	Purpose
C_crops (Bq/kg·FW)	Radionuclide concentration in crops	Used to calculate doses from ingestion of crops
C_soil_byCrops (Bq/kg·DW)	Mass radionuclide concentration in soil	Used to calculate doses from radionuclides deposited to soil
C_soil (Bq/m^3)	Volumetric radionuclide concentration in soil	Used to calculate doses from radionuclides deposited to soi
C_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Used to calculate doses from radionuclides in air

6.3. 'PASTURE LAND' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Pasture land' module.

6.3.1. Module description

In this section, detailed descriptions of the 'Pasture land' module are provided.

6.3.1.1. General description

The 'Pasture land' module is designed to assess exposure pathways associated with ingestion of meat and milk obtained from livestock grazing on contaminated pastureland.

The 'Pasture land' module dynamically simulates the vertical distribution of radionuclides in the soil of pastureland, the concentrations in fodder and in livestock products (i.e. meat and milk).

The mathematical model of radionuclide transfers in pasture land soil is the same as for the 'Cropland' module (see Section 6.2) and is based on the crop irrigation model described in Ref. [2]. The model accounts for inputs of radionuclides to the pasture land by deposition from the atmosphere and by irrigation with contaminated water. The model takes into account losses of radionuclides from the system through erosion and leaching processes (Fig. 22).

The module calculates radionuclide concentrations in livestock (i.e. meat and milk) resulting from cattle grazing on contaminated pasture. It can also account for ingestion of contaminated water by cattle.

The module provides an option for the user to specify the radionuclide concentration in soil and drinking water for animals (e.g. based on monitoring data). In this case, soil and water concentration values specified and fixed in time by the modeller are used to calculate radionuclide concentrations in fodder, milk and meat.

6.3.1.2. Conceptual model

The conceptual model of 'Pasture land' is illustrated in Fig. 23. It includes the following media:

— Soil is subdivided into two compartments:
  • Soil top (root) zone: This media is defined as the top soil layer hosting most of the active roots of the fodder plants. In this zone, transfer of radionuclides from soil to plants by root uptake takes place;
  • Soil deep zone: This media is defined as the deeper layer of soil, i.e. the soil layer which extends from below the root zone to the ground water table.
— Pasture: This media is defined as the fresh fodder that the livestock consumes when grazing on the pastureland area;
— Air: This media is defined as the outdoor air in the pastureland area;
— Livestock: This media is defined as cattle (e.g. cow and sheep) grazing in the pastureland and providing commodities to humans (e.g. milk and meat).
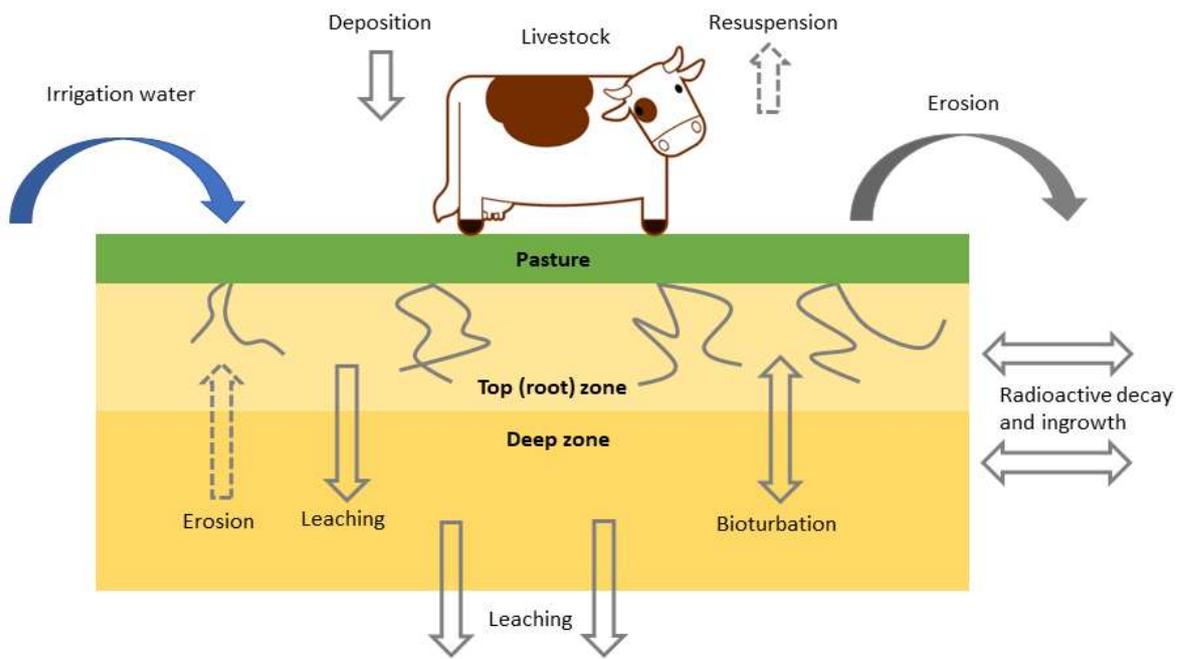
FIG. 22. Illustrative scheme of the 'Pasture land' module. Exchanges between media, loadings and losses are shown by arrows.
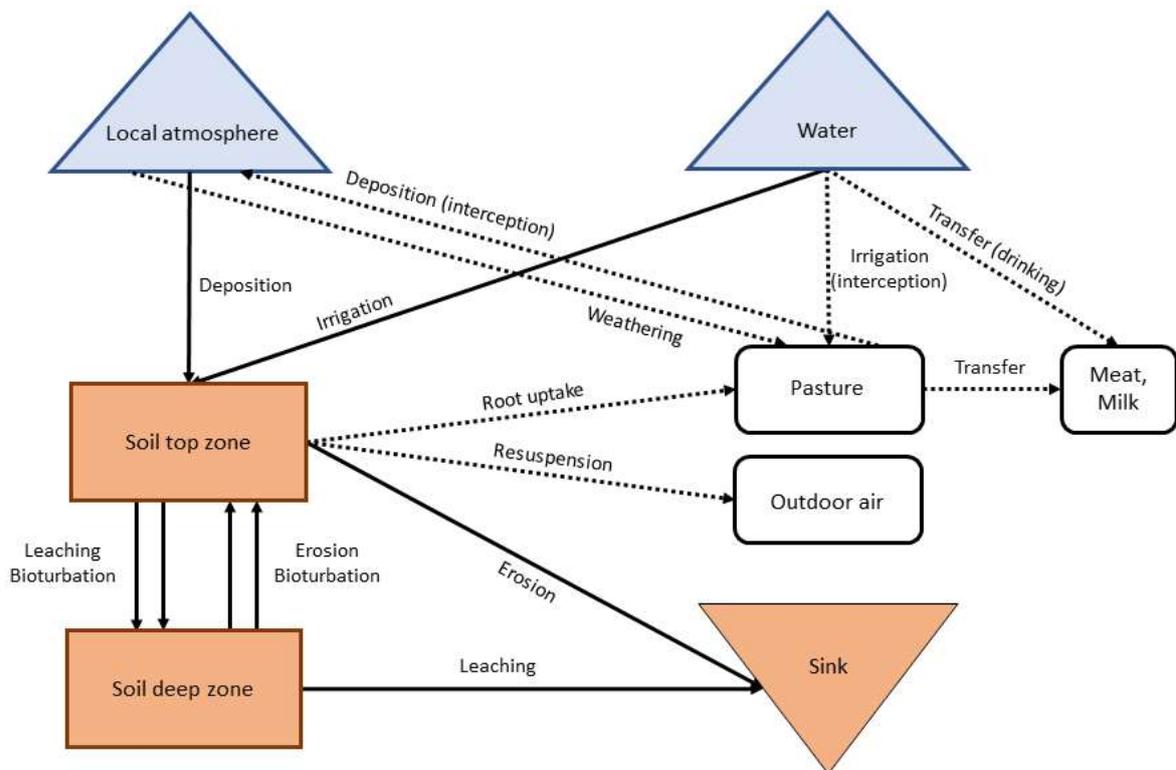
FIG. 23. Conceptual model of the 'Pasture land' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

The inputs of radionuclides into the modelled pastureland system may occur through the following mechanisms:

— Irrigation water coming from another receptor (e.g. a river or well);
— Deposition of radionuclides (dry and/or wet) from atmosphere in aerosol form and/or dissolved in rainwater;
— Ingrowth of daughter radionuclides due to radioactive decay of their parent nuclides.

The potential losses of contaminants from the 'Pasture land' system may occur through the following mechanisms:

— Erosion caused by wind and/or water action;
— Radioactive decay.

The exchanges of contaminants between the 'Soil Top Zone' (root zone) and' Soil Deep Zone' of the model may occur through the following mechanisms, which are modelled as first order rate process:

— Bioturbation (which is modelled as a diffusive process);
— Leaching (i.e. vertical transport of radionuclides dissolved in pore water by moisture flow);
— Erosion (removal of soil by wind resuspension and/or water runoff process).

Exchanges of radionuclides in the soil solid and liquid phases are modelled using instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

Radionuclide accumulation in fodder is calculated based on the radionuclide concentration in the topsoil (root zone) layer, and it accounts for root transfer from contaminated soil and interception by plant leaves. Radionuclide transfer to plants by root uptake is modelled using the Concentration Ratio (or Transfer Coefficients) approach [4]. Detailed model equations are given below (see Section 6.3.2).

The model takes into account the following types of livestock products:

— Beef;
— Sheep;
— Cow milk.

These livestock products have specific values of relevant radioecological parameters such as the transfer factors and ingestion rates of fodder (see Section 6.3.3).

Radionuclide concentration in air is calculated based on the radionuclide concentration in soil and assuming resuspension of the radioactivity to the atmosphere that is determined by the 'dust load' model parameter.

6.3.1.3. Potential coupled modules

TABLE 49. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'PASTURE LAND' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by following modules:	
'Atmosphere SR-19' 'Atmosphere chronic'	Deposition rates of radionuclides (Bq/m²·year)
'Fresh Water Body', 'Well'	Radionuclide concentration in irrigation water and drinking water (Bq/ m³)
Outputs from the module can be used by following modules:	
'Dose from ingestion of milk and meat'	Radionuclide concentration in milk (Bq/L) Radionuclide concentration in meat (Bq/kg·FW)
	Volumetric concentration of radionuclides in the soil root zone (Bq/m³)
'Dose from occupancy outdoors'	Mass radionuclide concentration in soil root zone (Bq/kg·DW)
	Concentration of radionuclides in outdoor air (Bq/m³)

6.3.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Pasture land' module are provided.

6.3.2.1. Mass balance equation for soil media

Radionuclide transfers in soil are described by the mathematical model that is similar to the model for the 'Cropland' receptor described in Sections 6.2.2.1–6.2.2.2 (Eqs (85)–(98)).

6.3.2.2. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air are calculated using the equations described in Section 6.2.2.3 (Eqs (99)–(100)).

6.3.2.3. Radionuclide concentration in pasture (fodder)

Radionuclide concentrations in pasture (fodder) are calculated using the model that is similar to the model radionuclides concentration in agricultural crops for 'Cropland' module described in Section 6.2.2.4 (Eqs (101)–(103)).

6.3.2.4. Radionuclide concentration in milk and meat

Radionuclide concentration in meat (C_{meat}, Bq/kg)

The radionuclide concentration in the meat of grazing cattle for all radionuclides is calculated as follows:

$$C_{meat} = TF_{meat} \times \left(C_{pasture} \times Rate_{ing.past,meat} + C_{water,drink,animals} \times Rate_{ing,water,meat} + C_{soil,calc} \times Rate_{ing.soil,meat} \times f_{grazing} \right) \quad (104)$$

where:

TF_{meat} is the transfer factor to livestock meat ((Bq/kg·FW)/(Bq/day));
$C_{pasture}$ is the radionuclide concentration in fodder (Bq/kg·DW);
$Rate_{ing.past,meat}$ is the cattle type-specific ingestion rate of pasture by cattle designated for meat production (meat animals) (kg·DW/day);

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$C_{water,drink,animals}$ is the radionuclide concentration in the drinking water of cattle (Bq/m³);
$Rate_{ing.water,meat}$ is the cattle type-specific ingestion rate of water by meat animals (m³/day);
$Rate_{ing.soil,mea}$ is the cattle type-specific ingestion rate of soil by meat animals (kg·DW/day); and
$f_{grazing}$ is the fraction of a year during which the meat animals are grazing pasture (unitless).

The inhalation uptake of radionuclides by cattle from airborne radionuclides or from radionuclides in resuspended soil particles is not included since its contribution is expected to be minor compared with the other activity transfers pathways.

Radionuclide concentration in milk (C_milk, Bq/L)

The radionuclide concentration in milk from grazing animals is calculated by:

$$C_{milk} = TF_{milk} \times (C_{pasture} \times Rate_{ing,past,milk} + C_{water,drink,animals} \times Rate_{ing,water,milk} + C_{soil} \times Rate_{ing,soil,milk} \times f_{grazing}) \qquad (105)$$

where:

TF_{milk} is the transfer factor to milk (d/L);
$Rate_{ing,past,milk}$ is the cattle type-specific ingestion rate of pasture by cattle designated for milk production (milk animals) (kg·DW/day);
$Rate_{ing.water,milk}$ is the cattle type-specific ingestion rate of water by meat animals (m³/day);
$Rate_{ing.soil,milk}$ is the cattle type-specific ingestion rate of soil by meat animals (kg·DW/day);
$f_{grazing}$ is the fraction of a year during which milk animals are grazing pasture (unitless).

6.3.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial conditions for soil compartments are zero (Table 50). However, modellers need to adapt these values according to their specific modelling case.

Input parameters related to contaminated land geometry and physicochemical properties of soils are provided in Table 142 (see Appendix).

TABLE 50. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON PASTURELAND'

Abbreviation and unit	Full name	Default value	Reference
C_air_atm (Bq/m³)	Concentration of radionuclide in atmospheric air	0	Site specific parameter
Dep_init (Bq)	Initial deposition on the pastureland	0	Site specific parameter
C_soil_meas* (Bq/kg·DW)	Measured radionuclide concentration in soil	0	Site specific parameter
Rate_dep (Bq/m²·year)	Deposition rate	0	Site specific parameter
C_water_irr (Bq/m³)	Concentration of radionuclides in irrigation water	0	Site specific parameter
C_water_drink_animals (Bq/m³)	Concentration of radionuclides in drinking water	0	Site specific parameter

Note: * The *c_soil_meas* value is needed in case radionuclide concentrations in pasture are calculated based on user-specified soil concentration values. Dynamic calculations of radionuclide concentrations in soil profile are not performed (see Section 6.3.1.1).

TABLE 51. INPUT PARAMETERS RELATED TO PASTURELAND

Abbreviation and Unit	Name	Default value	Reference
ET_pasture (m^3/(m^2·year))	Evapotranspiration rate	0	Site specific parameter
CR_pasture (kg·DW/kg·DW)	Concentration ratio for pasture	See Table 52	[8]
factor_interc_pasture (m^2/kg·FW)	Mass interception factor	3	See Table VII of Ref. [4]
Rate_irr_pasture	Irrigation rate for pasture	0.131	[10, 25]
T_exp_pasture (d)	Pasture exposure period	30	See Table VIII of Ref. [4]
T_irr_pasture (d)	The number of days that vegetation is exposed to irrigation	7.5	See Table VIII of Ref. [4]
T_weath (d)	Weathering half time	22.4	[8]
Biomass_pasture (kg·DW/m^2)	Biomass of pasture	0.33	See Table 17-9 of Ref. [24]
WC_pasture (unitless)	Fractional water content of the pasture	1.1E-1	[7]

TABLE 52. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO PASTURE, kg·DW/kg·DW [8]

Radionuclide	CR_pasture
Ac	1.06E-03
Cs	2.50E-01
Pa	1.06E-03
Pb	9.20E-02
Po	1.20E-01
Ra	7.20E-02
Sr	1.30E+00
Th	4.20E-02
U	4.60E-02

TABLE 53. PARAMETERS RELATED TO CATTLE

Abbreviation and Unit	Name	Default value	Reference
Rate_ing_past_meat (kg·DW/d)	The ingestion rates of pasture by meat producing animals	See Table 54	[26]
Rate_ing_past_milk (kg·DW/d)	The ingestion rates of pasture by milk producing animals	9.1	[26]
Rate_ing_soil_meat (kg·DW/d)	The ingestion rates of soil by meat producing animals	See Table 54	[10, 26]
Rate_ing_soil_milk (kg·DW/d)	The ingestion rates of soil by meat producing animals	0.6	[10]
Rate_ing_water_meat (m^3/d)	The ingestion rates of water by meat producing animals	See Table 54	[10; 26]
Rate_ing_water_milk (m^3/d)	The ingestion rates of water by meat producing animals	0.04	[10]
f_grazing (unitless)	The fraction of the year during which meat producing animals are grazing the pasture	0.25	[10]
TF_meat (d/kg·FW)	The transfer factor relating the uptake of elements in muscle tissue (meat) of an animal to the intake of food, water and soil by the meat animal	See Table 55	[8, 10]
TF_milk (d/L)	The transfer factor relating the concentration of radionuclides in milk to the intake of food, water and soil by the animal	See Table 55	[8, 10]

TABLE 54. DEFAULT VALUES OF CATTLE INGESTION RATES [10, 26]

Abbreviation and Unit	Beef	Sheep
Rate_ing_past_meat (kg·DW/d)	11.4	3
Rate_ing_water_meat (m³/d)	0.06	0.01
Rate_ing_soil_meat (kg·DW/d)	0.7	0.14

TABLE 55. DEFAULT VALUES OF TRANSFER FACTORS (TF) FOR LIVESTOCK PRODUCTS RELATING THE CONCENTRATION OF RADIONUCLIDES IN MILK AND MEAT TO THE INTAKE OF FOOD, WATER AND SOIL BY THE ANIMAL*

Radionuclide	TF meat d/kg		TF milk d/L
	Beef	Sheep	
Ac	1.30E-04	1.60E-03	4.20E-07
Cs	2.20E-02	5.30E-02	4.60E-03
Pa	1.30E-04	1.60E-03	4.20E-07
Pb	7.00E-04	9.20E-03	1.90E-04
Po	7.00E-04	1.40E-01	2.10E-04
Ra	1.70E-03	1.80E-01	3.80E-04
Sr	1.30E-03	7.60E-01	1.30E-03
Th	2.30E-04	6.20E-03	3.60E-06
U	3.90E-04	3.30E-01	1.80E-03

Note: *Literature sources for parameter values are listed in Table 53.

6.3.4. Output parameters

The main output parameter of the 'Pasture land' module is radionuclide concentrations in livestock products (milk and meat), that are used for calculating doses from ingestion of these products.

Other calculated parameters are radionuclide concentrations in soil and air of pastureland which are used for calculating doses to persons exposed to radioactivity on contaminated land (e.g. shepherds).

TABLE 56. OUTPUT PARAMETERS OF 'PASTURE LAND' MODULE

Abbreviation (unit)	Name	Purpose
C_meat (Bq/kg	Radionuclide concentration in meat	Used to calculate doses from ingestion of meat and milk
C_milk (Bq/L)	Radionuclide concentration in milk	Used to calculate doses from ingestion of meat and milk
C_soil_vol (Bq/kg·DW)	Mass radionuclide concentration in soil	Used to calculate doses from radionuclides in the soil
C_soil (Bq/m³)	Radionuclide volumetric concentration in soil	Used to calculate doses from radionuclides in the soil
C_air_outdoor (Bq/m³)	Concentration of radionuclides in outdoor air	Used to calculate doses from radionuclides in air

6.4. 'LAND' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Land' module.

6.4.1. Module description

In this section, detailed descriptions of the 'Land' module are provided.

6.4.1.1. General description

This module simulates the contaminated land where exposure of an individual can occur by external irradiation from radionuclides deposited on the soil, inhalation of radionuclides in the air and due to inadvertent ingestion of contaminated soil. It is assumed however, that the modelled contaminated land is not used for agricultural purposes.

The radioecological model used is based on the model described in Ref. [2] (see Fig. 24), which is the same model as for the 'Cropland' module. The model dynamically simulates vertical distribution of radionuclides in the soil profile consisting of 'top' and 'deep' soil compartments. The model takes into account input of radionuclides through deposition from the atmosphere and it accounts for losses from the soil through erosion, bioturbation (using diffusion type transfer models) and leaching processes. The model calculates the concentration of radionuclides in soil, as well as concentration of radionuclides in outdoor air due to resuspension from soil.

The module provides an option for the user to directly specify the radionuclide concentration in the soil (e.g. based on monitoring data) for subsequent dose calculations. In this case, dynamic calculations of radionuclide redistribution in the soil profile are not performed.

6.4.1.2. Conceptual model

The conceptual model of the 'Land' module is illustrated in Fig. 25. The model includes the following media:

— Soil is subdivided into two compartments:
  - Soil top (root) zone: This media is defined as the top soil layer hosting most of the active roots of plants;
  - Soil deep zone: This media is defined as the deeper layer of soil, i.e. the soil layer which extends from below the root zone to the ground water table.
— Air: This media is defined as the outdoor air in the modelled contaminated area.

The inputs of radionuclides into the modelled contaminated land system may occur through the following mechanisms:

— Deposition of radionuclides (dry and/or wet) from atmosphere in aerosol form and/or dissolved in rainwater;
— Ingrowth of daughter radionuclides due to radioactive decay of their parent nuclides.
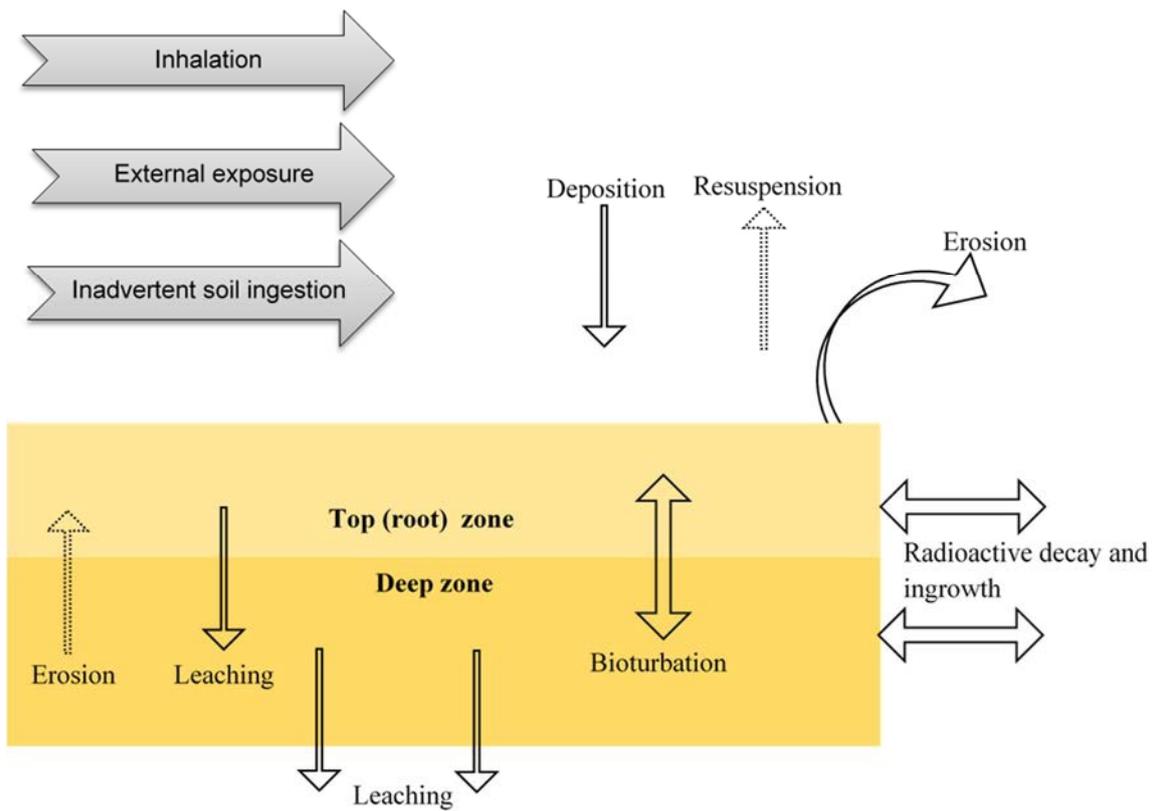
FIG. 24. Illustrative scheme of the 'Land' module. Exchanges between media, loadings and losses are shown by arrows.
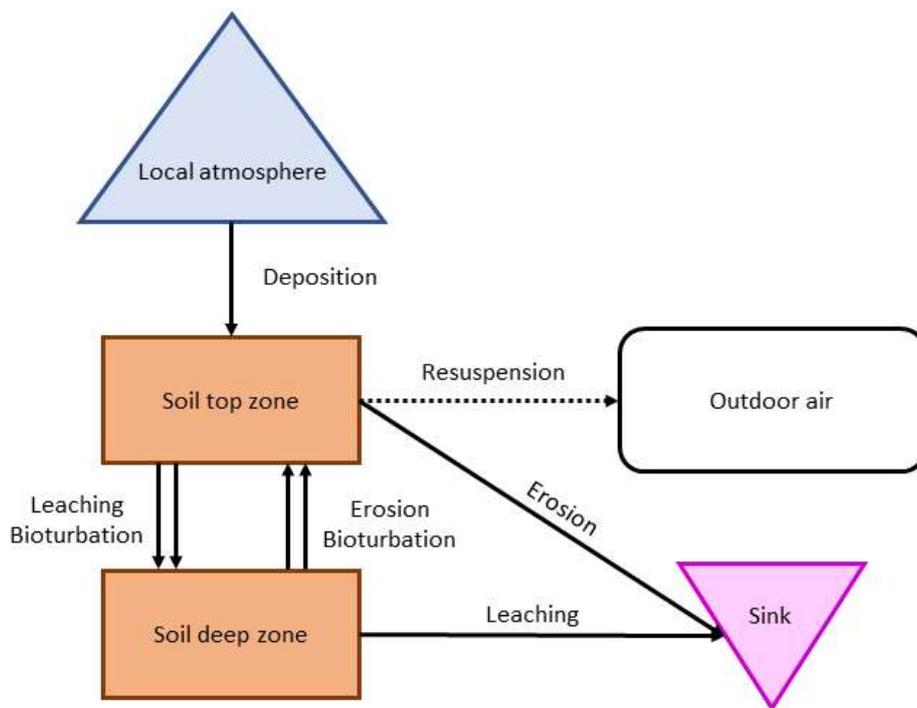
FIG. 25. Conceptual model of the 'Land' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

The potential losses of contaminants from the 'Land' system may occur through the following mechanisms:

— Leaching that involves the movement of dissolved radionuclides down through the soil profile due to water infiltration;
— Erosion caused by wind and/or water action;
— Radioactive decay.

The exchanges of contaminants between the 'Soil Top zone' (root zone) and 'Soil Deep Zone' of the model may occur through the following mechanisms that are modelled as the first order rate process:

— Bioturbation (which is modelled as a diffusive process);
— Leaching (i.e. vertical transport of radionuclides dissolved in pore water by moisture flow);
— Erosion (removal of soil by wind resuspension and/or water runoff processes).

Exchanges of radionuclides in the soil solid and liquid phases are modelled using an instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

The radionuclide concentration in air is calculated based on the radionuclide concentration in soil and assuming resuspension of the radioactivity to the atmosphere that is determined by the 'dust load' model parameter.

6.4.1.3. Potential coupled modules

TABLE 57. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'LAND' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by following modules:	
'Atmosphere SR-19', 'Atmosphere chronic'	Deposition rates of radionuclides ($Bq/m^2 \cdot year$)
Outputs from the module can be used by following modules:	
	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
'Dose from occupancy outdoors'	Mass radionuclide concentration in soil root zone ($Bq/kg \cdot DW$)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.4.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Land' module are provided.

6.4.2.1. Mass balance equation for soil media

Radionuclide transfers in soil are described by a mathematical model that is similar to the model for the 'Cropland' receptor described in Section 6.2.2.1–6.2.2.2 (Eqs (85)–(98)). It is assumed that there is no irrigation in the 'Land' module, therefore the respective terms of the mathematical model related to irrigation are not taken into account.

6.4.2.2.   Radionuclide concentration in outdoor air

The radionuclide concentrations in outdoor air are calculated using a model that is similar to the 'Cropland' module described in Section 6.2.2.3 (Eqs (99)–(100)).

6.4.3.   Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial conditions for soil compartments are zero (see Table 58). However, the modellers need to adapt these values according to their specific modelling case.

Input parameters related to the contaminated land geometry and physicochemical properties of soils are provided in Table 142 (see Appendix).

TABLE 58. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON 'LAND' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_air_atm (Bq/m^3)	Concentration of radionuclide in atmospheric air	0	Site specific parameter
Dep_init (Bq)	Initial deposition on the 'Land's	0	Site specific parameter
C_soil_meas* (Bq/kg·DW)	Measured radionuclide concentration in soil	0	Site specific parameter
Rate_dep (Bq/(m^2·year))	Deposition rate	0	Site specific parameter

Note: * The *c_soil_meas* value is needed in case radionuclide concentrations in soil are calculated based on user-specified soil concentration values. In this case dynamic calculations of radionuclide concentrations in the soil profile are not performed (see Section 6.4.1.1).

6.4.4.   Output parameters

The main output parameter of the 'Land' module is radionuclide concentration in the top (root) soil layer. The module also calculates radionuclide concentrations in air, that are used for calculating doses to persons exposed to radioactivity at the modelled contaminated site.

TABLE 59. OUTPUT PARAMETERS OF 'LAND' MODULE

Abbreviation (unit)	Name	Purpose
C_soil (Bq/kg·DW)	Mass radionuclide concentration in soil	Used to calculate doses from radionuclides deposited on soil
C_soil_vol (Bq/m^3)	Radionuclide volumetric concentration in soil	Used to calculate doses from radionuclides deposited on soil
C_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Used to calculate doses from radionuclides in the air

6.5.   'GARDEN PLOT' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Garden plot' module.

6.5.1. Module description

In this section, detailed descriptions of the 'Garden plot' module are provided.

6.5.1.1. General description

The 'Garden plot' module is designed to assess exposure pathways associated with cultivation of garden food in contaminated land.

The 'Garden plot' module simulates the dynamically vertical distribution of radionuclides in the soil and the radionuclide transfer to cultivated foods produced in a garden.

The mathematical model of radionuclide transfers in garden soil is the same as for the 'Cropland' module (see Section 6.2), and it is based on the crop irrigation model described in Ref. [2]. The model takes into account input of radionuclides through deposition from the atmosphere and irrigation with contaminated water and losses of radionuclides from the system through erosion and leaching processes (Fig. 26).

The module provides an option for the user to specify radionuclide concentration in soil (e.g. based on monitoring data). In this case, soil concentration values specified and fixed in time by the modeller are used to calculate radionuclide concentrations in garden food.
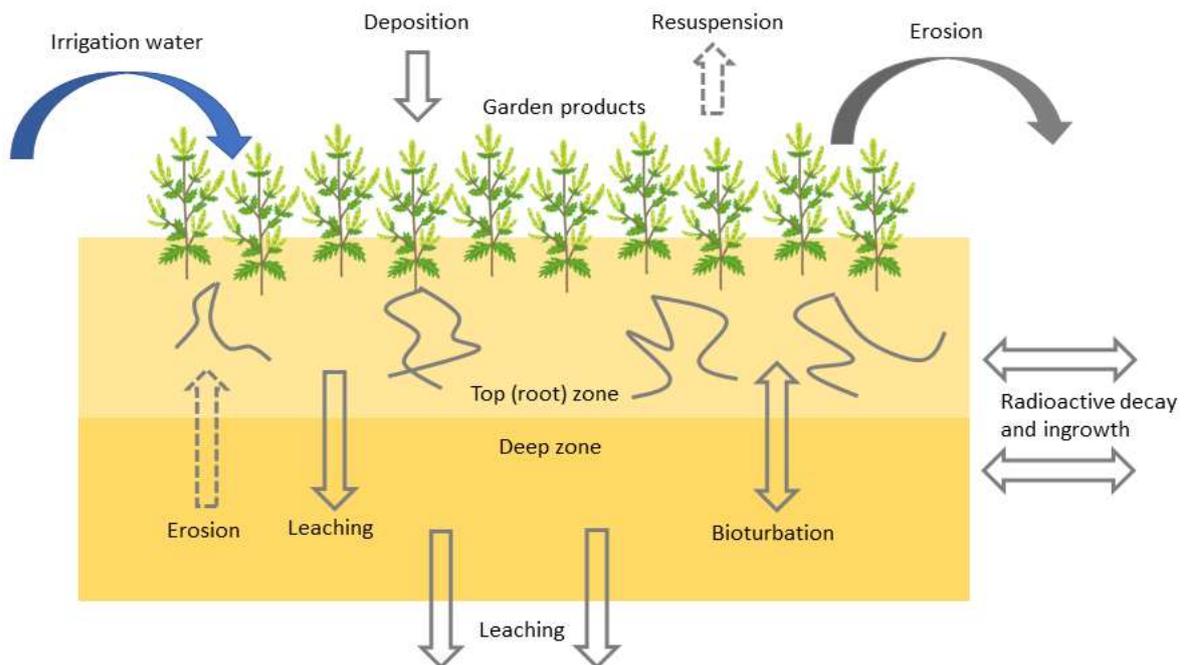
FIG. 26. Illustrative scheme of the 'Garden plot' module. Exchanges between media, loadings and losses are shown by arrows.
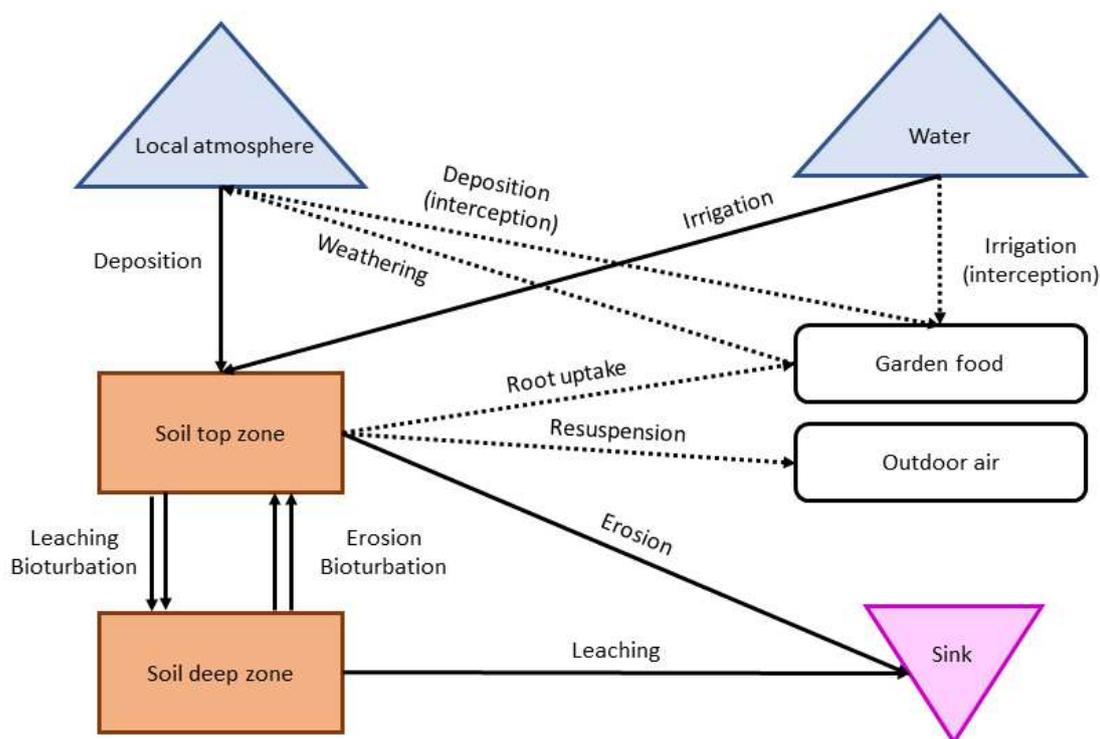
FIG. 27. Conceptual model of the 'Garden plot' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

6.5.1.2. Conceptual model

The conceptual model of the 'Garden plot' module is illustrated in Fig. 27. The 'Garden plot' model includes the following media:

⎯ Soil is subdivided into two compartments:
   • Soil top (root) zone: This media is defined as the top soil layer hosting most of the active roots of the garden food. In this zone, transfer of radionuclides from soil to plants by root uptake takes place;
   • Soil deep zone: This media is defined as the deeper layer of the garden soil, i.e. the soil layer which extends from below the root zone to the ground water table.
⎯ Garden food: This media is defined as the garden food cultivated on the garden plot being considered and are part of the human diet;
⎯ Air: This media is defined as the outdoor air in the garden area.

The inputs of radionuclides into the modelled 'Garden plot' system may occur through the following mechanisms:

⎯ Irrigation water coming from another receptor (e.g. a river/lake or well);
⎯ Deposition of radionuclides (dry and/or wet) from the atmosphere in aerosol form and/or dissolved in rainwater;
⎯ Ingrowth of daughter radionuclides due to the radioactive decay of their parents.

The potential losses of contaminants from the 'Garden plot' system may occur through the following mechanisms:

— Leaching that involves the movement of dissolved radionuclides down through the soil profile due to water infiltration;
— Erosion caused by wind and/or water action;
— Radioactive decay.

The exchanges of contaminants between the 'Soil Top Zone' (soil root zone) and 'Soil Deep Zone' of the model can occur through the following mechanisms which are modelled as the first order rate process:

— Bioturbation (which is modelled as a diffusive process);
— Leaching (i.e. vertical transport of radionuclides dissolved in pore water by moisture flow);
— Erosion (removal of soil by wind resuspension and/or water runoff process).

Exchanges of radionuclides in the soil solid and liquid phases are modelled using an instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

The radionuclide accumulation in plants is calculated based on the radionuclide concentration in the top soil (root zone) layer, and it accounts for the root transfer from contaminated soil and interception by plant leaves. The radionuclide transfer to plants by root uptake is modelled using Concentration Ratio (or Transfer Coefficients) approach [4].

The model takes into account five different garden products:

— Legumes;
— Leafy vegetables;
— Roots;
— Fruits;
— Garden berries.

These garden products have specific values of relevant radioecological parameters such as concentration ratio values describing radionuclide transfer to garden food from soil, biomass per area values, mass interception factors by plant surfaces, irrigation rates and evapotranspiration rates.

The radionuclide concentration in air is calculated based on the radionuclide concentration in soil and assuming resuspension of the radioactivity to the atmosphere that is determined by the 'dust load' model parameter.

6.5.1.3. Potential coupled modules

TABLE 60. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'GARDEN PLOT' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by following modules:	
'Atmosphere SR-19', 'Atmosphere chronic'	Deposition rates of radionuclides (Bq/m²·year)
'Fresh Water Body', 'Well'	Radionuclide concentration in irrigation water (Bq/m³)
Outputs from the module can be used by following modules:	
'Dose from ingestion of garden food'	Radionuclide concentration in garden food (Bq/kg·FW)
	Volumetric concentration of radionuclides in the soil root zone (Bq/m³)
'Dose from occupancy outdoors'	Radionuclide concentration in soil root zone (Bq/kg·DW)
	Concentration of radionuclides in outdoor air (Bq/m³)

6.5.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Garden plot' module are provided.

6.5.2.1. Mass balance equation for soil media

Radionuclide transfers in soil are described by mathematical model that is similar to the model for 'Cropland' receptor described in Section 6.2.2.1–6.2.2.2 (Eqs (85)–(98)).

6.5.2.2. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air are calculated using equations described Section 6.2.2.3 (Eqs (99)–(100)).

6.5.2.3. Radionuclide concentration in garden food

Radionuclide concentrations in garden food are calculated using model that is similar to the model radionuclides concentration in agricultural crops for 'Cropland' module described in Section 6.2.2.4 (Eqs (101)–(103)).

6.5.3. Input parameters

6.5.3.1. Initial contamination and radiological loads

By default, no contamination is assumed at the beginning of the simulation, hence the initial conditions of soil compartments are zero (see Table 61). However, the modellers need to adapt these values according to their specific case.

TABLE 61. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON 'GARDEN PLOT'

Abbreviation and unit	Full name	Default value	Reference
C_air_atm (Bq/m^3)	Concentration of radionuclide in atmospheric air	0	Site specific parameter
Dep_init (Bq)	Initial deposition on the 'Garden plot'	0	Site specific parameter
C_soil_meas* (Bq/kg·DW)	Measured radionuclide concentration in soil	0	Site specific parameter
Rate_dep (Bq/(m^2·year))	Deposition rate	0	Site specific parameter
C_water_irr (Bq/m^3)	Concentration of radionuclides in irrigation water	0	Site specific parameter

Note: * The *C_soil_meas* value is needed in case radionuclide concentrations in garden food are calculated based on user-specified soil concentration values. Dynamic calculations of radionuclide concentrations in soil profile are not performed (see Section 6.4.1.1).

Input parameters related to contaminated land geometry and physicochemical properties of soils are provided in Table 142 (see Appendix).

TABLE 62. INPUT PARAMETERS RELATED TO GARDEN FOOD

Abbreviation and Unit	Name	Default value	Reference
ET_garden_food (m/year)	Evapotranspiration rate	0	
Biomass_garden_food (kg·DW/m^2)	Biomass of garden food	See Table 63	See Table 17-9 of Ref. [24]
CR_garden_food (kg·DW/kg·DW)	Concentration ratio for garden food	See Table 64	[8, 11]
factor_interc_garden_food (m^2/kg·FW)	Mass interception factor	See Table 63	See Table VII of Ref. [4]
Rate_irr_garden_food (m/year)	Irrigation rate for garden food	0	[10, 25]
T_exp_garden_food (d)	Garden food exposure period	See Table 63	[26]
T_irr_garden_food* (d)	Time period of irrigation of garden food	0	See Table VIII of Ref. [4]
T_weath (d)	Weathering half time	22.4	[8]
WC_garden_food (unitless)	Fractional water content of the garden food	See Table 63	[7]

TABLE 63. DEFAULT VALUES OF PARAMETERS RELATED TO GARDEN FOOD*

Abbreviation and Unit	Legumes	Leafy vegetables	Roots	Fruits	Garden berries
Biomass_garden_food (kg·DW/m^2)	1.11	0.54	1.02	0.1	0.1
factor_interc_garden_food (m^2/kg·FW)	0.3	0.3	0.3	0.1	0.1
T_exp_garden_food (d)	75	90	75	75	75
WC_garden_food (unitless)	1.2E-1	1.03E-1	1.1E-1	1.1E-1	7.5E-1

Note: *Literature sources for parameter values are listed in Table 62.

TABLE 64. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO GARDEN FOOD, (UNITLESS) [8, 11]

Radionuclide	Legumes	Leafy vegetables	Roots	Fruits	Garden berries
Ac	3.90E-04	2.44E-03	5.70E-03	3.60E-04	3.60E-04
Cs	4.00E-02	6.00E-02	4.20E-02	2.10E-02	2.10E-02
Pa	3.90E-04	2.44E-03	5.70E-03	6.50E-05	6.50E-05
Pb	1.50E-03	8.00E-02	1.50E-02	1.50E-02	1.50E-02
Po	2.70E-04	7.40E-03	5.80E-03	1.90E-04	1.90E-04
Ra	1.40E-02	9.10E-02	7.00E-02	1.70E-02	1.70E-02
Sr	1.40E+00	7.60E-01	7.20E-01	3.60E–01	3.60E–01
Th	5.30E-04	1.20E-03	8.00E-04	7.80E-04	7.80E-04
U	2.20E-03	2.00E-02	8.40E-03	1.50E-02	1.50E-02

6.5.4. Output parameters

The main output parameter of the 'Garden plot' module is the radionuclide concentration in garden food, which are used for calculating doses from ingestion of garden food. Other calculated parameters are radionuclide concentrations in soil and air of the garden plot which are used for calculating doses to persons exposed to radioactivity at the garden plot.

TABLE 65. OUTPUT PARAMETERS OF 'GARDEN PLOT' MODULE

Abbreviation (unit)	Name	Purpose
C_garden food (Bq/kg·FW)	Radionuclide concentration in garden food	Used to calculate doses from ingestion of garden food
C_soil_byGarden food (Bq/kg·DW)	Mass radionuclide concentration in soil	Used to calculate doses from radionuclides in the soil
C_soil (Bq/m^3)	Radionuclide volumetric concentration in soil	Used to calculate doses from radionuclides in the soil
C_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Used to calculate doses from radionuclides in air

6.6. 'FOREST' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Forest' module.

6.6.1. Module description

In this section, detailed descriptions of the 'Forest' module are provided.

6.6.1.1. General description

The 'Forest' module covers exposure pathways relevant for the reference persons utilizing a forest as a source of food.

The Forest module is based on mathematical models of forest ecosystems [3] that dynamically simulate the vertical distribution of radionuclides in soil and radionuclide uptake by tree leaves, tree wood, understorey, berries, mushrooms and game (see Fig. 28).
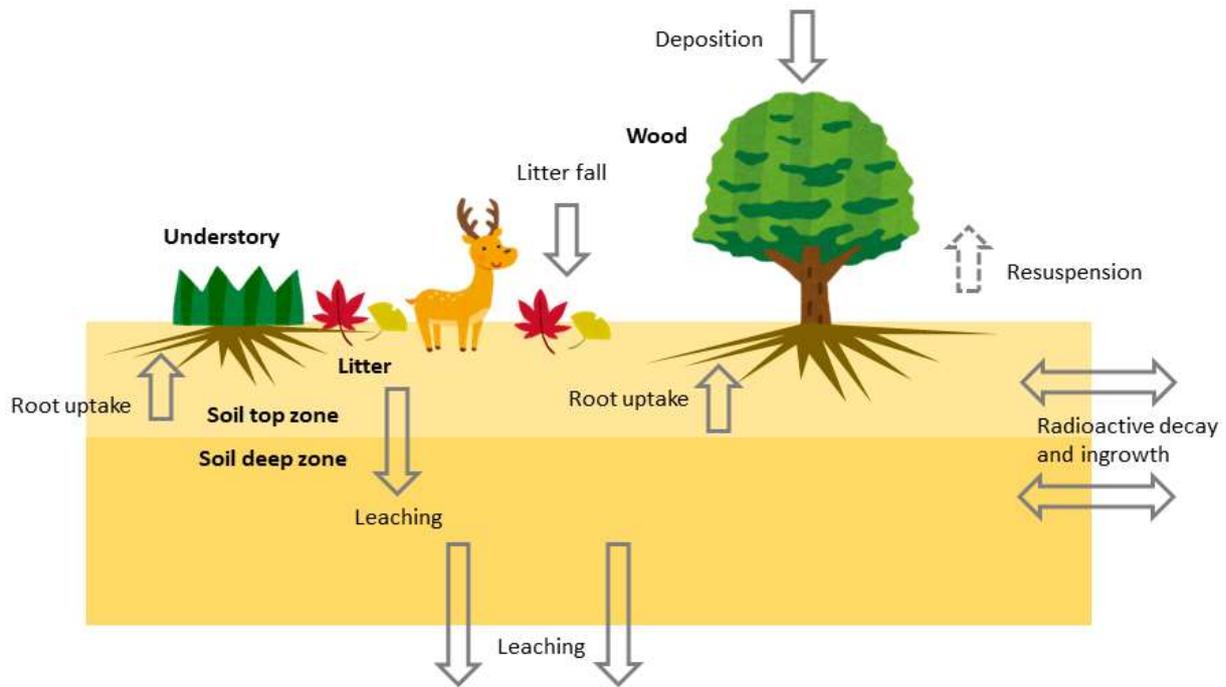
FIG. 28. Illustrative scheme of the 'Forest' module. Exchanges between media, loadings and losses are shown by arrows.

The module provides an option for the user to specify the radionuclide concentration in soil (e.g. based on monitoring data). In this case, soil concentration values specified and fixed in time by the modeller are used to calculate the radionuclide concentrations in other forest compartments.

6.6.1.2. Conceptual model

The conceptual model of the 'Forest' module is illustrated in Fig. 29. The 'Forest' module includes the following compartments:

— Soil top (root) zone: This media is defined as the top soil layer hosting most of the active roots of the forest species. In this soil zone, transfer of radionuclides from soil to plants by root uptake takes place;

— Soil deep zone: This media is defined as the deeper layer of the forest soil, i.e. the soil layer which extends from below the root zone to the ground water table;

— Litter: This media is defined as the layer above the soil and consists of the forest litter material (e.g. fallen leaves, branches, trees);

— Leaves: This media is defined as tree leaves;

— Understorey: This media is defined as the underbrush in the forest which comprises plant life growing beneath the forest canopy (e.g. seedlings and saplings of canopy trees together with bushes and herbs);

— Wood: This media represents the tree wood including living wood, dead wood and bark.
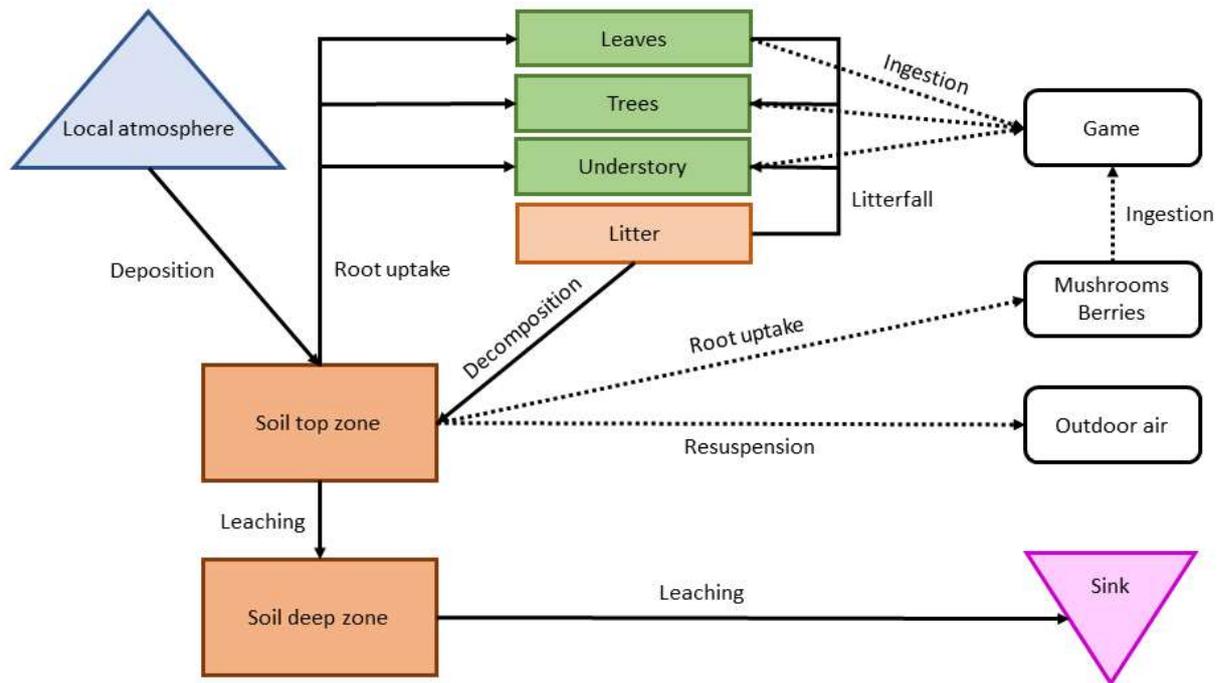
FIG. 29. Conceptual model of the 'Forest' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

The inputs of radionuclides into the modelled forest system may occur through the following mechanisms:

— Deposition of radionuclides (dry and/or wet) from atmosphere in aerosol form and/or dissolved in rainwater;
— Ingrowth of daughter radionuclides due to radioactive decay of their parent nuclides.

The potential losses of contaminants from the forest system may occur through the following mechanisms:

— Leaching that involves the movement of dissolved radionuclides down through the soil profile due to water infiltration;
— Radioactive decay.

The exchanges of contaminants between the 'Soil Top Zone' (root zone) and 'Soil Deep Zone' of the model can occur through leaching (i.e. vertical transport of radionuclides dissolved in pore water by moisture flow) that is modelled as a first order rate process.

Exchanges of radionuclides in the soil solid and liquid phases are modelled using an instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

The model being considered describes radionuclide accumulation from soil in wood, leaves, understorey, berries and mushrooms using the concentration ratio approach given in Ref. [3].

The following radionuclide fluxes that are modelled as a first order 'transfer' process are included in the model: flux from top soil to tree wood via root uptake, flux from top soil to tree leaves via root uptake, flux from top soil to understorey (plants and mushrooms) via root uptake, flux from tree leaves to litter by leaf fall, flux from tree wood to litter by wood fall, flux from understorey plants to litter by plant senescence, flux from litter to top soil layer following litter decomposition (see Fig. 29).

The model estimates radionuclide concentration in game calculated using the transfer coefficient approach based on the radionuclide concentrations in mushrooms, berries, leaves and wood according to game diet.

The model takes into account four different forest game/product species:

—— Roe deer;
—— Moose;
—— Mushroom;
—— Berries.

The radionuclide concentration in air is calculated based on the radionuclide concentration in soil and assuming resuspension of the radioactivity to the atmosphere that is determined by the 'dust load' model parameter.

6.6.1.3. *Potential coupled modules*

TABLE 66. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR 'FOREST' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Atmosphere SR-19', 'Atmosphere chronic'	Deposition rates of radionuclides (Bq/m^2·year)
Outputs from the module can be used by the following modules:	
'Dose from ingestion of forest food'	Radionuclides concentration in berries (Bq/kg·FW)
	Radionuclides concentration in mushrooms (Bq/kg·FW)
	Radionuclides concentration in game (Bq/kg·FW)
	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
'Dose from occupancy outdoors'	Radionuclide concentration in soil root zone (Bq/kg·DW)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.6.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Forest' module are provided.

The following sections present the main dynamic mathematical equations and formulas for calculating radionuclide redistributions and transfers in the 'soil – forest – game – atmosphere' media for the modelled forest system.

6.6.2.1. Mass balance equation for soil media

Radionuclide inventory in the root zone (Soil_RZ, Bq)

The mass balance for the activity of radionuclides in the soil root (top) zone *(Soil_RZ , Bq)* is given by the following differential equation:

$$\frac{dSoil_{RZ}}{dt} = Dep + Litter \times LitterToSoil + Lichens \times LichensToSoil - Soil_{RZ} \times RootUptake_{wood} - Soil_{RZ} \times RootUptake_{leaves} - Soil_{RZ} \times RootUptake_{understory} - Soil_{RZ} \times Leach_{RZ} - \lambda \times Soil_{RZ} + \sum_{p \in P_i} Br_p \qquad (106)$$

where:

Dep is the total deposition of radionuclides from the atmosphere on the receptor area (Bq/year);
Litter is the radionuclide inventory in the litter that lays on top of the soil (Bq);
Lichens is the radionuclide inventory in the lichens (Bq);
LitterToSoil is the transfer rate coefficient of radionuclide from litter to soil due to the decomposition process (1/year);
LichensToSoil is the transfer coefficient of radionuclide from lichens to soil due to the decomposition process (1/year);
$RootUptake_{wood}$ is the transfer coefficient of radionuclide from soil to tree wood via root uptake (1/year);
$RootUptake_{leaves}$ is the transfer coefficient of radionuclide from soil to tree leaves via root uptake (1/year); and
$RootUptake_{understory}$ is the transfer coefficient of radionuclide from soil to the understorey via root uptake (1/year).

The terms $\lambda \times Soil_{RZ}$ and $\sum_{p \in P} Br_p \times \lambda \times Soil_{RZ}$ in Eq. (106) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the root soil zone.

Deposition of radionuclides (Dep, Bq/year)

The equation for calculating the deposition of radionuclides is as follows:

$$Dep = Rate_{dep} \times A \qquad (107)$$

where:

$Rate_{dep}$ is the radionuclide deposition per unit area of receptor (Bq/(m²·year)); and
A is the area of the receptor (m²).

Transfer rate coefficient of radionuclide from lichens to soil (LichensToSoil, 1/year)

$$LichensToSoil = rate_{leach,lichens} \qquad (108)$$

where:

$Rate_{leac,lichens}$ is the rate of leaching of radionuclides from lichens (1/year).

Transfer rate coefficient of radionuclide from litter to soil (LitterToSoil, 1/year)

$$LitterToSoil = Rate_{decomp} \qquad (109)$$

where:

$Rate_{decomp}$ is the decomposition rate of litter (plant matter) in the object being considered (1/year).

Transfer rate coefficient of radionuclide due to leaching from the soil root (top) zone (Leach$_{RZ}$, 1/year)

$$Leach_{RZ} = \frac{max\ ((Rate_{prec}-ET_{forest}),0.0)}{(H_{soil,RZ}\times Porosity_{soil,RZ}\times Ret_{RZ})} \tag{110}$$

where:

$Rate_{prec}$ is the precipitation rate (m/year);
ET_{forest} is the evapotranspiration rate (m/year);
$Porosity_{soil,RZ}$ is the porosity of the soil root (top) zone (unitless);
$H_{soil,RZ}$ is the height of the soil root (top) zone (m); and
Ret_{RZ} is the radionuclide retardation factor for the soil root (top) zone (unitless).

The equation for calculating the radionuclide retardation factor in the soil root zone is:

$$Ret_{RZ} = 1.0 + Kd_{soil,RZ} \times Rho_{soil,RZ}/Porosity_{soil,RZ} \tag{111}$$

where:

$Rho_{soil,RZ}$ is the density of the rooting zone soil (kg·DW/m³); and
$Kd_{soil,RZ}$ is the distribution coefficient for the soil rooting zone (m³/kg·DW).

The equation for calculating the evapotranspiration rate (ET_{forest}, m/year) is:

$$ET_{forest} = Rate_{prec} \times Factor_{rain,interc} + Rate_{transp} \tag{112}$$

where:

$Rate_{transp}$ is the transpiration rate of considered vegetation (m/year); and
$Factor_{rain,interc}$ is the rain interception factor (unitless).

Mass transfer coefficient from soil to tree wood due to root uptake (rootUptake_wood, 1/year)

$$rootUptake\_wood = NPP_{wood} \times CR_{wood}/(Rho_{soil,RZ} \times H_{soil,RZ}) \tag{113}$$

where:

NPP_{wood} is the net primary production of wood (kg·DW/(m²·year)); and
CR_{wood} is the activity concentration ratio for wood (unitless).

Mass transfer coefficient from soil to leaves due to root uptake (rootUptake_leaves, 1/year)

$$rootUptake\_leaves = NPP_{leaves} \times CR_{leaves}/(Rho_{soil,RZ} \times H_{soil,RZ}) \tag{114}$$

where:

NPP_{leaves} is the net primary production of leaves (kg·DW/(m²·year)); and
CR_{leaves} is the activity concentration ratio for leaves (unitless).

Mass transfer coefficient from soil to understorey due to root uptake (rootUptake_understorey, 1/year)

$$rootUptake_{understorey} = NPP_{understorey} \times \frac{CR_{understorey}}{\left(Rho_{soil,RZ} \times H_{soil,RZ}\right)}$$

(115)

where:

$NPP_{understory}$ is the net primary production of the understorey (kg·DW/(m^2·year)); and $CR_{understorey}$ is the activity concentration ratio for the understorey (unitless).

6.6.2.2.   Mass balance equation for lichens

The mass balance for radionuclides in the 'Lichens' (Bq) media is given by the differential equation:

$$\frac{dLichens}{dt} = Dep_{liche} - Lichens \times LichensToSoil - \lambda \times Lichens + \sum_{p \in P_i} Br_p \times \lambda \times Licnens$$

(116)

where:

Dep$_{lichens}$ is the total deposition of radionuclides from the atmosphere on the lichens (Bq/year).

The fraction of deposition intercepted by lichens is calculated by the following equation:

$$Dep_{lichens} = Dep \times f_{lichens}$$

(117)

where:

$f_{lichens}$ is the fraction of the total deposition rate that is intercepted by lichens (unitless).

The terms $\lambda \times Lichens$ and $\sum_{p \in P_i} Br_p \times \lambda \times Lichens$ in Eq. (116) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the lichens.

6.6.2.3.   Radionuclide inventory in the deep zone

The mass balance for the activity of radionuclides in the soil deep zone ($Soil_{DZ}, (Bq)$) is given by the following differential equation:

$$\frac{dSoil_{DZ}}{dt} = Soil_{RZ} \times Leach_{RZ} - Soil_{DZ} \times Leach_{DZ} - \lambda \times Soil_{DZ} + \sum_{p \in P_i} Br_p \times \lambda \times Soil_{DZ}$$

(118)

where:

Leach$_{DZ}$ is the mass transfer coefficient of radionuclides from the deep zone by leaching (1/year).

The terms $\lambda \times Soil_{DZ}$ and $\sum_{p \in Pi} Br_p \times \lambda \times Soil_{DZ}$ in Eq. (118) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the deep zone.

_Transfer coefficient of radionuclides from the deep zone by leaching (Leach_DZ, 1/year)_

The equation for calculating the radionuclide mass transfer coefficient from the soil deep zone through water leaching is:

$$Leach_{DZ} = \frac{max\ ((Rate_{prec} - E_{\ forest}), 0.0)}{(H_{soil,DZ} \times Porosity_{soil,DZ} \times Ret_{DZ})} \tag{119}$$

where:

$Porosity_{soil,DZ}$ is the porosity of the soil deep zone (unitless);
$H_{soil,DZ}$ is the height of the soil deep zone (m); and
Ret_{DZ} is the retardation factor for the soil deep zone (unitless).

The equation for calculating the radionuclide retardation factor in the soil deep zone in the forest area is as follows:

$$Ret_{DZ} = 1.0 + Kd_{soil,DZ} \times Rho_{soil,DZ}/Porosity_{soil,DZ} \tag{120}$$

where:

$Rho_{soil,DZ}$ is the density of the soil deep zone (kg·DW/m^3); and
$Kd_{soil,DZ}$ is the radionuclide distribution coefficient for the soil deep zone (m^3/kg·DW).

6.6.2.4. Radionuclide concentration in soil media

Radionuclide concentrations in soil are calculated using equations that are similar to those described in Section 6.2.2.2 (Eqs (97) and (98)).

6.6.2.5. Mass balance equations for litter, understorey and wood

Mass balance equation for forest litter (Litter, Bq)

The mass balance for radionuclides in the 'Litter' media is given by the following differential equation:

$$\begin{aligned}
\frac{dLitter}{dt} &= Understorey \times UnderstoreyToLitter + Wood \times WoodToLitter \\
&+ Leaves \times LeavesToLitter - Litter \times LitterToSoil - \lambda \times Litter \\
&+ \textstyle\sum_{p \in P_i} Br_p \times \lambda \times Litter
\end{aligned} \tag{121}$$

where:

$Understorey$ is the radionuclide inventory in above ground part of understorey plants (Bq);
$Leaves$ is the radionuclide inventory in leaves including yearly and older leaves (Bq);
$Wood$ is the radionuclide inventory in tree wood including living and dead wood, as well as bark (Bq);
$UnderstoreyToLitter$ is the transfer coefficient of radionuclide from the above ground part of understorey plants to the litter or soil (1/year);
$WoodToLitter$ is the transfer coefficient of radionuclide from tree wood including living and dead wood, as well as bark, to the litter or soil (1/year); and
$LeavesToLitter$ is the transfer coefficient of radionuclide from leaves including yearly and older leaves to the litter or soil (1/year).

Mass transfer coefficient from leaves to litter (LeavesToLitter, 1/year)

$$LeavesToLitter = NPP_{leaves}/Biomass_{leaves} \tag{122}$$

where:

$Biomass_{leaves}$ is the biomass of the leaves (kg·DW/m²).

Mass transfer coefficient from understorey to litter (UnderstoryToLitter, 1/year)

$$UnderstoreyToLitter = NPP_{understorey}/Biomass_{understorey} \tag{123}$$

where:

$Biomass_{understory}$ is the biomass of the understorey (kg·DW/m²).

Mass transfer coefficient from tree wood to litter (WoodToLitter, 1/year)

$$WoodToLitter = NPP_{wood}/Biomass_{wood} \tag{124}$$

where:

$Biomass_{wood}$ is the biomass of the wood (kg·DW/m²).

6.6.2.6.   Mass balance equation for tree leaves

The mass balance for radionuclides in the 'Leaves' (Bq) media is given by the following differential equation:

$$\frac{dLeaves}{dt} = Soil_{RZ} \times RootUptake_{leaves} - Leaves \times LeavesToLitter - \lambda \times Leaves + \sum_{p \in P_i} Br_p \times \lambda \times Leaves \tag{125}$$

6.6.2.7.   Mass balance equation for forest understorey

The mass balance for radionuclide in the 'Understorey' (Bq) media is given by the following differential equation:

$$\frac{dUnderstorey}{dt} = Soil_{RZ} \times rootUptake_{understorey} - Understorey \times UnderstoreyToLitter - \lambda \times Understorey + \sum_{p \in P_i} Br_p \times \lambda \times Understorey \tag{126}$$

6.6.2.8.   Mass balance equation for tree wood

The mass balance for radionuclide in the 'Wood' (Bq) media is given by the differential following equation:

$$\frac{dWood}{dt} = Soil_{RZ} \times RootUptake_{wood} - Wood \times WoodToLitter - \lambda \times Wood + \sum_{p \in P_i} Br_p \times \lambda \times Wood \tag{127}$$

6.6.2.9. Radionuclide concentrations in forest vegetation compartments

Radionuclide concentration in leaves (C_{leaves}, Bq/kg DW)

$$C_{leaves} = Leaves/(Biomass_{leaves} \times A)$$

Radionuclide concentration in lichens ($C_{lichens}$, Bq/kg DW)

$$C_{lichens} = Lichens/(Biomass_{lichens} \times A)$$

Radionuclide concentration in understory ($C_{understorey}$, Bq/kg DW)

$$C_{understorey} = Understorey/(Biomass_{understorey} \times A)$$

Radionuclide concentration in wood (C_{wood}, Bq/kg DW)

$$C_{wood} = Wood/(Biomass_{wood} \times A)$$

6.6.2.10. Radionuclide concentrations in forest foods

Radionuclide concentration in berries ($C_{berries}$, Bq/kg FW)

$$C_{berries} = CR_{berries} \times C_{soil} \times (1.0 - WC_{berries}) \times UnitCorr_{DW,FW} \tag{128}$$

where:

$WC_{berries}$ is the fractional water content of berries (unitless);
$CR_{berries}$ is the concentration ratio coefficient for berries (unitless); and
$UnitCorr_{DW,FW}$, is the unit correction from DW to FW (kg·DW/kg·FW).

Radionuclide concentration in mushrooms ($C_{mushroom}$, Bq/kg FW)

$$C_{mushroom} = CR_{mushroom} \times C_{soil} \times (1.0 - WC_{mushroom}) \times UnitCorr_{DW,FW} \tag{129}$$

where:

$WC_{mushroom}$ is the fractional water content of mushrooms (unitless); and
$CR_{mushroom}$ is the concentration ratio coefficient for mushrooms (unitless).

Radionuclide concentration in game (C_{game}, Bq/kg·FW)

$$C_{game} = CR_{game} \times C_{game,diet} \times (1.0 - WC_{game}) \times UnitCorr_{DW,FW}, \tag{130}$$

where:

WC_{game} is the fractional water content of game (unitless); and
CR_{game} is the concentration ratio coefficient for game (unitless).

Here radionuclide concentration in game diet ($c_{game,diet}$, Bq/kg·FW) are calculated as follows:

$$C_{game,diet} = f_{mushroom,game} \times C_{mushroom}/((1.0 - WC_{mushrooms}) \times UnitCorr_{DW,FW}) + f_{leaves,game} \times C_{leaves} + f_{understorey,game} \times C_{understorey} + f_{wood,game} \times C_{wood} + f_{lichens,game} \times C_{lichens} \tag{131}$$

where:

$f_{mushroom,game}$ is the fraction of mushrooms in game diet (unitless);

$f_{leaves,game}$ is the fraction of leaves in game diet (unitless);

$f_{understorey,game}$ is the fraction of understorey in game diet (unitless);

$f_{wood,game}$ is the fraction of wood in game diet (unitless); and

$f_{lichens,game}$ is the fraction of lichens in game diet (unitless).

6.6.2.11. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air ($C_{air,outdoor}, Bq/m^3$) are calculated using equations that are similar to those described in Section 6.2.2.3 (Eqs (99) and (100)).

6.6.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial radionuclide concentrations in forest compartments are zero (see Table 67). However, the modellers need to adapt these values according to their specific case.

TABLE 67. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON 'FOREST'

Abbreviation and unit	Full name	Default value	Reference
C_air_atm (Bq/m³)	Concentration of radionuclide in atmospheric air	0	Site specific parameter
Dep_init (Bq)	Initial deposition in the top soil layer in the 'Forest'	0	Site specific parameter
C_soil_meas* (Bq/kg·DW)	Measured radionuclide concentration in soil	0	Site specific parameter
Rate_dep (Bq/(m²·year¹))	Deposition rate	0	Site specific parameter

Note: * The *C_soil_meas* value is needed in case radionuclide concentrations in forest food are calculated based on user-specified soil concentration values. Dynamic calculations of radionuclide concentrations in soil profile are not performed (see Section 6.4.1.1).

Input parameters related to contaminated land geometry and physicochemical properties of soils are provided in Table 142 (see Appendix).

TABLE 68. INPUT PARAMETERS RELATED TO PLANT SPECIES

Abbreviation and unit	Full name	Default value	Reference
Biomass_leaves (kg·DW/m^2)	Biomass of leaves	0.5	See Table 3-2 of Ref. [3]
Biomass_lichens (kg·DW/m^2)	Biomass of lichens	0.5	See Table 3-2 of Ref. [3]
Biomass_understorey (kg·DW/m^2)	Biomass of understorey	0.08	See Table 3-2 of Ref. [3]
Biomass_wood (kg·DW/m^2)	Biomass of wood	5.1	See Table 3-2 of Ref. [3]
factor_rain_interc (unitless)	Fraction of the rain that is intercepted by the vegetation	0.3	See Table 3-4 of Ref. [3]
Rate_leach_lichens (1/year)	Rate of leaching of radionuclides from lichens	0.2	[3]
Rate_transp (m/year)	The transpiration rate of considered vegetation. Default values are from (	0.335	[3]
Rate_decomp (1/year)	The decomposition rate of litter (plant matter) in the considered object.	0.9	[3]
NPP_leaves (kg·DW/(m^2·year))	The net primary production of tree leaves in forest.	0.08	[3]
NPP_understorey (kg·DW/(m^2·year))	The net primary production of tree wood in forest.	0.08	[3]
NPP_wood (kg·DW/(m^2·year))	The net primary production of tree understorey in forest.	0.18	[3]
f_lichens (unitless)	Fraction of the total deposition rate that is intercepted by lichens.	1	[3]

TABLE 69. INPUT PARAMETERS RELATED TO RADIONUCLIDE UPTAKE BY FOREST BERRIES, MUSHROOMS, PLANTS AND GAME

Abbreviation and Unit	Name	Default value	Reference
CR_berries (unitless)	Concentration ratio for berries	See Table 72	[8]
CR_mushrooms (unitless)	Concentration ratio for mushrooms	See Table 72	[11]
CR_leaves (unitless)	Concentration ratio for leaves	See Table 72	[11]
CR_understorey (unitless)	Concentration ratio for understorey	See Table 72	[11]
CR_wood (unitless)	Concentration ratio for wood	See Table 72	[11]
CR_game (unitless)	Concentration ratio for game animals	See Table 72	[11]

TABLE 70. DEFAULT VALUES OF GAME DIET PARAMETERS [3]

Abbreviation and Unit	Moose	Roe deer
f_lichens_game (unitless)	54	8.5
f_mushroom_game (unitless)	0.9	13.7
f_understorey_game (unitless)	43.5	77
f_wood_game (unitless)	1.6	0.9
f_leaves_game (unitless)	30	30

TABLE 71. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO GAME ANIMALS [11]

Radionuclide	Moose	Roe deer
Ac	1.79E-01	1.79E-01
Cs	8.39E+00	8.39E+00
Pa	1.79E-01	1.79E-01
Pb	3.78E+00	3.78E+00
Po	3.78E+00	3.78E+00
Ra	1.70E-01	1.70E-01
Sr	4.90E-02	4.90E-02
Th	1.40E+00	1.40E+00
U	2.23E-01	2.23E-01

TABLE 72. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO FOREST BERRIES, MUSHROOMS AND PLANT TYPES*

Radionuclide	Berries	Mushrooms	Leaves	Understorey	Wood
Ac	3.60E-04	1.06E-03	1.06E-03	1.06E-03	1.06E-03
Cs	2.10E-02	1.49E+01	1.84E-01	1.84E-01	1.84E-01
Pa	6.50E-05	1.06E-03	1.06E-03	1.06E-03	1.06E-03
Pb	1.50E-02	1.45E-02	1.70E-02	1.70E-02	1.70E-02
Po	1.90E-04	3.01E-03	3.01E-03	3.01E-03	3.01E-03
Ra	1.70E-02	3.10E-02	2.87E-02	2.87E-02	2.87E-02
Sr	3.60E–01	3.10E-02	4.88E-01	4.88E-01	4.88E-01
Th	7.80E-04	4.63E-03	5.69E-03	5.69E-03	5.69E-03
U	1.50E-02	4.07E-03	5.40E-04	5.40E-04	5.40E-04

Note: * literature sources for parameter values are listed in Table 69.

6.6.4. Output parameters

The main output parameter of the 'Forest' module is radionuclide concentration in forest food, which can be used for calculating doses from ingestion of forest food. Other calculated parameters are radionuclide concentrations in soil and air of forest, that can be used for calculating doses to persons exposed to radioactivity in forest areas (e.g. forestry workers).

TABLE 73. OUTPUT PARAMETERS OF 'FOREST' MODULE

Abbreviation (unit)	Name	Purpose
C_berries (Bq/kg·FW)	Radionuclide concentration in berries	Used to calculate doses from ingestion of forest food
C_mushroom (Bq/kg·FW)	Radionuclide concentration in mushroom	Same
C_game (Bq/kg·FW)	Radionuclide concentration in game	Same
C_soil (Bq/kg·DW)	Mass radionuclide concentration in soil	Same
C_soil_vol (Bq/m^3)	Radionuclide volumetric concentration in soil	Same
C_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Same

6.7. 'HOUSE' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'House' module.

6.7.1. Module description

In this section, detailed descriptions of the 'House' module are provided.

6.7.1.1. General description

The 'House' module is designed to estimate radiation parameters that are required for assessment of indoor exposure. In particular, the objective of the 'House' module is the assessment of indoor air concentrations of radionuclides, including radon (^{222}Rn).

For all radionuclides (except radon) the simple mixing model is used for air concentrations inside the house, that is described by the '*ReductionFactor*' parameter.

For indoor radon air concentration, the mixing model described in Ref. [27] is used which accounts for radon diffusive flux through the house basement slab from the underlying radioactive source, and also takes into account the indoor air exchange by ventilation with the outdoor air. The conceptual model of the 'House' receptor (for ^{222}Rn) is illustrated in Fig. 30.

6.7.1.2. Potential coupled modules

TABLE 74. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'HOUSE' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by following modules:	
'Tailings without cover', 'Contaminated Land Without Cover' with (or without) 'House Slab' modules	Radon concentration in outdoor air Bq/m³) Radon flux into the house Bq/(m²·s)
Outputs from the module can be used by following module:	
'Dose from occupancy indoors'	Concentration of radionuclides and radon in indoor air (Bq/m³)
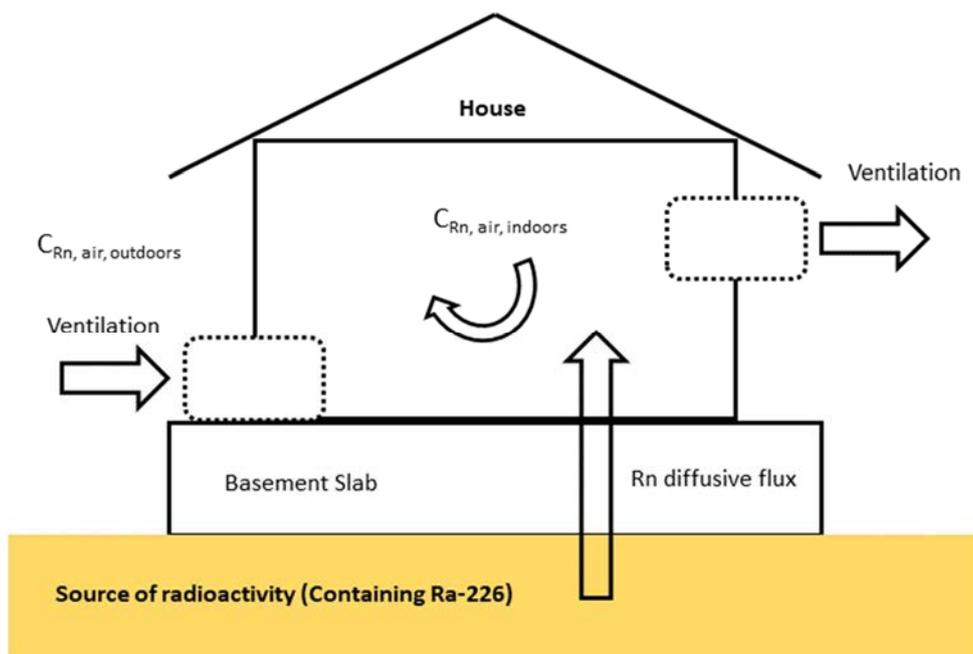
FIG. 30. Conceptual model of ^{222}Rn mixing indoors for the 'House' receptor.

6.7.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'House' module are provided.

6.7.2.1. Radionuclide concentration in air

Radionuclide (except ^{222}Rn) concentrations indoors ($C_{air,indoor}$, Bq/m³)

$$C_{air,indoor} = C_{air,outdoor} \times ReductionFactor \tag{132}$$

where:

$C_{air,outdoor}$ is the radionuclide concentration in outdoor air (Bq/m³); and
$ReductionFactor$ is the parameter determining mixing ratio between indoor and outdoor air concentrations (values between zero and one) (unitless).

Radon (^{222}Rn) concentration in air indoors ($C_{air,indoor,Rn}$ Bq/m³)

Radon concentration in indoor air indoors is calculated in accordance Ref. [27]:

$$C_{air,indoor,Rn} = C_{air,outdoor,Rn} + RadonFlux_{in} \times \frac{Area}{\left(V \times \left(\frac{Rate_{exc}}{SecPerHour} + \frac{\lambda}{SecPerYear}\right)\right)}$$

$$\tag{133}$$

where:

$RadonFlux_{in}$ is the radon flux density into the house from the house floor (or through basement slab) (Bq/m²·sec);
$Area$ is the area of the house floor (m²);
V is the volume of the house (m³);
$Rate_{exch}$ is the exchange rate of air in the house (1/h);
λ is the radon decay constant (1/year);
$SecPerHour$ is the seconds per hour (sec/h); and
$SecPerYear$ is the seconds per year (sec/year).

6.7.3. Input parameters

TABLE 75. INPUT PARAMETERS RELATED TO INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON RECEPTOR

Abbreviation and unit	Full name	Default value	Reference
C_air_outdoor (Bq/m³)	Concentration of radionuclide in outdoor air	0	Site specific parameter
C_air_outdoor_Rn (Bq/m³)	Concentration of radon in outdoor air	0	Site specific parameter
RadonFlux_in (Bq/(m²·sec))	Radon flux density into the house from the fundament	0	Site specific parameter

TABLE 76. INPUT PARAMETERS RELATED TO HOUSE PROPERTIES

Abbreviation and unit	Full name	Default value	Reference
Area (m^2)	Area of the house	100	Site specific parameter
V (m^3)	Volume of the house	500	Site specific parameter
Rate_exch (1/h)	Exchange of air in the house	0.5	Site specific parameter
ReductionFactor (unitless)	Parameter specifying ratio between indoor and outdoor radionuclide air concentrations	1	Site specific parameter

6.7.4. Output parameters

Calculated parameters are radionuclide concentrations in indoor air of the house, that are used for calculating doses to persons exposed to radioactivity in the 'House' receptor.

TABLE 77. OUTPUT PARAMETERS OF 'HOUSE' MODULE

Abbreviation (unit)	Name	Purpose
C_air_indoor (Bq/m^3)	Radionuclide concentration in air indoors	Used to calculate doses from occupancy indoors
C_air_indoor_Rn (Bq/m^3)	Radon concentration in air indoors	Used to calculate doses from occupancy indoors

6.8. 'WELL' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Well' module.

6.8.1. Module description

In this section, detailed descriptions of the 'Well' module are provided.

6.8.1.1. General description

This module calculates the radionuclide concentration in groundwater pumped by a water well, that can be further used for calculating doses from the drinking water pathway or other similar purposes (see below).

This module usually receives input from the modules simulating radionuclide transport in the groundwater aquifer (such as the 'Aquifer' or 'Aquifer Mixing' modules; see the block scheme illustrated in Fig. 10 located in Section 5).

The output of the 'Well' module (i.e. radionuclide concentration in pumped water) is used as an input to the module from the 'Doses' library (i.e. 'Ingestion of water' module), that calculates doses from the drinking water pathway. It can also be used by other receptor modules (e.g. 'Cropland', 'Pasture land' or 'Garden Plot') for contaminant concentrations in irrigation water and/or water for the watering of cattle.
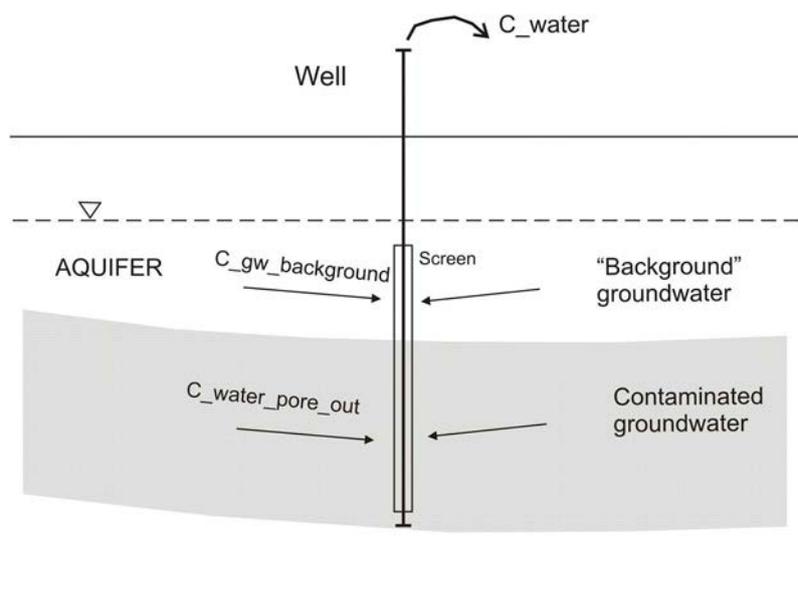
FIG. 31. Conceptual model of 'Well' receptor.

6.8.1.2. Conceptual model

The module employs a simple mixing module to calculate radionuclide concentrations in the well water. It is assumed that some fraction of the well debit is formed by contaminated groundwater originating from the contaminated site, while the other part of the well debit is formed by 'background' groundwater (see Fig. 31).

6.8.1.3. Potential coupled modules

TABLE 78. POTENTIAL COUPLED MODELS FROM THE NORMALYSA LIBRARY FOR 'WELL' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by following modules:	
'Aquifer', 'Aquifer Mixing'	Radionuclide concentrations (Bq/m^3) in groundwater originating from the contaminated site
Outputs from module can be used by following modules:	
'Ingestion of water' (Doses)	Radionuclide concentration (Bq/m^3) in drinking water
'Cropland', 'Pasture land', 'Garden Plot'	Radionuclide concentration (Bq/m^3) in irrigation water and/or water for watering cattle

6.8.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Well' module are provided.

As already discussed previously, a simple mixing model is employed to calculate the radionuclide concentrations in the well water (C_{water}, Bq/m^3) resulting from the mixing of contaminated groundwater originating from the contaminated site with 'background' groundwater:

$$C_{water} = f_{debit\_flowtube} \times C_{water\_pore\_out} + (1 - f_{debit\_flowtube}) \times C_{gw\_background} \tag{134}$$

where:

$f_{debit\_flowtube}$ is the well debit fraction formed by contaminated groundwater originating from the contaminated site (unitless);

$C_{water\_pore\_out}$ is the radionuclide concentration in groundwater originating from the contaminated site (Bq/m^3); and

$C_{gw\_background}$ is the radionuclide concentration in 'background' groundwater within the aquifer (Bq/m^3).

6.8.3. Input parameters

TABLE 79. INPUT PARAMETERS FOR THE 'WELL' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_water_pore_out (Bq/m^3)	Radionuclide concentration in groundwater originating from the contaminated site	0	Site specific parameter
C_gw_background (Bq/m^3)	Radionuclide concentration in 'background' groundwater within the aquifer	0	Site specific parameter
f_debit_flowtube (unitless)	Well debit fraction formed by contaminated groundwater originating from the contaminated site	1	Site specific parameter

6.8.4. Output parameters

The main output parameter of the 'Well' module is radionuclide concentration in water pumped by well (see Eq. (134)).

TABLE 80. OUTPUT PARAMETERS OF 'WELL' MODULE

Abbreviation and unit	Full name	Purpose
C_water (Bq/m^3)	Radioactive contaminant concentration in water pumped by well	Used to calculate doses from drinking water pathway or used for radionuclide concentrations in water used for irrigation and watering cattle (see Table 78)

6.9. 'FRESH WATER BODY' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Fresh Water Body' module.

6.9.1. Module description

In this section, detailed descriptions of the 'Fresh water body' module are provided.

6.9.1.1. General description

The 'Fresh Water Body' (FWB) module is designed for the assessment of exposure pathways associated with utilizing the modelled surface water reservoir as a source of drinking water and/or food (e.g. fish) as well as for recreational activities such as swimming and boating.

The FWB module is designed to simulate the radionuclide transport and fate in lakes, rivers, streams and similar freshwater objects. This module dynamically simulates the distribution of radionuclides both in abiotic media (i.e. surface water, suspended particulate matter and the bottom sediments of the reservoir) and biotic media (e.g. fish and other edible freshwater organisms) (see Fig. 32).
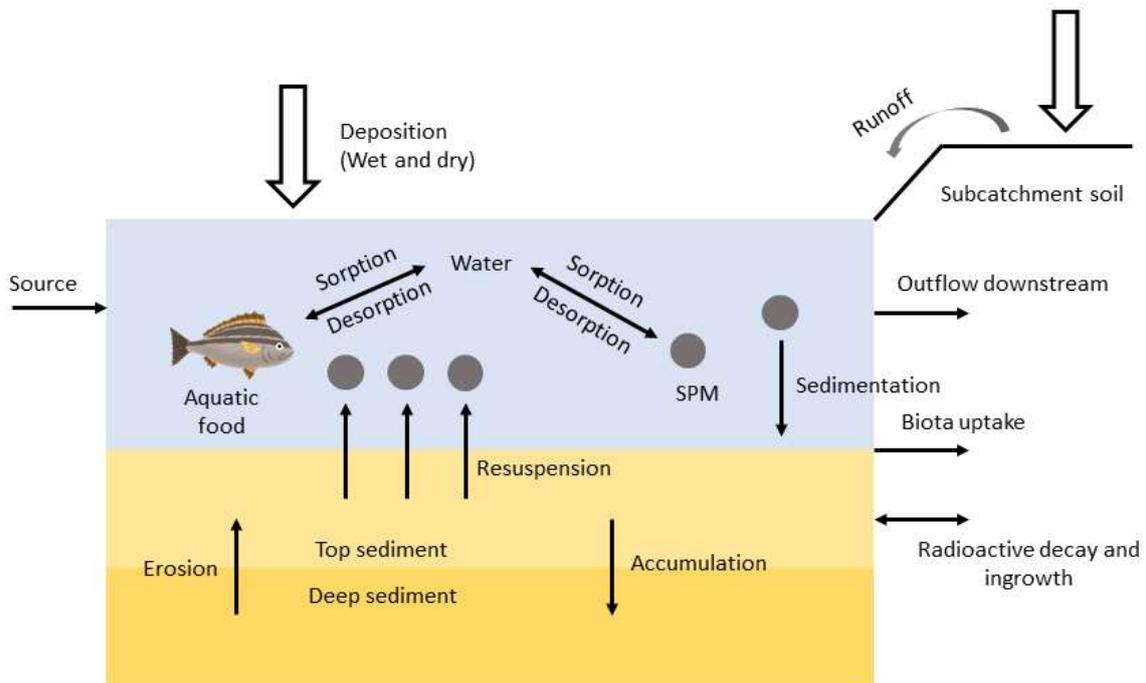
FIG. 32. Scheme illustrating the 'Fresh Water Body' module.

The mathematical model of radionuclide transfers in the FWB system is based on the 'Lake' model described in Ref. [2]. The modelled water objects receive radionuclides by deposition from the atmosphere directly on to the water surface and/or due to runoff from the adjacent contaminated catchment area, as well as due to direct radionuclide discharges to water from various sources (e.g. upstream water bodies, contaminated groundwater discharge, releases from nuclear facilities etc.).

The module provides an option for the user to directly specify the radionuclide concentration on the surface water (e.g. based on monitoring data). In this case, surface water concentration values specified and fixed in time by the modeller are used to calculate the radionuclide concentrations in freshwater foods.

6.9.1.2. *Conceptual model*

The conceptual model of the FWB receptor is illustrated in Fig. 33 and it includes the following main compartments: 'Water' compartment, bottom sediments divided into two compartments – 'Top Sediment' and 'Deep Sediment', and 'Subcatchment' (i.e. catchment soils of the water body that provide contaminated runoff to the 'Water' compartment).

Exchanges of radionuclides in the solid (sediment, soil) and liquid phases are modelled throughout the module using an instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

It is assumed that the radionuclide activity stored in 'Water' compartment is distributed between activity dissolved in water and activity adsorbed on suspended matter (see Fig. 34). Radionuclides dissolved in water and adsorbed on suspended particles are assumed to be in equilibrium as described by the respective distribution coefficient (Kd_SPM).

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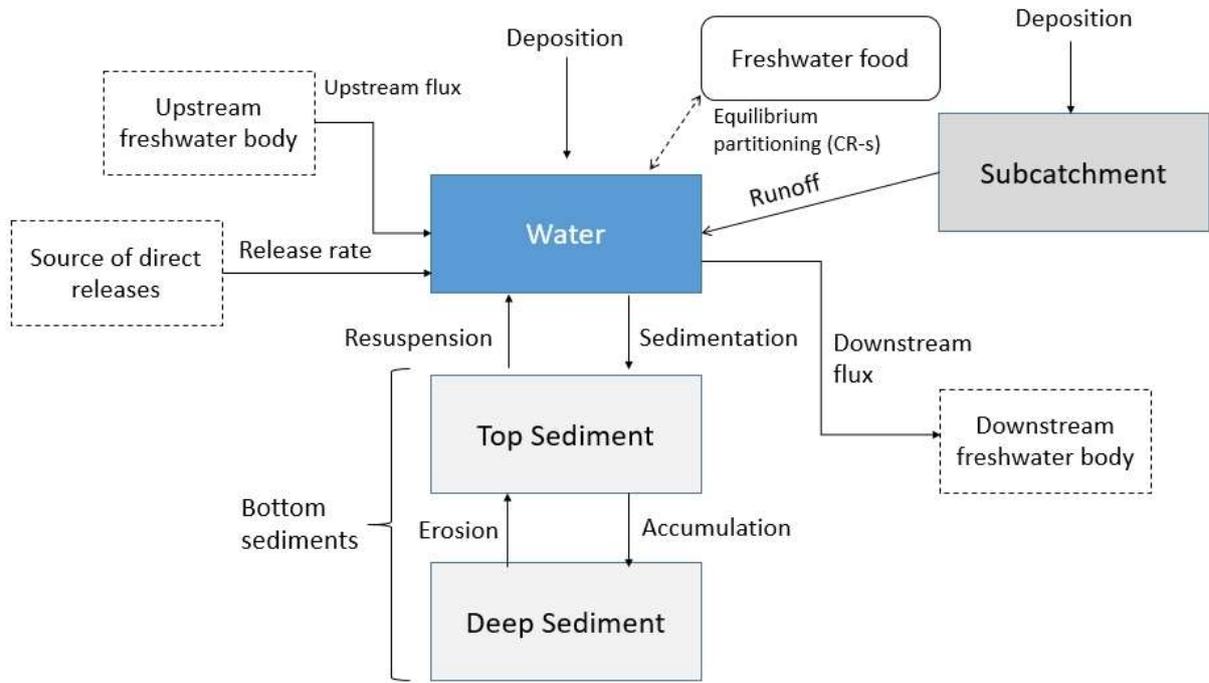
FIG. 33. Conceptual scheme of the 'Fresh Water Body' module.
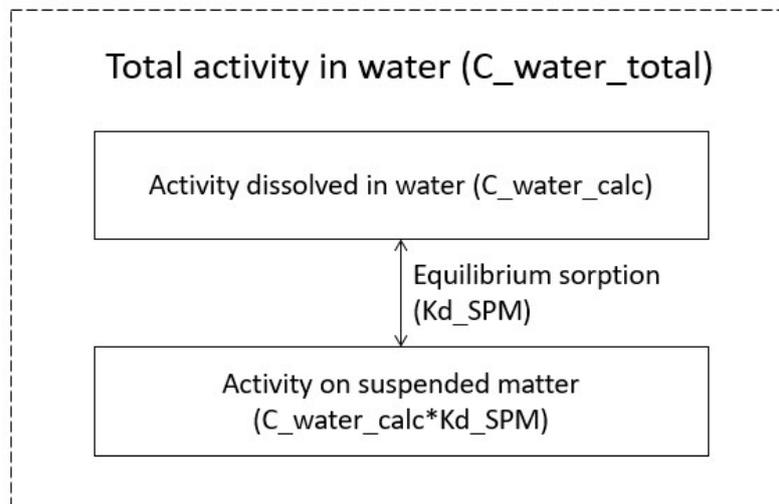
FIG. 34. Partitioning of radionuclide activity in the water between the dissolved phase and adsorbed on suspended particles.

The inputs of radionuclides to the modelled FWB system may have the following origins (see Fig. 33 above):

—— Flux of radionuclides from the upstream water body into inflowing surface water;
—— Direct discharges of radionuclides to the water column of the FWB from various external sources (e.g. nuclear facilities, contaminated groundwater discharge).
—— Deposition of radionuclides (dry and/or wet) from the atmosphere in aerosol form on to the surface of the FWB;
—— Inflow of radionuclides with the contaminated runoff from the subcatchment area of the FWB;
—— Ingrowth of daughter radionuclides by radioactive decay of their parent nuclides.

The potential losses of radionuclides from the FWB system can be due to:

—— Downstream flux of radionuclides with outflowing surface water;
—— Radioactive decay.

Radionuclide exchanges between the 'Water' and 'Top Sediment' compartments include transfers due to sedimentation of suspended particles and the process of bottom sediment resuspension to the water column. Transfers between 'Top Sediment' and 'Deep Sediment' include 'accumulation' and 'erosion' (to compensate for the 'resuspension' process) (see Fig. 33). The volume of the 'Top Sediment' compartment is assumed to be constant. The creation of new top sediment due to sedimentation thus transfers the bottom of the accumulation sediment to the 'Deep Sediment'. More details on these processes and their parametrization can be found in Ref. [2].

The 'Subcatchment' compartment can receive radionuclides due to the atmospheric deposition process. Radionuclide transport in runoff from subcatchment is modelled as a first order process assuming that radionuclide distribution between the runoff water and contaminated catchment soil is described by a *Kd* based sorption model (using specific distribution coefficient value, Kd_soil_subcatch).

Radionuclide accumulation in freshwater organisms (e.g. fish) is calculated based on the radionuclide concentration in water. Radionuclide transfer to freshwater biota species is modelled using Concentration Ratio (or Transfer Coefficients) approach [4].

The FWB module takes into account three different types of freshwater food species:

—— Fish;
—— Cray fish;
—— Mussels.

These types of freshwater organisms have specific values of relevant radioecological parameters such as concentration ratio values describing radionuclide transfer from water to biota.

The FWB module assumes that radionuclides are homogeneously distributed in the main model compartments, both laterally and vertically. The relevant spatial scale and resolution of the model are thus governed by the homogeneity of the water body under investigation (e.g. homogeneity with respect to contamination levels, physical and geochemical parameters).

For water bodies showing significant spatial variations in the properties of the main compartments mentioned above, it is recommended to subdivide the latter into several submodels and to couple them which each other, as appropriate, by means of mass fluxes (e.g. inflowing fluxes from upstream FWB submodels and outflowing fluxes to downstream submodels) (see Fig. 33).

6.9.1.3. *Potential coupled modules*

The FWB module can be combined with a large list of other NORMALYSA modules. The latter can be used to specify radiological loads on the FWB module (e.g. radionuclide deposition rates from the atmosphere, inputs with surface runoff and groundwater). In turn, the FWB module can provide data on radionuclide concentration in water which can be used by other receptors (e.g. concentrations in irrigation water for the 'Cropland' module etc.) or outputs of the FWB module (e.g. radionuclide concentrations in water and freshwater foods) can be used directly for dose calculations (see Table 81).

TABLE 81. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'FRESH WATER BODY' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by following modules:	
'Atmosphere SR-19', 'Atmosphere Chronic'	Radionuclide deposition rates from the atmosphere (Bq/(m^2·year))
'Surface Runoff'	Radionuclide release rate (Bq/year) to FWB from contaminated watershed in surface runoff
'Aquifer'	Radionuclide concentrations (Bq/m^3) in groundwater originating from the contaminated site
Other 'Fresh Water Body' module (upstream object)	Radionuclide concentrations (Bq/m^3) in inflowing surface water originating from the contaminated FWB
'Chronic release'	Radionuclide release rate (Bq/year) from a source of direct release to aquatic object
Outputs from module can be used by following modules:	
'Ingestion of water' (dose)	Radionuclide concentration (Bq/m^3) in drinking water
'Ingestion of freshwater food' (dose)	Radionuclide concentrations (Bq/kg·FW) in freshwater food
'Dose from Marine Activities'	Radionuclide concentrations in water (Bq/m^3) of reservoir used for recreational/marine activities (swimming, boating etc.)
Other 'Fresh Water Body' module (downstream object)	Radionuclide concentrations (Bq/m^3) in outflowing surface water originating from the contaminated FWB
'Cropland', 'Pasture land', 'Garden Plot'	Radionuclide concentration (Bq/m^3) in irrigation water and/or water for watering cattle

6.9.2. Mathematical model

This section provides detailed descriptions of the mathematical model for the 'Fresh Water Body' module.

6.9.2.1. *Mass balance equation for water media (Water, Bq)*

$$\frac{dWater}{dt} = Dep + SubCatch \times Outflow_{SubCatch} + TopSediment \times$$
$$\times TC_{res} - Water \times Flux_{WaterToDownstream} + \text{Re}lease - Water \times TC_{sed} - \lambda \times Water + \sum_{p \in Pi} Br_p \times \lambda \times Water$$

$$(135)$$

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where:

Dep is the radionuclide transfer by deposition from atmosphere on the water surface of FWB (Bq/year);

SubCatch is the radionuclide inventory in soil of subcatchment providing surface runoff to FWB (Bq);

Outflow$_{SubCatch}$ is the transfer coefficient for radionuclide transport in surface runoff from the subcatchment (1/year);

TopSediment is the radionuclide inventory in the top sediment layer (Bq);

TC$_{Res}$ is the radionuclide transfer coefficient to the water column from the top bottom sediment layer by resuspension (1/year);

TC$_{Sed}$ is the radionuclide transfer coefficient from the water column to the top bottom sediment layer by sedimentation (1/year);

Flux$_{WaterToDownstream}$ is the radionuclide transfer coefficient from FWB to a downstream object by surface water flow (1/year); and

Release is the radionuclide transfer to FWB by direct releases (Bq/year).

The terms $\lambda \times Water$ and $\sum_{p \in Pi} Br_p \times \lambda \times Water$ in Eq. (135) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in water.

Deposition rate of radionuclides on water surface of FWB (Dep, Bq/year)

$$Dep = Rate_{dep,FWB} \times Area_{FWB} \qquad (136)$$

where:

Rate$_{dep,FWB}$ is the radionuclide deposition rate on FWB (Bq/(m^2·year)); and
Area$_{FWB}$ is the area of FWB (m^2).

Transfer coefficient for radionuclide transport in surface runoff (Outflow$_{SubCatch}$, 1/year)

$$Outflow_{subcatch} = Runoff/(H_{subcatch} \times Porosity_{subcatch} \times Ret_{subcatch}) \qquad (137)$$

where:

Runoff is the surface runoff expressed as water layer (m/year);

H$_{subcatch}$ is the thickness of the soil layer in the subcatchment area involved in the exchange with surface runoff water (m);

Porosity$_{subcatch}$ is the porosity of the soil in the subcatchment area (unitless); and

Ret$_{subcatch}$ is the radionuclide sorption retardation coefficient of the soil in the subcatchment area (unitless).

Here:

$$Ret_{subcatch} = 1.0 + \frac{Rho_{subcatch}}{Porosity_{subcatch}} \times Kd_{soil,subcatch} \qquad (138)$$

where:

Rho$_{subcatch}$ is the density of the soil in the subcatchment area (kg·DW/m^3); and

Kd$_{soil,subcatch}$ is the sorption distribution coefficient of the soil in the subcatchment area (m^3/kg·DW).

Transfer coefficient from the top bottom sediment to the water by resuspension (TC$_{res}$, 1/year)

$$TC_{res} = Rate_{res} \times \frac{Kd_{sed}}{H_{sed,top} \times Porosity_{sed,top} \times \left(1.0 + Kd_{sed} \times \frac{Rho_{sed,top}}{Porosity_{sed,top}}\right)} \qquad (139)$$

where:

$Rate_{res}$ is the bottom sediment resuspension (the renewed suspension of a precipitated sediment) rate from the top sediment layer in the FWB (kg·DW/(m^2·year));

$H_{sed,top}$ is the height (thickness) of the top sediment layer of the FWB, this is considered to be the bioturbated layer of the sediment and it's thickness is kept constant in time (m);

$Porosity_{sed,top}$ is the porosity of the top sediment layer of the FWB (unitless);

$Rho_{sed,top}$ is the density of the top sediment layer of the FWB (kg·DW/m^3); and

Kd_{sed} is the sorption distribution coefficient of the sediment layer in FWB (m^3/kg·DW).

Transfer coefficient from water to top bottom sediment by sedimentation (TC_{sed}, 1/year)

$$TC_{sed} = Rate_{sed} \times Kd_{SPM}/(H_{average}(1.0 + Kd_{SPM} \times C_{SPM}) \tag{140}$$

where:

$Rate_{sed}$ is the sedimentation rate of particles to the FWB bottom, i.e. the rate at which particles in suspension in water settle out to the lake bottom (kg·DW/(m^2·year));

$H_{average}$ is the average depth of FWB (m);

C_{SPM} is the concentration of suspended particulate matter in the FWB water (kg·DW/m^3); and

Kd_{SPM} is the sorption distribution coefficient of the suspended particulate matter in FWB (m^3/kg·DW).

Transfer coefficient to downstream object by surface water flow ($Flux_{WaterToDownstream}$, m^3/year)

$$Flux_{WaterToDownStream} = Discharge_{water,downstream}/(Area_{FWB} \times H_{average}) \tag{141}$$

where:

$Discharge_{water,downstream}$ is the surface water flow rate from the FWB to the downstream water object (m^3/year); and

$Area_{FWB}$ is the surface water area of the FWB (m^2).

6.9.2.2.   Mass balance equation for Top Sediment layer (TopSediment, Bq)

$$\frac{dTopSediment}{dt} = Water \times TC_{sed} + DeepSediment \times TC_{erosionSed} -$$
$$- TopSediment \times TC_{res} - TopSediment \times TC_{accumSed} \tag{142}$$
$$- \lambda \times TopSediment + \sum_{p \in Pi} Br_p \times \lambda \times TopSediment$$

where:

$DeepSediment$ is the radionuclide inventory in the deep sediment layer (Bq);

$TC_{erosionSed}$ is the radionuclide transfer coefficient from the deep sediment layer to the top layer account for sediment erosion (as layer thickness stays constant in time) (1/year);

$TC_{accumSed}$ is the radionuclide transfer coefficient from the top layer to the deep sediment layer to account for sedimentation (as layer thickness stays constant in time) (1/year).

The terms $\lambda \times TopSediment$ and $\sum_{p \in Pi} Br_p \times \lambda \times TopSediment$ in Eq. (142) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the Top Sediment layer.

Transfer coefficient from the deep sediment to top sediment layer by erosion ($TC_{erosionSed}$, 1/year)

$$TC_{erosionSed} = Rate_{res}/(Rho_{sed,deep} \times H_{sed,deep}) \tag{143}$$

where:

$Rho_{sed,deep}$ is the density of the deep sediment layer (kg·DW/m^3); and
$H_{sed,deep}$ is the height (thickness) of the deep sediment layer of the FWB (m).

Transfer coefficient from the top sediment to deep sediment layer by accumulation ($TC_{accumSed}$, 1/year)

$$TC_{accumSed} = Rate_{sed}/(Rho_{sed,top} \times hH_{sed,top}) \tag{144}$$

6.9.2.3.   Mass balance equation for Deep Sediment layer (DeepSediment, Bq)

$$
\frac{dDeepSediment}{dt} = TopSediment \times TC_{accumSed} - DeepSediment \times TC_{erosionSed} -
$$
$$
- \lambda \times DeepSediment + \sum_{p \in Pi} Br_p \times \lambda \times DeepSediment \tag{145}
$$

All parameters on the right-hand side of Eq. (145) have already been defined previously.

6.9.2.4.   Mass balance equation for Subcatchment soil (SubCatch, Bq)

$$
\frac{dSubCatch}{dt} = Dep_{SubCatch} - SubCatch \times Outflow_{SubCatch} - \lambda \times SubCatch +
$$
$$
\sum_{p \in P} Br_p \times \lambda \times SubCatch \tag{146}
$$

where:

$Dep_{SubCatch}$ is the radionuclide transfer by deposition from the atmosphere on to the subcatchment (Bq/year).

Other parameters of Eq. (146) were defined previously.

Here:

$$Dep_{SubCatch} = Rate_{dep,SubCatch} \times Area_{SubCatch}. \tag{147}$$

where:

$Rate_{dep,SubCatch}$ is the radionuclide deposition rate from the atmosphere on to the subcatchment (Bq/(m^2·year)); and
$Area_{SubCatch}$ is the area of the subcatchment (m^2).

6.9.2.5.   Radionuclide concentration in water of FWB ($C_{water,calc}$, Bq/m^3)

The radionuclide concentration in water in the dissolved phase is calculated as:

$$C_{water,calc} = C_{water,total}/(1.0 + Kd_{SPM} \times C_{SPM}) \tag{148}$$

where:

$C_{water,total}$ is the total radionuclide concentration in water (including radionuclides dissolved in the water and those associated with the suspended particles) (Bq/m^3).

Here:

$$C_{water,total} = Water/V \tag{149}$$

where:

V is the volume of water in the FWB (m^3);

which is calculated as follows:

$$V = Area_{FWB} \times H_{average} \tag{150}$$

6.9.2.6. Radionuclide concentration in freshwater food (C_FreshWaterFood, Bq/kg·FW)

$$C_{FreshWaterFoo} = C_{water} \times CR_{FreshWaterFo} \times (1.0 - WC_{freshwater,food}) \times UnitCorr_{DW,FW} \tag{151}$$

where:

$CR_{FreshWaterFood}$ is the concentration ratio (radionuclide concentration in aquatic food per element concentration in water) for freshwater food; values are element specific (m^3/kg·DW);

$WC_{freshwater,food}$ is the water content in aquatic food (unitless); and

$UnitCorr_{DW,FW}$ is the unit conversion coefficient from DW to FW (kg·DW/kg·FW).

6.9.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation in water bottom sediments and soil of the subcatchment, hence the initial conditions are zero. However, modellers need to adapt these values according to their specific cases.

TABLE 82. INPUT PARAMETERS RELATED TO THE INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON THE RECEPTOR

Abbreviation and unit	Full name	Default value	Reference
Dep_init (Bq)	Initial activity deposition (inventory) in water of FWB at time t=0	0	Site specific parameter
Dep_init_subcatch (Bq)	Initial activity deposition (inventory) in soil of subcatchment at time t=0	0	Site specific parameter
Dep_init_top_sediments (Bq)	Initial activity deposition (inventory) in top sediments at time t=0	0	Site specific parameter
Dep_init_deep_sediments (Bq)	Initial activity deposition (inventory) in deep sediments at time t=0	0	Site specific parameter
C_water_meas* (Bq/m^3)	Measured radionuclide concentration in water	0	Site specific parameter
Rate_dep_FWB (Bq/(m^2·year))	Deposition rate of radionuclides from air on FWB	0	Site specific parameter
Rate_dep_subcatch (Bq/(m^2·year))	Deposition rate of radionuclides from air on subcatchment	0	Site specific parameter
Rate_rel (Bq/year)	Radionuclide release rate to FWB by direct releases	0	Site specific parameter

Note: * The *C_water_meas* value is needed in case radionuclide concentrations in freshwater food are calculated based on user-specified water concentration values. Dynamic calculations of the radionuclide concentrations in water are not performed (see Section 6.9.1.1).

TABLE 83. INPUT PARAMETERS RELATED TO WATER RESERVOIR GEOMETRY, HYDROLOGICAL AND GEOCHEMICAL CHARACTERISTICS

Abbreviation and Unit	Name	Default value	Reference
Area_FWB (m^2)	FWB area	1.8E6	Site specific parameter value needed
H_aver (m)	Average depth of FWB	5.6	Site specific parameter value needed
Flux_water_upstream (m^3/year)	Water flux from water body upstream (e.g. river, lake)	0	Site specific parameter value needed
C_SPM (kg·DW/m^3)	Concentration of suspended particulate matter in FWB water	0.026	See Table 10–30 of Ref. [24]
Rate_sed (kg·DW/(m^2·year))	The sedimentation rate of particles in the FWB water	3.49	See Table 5–11 of Ref. [24]
Kd_SPM (m^3/kg·DW)	Sorption distribution coefficient for the suspended particulate matter	See Table 141, Appendix	[8, 11]

TABLE 84. INPUT PARAMETERS RELATED TO BOTTOM SEDIMENT GEOMETRY AND PHYSICOCHEMICAL PROPERTIES

Abbreviation and Unit	Name	Default value	Reference
H_sed_top (m)	Height of the top sediment layer	0.05	See Table 2-1 of Ref. [11]
Porosity_sed_top (m^3/m^3)	Porosity of the top sediment layer	0.92	See Table 2-1 of Ref. [11]
Rho_sed_top (kg·DW/m^3)	Density of the top sediment layer	179.0	See Table 2-1 of Ref. [11]
H_sed_deep (m)	Height of the deep sediment layer	0.96	See Table 2-1 of Ref. [11]
Rho_sed_deep (kg·DW/m^3)	Density of the deep sediment layer	71.7	See Table 2-1 of Ref. [11]
Kd_sed (m^3/kg·DW)	Sorption distribution coefficient for the bottom sediments of FWB	Table 85	[8 11]
Rate_res (kg·DW/(m^2·year)	The bottom sediment resuspension rate in FWB	0	Site specific parameter

TABLE 85. DEFAULT RADIONUCLIDE *Kd* VALUES FOR THE BOTTOM SEDIMENTS OF THE FWB

Radionuclide	*Kd*, m^3/kg·DW	Reference
Ac	8.8 E+01	See Table 5–17 of Ref. [11]
Cs	9.5 E+01	See Table 53 of Ref. [8]
Pa	8.8 E+01	See Table 5-17 of Ref. [11]
Pb	1.4 E+02	See Table 5-17 of Ref. [11]
Po	5.5 E+01	See Table 5-17 of Ref. [11]
Ra	7.4 E+01	See Table 53 of Ref. [8]
Sr	1.9 E-01	See Table 53 of Ref. [8]
Th	1.9 E+02	See Table 53 of Ref. [8]
U	5.0 E-01	See Table 54 of Ref. [8]

TABLE 86. INPUT PARAMETERS RELATED TO 'FRESH WATER BODY' SUBCATCHMENT GEOMETRY AND SOIL PROPERTIES

Abbreviation and Unit	Name	Default value	Reference
Area_subcatch (m^2)	Area of subcatchment	1.5E7	Site specific parameter value needed
H_subcatch (m)	Thickness of soil in subcatchment area involved in radionuclide exchange process during runoff	0.5	Site specific parameter value needed
Runoff (m/year)	Water runoff layer from subcatchment	0.2	Site specific parameter value needed
Porosity_subcatch (m^3/m^3)	Porosity of soil in subcatchment	0.21	Site specific parameter value needed
Rho_subcatch (kg·DW/m^3)	Density of soil in subcatchment	2115.0	Site specific parameter value needed
Kd_soil_subcatch (m^3/kg·DW)	Sorption distribution coefficient for the soil of subcatchment	See Table 141, Appendix	[8]

TABLE 87. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO FRESHWATER FOOD (UNITLESS) [8, 11]

Radionuclide	Fish	Cray Fish	Mussels
Ac	5.5E-03	8.4E+00	8.4E+00
Cs	5.2E+00	1.7E+00	1.7E+00
Pa	5.5E-03	8.4E+00	8.4E+00
Pb	1.0E-01	3.4E+01	3.4E+01
Po	1.4E-01	4.0E+01	4.0E+01
Ra	1.4E-02	4.6E+00	4.6E+00
Sr	1.2E-02	1.4E+00	1.4E+00
Th	3.1E-01	1.5E+00	1.5E+00
U	2.7E-04	1.1E-01	1.1E-01

TABLE 88. DEFAULT VALUES OF WATER CONTENT OF FRESHWATER FOODS ($WC_{freshwater,food}$) (UNITLESS) [7]

Food type	Fish	Cray Fish	Mussels
$WC_{freshwater,food}$	0.78	0.78	0.78

6.9.4. Output parameters

The main output parameters of the FWB module are radionuclide concentrations in surface water of FWB and radionuclide concentrations in freshwater foods. As discussed in Section 6.9.1.3, these output data can be used by other receptors (e.g. as concentrations in irrigation water etc.) or used directly for dose calculations (see Table 89).

TABLE 89. OUTPUT PARAMETERS OF 'FRESH WATER BODY' MODULE

Abbreviation and unit	Full name	Purpose
C_water_calc (Bq/m³)	Radioactive contaminant concentrations in surface water of FWB receptor	Used to calculate doses from drinking water pathway or used for radionuclide concentrations in water used for irrigation and watering cattle. Can be used also by downstream FWB module as concentration in water entering downstream object (see Table 81)
C_FreshWaterFood (Bq/kg·FW)	Radioactive contaminant concentrations in food of FWB receptor	Used to calculate doses from consumption of freshwater foods (see Table 81)
Flux_water_to_dowstream (Bq/year)	Flux with water of radionuclides from the FWB in downstream reservoir	Used as input for the next FWB module.

6.10. 'MARINE' MODULE

This section provides detailed descriptions of module, mathematical model, input parameters and output parameters of the 'Marine' module.

6.10.1. Module description

6.10.1.1. General description

The 'Marine' module allows the assessment of exposure pathways associated with the use of a sea coastal area as a source of food, as well as with the use of the sea for recreational activities such as swimming and boating.

The objective of the 'Marine' module is to simulate sea coastal areas that might receive radionuclides deposited from the atmosphere on the sea water surface, as well as direct radionuclide discharges to water from a source (see Fig. 35). The 'Marine' module dynamically simulates the distribution of radionuclides in abiotic media (i.e. sea water, suspended particulate matter and bottom and beach sediments) and biotic media (e.g. fish and other edible sea organisms).

The mathematical model for the sea water compartment implemented in the 'Marine' module is based on the 'POSEIDON' model described in Ref. [19]. The model for radionuclide accumulation in the beach sediment is based on information given in Ref. [4], specifically under Section 4.7.5.

The module provides an option for the user to directly specify the radionuclide concentration in sea water (e.g. based on monitoring data). In this case, sea water concentration values specified and fixed in time by the modeller are used to calculate the radionuclide concentrations in the marine food species.

6.10.1.2. Conceptual model

The conceptual model of the 'Marine' receptor is illustrated in Fig. 36. The modelled coastal marine environment is divided into several distinct compartments. Of main interest is the local sea water ('Water') compartment ('inner water compartment') which can receive direct radionuclide depositions from the atmosphere and direct releases of radioactivity from other sources (e.g. liquid releases from nuclear facilities or contaminated groundwater discharge).
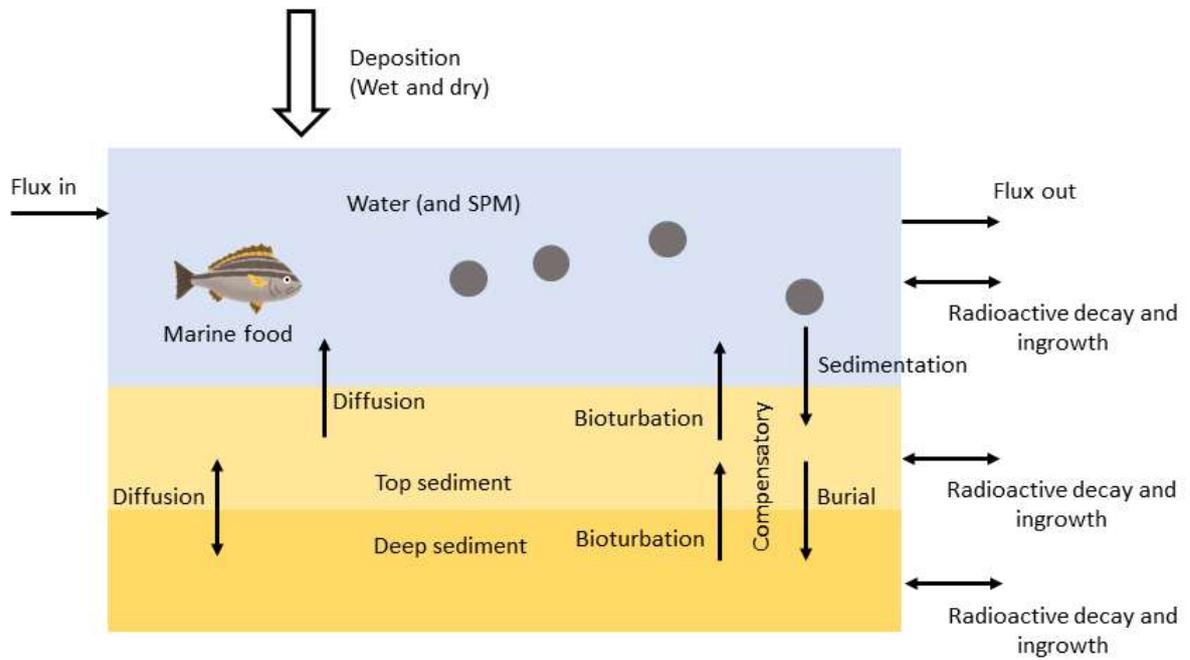
FIG. 35. Scheme illustrating the 'Marine' module.
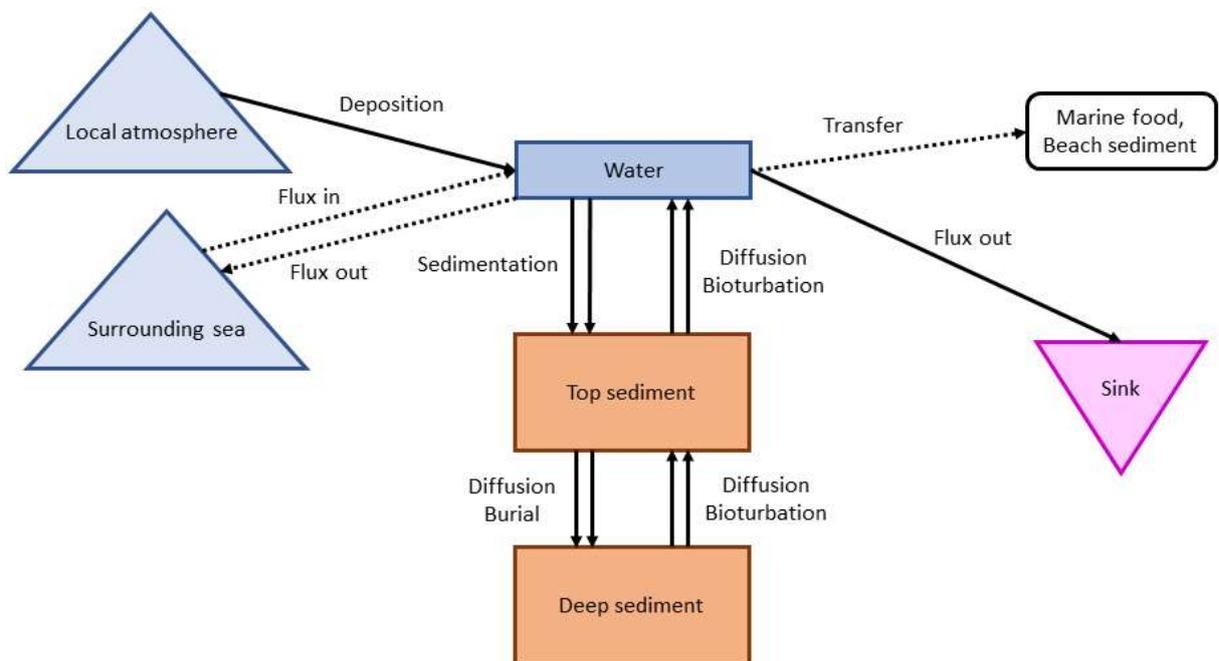
FIG. 36. Conceptual scheme of the 'Marine' receptor.

The area of the local sea compartment is set to the minimum required for sustaining fish production that is sufficient to feed a small group of individuals. The geometry of the local sea water compartment is defined by its area and average depth parameters. The surrounding sea is treated as a sink for radionuclides entering it (see Fig. 36). The sediment is divided into two compartments (i.e. top sediment and deep sediment) which are defined by the area of the marine compartment and the thicknesses of the sediment layers.

The different compartments in the 'Marine' module are assumed to be homogeneous with respect to contamination levels, geochemical properties, etc.

Exchanges of radionuclides in the solid (sediment suspended in water, bottom sediments) and liquid phases are modelled throughout the module using an instantaneous equilibrium reversible sorption model (i.e. *Kd* model, where *Kd* is the distribution coefficient) [8].

It is assumed that radionuclide activity stored in the 'Water' compartment is distributed between activity dissolved in water and activity adsorbed on suspended matter (see Fig. 34). Radionuclides dissolved in water and adsorbed on suspended particles are assumed to be in equilibrium with those described by the respective distribution coefficient (Kd_SPM).

The inputs of radioactive contaminant(s) into the 'Marine' system may have the following origins:

— Contaminants originating from atmospheric deposition on the surface of the sea waterbody (total deposition rate, i.e. dry and wet deposition of radionuclides over the water);
— Direct radionuclide release from the source(s) of radioactivity (e.g. industrial releases or contaminated groundwater or surface water discharge);
— Contaminants originating from the surrounding sea waterbodies (i.e. inflowing water fluxes);
— Ingrowth of daughter radionuclides from the parent radionuclides.

The potential losses of contaminants from the 'Marine' system may be:

— Outflux in sea water of the radionuclides to adjacent marine areas;
— Radioactive decay.

The exchanges of the 'Water' compartment with surrounding marine system (or submodels) discussed here are schematically represented in Fig. 37.

The potential exchanges ('transfers') of contaminants between the compartments of the modelled 'Marine' ecosystem are:

— Sedimentation of suspended particulate matter (SPM) from the sea water column to the bottom sediment (top layer);
— Resuspension of radionuclides from bottom sediments (top layer) to the water column. This includes radionuclide contaminant(s) in the sediment solids, as well as radionuclides in the pore water;
— Transfer of radionuclides by diffusion throughout the sediment pore water;
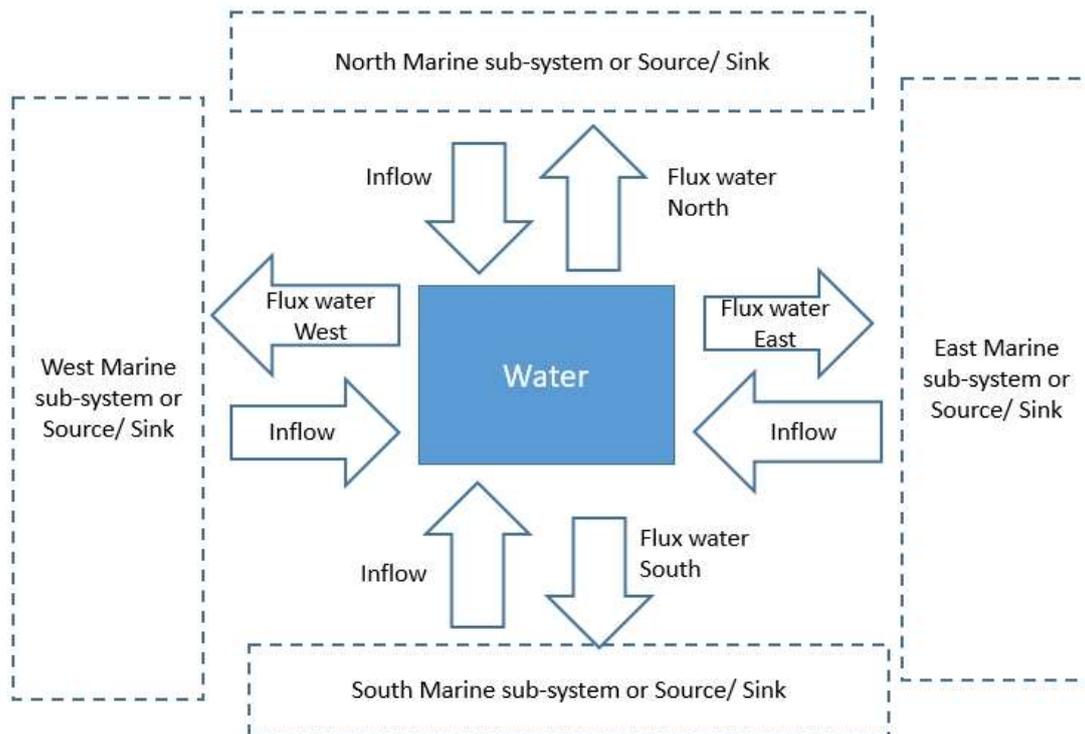
FIG. 37. Schematization of exchanges of the 'Water' compartment of the 'Marine' system by water fluxes with the surrounding marine environment.

— Exchange between the top layer of the sediment and the water column through bioturbation due to sediment steering by organisms living at the benthic zone of the marine ecosystem (modelled as a diffusion process). If resuspension of particulate matter is larger than the sedimentation, there will be a net loss of sediments from the top sediment layer due to bioturbation;

— Transfer of radioactive contaminant(s) due to burial. If the sedimentation of particulate matter is larger than the resuspension it will result in an accumulation of sediments, and the total depth top layer will therefore grow. This process is modelled as a translocation of radioactive contaminant(s) from the top sediment to deeper layers by 'burial' processes.

Radionuclide accumulation in aquatic organisms (e.g. fish) is calculated based on the radionuclide concentration in the water. Radionuclide transfer to marine biota species is modelled using a concentration ratio (or transfer coefficients) approach [4].

The surface activity concentration of a radionuclide in shore/beach sediment is calculated assuming these sediments are composed from particles in sorption equilibrium with water, taking into account radioactive decay occurring while radionuclides from the water column are accumulating in the shore or beach sediment, see Ref. [4], specifically Section 4.7.5.

This module takes three different types of aquatic food species into account:

— Fish;
— Cray fish;
— Mussels.

These types of aquatic organisms have specific values of relevant radioecological parameters, such as concentration ratios values, describing the radionuclide transfer from sea water to biota.

The module also calculates accumulation of radioactivity in the sea beach sediments from suspended particles in the sea water. The derived activity values are used for estimating exposure resulting from recreational activities at the sea beach.

The 'Marine' module assumes that radionuclides are homogeneously distributed in the main model compartments, both laterally and vertically. The relevant spatial scale and resolution of the model are thus governed by the homogeneity of the marine body under investigation (e.g. homogeneity with respect to contamination levels, physical and geochemical parameters).

For marine environments showing significant spatial variations in properties of the main compartments mentioned above, it is recommended to subdivide the latter into several submodels and to couple them which each other, as appropriate, by means of mass fluxes (e.g. inflowing/outflowing sea water fluxes from the adjacent marine subsystem) (see Fig. 37).

6.10.1.3. *Potential coupled modules*

The 'Marine' module can be combined with a number of other NORMALYSA modules. The latter can be used to specify radiological loads on the 'Marine' receptor (e.g. radionuclide deposition rates from atmosphere, inputs with surface water and groundwater inflow). In turn, the 'Marine' module can provide data on radionuclide concentrations in sea water, beach sediments and aquatic foods that are used for dose calculations (see Table 90).

TABLE 90. POTENTIAL COUPLED MODELS FROM NORMALYSA LIBRARY FOR 'MARINE' MODULE

Coupled model	Description of parameters used as loadings/inputs or outputs/losses
Inputs to module can be provided by following modules:	
'Atmosphere SR-19', 'Atmosphere Chronic'	Radionuclide deposition rates from the atmosphere ($Bq/(m^2 \cdot year)$)
'Surface Runoff'	Radionuclide release rate (Bq/year) from contaminated watershed in surface runoff
'Aquifer'	Radionuclide concentrations (Bq/m^3) in groundwater originating from the contaminated site
Other 'Marine' module (adjacent object representing a source of releases of radioactivity)	Radionuclide concentrations (Bq/m^3) in inflowing sea water originating from the adjacent contaminated 'Marine' subsystem
'Chronic release'	Radionuclide release rate (Bq/year) from a source of direct release to aquatic object
Outputs from module can be used by following modules:	
'Dose from Ingestion of marine food'	Radionuclide concentrations ($Bq/kg \cdot FW$) in marine foods
'Dose from Marine Activities'	Radionuclide concentrations in water (Bq/m^3) and beach sediment (Bq/m^2) of reservoir used for recreational/marine activities (e.g. swimming, boating, visiting beach)
Other 'Marine' module (adjacent object representing a sink of releases of radioactivity)	Radionuclide concentrations (Bq/m^3) in outflowing surface water originating from the contaminated FWB

6.10.2. Mathematical model

In this section, detailed descriptions of the mathematical model of the 'Marine' module are provided.

6.10.2.1. Mass balance equation for sea water media (Water, Bq)

$$\frac{dWater}{dt} = Release + Dep + Flux_{in} + TopSediment \times BioturbationToWater$$
$$+TopSediment \times DiffusionToWater - Water \times SedFromWater$$
$$-Water \times TC_{out} - \lambda \times Water + \sum_{p \in P_i} Br_p \times \lambda \times Water \qquad (152)$$

where:

Release is the radionuclide transfer to the 'Marine' receptor by direct releases (Bq/year);

Dep is the radionuclide transfer by deposition from the atmosphere on to the water surface of the 'Marine' receptor (Bq/year);

Flux$_{in}$ is the radionuclide transfer to the 'Marine' receptor by inflow from other (adjacent) sea water objects (compartments) (Bq/year);

TopSediment is the radionuclide inventory in the top sediment layer (Bq);

BioturbationToWater is the radionuclide transfer coefficient to the water column from the top bottom sediment layer by bioturbation (1/year);

DiffusionToWater is the radionuclide transfer coefficient to the water column from the top bottom sediment layer by diffusion exchange (1/year);

SedFromWater is the radionuclide transfer coefficient from the water column to the top bottom sediment layer by sedimentation (1/year); and

TC$_{out}$ is the radionuclide transfer coefficient from the 'Marine' receptor to adjacent marine subsystem(s) by sea water flows (1/year).

The terms $\lambda \times Water$ and $\sum_{p \in Pi} Br_p \times \lambda \times Water$ in Eq. (152) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in water.

Deposition rate of radionuclides on water surface of 'Marine' receptor (Dep, Bq/year)

$$Dep = Rate_{dep} \times Area \qquad (153)$$

where:

rate$_{dep}$ is the radionuclide deposition rate on the 'Marine' receptor (Bq/(m^2·year)); and

area is the area of the 'Marine' receptor (m^2).

Radionuclide transfer by direct releases (Release, Bq/year)

$$Release = Rate_{rel,} \qquad (154)$$

where:

Rate$_{rel}$ is the parameter specifying radionuclide release rate to the 'Marine' receptor by direct releases (Bq/year).

Radionuclide transfer by inflow from other sea water objects (Flux$_{in}$, Bq/year)

$$Flux_{in} = FluxIn_{Par,} \qquad (155)$$

FluxIn$_{Par}$ is the parameter specifying radionuclide release rate to the 'Marine' receptor by direct inflows of water from adjacent sea boxes (Bq/year).

Radionuclide transfer coefficient from top bottom sediment layer to water by bioturbation (BioturbationToWater, 1/year)

$$BioturbationToWater = (Ret_{sed} - 1.0)/Ret_{sed} \times B_k/(Lt \times Lt/2.0) \qquad (156)$$

where:

Ret_{sed} is the radionuclide retardation factor for bottom sediments (unitless);
B_k is the bioturbation coefficient for bottom sediments (m^2/year); and
Lt is the characteristic length of the top sediment layer (m).

Here:

$$Ret_{sed} = 1.0 + \left(\frac{Rho_{sed,particles}}{Porosity} \times (1.0 - Porosity) \right) \times Kd_{sed} \qquad (157)$$

where:

$Rho_{sed,particles}$ is the density of the bottom sediment particles (kg/ m^3);
$Porosity$ is the porosity of the bottom sediments (unitless); and
Kd_{sed} is the radionuclide distribution coefficient for bottom sediments (m^3/kg).

Transfer coefficient from top sediment layer by diffusion (DiffusionToWater, 1/year)

$$DiffusionToWater = 1.0/Ret_{sed} \times D_k/(Lt \times Lt/2.0) \qquad (158)$$

where:

D_k is the diffusion coefficient for bottom sediments (m^2/year),

Other notations are same as in Eq. (156).

Transfer coefficient from water column to bottom sediment by sedimentation (SedFromWater, 1/year)

$$SedFromWater = Kd_{SPM} \times Rate_{sed}/(Hw \times (1.0 + Kd_{SPM} \times C_{SPM})) \qquad (159)$$

where:

Kd_{SPM} is the radionuclide distribution coefficient for suspended particles in the water column of sea water (m^3/kg);
$Rate_{sed}$ is the sedimentation rate of suspended particles from the water column to bottom sediments (kg /(m^2·year));
Hw is the depth of the water body (m); and
C_{SPM} is the concentration of suspended particles in sea water (kg/m^3).

Transfer coefficient to adjacent marine subsystem(s) by sea water flows (TC$_{out}$, 1/year)

$$TC_{out} = \frac{Flux_{out}}{Volume} \qquad (160)$$

where:

$Flux_{out}$ is the sea water flux from the 'Marine' receptor (m^3/year); and $Volume$ is the volume of the 'Marine' receptor (m^3).
Here sea water flux represents a sum of water fluxes in North, South, West and East directions:

$$Flux_{out} = Flux_{Water,North} + Flux_{Water,South} + Flux_{Water,East} + Flux_{Water,West} \qquad (161)$$

The volume of water in the 'Marine' receptor is calculated as:

$$Volume = Hw \times Area \qquad (162)$$

6.10.2.2. Mass balance equation for Top Sediment layer (TopSediment, Bq)

$$
\begin{aligned}
\frac{dTopSediment}{dt} = {} & DeepSediment \times DiffusionToTopSed + \\
& Water \times SedFromWater + DeepSediment \times BioturbationToTopSed \\
& - TopSediment \times BioturbationToWater \\
& - TopSediment \times BurialFromTopSed \\
& - TopSediment \times DiffusionToWater \\
& - TopSediment \times DiffusionToDeepSed - \lambda \times TopSediment \\
& + \sum_{p \in P_i} Br_p \times \lambda \times TopSediment
\end{aligned}
$$

$$(163)$$

where:

DeepSediment is the radionuclide inventory in the deep sediment layer (Bq);

DiffusionToTopSed is the radionuclide transfer coefficient from the deep sediment layer to the top layer by diffusion exchange (1/year);

BioturbationToTopSed is the radionuclide transfer coefficient from the deep sediment layer to the top layer to compensate bioturbation loss from the top layer to the water column (1/year);

BurialFromTopSed is the radionuclide transfer coefficient from the top layer to the deep sediment layer to account for deep layer burial due to sedimentation (as the layer thickness stays constant in time) (1/year); and

DiffusionToDeepSed is the radionuclide transfer coefficient from the top sediment layer to the deep layer by diffusion exchange (1/year).

The terms $\lambda \times TopSediment$ and $\sum_{p \in Pi} Br_p \times \lambda \times TopSediment$ in Eq. (163) describe, respectively, the radioactive decay and ingrowth of radionuclides from the parent nuclides in the 'Top Sediment' compartment. Other equation terms and parameters have been already described above.

Transfer coefficient from deep to top sediment layer by diffusion (DiffusionToTopSed, 1/year)

$$DiffusionToTopSed = \frac{1.0}{Ret_{sed}} \times D_k / \left(L_m \times \left(\frac{Lt}{2.0} + \frac{Lm}{2.0} \right) \right) \qquad (164)$$

where:

Lm is the characteristic length of the deep sediment layer (m).

Other notations are same as in the previous formula.

Transfer coefficient from top to deep layer by diffusion (DiffusionToDeepSed, 1/year)

$$DiffusionToDeepSed = \frac{1.0}{Ret_{sed}} \times D_k / \left(L_t \times \left(\frac{Lt}{2.0} + \frac{Lm}{2.0} \right) \right) \qquad (165)$$

Radionuclide transfer coefficient from deep to top sediment layer to compensate bioturbation (BioturbationToTopSed, 1/year)

$$BioturbationToTopSed = \frac{1.0}{Ret_{sed}} \times B_k / \left(L_m \times \left(\frac{Lt}{2.0} + \frac{Lm}{2.0} \right) \right) \qquad (166)$$

Transfer coefficient from top layer to deep layer describing 'burial' due to sedimentation (BurialFromTopSed, 1/year)

$$Burial\_From\_TopSed = (Ret_{sed} - 1.0)/Ret_{sed} \times Rate_{sed}/(Lt \times (1.0 - Porosity) \times Rho_{sed,particles}) \qquad (167)$$

6.10.2.3.   *Mass balance equation for Deep Sediment layer (DeepSediment, Bq)*

$$\frac{dDeepSediment}{dt} = TopSediment \times BurialFromTopSed$$
$$+ TopSediment \times DiffusionToDeepSed - DeepSed \times DiffusionToTopSed$$
$$- DeepSediment \times BioturbationToTopSed - \lambda \times DeepSediment$$
$$+ \sum_{p \in P_i} Br_p \times \lambda \times DeepSediment$$

$$(168)$$

6.10.2.4.   *Radionuclide concentration in water of 'Marine' receptor (C$_{water,calc}$, Bq/m^3)*

Radionuclide concentration in water in the dissolved phase is calculated as:

$$C_{water,calc} = C_{water,total}/(1.0 + Kd_{SPM} \times C_{SPM}) \qquad (169)$$

where:

$C_{water,total}$ is the total radionuclide concentration in water (including radionuclides dissolved in the water and those associated with the suspended particles) (Bq/m^3), given by:

$$C_{water,total} = Water/Volume \qquad (170)$$

6.10.2.5.   *Radionuclide concentration in marine food (C$_{marine,food}$, Bq/kg·FW)*

$$C_{marine,food} = C_{water,calc} \times CR_{marine,food} \times (1.0 - WC_{marine,food}) \times UnitCorr_{DW,FW}$$

$$(171)$$

where:

$CR_{MarineFood}$ is the concentration ratio (radionuclide concentration in aquatic food per element concentration in water) for marine food; values are element specific (m^3/kg·DW);
$WC_{marine,food}$ is the water content in aquatic food (unitless); and
$UnitCorr_{DW,FW}$ is the unit conversion coefficient from DW to FW (kg·DW/kg·FW).

6.10.2.6.   *Radionuclide surface activity concentration in shore/beach sediment (C$_{sed,beach}$, Bq/m^2)*

$$C_{sed,beach} = C_{water,total} \times Kd_{SPM} \times Rho_{sed,beach} \times H_{sed,beach} \times \left(\frac{1.0 - exp(-\lambda \times T_{ac,be})}{\lambda \times T_{acc,beach}} \right)$$

$$(172)$$

where:

$H_{sed,beach}$ is the thickness of the top layer of the beach sediment (m);
$Rho_{sed,beach}$ is the density of the beach sediments (m^3/kg); and
$T_{acc,beach}$ is the accumulation time for the beach sediments (years).

6.10.2.7. Radionuclide flux from 'Marine' receptor (Flux$_{out}$, Bq/year)

$$Flux_{out} = Water \times TC_{out} \qquad (173)$$

6.10.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation in water and bottom sediments, hence the initial conditions are zero. However, modellers need to adapt these values according to their specific cases.

TABLE 91. INPUT PARAMETERS RELATED TO THE INITIAL CONTAMINATION AND RADIOLOGICAL LOADS ON THE RECEPTOR

Abbreviation and unit	Full name	Default value	Reference
Dep_init (Bq$^)$	Initial activity deposition (inventory) in water at time t=0	0	Site specific parameter
Dep_init_top_sediments (Bq)	Initial activity deposition (inventory) in top sediments at time t=0	0	Site specific parameter
Dep_init_deep_sediments (Bq)	Initial activity deposition (inventory) in deep sediments at time t=0	0	Site specific parameter
C_water_meas* (Bq/m^3)	Measured radionuclide concentration in water	0	Site specific parameter
Rate_dep (Bq/(m^2·year))	Deposition rate of radionuclides from air on the receptor	0	Site specific parameter
Rate_rel (Bq/year)	Radionuclide release rate to the receptor by direct releases	0	Site specific parameter
FluxInPar (Bq/year)	Radionuclide influx to the receptor by inflow from other (adjacent) sea water objects	0	Site specific parameter

Note: * The *C_water_meas* value is needed in case radionuclide concentrations in marine food are calculated based on user-specified water concentration values. Dynamic calculations of radionuclide concentrations in water are not performed (see Section 6.10.1.1).

TABLE 92. INPUT PARAMETERS RELATED TO THE 'MARINE' RECEPTOR AQUATIC BODY GEOMETRY, HYDROLOGICAL AND GEOCHEMICAL CHARACTERISTICS

Abbreviation and Unit	Name	Default value	Reference
Area (m^2)	Area of receptor	1.0E6	Site specific parameter value needed
hw (m)	Average depth of water body	10.0	Site specific parameter value needed
FluxInPar (m^3/year)	Water inflow from adjacent sea boxes	0	Site specific parameter value needed
C_SPM (kg·DW/m^3)	Concentration of suspended particulate matter in water	0.001	[19]
vel_sed (m/year)	The sedimentation velocity of particles in water to bottom sediments	1E3	[19]
Kd_SPM (m^3/kg·DW)	Sorption distribution coefficient for the suspended particulate matter	See Table 141, Appendix	[8, 11]

TABLE 93. INPUT PARAMETERS RELATED TO THE BOTTOM SEDIMENT GEOMETRY AND PHYSICOCHEMICAL PROPERTIES

Abbreviation and Unit	Name	Default value	Reference
Lt (m)	Height of the top sediment layer	0.1	[19]
Lm (m)	Height of the deep sediment layer	1.9	[19]
Porosity (m^3/m^3)	Porosity of the bottom sediment	0.75	[19]
rho_sed_particles (kg·DW/m^3)	Density of sediment particles	2600	[19]
Kd_sed (m^3/kg·DW)	Sorption distribution coefficient for the bottom sediments	Table 85	[8, 11]
D_k (m^2/year)	Solute diffusion coefficient in bottom sediments	3.15E-02	[19]
B_k (m^2/year)	Bioturbation coefficient in bottom sediments	3.6E-05	[19]

TABLE 94. INPUT PARAMETERS RELATED TO 'MARINE' BEACH SEDIMENT GEOMETRY AND PHYSICOCHEMICAL PROPERTIES

Abbreviation and Unit	Name	Default value	Reference
H_sed_beach (m)	Thickness of the beach sediment layer	0.05	[9]
Rho_sed_beach (kg·DW/m^3)	Density of beach sediments	1200	[9]
T_acc_beach (years)	Accumulation time for beach sediments	1	Site specific parameter

TABLE 95. DEFAULT VALUES OF CONCENTRATION RATIOS (CRs) DESCRIBING RADIONUCLIDE TRANSFER TO MARINE FOOD (UNITLESS) [8, 11]

Radionuclide	Fish	Cray Fish	Mussels
Ac	5.5E-03	8.4E+00	8.4E+00
Cs	5.2E+00	1.7E+00	1.7E+00
Pa	5.5E-03	8.4E+00	8.4E+00
Pb	1.0E-01	3.4E+01	3.4E+01
Po	1.4E-01	4.0E+01	4.0E+01
Ra	1.4E-02	4.6E+00	4.6E+00
Sr	1.2E-02	1.4E+00	1.4E+00
Th	3.1E-01	1.5E+00	1.5E+00
U	2.7E-04	1.1E-01	1.1E-01

TABLE 96. DEFAULT VALUES OF WATER CONTENT OF FRESHWATER FOODS ($WC_{marine,food}$) (UNITLESS) [7]

Food type	Fish	Cray Fish	Mussels
$WC_{freshater,food}$	0.78	0.78	0.78

6.10.4. Output parameters

The main output parameters of the 'Marine' module are radionuclide concentrations in water, beach sediments and radionuclide concentrations in marine foods. As discussed in Section 6.9.1.3 above, these output data can be used for dose calculations by respective module from the 'Doses' library (see Table 89).

TABLE 97. OUTPUT PARAMETERS OF THE 'MARINE' MODULE

Abbreviation and unit	Full name	Purpose
C_MarineFood (Bq/kg·FW)	Radioactive contaminant concentrations in sea food of the 'Marine' receptor	Used to calculate doses from the consumption of marine foods (see Table 90)
C_water_calc (Bq/m³)	Radioactive contaminant concentrations in the surface water and beach sediment of the 'Marine' receptor	Used to calculate doses from marine activities (e.g. swimming, boating) (see Table 90)
C_SED_BEACH (Bq/m²)	Radioactive contaminant concentrations in beach sediment of the Marine receptor	Used to calculate doses from visiting the beach (see Table 90)
Flux_out (Bq/year)	Radioactive contaminant flux in surface water to adjacent Marine boxes	Used to calculate exchanges of radioactivity with the adjacent Marine boxes

7.   'DOSES' MODULE LIBRARY

7.1.   GENERAL DESCRIPTION OF THE LIBRARY

A set of modules contained in the 'Doses' library allow assessment of doses to humans based on the radionuclide concentrations in different environmental media (e.g. soil, air, water and various foodstuffs) calculated using the receptor modules described in previous sections of this publication.

The 'Dose' library includes three sub-libraries:

— Doses from occupancy;
— Ingestion;
— Total dose.

The first sub-library contains modules that allow the calculation of effective doses to reference persons exposed to radioactivity in soil, air and water in the outdoor environment (i.e. on contaminated land), indoors and in a contaminated marine environment.

The second sub-library includes a set of modules for calculating the effective internal doses caused by the consumption of various contaminated foodstuffs related to respective receptor environments (e.g. crops, forest products, aquatic foods etc.) by reference persons.

The third sub-library includes the 'Total Dose' module allowing the calculation of the total annual effective dose summed over all relevant radionuclides and exposure pathways that use doses assessed using the first two sub-libraries as input data.

The dose modules allow simultaneous calculation of doses to three reference persons, i.e. 'Reference person 1', 'Reference person 2', and 'Reference person 3'. These reference persons may belong to three different age groups:

— Adults;
— Children (represented by 10 year olds);
— Infants (represented by 1 year olds).

The groups mentioned above have age specific radiological and physiological parameters (e.g. dose conversion coefficients for relevant exposure pathways, inhalation rates).

Different reference persons may also be differentiated by a set of parameters defining their habits which may influence exposure patterns (e.g. time spent outdoors in the contaminated site, diet habits).

With regard to input radiological data, there are two options for dose calculations:

— Radionuclide concentrations in environmental media and foodstuffs used for dose calculations can be provided (dynamically) by respective 'receptor' modules; or
— Radionuclide concentrations in environmental media and foodstuffs and/or external ambient dose rates can be directly specified by the modeller (e.g. based on monitoring data).

Dose coefficients for effective doses from external irradiation from surface deposition and immersion into a radioactive cloud and water are based on Ref. [13]. Dose coefficients for internal exposure through inhalation and ingestion pathways are based on Ref. [14]. The dose coefficient values for inhalation found in the tables given in Ref. [14] are assumed to be Type S: 'Deposited materials that are relatively insoluble in the respiratory tract', if not specified differently.

Respective dose conversion coefficients (DCCs) for various pathways and other parameters for dose assessment (e.g. inhalation rates, ingestion rates) are listed in the Appendix in Tables 143–149.

7.2. 'DOSES FROM OCCUPANCY' SET OF MODULES

The 'Doses from Occupancy' subset of modules includes three different modules:

— Dose from Occupancy Outdoors;
— Dose from Occupancy Indoors;
— Dose from Marine Activities.

These modules are described in more detail in Sections 7.2.1–7.2.3.

7.2.1. Doses from occupancy outdoors

In this section, detailed descriptions of doses from occupancy outdoors are provided.

7.2.1.1. Module description

The 'Dose from Occupancy Outdoors' module is used to calculate the total annual effective dose received by a 'reference person' during outdoor activities in the respective 'receptor environment' (radioactively contaminated site). The following exposure pathways are taken into account:

— External exposure;
— Inhalation pathway;
— Dose from inadvertent ingestion of soil.

Radionuclide concentrations in soil and air of the contaminated site used as input data for dose calculations can be passed from the respective 'receptor environment' module, or these can be directly specified by the modeller (e.g. based on monitoring data).

The external exposure dose rate can either be estimated by the module based on the radionuclide concentrations in soil which are provided, or the modeller can provide a measured ambient external dose rate.

7.2.1.2. Potential coupled modules

TABLE 98. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM OCCUPANCY OUTDOORS' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Land', 'Forest', 'Garden', 'Cropland', 'Pastureland'	Volumetric concentration of radionuclides in soil (Bq/m³) Mass radionuclide concentration in soil (Bq/kg·DW) Concentration of radionuclides in outdoor air (Bq/m³)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from external irradiation (Sv/year) Dose from inadvertent soil ingestion (Sv/year) Dose from inhalation (Sv/year)

7.2.1.3. Mathematical equations

The total annual dose from outdoor occupancy in a specific receptor ($Dose_{occup,outdoor}$, $Sv/year$)

$$Dose_{occup,outdoor} = Dose_{ext,total} + Dose_{inh,outdoor} + Dose_{ing.soil,total} \qquad (174)$$

where:

$Dose_{ext,total}$ is the dose from external irradiation (Sv/year);
$Dose_{inh,outdoor}$ is the dose from inhalation outdoors (Sv/year); and
$Dose_{ing.soil,total}$ is the dose from inadvertent ingestion of soil (Sv/year).

The annual dose from external exposure ($Dose_{ext,total}$, $Sv/year$)

The annual dose from external exposure (Sv/year) is calculated by:

$$Dose_{ext,total} = f_{occup,outdoor} \times \text{HoursPerYear} \times DoseRate_{eff,out} \qquad (175)$$

where:

$DoseRate_{eff,out}$ is the efficient external dose rate (Sv/h);
$f_{occup,outdoor}$ is the fraction of time that a person is exposed outdoors (unitless); and
$HoursPerYear$ is the number of hours in a year (h/year).

Depending on the input data specified by the modeller, the efficient external dose rate ($doseRate_{eff,out}$) can be calculated as follows:

In the case that the known value of ambient external dose rate is specified, then:

$$DoseRate_{eff,out,Eq1} = DoseRate_{amb,out} \times Conv_{amb,eff} \qquad (176)$$

where:

$DoseRate_{amb,out}$ is the specified ambient external dose rate outdoors (Sv/h); and
$Conv_{amb,eff}$ is the conversion factor from ambient to effective dose (unitless).

The second option is calculating the efficient external dose rate based on the provided radionuclide concentrations in soil and air:

$$DoseRate_{eff,out,Eq2} = DoseRate_{eff,dep} + DoseRate_{eff,imm} \qquad (177)$$

where:

$DoseRate_{eff,dep}$ is the estimated dose rate for external irradiation from the ground (from deposited radionuclides) (Sv/h); and

$DoseRate_{eff,imm}$ is the estimated dose rate from cloud immersion (Sv/h).

The effective dose rate outdoors from the deposited radionuclides (DoseRate_{eff,dep}, Sv/h) is calculated by:

$$DoseRate_{eff,dep} = \sum_{RN} DoseRate_{eff,dep,RN} \qquad (178)$$

Where the dose rate for external irradiation from each radionuclide ($doseRate_{eff,dep,RN}$, Sv/h) is calculated by:

$$DoseRate_{eff,dep,RN} = C_{soil,vol} \times DCC_{ext,dep} \qquad (179)$$

where:

$C_{soil,vol}$ is the radionuclide volumetric concentration in soil (provided by the respective receptor module) (Bq/m^3); and

$DCC_{ext,dep}$ is the age group and radionuclide specific dose conversion factor for external irradiation (Sv·m^3·Bq^{-1}·h^{-1}).

The effective dose rate outdoors from immersion in the radioactive cloud (DoseRate_{eff,imm}, Sv/h) is calculated by:

$$DoseRate_{eff,imm} = \sum_{RN} DoseRate_{eff,imm,RN} \qquad (180)$$

Where the dose rate for cloud immersion from each radionuclide ($DoseRate_{eff,imm,RN}$, Sv/h) is calculated by:

$$DoseRate_{eff,imm,RN} = C_{air,outdoor} \times DCC_{ext,imm} \qquad (181)$$

where:

$C_{air,outdoor}$ is the radionuclide concentration in outdoor air in a given receptor (Bq/m^3); and

$DCC_{ext,imm}$ is the age group and radionuclide specific dose conversion factor for external irradiation due to immersion in the radioactive cloud (Sv·m^3·Bq^{-1}·h^{-1})

The annual dose from inhalation of radionuclides (except radon) (Dose_{inh,total}, Sv/year) is calculated by:

$$Dose_{inh,total} = \sum_{RN} Dose_{inh,RN} + Dose_{inhRn,RN} \qquad (182)$$

Where the annual dose from inhalation of each radionuclide ($Dose_{inh,RN}$, Sv/year) is calculated by:

$$Dose_{inh,RN} = f_{occup,outdoor} \times C_{air,outdoor} \times Rate_{inh} \times DCC_{inh} \times HoursPerYear$$

$$(183)$$

where:

$f_{occup,outdoor}$ is the fraction of time when the reference person is exposed outdoors (unitless);
$C_{air,outdoor}$ is the radionuclide concentration in outdoor air (Bq/m^3);
$Rate_{inh}$ is the age group specific inhalation rate (m^3/h); and
DCC_{inh} is the age group and radionuclide specific inhalation dose coefficient (Sv/Bq).

The annual dose from inhalation of ^{222}Rn ($Dose_{inh,RN}$, Sv/year) is calculated by:

$$Dose_{inhRn,RN} = f_{occup,outdoor} \times C_{air,outdoor} \times factor_{eq,outdoor} \times DCC_{inh,Rn} \times HoursPerYear$$

$$(184)$$

where:

$factor_{eq,outdoor}$ is the equilibrium factor outdoors which describes the radioactive equilibrium between ^{222}Rn and its short lived progeny (unitless); and
$DCC_{inh,Rn}$ is the age group and ^{222}Rn specific inhalation dose coefficient (Sv·m^3·Bq^{-1}·h^{-1})).

The annual dose from inadvertent ingestion of soil (Dose_{ing,soil,total}, Sv/year) is calculated by:

$$Dose_{ing,soil,total} = \sum_{RN} Dose_{ing,soil,RN}$$

$$(185)$$

Where the annual dose from ingestion of soil for each radionuclide ($Dose_{ing.soil,RN}$, Sv/year) is calculated by:

$$Dose_{ing,soil,RN} = f_{occup,outdoor} \times C_{soil} \times Rate_{ing.soil} \times DCC_{ing} \times HoursPerYear$$

$$(186)$$

where:

C_{soil} is the radionuclide concentration in soil in a given receptor (Bq/kg·DW);
$Rate_{ing.soil}$ is the age group specific ingestion rate of soil (kg·DW/h); and
DCC_{ing} is the age group and radionuclide specific ingestion dose coefficient (Sv/Bq).

7.2.1.4.   Input parameters

TABLE 99. INPUT PARAMETERS RELATED TO THE RADIATION CHARACTERISTICS OF ENVIRONMENTAL MEDIA FOR THE 'DOSE FROM OCCUPANCY OUTDOORS' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_soil (Bq/kg·DW)	Mass concentration of radionuclide in soil	0	Site specific parameter
C_soil_vol (Bq/m³)	Volumetric concentration of radionuclide in soil	0	Site specific parameter
C_air_outdoor (Bq/m³)	Concentration of radionuclide in outdoor air	0	Site specific parameter
DoseRate_amb_out (Sv/h)	Ambient external dose rate outdoors	0	Site specific parameter
Dens_soil (kg·DW/m³)	Soil bulk density	1600	[13]

TABLE 100. PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_occup_outdoor (unitless)	Fraction of the year that the reference person stays in a specific receptor	0.25	Specific for respective reference person parameter

7.2.1.5.   *Output parameters*

TABLE 101. OUTPUT PARAMETERS OF 'DOSE FROM OCCUPANCY OUTDOORS' MODULE

Abbreviation (unit)	Name
Dose_ext_total (Sv/year)	Annual effective dose from external exposure summed over all radionuclides
Dose_ing_soil_total (Sv/year)	Dose from soil ingestion summed over all radionuclides
Dose_inh_total (Sv/year)	Dose from inhalation outdoors summed over all radionuclides
Dose_ext_RN (Sv/year)	Annual effective dose from external exposure outdoors for each radionuclide
Dose_ing_soil_RN (Sv/year)	Dose from soil ingestion for each radionuclide
Dose_inh_RN (Sv/year)	Dose from inhalation for each radionuclide

7.2.2.   Doses from occupancy indoors

In this section, detailed descriptions of doses from occupancy indoors are provided.

7.2.2.1.   *Module description*

The 'Dose from Occupancy indoors' module is used for calculations of total annual effective dose indoors and two exposure pathways are taken into account:

— External exposure;
— Inhalation.

The external exposure dose rate can be calculated from a measured ambient dose rate outdoors (using shielding factor), or from a measured effective dose rate indoors (using a conversion factor from ambient to effective dose), i.e.:

— The radionuclide concentrations in indoor air used as input data for the dose calculation can be passed from the respective 'receptor environment' module, or these can be directly specified by the modeller (e.g. based on monitoring data);
— The module can use the measured air radionuclide concentration in the building, or the radionuclide concentration in the building can be calculated from the air concentration outdoors (using 'ReductionFactor' parameter).

TABLE 102. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'DOSE FROM OCCUPANCY INDOOR' MODULE

Coupled module	Description of parameters used as loadings/inputs or inputs
Inputs to module can be provided by the following modules:	
'House'	Concentration of radionuclides in indoor air (Bq/m^3)
'Dose from occupancy outdoors'	Concentration of radionuclides in outdoor air (Bq/m^3)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from external irradiation (Sv/year) Dose from inhalation (Sv/year)

7.2.2.3. *Mathematical equations*

The total annual dose from indoor occupancy ($Dose_{occup,indoor}$, $Sv/year$)

$$Dose_{occup,indoor} = Dose_{ext,total} + Dose_{inh,indoor} \qquad (187)$$

where:

$Dose_{ext,total}$ is the dose from external irradiation (Sv/year); and
$Dose_{inh,indoor}$ is the dose from inhalation indoors (Sv/year).

The annual dose from external exposure ($Dose_{ext,total}$, $Sv/year$)

The annual dose from external exposure (Sv/year) is calculated by:

$$Dose_{ext,total} = f_{occup,indoor} \times \text{HoursPerYear} \times DoseRate_{eff,indoor} \qquad (188)$$

where:

$DoseRate_{eff,indoor}$ is the efficient external dose rate (Sv/h);
$f_{occup,indoor}$ is the fraction of time that a person is exposed indoors (unitless); and
$HoursPerYear$ is the number of hours in a year (h/year).

Depending on the input data specified by the modeller, the efficient external dose rate ($DoseRate_{eff,indoor}$) can be calculated as follows:

In the case that the known value of ambient external dose rate is specified:

$$DoseRate_{eff,indoor,Eq1} = DoseRate_{amb,indoor} \times Conv_{amb,eff} \qquad (189)$$

where:

$DoseRate_{amb,indoor}$ is the specified ambient external dose rate indoors (Sv/h); and
$Conv_{amb,eff}$ is the conversion factor from ambient to effective dose (unitless).

The second option is the calculation of the efficient external dose rate based on effective dose rate outdoor as follows:

$$DoseRate_{eff,indoor,Eq2} = doseRate_{eff,out} \times \text{ShieldingFactor} \qquad (190)$$

where:

$DoseRate_{eff,out}$ is the external dose rate outdoors (Sv/h);

ShieldingFactor is the shielding effect of the building. If the shielding by buildings is not considered in the assessment, the value for this parameter need to be set to 1 (unitless).

The total dose from inhalation summed over all radionuclides (*Dose_{inh,indoor}*, Sv/year):

$$Dose_{inh,indoor} = \sum_{RN} Dose_{in,RN} + Dose_{inhRn,RN} \tag{191}$$

The annual dose from inhalation of air (*Dose_{inh,RN}*, Sv/year)

The annual dose from inhalation of air (Sv/year) for each radionuclide is calculated by:

$$Dose_{in,RN} = f_{occup,indoor} \times C_{air,indoor} \times Rate_{inh} \times DCC_{inh} \times \text{HoursPerYear} \tag{192}$$

where:

$f_{occup,indoor}$ is the fraction of time exposed indoors (unitless);
$C_{air,indoor}$ is the radionuclide concentration in indoor air (Bq/m^3);
$Rate_{inh}$ is the age group specific inhalation rate (m^3/h);
DCC_{inh} is the age group and radionuclide specific inhalation dose coefficient (Sv/Bq); and
$HoursPerYear$ is the number of hours in a year (hour/year).

The annual dose from inhalation of ^{222}Rn (*Dose_{inh,RN}*, Sv/year)

The annual dose from the inhalation of ^{222}Rn is calculated by:

$$Dose_{inh,RN} = f_{occup,indoor} \times C_{air,indoor} \times Rate_{inh} \times DCC_{inh,Rn} \times HoursPerYear \tag{193}$$

where:

$C_{air,indoor}$ is the radionuclide concentration in indoor air (Bq/m^3);
$factor_{eq,indoor}$ is the equilibrium factor indoors which describes the radioactive equilibrium between ^{222}Rn and its short lived progeny (unitless);
$DCC_{inh,Rn}$ is the age group and ^{222}Rn specific inhalation dose coefficient (Sv·m^3·Bq^{-1}·h^{-1}).

In the case that radionuclide concentration indoor ($c_{air,indoor}$) is calculated based on the concentration in outdoor air, the following equation is used:

$$C_{air,indoor} = C_{air,outdoor} \times ReductionFactor \tag{194}$$

where:

$C_{air,outdoor}$ is the radionuclide concentration in outdoor air (Bq/m^3)'; and
$ReductionFactor$ is the ratio between indoor and outdoor air concentrations (values between zero and one) (unitless) specified by the modeller.

TABLE 103. INPUT PARAMETERS RELATED TO THE RADIATION CHARACTERISTICS OF ENVIRONMENTAL MEDIA FOR THE 'DOSE FROM OCCUPANCY INDOORS' MODULE

Abbreviation and unit	Full name	Default value	Reference
DoseRate_amb_out (Sv/h)	Ambient dose rate outdoors	0	Site specific parameter
DoseRate_eff_indoor (Sv/h)	Effective dose rate indoors	0	Site specific parameter
C_air_indoor (Bq/m^3)	Concentration of radionuclide in indoor air	0	Site specific parameter

TABLE 104. PARAMETERS SPECIFYING THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_occup_indoor (unitless)	Fraction of the year that the reference person stays indoors	0.25	Specific for respective reference person parameter

7.2.2.5.   Output parameters

TABLE 105. OUTPUT PARAMETERS OF THE 'DOSE FROM OCCUPANCY INDOORS' MODULE

Abbreviation (unit)	Name
Dose_ext_total (Sv/year)	Annual effective dose from external exposure summed over all radionuclides
Dose_inh_total (Sv/year)	Dose from inhalation outdoors summed over all radionuclides
Dose_ext_RN (Sv/year)	Annual effective dose from external exposure outdoors for each radionuclide
Dose_inh_RN (Sv/year)	Dose from inhalation for each radionuclide

7.2.3.   Doses from marine activities

In this section, detailed descriptions of doses from marine activities are provided.

7.2.3.1.   Module description

This module is used for the calculation of dose from external irradiation during marine activities. Activities taken into account are, e.g. boating, swimming in the sea and beach occupancy. The exposure pathways taken into account are:

—— External exposure from contaminated sediments (beach occupancy);
—— External exposure due to immersion in water (boating and swimming).

7.2.3.2.   Potential coupled modules

TABLE 106. POTENTIAL COUPLED MODULES FROM NORMALYSA LIBRARY FOR 'DOSE FROM MARINE ACTIVITIES' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Marine'	Radionuclide concentration in seawater (Bq/m^3) Radionuclide surface contamination density in the shore and beach sediment (Bq/m^2)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from external irradiation (Sv/year)

7.2.3.3. *Mathematical equations*

The total annual dose from marine activities ($Dose_{ext,total}$, $Sv/year$)

$$Dose_{ext,total} = Dose_{beach,total} + Dose_{boating,total} + Dose_{swimming,total} \qquad (195)$$

where:

$Dose_{beach,total}$ is the annual external dose due to external irradiation received during beach occupancy (considering surface deposition) (Sv/year);
$Dose_{boating,total}$ is the external annual dose for boating (Sv/year); and
$Dose_{swimming,total}$ is the external annual dose from swimming (Sv/year).

$$Dose_{bea\ ,total} = \Sigma_{RN}\, Dose_{beach,RN} \qquad (196)$$

$$Dose_{boating,total} = \Sigma_{RN}\, Dose_{boating,RN} \qquad (197)$$

$$Dose_{swimming,total} = \Sigma_{RN}\, Dose_{swimming,RN} \qquad (198)$$

where:

$Dose_{bea\ ,RN}$ is the annual external dose due to external irradiation received during beach occupancy for each radionuclide (Sv/year);
$Dose_{boating,RN}$ is the external annual dose for boating for each radionuclide (Sv/year); and
$Dose_{swimming,RN}$ is the external annual dose from swimming for each radionuclide (Sv/year).

The annual external dose due to external irradiation received during beach occupancy ($Dose_{beach,RN}$, $Sv/year$)

The annual dose from external exposure (Sv/year) is calculated by:

$$Dose_{bea\ ,RN} = DCC_{ext,dep,5cm} \times C_{beach} \times f_{beac} \times HoursPerYear \qquad (199)$$

where:

C_{beach} is the nuclide specific surface contamination density in the shore and beach sediment (Bq/m^2);
f_{beach} is the fraction of the year spent on the beach (unitless);
$DCC_{ext,dep,5cm}$ is the dose coefficient for external exposure to a 5 cm thick surface layer (Sv·m^2·Bq^{-1}·h^{-1})); and
$HoursPerYear$ is the number of hours in a year (h/year).

The external annual dose from swimming ($Dose_{swimming}$, $Sv/year$)

The external annual dose from swimming $Dose_{swimming}$ (Sv/year) is derived as follows:

$$Dose_{swimming,RN} = DCC_{submersion} \times C_{water,total} \times f_{swimming} \times HoursPerYear \qquad (200)$$

where:

$C_{water,total}$ is the nuclide concentration in the sea water (Bq/m^3);
$DCC_{submersion}$ is the dose coefficient for water submersion (Sv·m^3·Bq^{-1}·h^{-1}); and
$f_{swimming}$ is the fraction of the year spent swimming in the sea (unitless).

The external annual dose for boating (Dose_boating, Sv/year)

$$Dose_{boating,RN} = 0.5 \times DCC_{submersion} \times C_{water,total} \times f_{boating} \times HoursPerYear \quad (201)$$

where:

$f_{boating}$ is the fraction of the year spent boating on the sea (unitless).

Here, the dose coefficients for water submersion are also conservatively used for boating even though the dose due to boating activities is related to the external effective dose rate above water. Multiplying with the factor 0.5 in Eq. (201) above is used to lower the value of the dose. The dose reduction factor takes into account that the source region is effectively semi-infinite in extent for an exposed individual located at the boundary of the air–water interface.

7.2.3.4. Input parameters

TABLE 107. INPUT PARAMETERS RELATED TO THE RADIATION CHARACTERISTICS OF ENVIRONMENTAL MEDIA FOR THE 'DOSE FROM MARINE ACTIVITIES' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_water_total (Bq/m³)	Concentration of radionuclide in sea water	0	Site specific parameter
C_sed_beach (Bq/m²)	Radionuclide concentration in beach sediments	0	Site specific parameter

TABLE 108. INPUT PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_boating (unitless)	The fraction of the year spent boating on the sea	0.1	Specific for respective reference person parameter
f_swimming (unitless)	The fraction of the year spent swimming in the sea	0.1	Same as above
f_beach (unitless)	The fraction of the year spent on the beach	0.1	Same as above

7.2.3.5. Output parameters

TABLE 109. OUTPUT PARAMETERS OF THE 'DOSE FROM MARINE ACTIVITIES' MODULE

Abbreviation (unit)	Name
Dose_ext_total (Sv/year)	Annual effective dose from external exposure due to marine activities summed over all radionuclides
Dose_ext_RN (Sv/year)	Annual effective dose from external exposure due to marine activities for each radionuclide

7.3. 'DOSES FROM INGESTION' SET OF MODULES

The 'Doses from ingestion' subset of modules includes seven different modules:

— Dose from ingestion of water;
— Dose from ingestion of crops;
— Dose from ingestion of garden food;
— Dose from ingestion of forest food;
— Dose from ingestion of freshwater food;
— Dose from ingestion of marine water;
— Dose from ingestion of milk and meat.

These modules are described in more detail in Sections 7.3.1–7.3.8.

All of the above mentioned modules use the same mathematical equation for the calculation of internal doses for ingestion of various foodstuffs as shown in Section 7.3.1 (i.e. Eq. (204)). Age dependent dose coefficients for effective dose by ingestion are shown in Table 145 (see Appendix). Ingestion rates for all types of foodstuffs for all age groups are shown in Table 149 (see Appendix).

7.3.1. Mathematical equations

Total dose from ingestion of all foodstuff summed over all radionuclide ($Dose_{ing,foodstuff,total}$, Sv/year) is calculated by:

$$Dose_{ing,foodstuff,total} = \sum_{foodstuff} Dose_{ing,foodstuff} \qquad (202)$$

The total dose from ingestion of foodstuff summed over all radionuclides ($Dose_{ing,foodstuff}$, Sv/year) is calculated by:

$$Dose_{ing,foodstuff} = \sum_{RN} Dose_{ing,foodstuff,RN} \qquad (203)$$

The dose from ingestion of foodstuff for each radionuclide ($Dose_{ing,foodstuff,RN}$, Sv/year)

$$Dose_{ing,foodstuff,RN} = f_{foodstuff} \times C_{foodstuff} \times Rate_{ing,foodstuff} \times DCC_{ing} \quad (204)$$

where:

$f_{foodstuff}$ is the fractional contribution of foodstuff from the contaminated receptor to the total ingestion of foodstuff (unitless);
$C_{foodstuff}$ is the radionuclide concentration in the foodstuff from the respective receptor model (Bq/m^3 or Bq/kg·FW);
$Rate_{ing,foodstuff}$ is the age group specific ingestion rate of foodstuff (m^3/year or kg·FW/ year); and
DCC_{ing} is the age group and radionuclide specific ingestion dose coefficient (Sv/Bq).

7.3.2. 'Dose from ingestion of water' module

In this section, detailed descriptions of the 'Doses from ingestion of water' module are provided.

7.3.2.1. General description

This module calculates the dose from ingestion of water to the respective reference person.

7.3.2.2. Potential coupled modules

TABLE 110. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR 'DOSE FROM INGESTION OF WATER' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Well' 'Freshwater body'	Radionuclide concentration in water (Bq/m^3)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of water (Sv/year)

7.3.2.3. Input parameters

TABLE 111. INPUT PARAMETERS RELATED TO CONCENTRATION IN FOODSTUFF 'DOSE FROM INGESTION OF WATER'

Abbreviation and unit	Full name	Default value	Reference
C_water (Bq/m^3)	Concentration of radionuclide in water	0	Site specific parameter

TABLE 112. INPUT PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_water (unitless)	Fractional contribution of water from the freshwater body receptor to the total ingestion of water	1	Specific for respective reference person parameter

7.3.2.4. Output parameters

TABLE 113. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF WATER' MODULE

Abbreviation (unit)	Name
Dose_ing_water_total (Sv/year)	Dose from water ingestion summed over all radionuclides
Dose_ing_water_RN (Sv/year)	Dose from water ingestion for each radionuclide

7.3.3. 'Dose from ingestion of garden food' module

In this section, detailed descriptions of the 'Doses from ingestion of garden foods' module are provided.

7.3.3.1. General description

This module calculates the dose from ingestion of foodstuff from a contaminated garden (e.g. leafy vegetables, legumes, roots, fruits, garden berries) to the respective reference person.

7.3.3.2. Potential coupled modules

TABLE 114. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF GARDEN FOODS' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Garden plot'	Radionuclide concentration in garden food (Bq/kg·FW)
Outputs from the module can be used by the following modules:	
'Total dose'	Dose from ingestion of garden foods (Sv/year)

7.3.3.3. Input parameters

TABLE 115. INPUT PARAMETERS RELATED TO THE CONCENTRATION IN FOODSTUFF 'DOSE FROM INGESTION OF GARDEN FOODS'

Abbreviation and unit	Full name	Default value	Reference
C_garden_food (Bq/kg·FW)	Concentration of radionuclide in garden food	0	Site specific parameter

TABLE 116. INPUT PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_garden_food (unitless)	Fractional contribution of garden food from the garden receptor to the total ingestion of garden food	1	Specific for the respective reference person parameter

7.3.3.4. Output parameters

TABLE 117. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF GARDEN FOODS' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from garden food ingestion summed over all radionuclides and all foodstuff types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion of garden food for each radionuclide summed over all foodstuff types

7.3.4. 'Dose from ingestion of forest food' module

In this section, detailed descriptions of the 'Doses from ingestion of forest food' module are provided.

7.3.4.1.   General description

This module calculates the dose from the ingestion of forest food (i.e. mushrooms, wild berries, roe deer and moose) to the respective reference person.

7.3.4.2.   Potential coupled modules

TABLE 118. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF FOREST FOOD' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Forest'	Radionuclide concentration in mushrooms (Bq/kg·FW) Radionuclide concentration in berries (Bq/kg·FW) Radionuclide concentration in game (roe deer and moose) (Bq/kg·FW)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of food (Sv/year)

7.3.4.3.   Input parameters

TABLE 119. INPUT PARAMETERS RELATED TO THE CONCENTRATION IN FOODSTUFF FOR THE 'DOSE FROM INGESTION OF FOREST FOODS' MODULE

Abbreviation and unit	Full name	Default value	Reference
C_berries (Bq/kg·FW)	Concentration of radionuclide in wild berries	0	Site specific parameter
C_mushroom (Bq/kg·FW)	Concentration of radionuclide in mushrooms	0	Site specific parameter
C_game (Bq/kg·FW)	Concentration of radionuclide in game (for respective types of game)	0	Site specific parameter

TABLE 120. INPUT PARAMETERS RELATED TO THE HABITS OF THE REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_berries f_mushroom f_game (unitless)	Fractional contribution of forest food from the receptor to the total ingestion of forest food	1	Specific for respective reference person parameter

7.3.4.4.   Output parameters

TABLE 121. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF FOREST FOODS' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from forest food ingestion summed over all radionuclides and all forest food types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion of forest food for each radionuclide summed over all forest food types

7.3.5. 'Dose from ingestion of crops' module

In this section, detailed descriptions of the 'Doses from ingestion of crops' module are provided.

7.3.5.1. General description

This model derives the doses to the respective reference person due to the intake of contaminated foodstuff (fruits and vegetables) cultivated in a cropland. Four different types of crops are considered:

—— Leafy vegetables;
—— Cereals;
—— Legumes;
—— Roots.

7.3.5.2. Potential coupled modules

TABLE 122. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF CROPS' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Cropland'	Radionuclide concentration in crops (Bq/kg·FW)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of crops (Sv/year)

7.3.5.3. Input parameters

TABLE 123. INPUT PARAMETERS RELATED TO THE CONCENTRATION IN FOODSTUFF 'DOSE FROM INGESTION OF CROPS'

Abbreviation and unit	Full name	Default value	Reference
C_crops (Bq/kg·DW)	Concentration of radionuclides in crops (for respective crop types)	0	Site specific parameter

TABLE 124. INPUT PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_crops (unitless)	Fractional contribution crops from the cropland to the total ingestion of crops	1	Specific for the respective reference person parameter

7.3.5.4. Output parameters

TABLE 125. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF CROPS' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from crops ingestion summed over all radionuclides and all crop types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion e of crops summed over all crop types for each radionuclide

7.3.6. 'Dose from ingestion of milk and meat' module

In this section, detailed descriptions of the 'Doses from ingestion of milk and meat' module are provided.

7.3.6.1. General description

This module derives the doses to the respective reference person due to intake of animal products (i.e. milk and meat) from livestock grazing on contaminated pasture lands.

7.3.6.2. Potential coupled modules

TABLE 126. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF MILK AND MEAT' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Pastureland'	Radionuclide concentration in milk and meat (Bq/kg·FW, Bq/L)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of milk and meat (Sv/year)

7.3.6.3. Input parameters

TABLE 127. INPUT PARAMETERS RELATED TO CONCETRATION IN FOODSTUFF 'DOSE FROM INGESTION OF MILK AND MEAT'

Abbreviation and unit	Full name	Default value	Reference
C_milk (Bq/L)	Concentration of radionuclide in milk	0	Site specific parameter
C_meat (Bq/kg·DW)	Concentration of radionuclide in meat	0	Site specific parameter

TABLE 128. INPUT PARAMETERS RELATED TO THE HABITS OF REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_milk (unitless) f_meat (unitless)	Fractional contribution milk and meat from the cropland to the total ingestion of milk and meat	1	Specific for the respective reference person parameter

7.3.6.4. Output parameters

TABLE 129. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF MILK AND MEAT' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from milk and meat food ingestion summed over all radionuclides and all meat types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion of milk and meat summed over all meat types for each radionuclide

7.3.7. 'Dose from ingestion of freshwater food' module

In this section, detailed descriptions of the 'Doses from ingestion of freshwater food' module are provided.

7.3.7.1. General description

This module derives the doses to the respective reference person due to intake of freshwater foods from a contaminated river or lake. The aquatic food types considered are:

— Cray fish;
— Mussels;
— Fish.

7.3.7.2. Potential coupled modules

The 'Dose from ingestion of freshwater food' module can be coupled to other modules of the NORMALYSA library.

TABLE 130. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF FRESHWATER FOOD' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Freshwater body'	Radionuclide concentration in freshwater food (Bq/kg·FW)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of freshwater food (Sv/year)

7.3.7.3. Input parameters

For running the 'Dose from ingestion of freshwater food' module, the input parameters given in Tables 131 and 132 need to be specified.

TABLE 131. INPUT PARAMETERS RELATED TO CONCENTRATION IN FOODSTUFF 'DOSE FROM INGESTION OF FRESHWATER FOOD'

Abbreviation and unit	Full name	Default value	Reference
C_freshwater_food (Bq/kg·DW)	Concentration of radionuclide in freshwater food	0	Site specific parameter

TABLE 132. INPUT PARAMETERS RELATED TO THE HABITS OF THE REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_freshwater_food	Fractional contribution of freshwater food from the FWB to the total ingestion of freshwater food	1	Specific for respective the reference person parameter

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TABLE 133. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF FRESHWATER FOOD' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from freshwater food ingestion summed over all radionuclides and all food types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion of freshwater food summed over all food types for each radionuclide

7.3.8. 'Dose from ingestion of marine food' module

In this section, detailed descriptions of the 'Doses from ingestion of marine food' module are provided.

7.3.8.1. General description

This module derives the doses to the respective reference person due to intake of marine food from contaminated sea water. The aquatic food types considered are:

—— Cray fish;
—— Mussels;
—— Fish.

7.3.8.2. Potential coupled modules

TABLE 134. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'DOSE FROM INGESTION OF MARINE FOOD' MODULE

Coupled module	Description of parameters used as loadings/inputs or outputs
Inputs to module can be provided by the following modules:	
'Marine body'	Radionuclide concentration in marine food (Bq/kg·FW)
Outputs from module can be used by the following modules:	
'Total dose'	Dose from ingestion of marine food (Sv/year)

7.3.8.3. Input parameters

TABLE 135. INPUT PARAMETERS RELATED TO THE CONCENTRATION IN FOODSTUFF 'DOSE FROM INGESTION OF MARINE FOOD'

Abbreviation and unit	Full name	Default value	Reference
C_marine_food (Bq/kg·DW)	Concentration of radionuclide in marine food	0	Site specific parameter

TABLE 136. INPUT PARAMETERS RELATED TO THE HABITS OF THE REFERENCE PERSONS

Abbreviation and Unit	Name	Default value	Reference
f_marine_food (unitless)	Fractional contribution marine food from the marine receptor to the total ingestion of marine food	1	Specific for the respective reference person parameter

7.3.8.4. *Output parameters*

TABLE 137. OUTPUT PARAMETERS OF THE 'DOSE FROM INGESTION OF MARINE FOOD' MODULE

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/year)	Dose from marine food ingestion summed over all radionuclides and all food types
Dose_ing_Food_RN (Sv/year)	Dose from ingestion of marine food summed over all food types for each radionuclide

7.4. TOTAL DOSE

7.4.1. General description

This module calculates the total dose to different reference persons defined by the modeller, via all relevant exposure pathways, taking into account the contributions from all objects (receptors) and radionuclides.

7.4.2. Potential coupled modules

The inputs to the 'Total dose' module are provided by the respective dose modules, that calculates doses from the specific receptor for environment through relevant pathways (see Table 138).

TABLE 138. POTENTIAL COUPLED MODULES FROM THE NORMALYSA LIBRARY FOR THE 'TOTAL DOSE' MODULE

Coupled module	Description of parameters used as loadings/inputs
Inputs to module can be provided by the following modules:	
'Dose from occupancy outdoor' 'Dose from occupancy indoor' 'Dose from marine activities' 'Dose from ingestion of forest food' 'Dose from ingestion of garden food' 'Dose from ingestion of freshwater food' 'Dose from ingestion of marine food' 'Dose from ingestion of crops' 'Dose from ingestion of water' 'Dose from ingestion of milk and meat'	Dose from external exposure summed over all radionuclides (Sv/year) Dose from ingestion of food summed over all radionuclides (Sv/year) Dose from inadvertent soil ingestion summed over all radionuclides (Sv/year) Dose from ingestion of water summed over all radionuclides (Sv/year) Dose from inhalation summed over all radionuclides (Sv/year)

7.4.3. Mathematical equation

The total dose ($Dose_{total}$, $Sv/year$) is calculated by:

$$Dose_{total} = Dose_{ext,total} + Dose_{inh,total} + Dose_{ing,soil,total} + Dose_{ing,water,total} + Dose_{ing,Food,total} \quad (205)$$

where:

$Dose_{ext,total}$ is the total dose from external exposure (Sv/year);
$Dose_{inh,total}$ is the total dose from inhalation (Sv/year);
$Dose_{ing,soil,total}$ is the total dose from inadvertent soil ingestion Sv/year);
$Dose_{ing,water,total}$ is the total dose from ingestion of water (Sv/year); and
$Dose_{ing,Food,total}$ is the total dose from ingestion of food (Sv/year).

7.4.4. Input parameters

For running the 'Total dose' module, the input parameters given in Table 140 need to be specified.

TABLE 139. INPUT PARAMETERS OF THE 'TOTAL DOSE MODULE'

Abbreviation and unit	Full name	Default value
Dose_ext_total (Sv/year)	Total dose from external exposure	0
Dose_ing_Food_total (Sv/year)	Total dose from ingestion of food	0
Dose_ing_soil_total (Sv/year)	Total dose from inadvertent soil ingestion	0
Dose_ing_water_total (Sv/year)	Total dose from water ingestion	0
Dose_inh_total (Sv/year)	Total dose from inhalation	0

7.4.5. Output parameters

TABLE 140. OUTPUT PARAMETERS OF 'TOTAL DOSE' MODULE

Abbreviation (unit)	Name
Total dose (Sv/year)	Total dose from all exposure pathways summed over all radionuclides

COMMON RADIOECOLOGICAL AND DOSE ASSESSMENT PARAMETERS USED BY DIFFERENT NORMALYSA MODULES

TABLE 141. RADIONUCLIDE DISTRIBUTION COEFFICIENTS *Kd* FOR 'SOIL' MATERIAL [8]

Radionuclide	*Kd*, m^3/kg·DW
Ac	1.7 E+00
Cs	1.2 E+00
Pa	2.0 E+00
Pb	2.0 E+00
Po	2.1 E-01
Ra	2.5E+00
Sr	5.2 E-02
Th	1.9 E+00
U	2.0 E-01

TABLE 142. INPUT PARAMETERS RELATED TO THE CONTAMINATED LAND GEOMETRY AND PHYSICOCHEMICAL PROPERTIES OF SOILS

Abbreviation and Unit	Name	Default value	Reference
Area (m^2)	'Cropland' area	30 000	Site specific parameter value needed
C_dust (kg·DW/m^3)	Concentration of dust in atmospheric air	5E-8	[10]
H_soil_RZ (m)	Height of the soil rooting zone	0.25	[10]
H_soil_DZ (m)	Height of the deep soil zone	0.5	[10]
Porosity_soil_RZ (m^3/m^3)	Porosity of the soil rooting zone	0.36	See Table 2-1 of Ref. [11]
Porosity_soil_DZ (m^3/m^3)	Porosity of the deep soil zone	0.21	See Table 2-1 of Ref. [11]
Rho_soil_RZ (kg·DW/m^3)	Density of the rooting zone soil	1626.0	See Table 2-1 of Ref. [11]
Rho_soil_DZ (kg·DW/m^3)	Density of the deep zone soil	2115.0	See Table 2-1 of Ref. [11]
Rate_erosion (kg·DW/(m^2·year))	Erosion rate	0.05	[28]
BioT (kg·DW/(m^2·year))	Bioturbation coefficient	5.858	[29]
Kd_soil_RZ (m^3/kg·DW)	Distribution coefficient for the soil rooting zone	Table 141 (Appendix)	[8]
Kd_soil_DZ (m^3/kg·DW)	Distribution coefficient for the deep soil zone	Table 141 (Appendix)	[8]
Rate_prec m^3/(m^2·year)	The precipitation rate in the considered area	0.674	[11]

TABLE 143. RADIOLOGICAL PARAMETERS RELATED TO THE DOSE CALCULATIONS

Abbreviation and Unit	Name	Default value	Reference
Conv_amb_eff (unitless)	Conversion factor to obtain effective dose rate from ambient external dose rate	0.6	[30]
Factor_eq_outdoor (unitless)	The equilibrium factor which describes the radioactive equilibrium between Rn-222 and its short lived progeny	0.4	[30]
ShieldingFactor (unitless)	Shielding factor against external exposure to outdoor radiation that is provided by the building	1	Site specific parameter
ReductionFactor (unitless)	Ratio between indoor and outdoor air concentrations	1	Site specific parameter

TABLE 144. DOSE COEFFICIENT FOR EFFECTIVE DOSE FROM THE DEPOSITION ON SOIL AND IMMERSION IN CLOUD (Sv·m^3· Bq^{-1}·h^{-1}) [13]

Radionuclide	DCC_ext_dep	DCC_ext_imm
Ac-227	3.60E-14	1.84E-14
Cs-137	6.17E-14	9.19E-11
Pa-231	3.40E-15	5.65E-12
Pb-210	1.43E-16	1.61E-13
Po-210	9.50E-19	1.40E-15
Ra-226	2.05E-13	1.02E-12
Ra-228	0.00E+00	0.00E+00
Rn-222	4.21E-17	6.37E-14
Sr-90	7.86E-16	3.54E-13
Th-228	1.86E-13	2.92E-13
Th-230	2.06E-17	5.33E-14
Th-232	8.78E-18	2.61E-14
U-234	6.62E-18	2.20E-14
U-235	1.33E-14	2.33E-11
U-238	3.00E-15	9.00E-15

TABLE 145. DOSE COEFFICIENT FOR EFFECTIVE DOSE BY INGESTION (AGE DEPENDENT), Sv/Bq [14]

Radionuclide	Adults	Children	Infants
Ac-227	1.10E-06	1.50E-06	3.60E-06
Cs-137	1.30E-08	1.00E-08	8.80E-06
Pa-231	7.10E-07	9.20E-07	5.70E-06
Pb-210	6.90E-07	1.90E-06	9.60E-07
Po-210	1.20E-06	2.60E-06	7.30E-08
Ra-226	2.80E-07	8.00E-07	0.00E+00
Ra-228	6.90E-07	3.90E-06	4.10E-07
Rn-222	0.00E+00	0.00E+00	3.70E-07
Sr-90	2.80E-08	6.00E-08	1.30E-07
Th-228	7.20E-08	1.40E-07	4.50E-07
Th-230	2.10E-07	2.40E-07	1.20E-07
Th-232	2.30E-07	2.90E-07	1.30E-07
U-234	4.90E-08	7.40E-08	1.20E-08
U-235	4.70E-08	7.10E-08	1.30E-06
U-238	4.50E-08	6.80E-08	3.10E-06

TABLE 146. DOSE COEFFICIENT FOR EFFECTIVE DOSE BY INHALATION (AGE DEPENDENT), Sv/Bq [14]

Radionuclide	Adults	Children	Infants
Ac-227	5.50E-04	7.20E-04	1.60E-03
Cs-137	3.90E-08	4.80E-08	1.00E-07
Pa-231	1.40E-04	1.50E-04	2.30E-04
Pb-210	5.60E-06	7.20E-06	1.80E-05
Po-210	4.30E-06	5.90E-06	1.40E-05
Ra-226	9.50E-06	1.20E-05	2.90E-05
Ra-228	1.60E-05	2.00E-05	4.80E-05
Rn-222	0	0	0
Sr-90	1.60E-07	1.80E-07	4.00E-07
Th-228	4.00E-05	5.50E-05	1.50E-04
Th-230	1.00E-04	1.10E-04	2.00E-04
Th-232	1.10E-04	1.30E-04	2.20E-04
U-234	9.40E-06	1.20E-05	2.90E-05
U-235	8.50E-06	1.10E-05	2.60E-05
U-238	8.00E-06	1.00E-05	2.50E-05

TABLE 147. DOSE COEFFICIENT FOR EFFECTIVE DOSE BY RADON INHALATION, $(Sv·m^3· Bq^{-1}·h^{-1})$ [30]

Abbreviation and Unit	Name	Default value
DCC_inh_Rn	Dose coefficient for effective dose by radon inhalation	6.1E-9

TABLE 148. DOSE COEFFICIENT FOR EFFECTIVE DOSES BY EXTERNAL IRRADIATION FOR DEPOSITION (FOR CONTAMINATED LAYER THICKNESS OF 5 cm) AND IMMERSION IN WATER [13]

Radionuclide	DCC_ext_dep_5cm $(Sv·m^2·· Bq^{-1}·h^{-1})$	DCC_submersion $(Sv·m^3· Bq^{-1}·h^{-1}))$
Ac-227	0	0
Cs-137	3.51E-14	1.99E-13
Pa-231	0	0
Pb-210	0	0
Po-210	0	0
Ra-226	0	0
Ra-228	0	0
Rn-222	0	0
Sr-90	9.72E-18	3.92E-16
Th-228	0	0
Th-230	0	0
Th-232	0	0
U-234	0	0
U-235	0	0
U-238	0	0

TABLE 149. PARAMETERS DESCRIBING THE INHALATION AND INGESTION RATES (FOR DIFFERENT TYPES OF FOOD) OF REFERENCE PERSONS BELONGING TO DIFFERENT AGE GROUPS

Parameter	Name	Adults	Children	Infants	Reference
Rate_inh (m³/year)	Inhalation rate	9.20E-01	8.30E-01	1.20E-01	[14]
Rate_ing_water (m³/year)	Ingestion rate of water	6.00E-01	4.20E-01*	2.60E-01	Based on Ref. [4]
Rate_ing_garden_food (kg·FW/year)	Ingestion rate of leafy vegetables	1.13E+02	7.9E+01*	5.6E+01**	Based on Ref. [31]
	Ingestion rate of legumes	4.74E+00	3.32E+00*	2.37E+01**	Based on Ref. [31]
	Ingestion rate of roots	7.70E+01	5.40E+01*	3.80E+01**	Based on Ref. [31]
	Ingestion rate of fruits	5.90E+01	4.13E+01*	2.95E+00**	Based on Ref. [31]
	Ingestion rate of garden berries	2.5E+01	1.75E+01*	1.25E+01**	Based on Ref. [31]
Rate_ing_berries (kg·FW/year)	Ingestion rate of berries	0	0	0	This parameter is dependent on social habits
Rate_ing_mushroom (kg·FW/year)	Ingestion rate of mushrooms	0	0	0	This parameter is dependent on social habits
Rate_ing_game (kg·FW/year	Roe deer	0	0	0	This parameter is dependent on social habits
	Moose	0	0	0	This parameter is dependent on social habits
Rate_ing_crops (kg·FW/year)	Ingestion rate of legumes	4.74E+00	3.32E+00*	2.37E+01**	Based on Ref. [31]
	Ingestion rate of leafy vegetables	1.13E+02	7.9E+01*	5.6E+01**	Based on Ref. [31]
	Ingestion rate of cereals	1.57E+01	1.10E+01*	7.90E+00**	Based on Ref. [31]
	Ingestion rate of roots	7.70E+01	5.40E+01*	3.80E+01**	Based on Ref. [31]
Rate_ing_meat (kg·FW/year)	Ingestion rate of Beef meat	10.00E+02	7.00E+01*	4.00E+01	Based on Ref. [4]
	Ingestion rate of Sheep meat	0	0	0	This parameter is dependent on social habits
Rate_ing_milk (L/year)	Ingestion rate of cow milk	2.50E+02	1.75E+02*	3.00E+02	Based on Ref. [4]
Rate_ing_marine_food (kg·FW/year)	Ingestion rate of fish	5.00E+01	3.50E+01*	2.50E+01	Based on Ref. [4]
	Ingestion rate of cray fish	0	0	0	This parameter is dependent on social habits
	Ingestion rate of mussels	1.50E+01	1.05E+01*	0	Based on Ref. [4]
Rate_ing_freshwater_food (kg·FW/year)	Ingestion rate of fish	3.00E+01	2.10E+01*	1.50E+01	Based on Ref. [4]
	Ingestion rate of cray fish	0	0	0	This parameter is dependent on social habits
	Ingestion rate of mussels	0	0	0	This parameter is dependent on social habits
Rate_ing_soil (kg·DW/h)	Ingestion rate of soil	5.00E-06	1.00E-05	0	[20]

* Calculated from the value for adult by multiplying by 0.7.
** Calculated from the value for adult by multiplying by 0.5.

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NORMALYSA TRAINING MATERIAL, EXERCISE 1: CALCULATION OF OUTDOOR EXPOSURE OF THE REFERENCE INDIVIDUAL USING RADIATION MONITORING DATA

I-1. GENERAL DESCRIPTION OF THE PROBLEM

In this exercise, NORMALYSA is used to calculate radiation exposure of an individual carrying out works at a radioactively contaminated site. As an input data for dose calculations radiation monitoring (measurements), data on ambient dose rate and radionuclide concentrations in the air and in the soil are used.

I-1.1. Contamination source term (contaminated site)

A radioactively contaminated site that is used as an industrial area is considered, where the soil of site is contaminated by ^{137}Cs and ^{90}Sr. Within the site, two areas are distinguished, i.e. 'Area A' and 'Area B', that differ with regard to contamination level, and for which different sets of radiation monitoring data are available (see Fig. I-1).

I-1.2. Reference persons and exposure scenario

The reference individual for dose calculations is an adult (industrial worker) visiting the contaminated site (including both Areas A and B) to perform outdoor works at these sites. It is assumed that the reference individual annually spends 20% of his/her working time in Area A and 10% of his/her time in Area B. The following exposure pathways are taken into account:

—— External exposure;
—— Inhalation of radioactive aerosols;
—— Inadvertent ingestion of contaminated soil.

It is assumed that the reference individual does not use any protective equipment (e.g. respirator).

I-1.3. Calculation end points

The calculation end points are annual effective doses received by the reference individual for the exposure scenario described above. The doses need to be calculated:

—— For each exposure pathway;
—— For each area (Area A and Area B);
—— For each radionuclide (^{137}Cs and ^{90}Sr) – for Area B.

In addition, the total annual effective dose needs to be calculated.

I-2. INPUT DATA

The input data include radiation monitoring data for both Areas A and B. All radiation monitoring data presented below needs to be interpreted as an excess above background contamination levels.
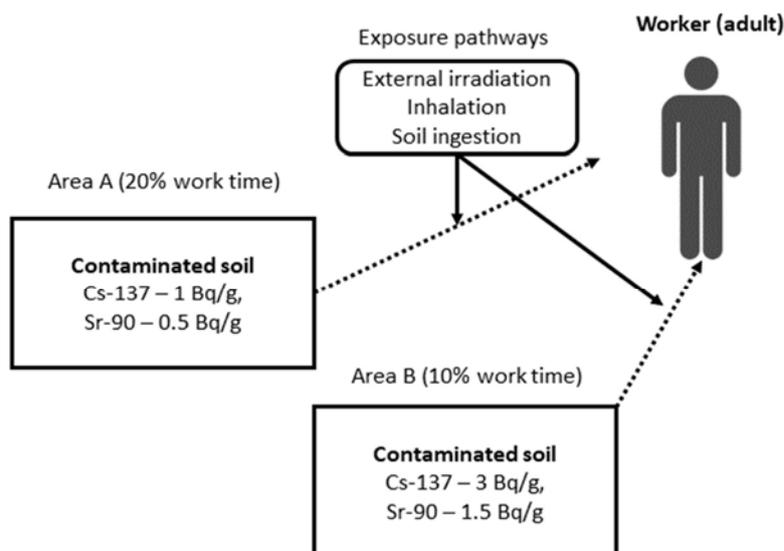
FIG. I-1. Illustrative scheme of exposure of reference individual for Exercise 1.

I-2.1. Radiation monitoring data for Area A

For 'Area A', already known radiation monitoring data include the annual average ambient dose rate and the radionuclide concentrations in air and soil.

The annual average ambient dose rate above background is 0.12 µSv/hour. Soil and air activity data are listed in Table I-1.

I-2.2. Radiation monitoring data for Area B

For 'Area B', the only known parameter is radionuclide concentration in soil.

The soil activity data is complemented with air activity data, which is calculated from soil concentration assuming a dust load of 5×10^{-8} kg/m^3 (see Table I-2).

I-2.3. Habits of reference individual

It is assumed that the reference individual annually spends 20% of his/her working time in Area A, and 10% of his/her time in Area B.

TABLE I-1. RADIONUCLIDE CONCENTRATIONS IN AIR AND SOIL OF AREA A

Radionuclide	Soil concentration, Bq/g	Air concentration, Bq/m^3
Cs-137	1	4E-5
Sr-90	0.5	1.5E-5

TABLE I-2. RADIONUCLIDE CONCENTRATIONS IN AIR AND SOIL OF AREA B

Radionuclide	Soil concentration, Bq/g	Air concentration, Bq/m^3 *
Cs-137	3	1.5 E-4
Sr-90	1.5	0.75 E-4

* Calculated from soil concentration assuming a dust load of 5E-8 kg/m^3.

I-3. GENERAL DESCRIPTION OF THE IMPLEMENTATION OF THE PROBLEM IN NORMALYSA

This section provides detailed descriptions of modules and modelling options used, the NORMALYSA model structure, and data exchanges between modules and general description of modelling steps.

I-3.1. Modules and modelling options used

To perform calculations for the problem described above, two modules will be used, i.e. 'Dose from occupancy outdoors' from 'Doses' library of NORMALYSA. These modules will be configured to perform calculations for both Areas A and B, respectively.

To calculate the total (integral) dose received in Areas A and B, the 'Total Dose' module will be used, which will summing up doses calculated by the respective 'Dose from occupancy outdoors' modules.

In order to calculate some end point parameters (e.g. doses per work area, doses per radionuclide for Area B) calculation results will be exported to an Excel file, and additional calculations will be performed using an Excel spreadsheet.

I-3.1.1. Modelling options

When calculating radiation exposure in Area A, radiation monitoring data on annual average ambient dose rate and radionuclide concentrations in soil and air will be used at the start.

When calculating radiation exposure in Area B, a modelling option allowing the calculation of the ambient dose rate (which is not available from monitoring data) from radionuclide concentrations in soil and air will be used.

I-3.2. NORMALYSA model structure and data exchanges between modules

The structure of the NORMAYSA model for Exercise 1 is shown in Fig. I-2 in the form of a block scheme.
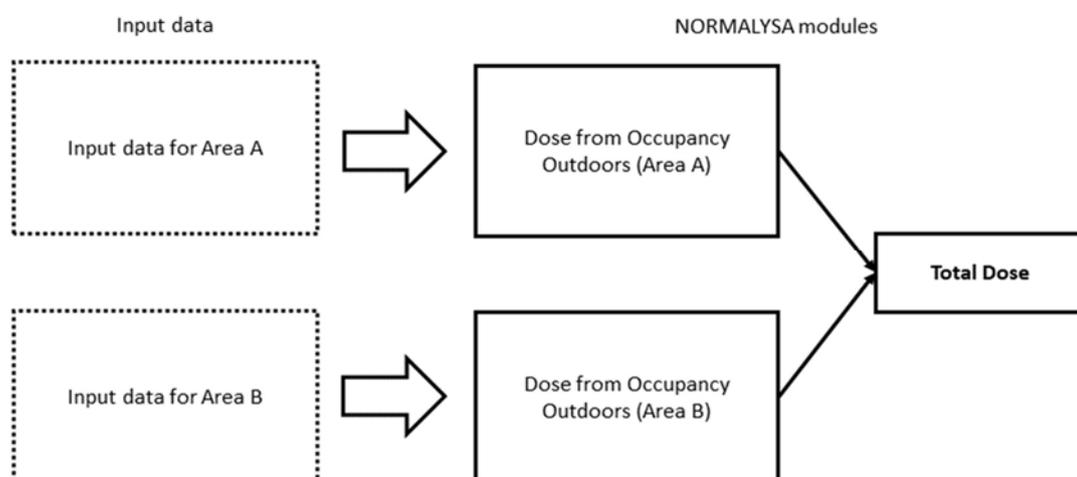
FIG. I-2. The structure of NORMALYSA model for Exercise 1.
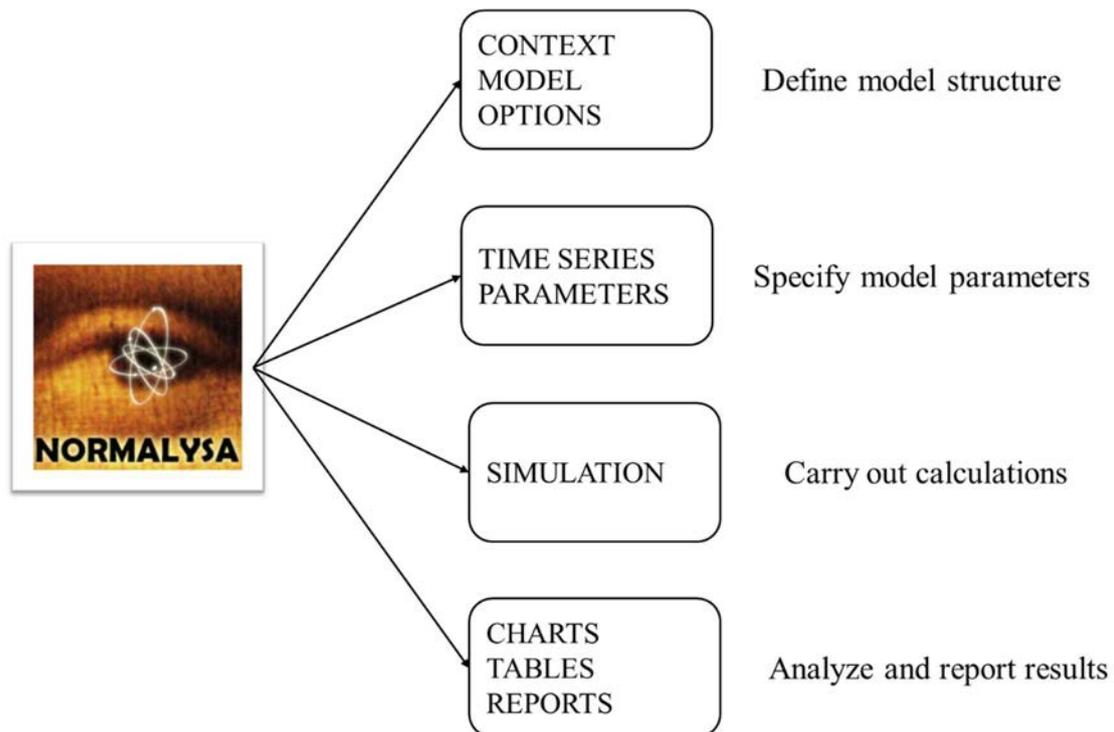
FIG. I-3. Sequence of modelling steps.

I-3.3. General description of modelling steps

In order to solve the problem described above using NORMALYSA, the modeller needs to follow the general sequence of steps shown in Fig. I-3. This is accomplished by going through different positions of the NORMALYSA main menu (shown to the left in the main software interface window).

The rationale of each NORMALYSA menu position (and respective modelling step) is briefly explained in the following Sections I-3.3.1 to I-3.3.8.

I-3.3.1. Setting the assessment context ('Context')

In this step, the NORMALYSA project file is created defining the simulation case. In particular, the user specifies the name of the project file and selects radionuclides to be included in the simulation case.

The modeller also has the possibility to activate or deactivate specific index lists relevant to the modelled case, such as e.g., 'Exposed Groups', included in the simulation.

Moreover, the user may also manage specific interface options, such as the language of software interface, as well as some other options.

I-3.3.2. Defining the model ('Model')

This is the key step in setting up the modelling case where user sets up the radioecological model. For composing the model, the Simulator supports classical 'Interaction Matrix' and graphical 'Block Scheme' ('Graph') interfaces.

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The radioecological model may be composed from modules included in libraries. The user selects the particular modules needed for the respective modelling case and then sets up data exchanges between these modules.

I-3.3.3.   Specifying modelling options ('Options')

In this step, the user specifies particular modelling options available in the relevant modules being used to setup the radioecological model.

I-3.3.4.   Specifying time dependent input parameters in table format ('Time Series')

In the case that the model includes time dependent input parameters that need to be specified in table format, input of such parameters is carried out in this menu position.

I-3.3.5.   Entering model parameters ('Parameters')

In this menu, the user has the possibility to modify all model parameters.

The NORMALYSA modules are supplied with the default values of all model parameters. Some of these do not necessarily need to be changed (e.g. dose coefficients for dose assessment calculations). However, almost all models include site specific and/or modelling case specific parameters that will need to be specified by user.

I-3.3.6.   Running the simulation ('Simulation')

This menu allows the user to set up simulation options (e.g. start and end times, specifying output parameters) and to eventually run the model.

I-3.3.7.   Analyzing results ('Tables' and 'Charts')

The Simulator menu includes two menu items for analyzing simulation results, i.e. 'Charts' and 'Tables'. These menu items allow the modeller to view data in either chart or table format. Simulation data can also be exported to MS Excel file format.

I-3.3.8.   Generating reports ('Reports')

This menu allows the automatic generation of a modelling report describing the simulation case, model used, input parameters and simulation results. The report can be printed or be exported to PDF format.

Additional information on the user interface of the NORMALYSA Simulator can be obtained from the context sensitive 'Help Contents' menu.

A detailed explanation is provided below on how to perform the modelling operations for the respective exercise for each step specified above (i.e. for the main menu positions).

I-4.   DETAILED DESCRIPTION OF COMPOSING AND RUNNING THE MODEL IN NORMALYSA

As already discussed above, this exercise provides the user with experience in using the 'Dose from occupancy outdoors' and 'Total dose' modules from the 'Doses' library.

Two modules for the 'Dose from occupancy outdoors' will be used, which are configured for two areas (Area A and Area B). In addition, the 'Total Dose' module will be used for summing up the resulting doses for specific areas to integral dose.

I-4.1. 'Context' menu position

The user begins by defining the 'context' for the model simulation, which includes defining the model name and selecting the list of radionuclides to be included in the simulation.

By default, the 'Context' window is shown in NORMALYSA when the tool is opened. The following steps can then be followed:

(1) Click the 'New' button in the context menu to create a new model file. Press the 'Edit' button to gain access to the model description field (see Fig. I-4).
Give a name to the model ('Exercise 1'), fill in your name in the 'Author' field (optional) and type a short description of the exercise into the 'Description' field (optional).

(2) In the context menu, click the 'Save As' button, then name and save the model file to an appropriate location on your computer.

(3) A list of 'Contaminants' (radionuclides) are shown on the right hand side of the 'Context' window and when you create a new model, all radionuclides and decay chains are enabled by default.

(4) For the current example, doses from ^{137}Cs and ^{90}Sr will be calculated. In order to select these specific radionuclides, all radionuclides in the 'Nuclides' window need to be disabled and then ^{90}Sr and ^{137}Cs need to be selected (see Fig. I-5).
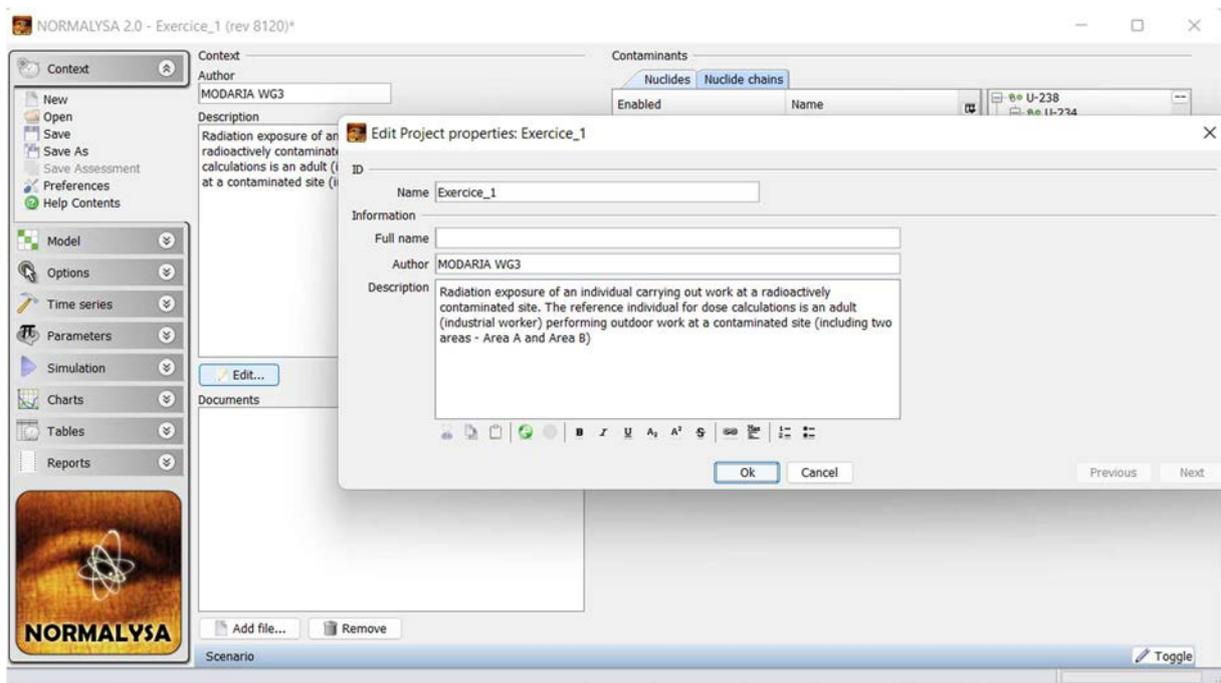
FIG. I-4. Editing 'Project properties' window.
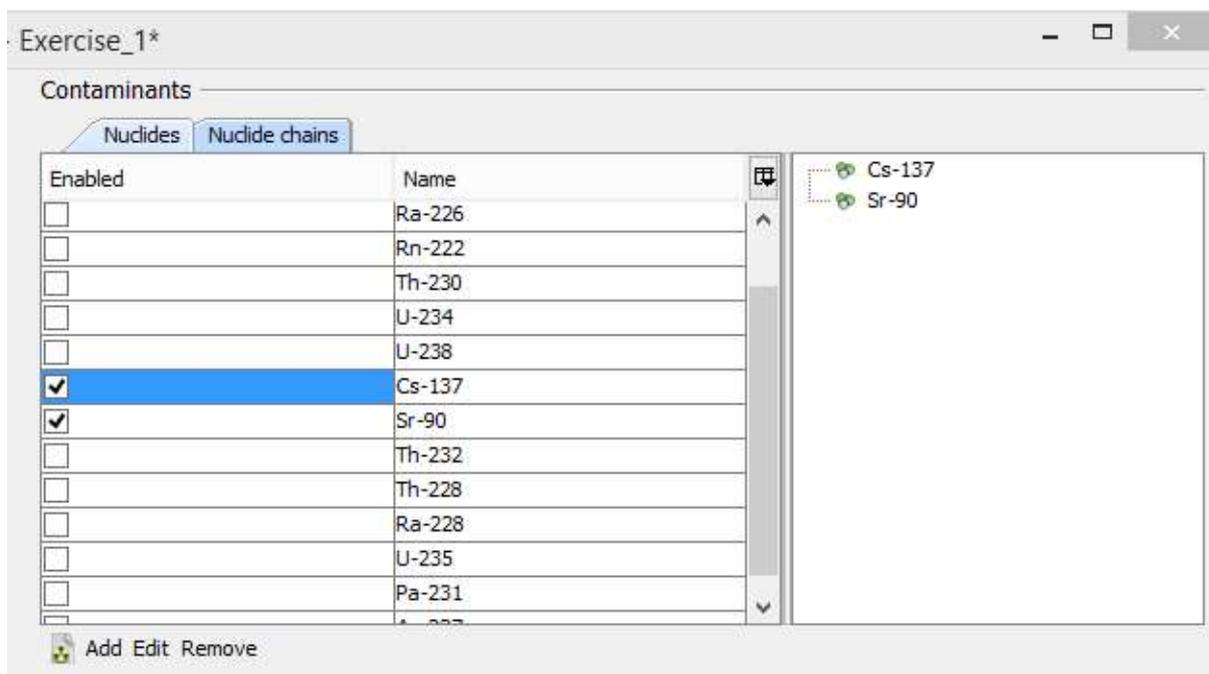
FIG. I-5. 'Contaminants' window with selected radionuclides.

I-4.2. 'Model' menu position

Once the 'Context' has been defined the model may be assesmbled. In this menu position, the model will be created by using the module library and 'connectors' to exchange output and input data between the different modules.

The user needs to click on the 'Model' button in the menu to open the model window. NORMALYSA provides two means to visualize the model, i.e. either as a box diagram (graph) or as an interaction matrix. The user can toggle between the two modes at any time by clicking on the tabs in the upper right corner of the 'Model' window.

Next to the 'Graph' button (which is selected by default) the 'Matrix' button can be clicked on to select the 'matrix view'.

In order to compose the NORMALYSA model for Exercise 1 using the modules from the 'Dose' library, the following steps need to be taken:

(1) The user needs to right click on an empty diagonal element in the matrix (or empty graph area for a graph model view) and choose 'Get from the library...' (or 'Add…') from the pop up menu that appears.
(To add more empty diagonal elements to the matrix, the user can right click with the mouse on a diagonal element and choose 'Insert Above' or 'Insert Below'.)
(2) In the list of modules, the 'Dose from occupancy outdoors' module needs to be selected from the 'Doses from occupancy' folder inside the 'Doses' folder (see Fig. I-6). A short description of the selected model is shown in the 'Description' field of 'Library' window. This module calculates doses from outdoor occupancy and it accounts for dose via inhalation, soil ingestion and external exposure.

(3)   The user needs to click on 'OK' and the selected module will appear as a 'box' on the model area.

(4)   The user needs to then right click in the matrix and choose 'Insert Above' or 'Insert Below' to add new diagonal elements.

(5)   Repeat steps 1–4 to insert the second module 'Dose from occupancy outdoors' for the second area.

(6)   Steps 1–4 need to be repeated to insert the 'Total Dose' module.

(7)   Each 'Dose from occupancy outdoors' module needs now to be connected to the 'Total dose' module using 'Connector' blocks to exchange data.

(8)   To create a new 'connector' block, the user needs to right click on the off diagonal element of the matrix window projected (horizontally, vertically) on blocks that need to be connected, and 'Connector' needs to be chosen from the pop up menu (see Fig. I-7).

(9)   The process of connecting modules needs to be repeated until both 'Dose from occupancy outdoors' boxes are connected to the 'Total Dose' box (see Fig. I-9).
'Dose from occupancy outdoors' blocks does not need to be connected with each other.

In order to avoid confusion with two similar 'Dose from occupancy outdoors' modules, the user needs to rename these modules as 'Dose from work on the Area A' and 'Dose from work on the Area B', respectively.

The following steps need to be taken to rename modules:

(1)   First, the user needs to double click on the 'Dose from occupancy outdoors' module.

(2)   In the tab 'Properties', the field 'Full name' needs to be changed to 'Dose from work on the Area A'.

(3)   In the tab 'Appearance', the field 'Display name' needs to be changed to 'Area A'.

(4)   The user needs to then click on the 'OK' button.

(5)   The second 'Dose from occupancy outdoors' module can then be renamed in a similar way to 'Dose from work on the Area B' and 'Area B'.
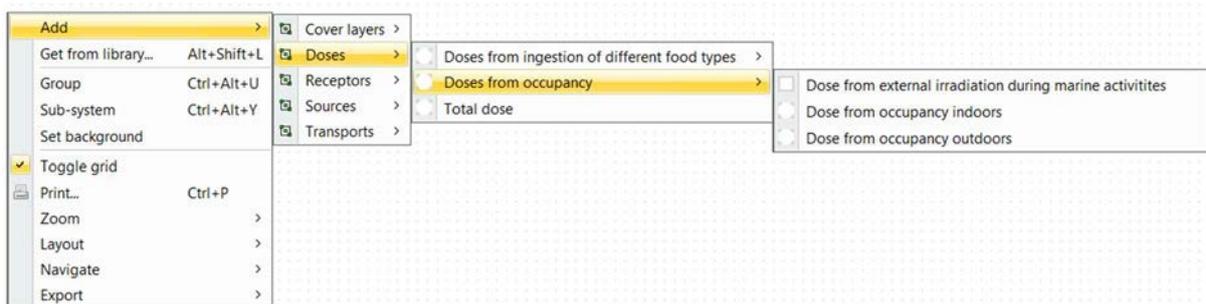
FIG. I-6. Inserting 'Dose from occupancy outdoors' module to the model.
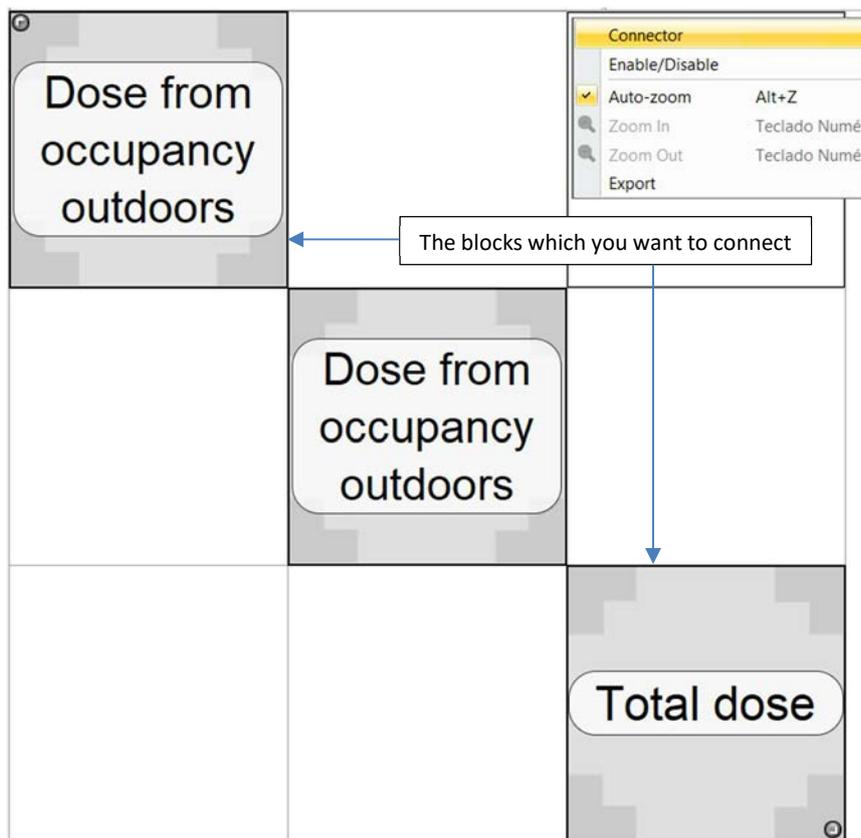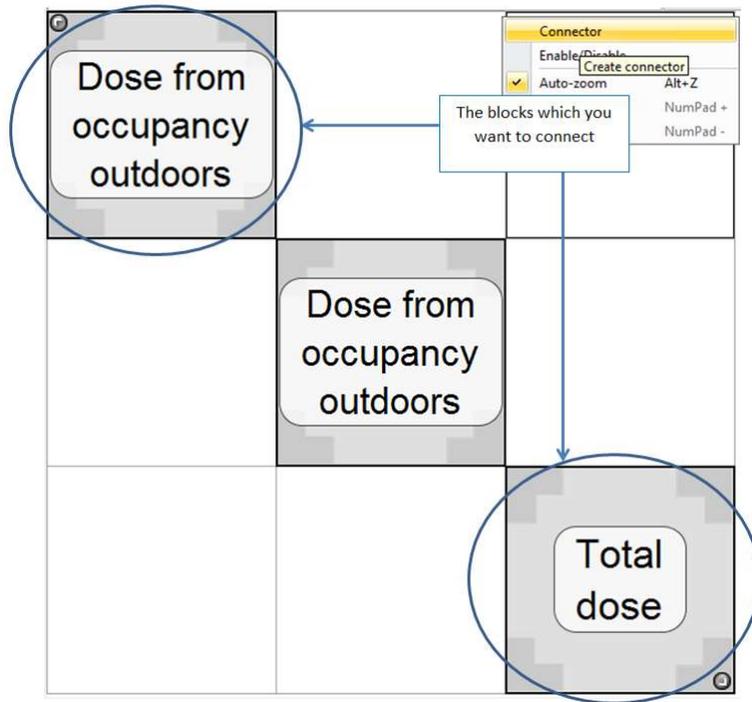
FIG. I-7. Connecting modules using 'connector' blocks for data exchanges.
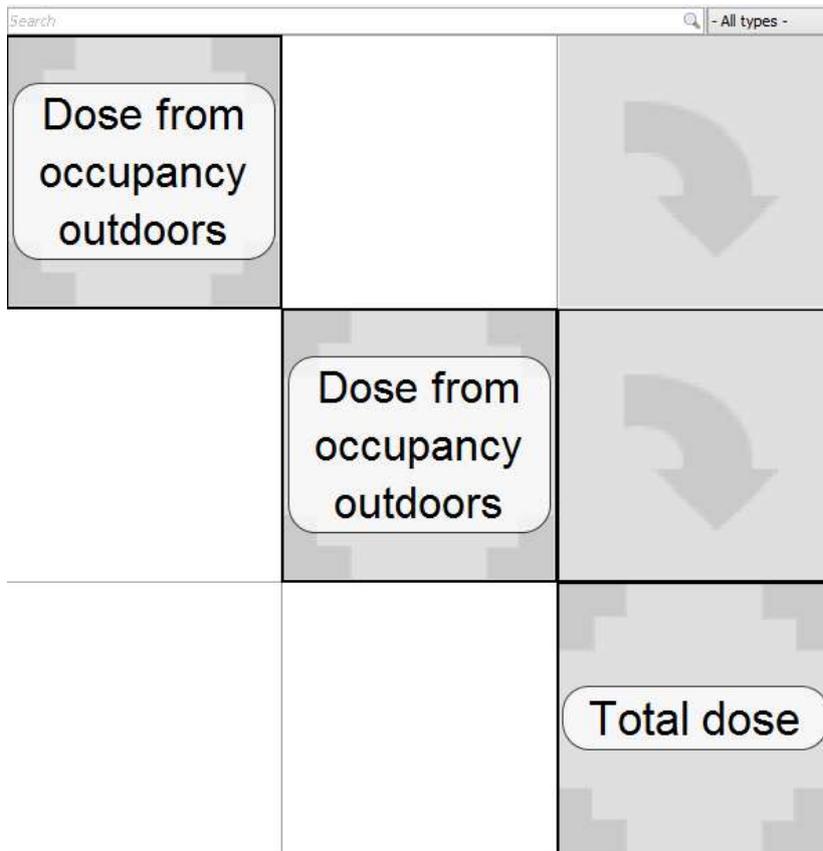
FIG. I-8. Full model for Exercise 1 including main modules and 'connectors' in 'Matrix' view.

FIG. I-9. Using 'Edit Connector' window to set up data exchanges between modules.

The next task is to tune the 'connector' blocks to set proper data exchanges between modules. This process is described below:

(1) The user needs to double click on the 'connector' block between 'Dose from work on the Area A' and 'Total Dose' modules. The 'Edit Connector' window will be opened, allowing the user to set up data exchanges between these modules (see Fig. I-9). The left column of the window lists the output parameters of the 'Dose from work on the Area A' module, while the right column lists the input parameters of the 'Total Dose' module. The user needs to ensure that the 'output – input' parameters are properly matched between these two columns. The specific parameter can be selected by right clicking the particular table cell, and selecting the need parameter from the pop up list that appears.

(2) The user needs to then connect the following 'output (left column) – input (right column)' parameter pairs:
> *'Annual effective dose from external exposure outdoors'* and *'Total dose from external exposure summed over all radionuclides',*
> *'Dose from soil ingestion summed over all radionuclides'* and *'Total dose from soil ingestion summed over all radionuclides',*
> *'Dose from inhalation outdoors summed over all radionuclides'* and *'Total dose from inhalation summed over all radionuclides'.*

(3) The steps described above should be repeated for the 'connector' block between 'Dose from work on the Area B' module and 'Total Dose' module.

Once the operations described above have been fulfilled, the setup of the NORMALYSA model structure and data exchanges is complete.

Before leaving the 'Model' window, the user can have a look at the NORMALYSA model which has been built using both the 'Matrix' (see Fig. I-8) and 'Graph' views.

When the NORMALYSA model is created using one or other combination of modules, a set of different 'Indices' (or 'index lists') required by these modules is automatically added to the 'Context' window (Fig. I-10).

Subsequent to setting up the model, the following provides reiteration of the use of the 'Context' window.

I-4.2.1. *Defining the 'Exposed Groups' index list*

In order to review the 'index lists' included to the model, the user needs to click on the 'Context' button in the main menu on the left side to reopen the respective window. The 'Context' window displays list of 'Indices' in the bottom right corner (see Fig. I-10).

The user can browse through the respective tabs to see which index lists have been added to NORMALYSA model. Two 'index lists', i.e. 'Exposed Groups' and 'Age Groups' can be seen. Moreover, by default, all available entries in index lists are selected (activated).
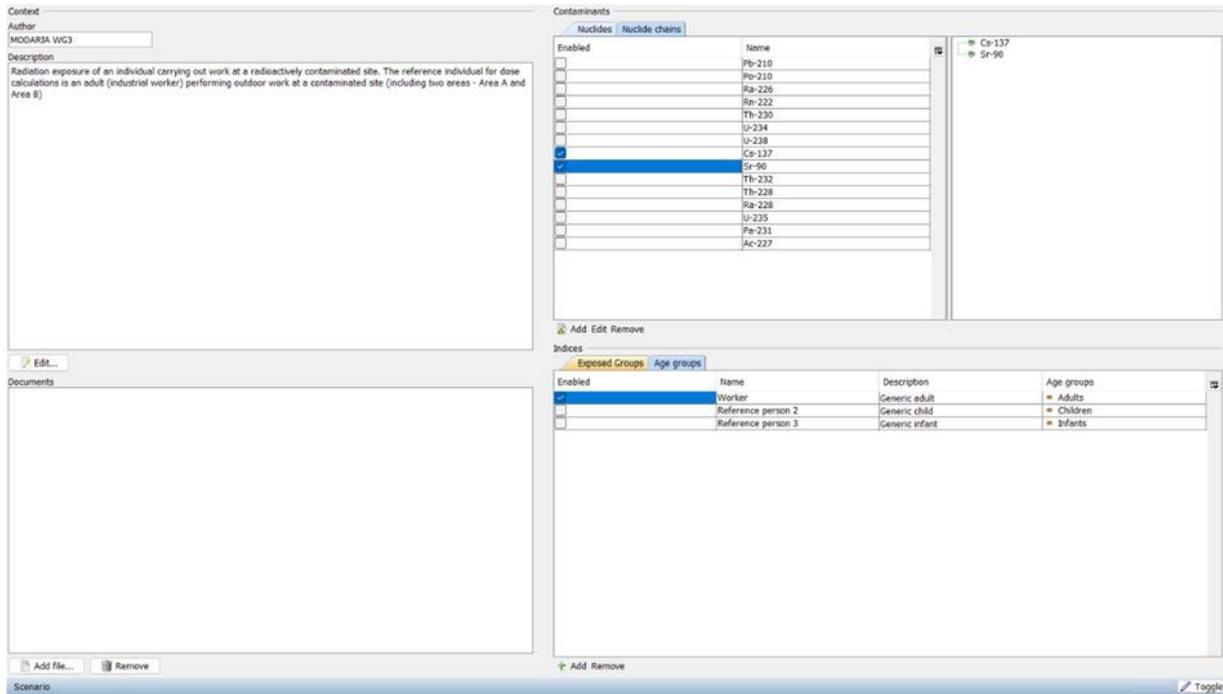
FIG. I-10. Viewing lists of 'Indices' of the newly created NORMALYSA model in 'Context' window.

In the case of Exercise 1, the 'Exposed Groups' index list will need to be utilized to define age characteristics of the reference person considered in this exercise. The following steps need to be undertaken:

(1) The user needs to click the 'Exposed Groups' tab.
(2) The existing group 'Reference person 1' needs to be renamed to 'Worker'. By default, this reference person belongs to the 'Age Group' category 'Adults' – for this example, this last setting needs not to be changed.
(3) The user then needs to deselect all other reference persons.

The 'Age groups' index list cannot be changed in NORMALYSA and only respective age groups from this list can be assigned to the reference persons listed in the 'Exposed Groups' window.

I-4.3.   'Options' menu position

In some NORMALYSA modules a number of different options can be chosen for calculation of model variables (parameters). These options (if available) are accessed through the 'Options' button. For the current example two ways of calculating the external irradiation of the reference person can be selected, i.e.:

(1) From measured ambient dose rates (this method is used for 'Area A'); or
(2) Indirectly from measured radionuclide concentrations in soil and air using respective dose conversion coefficients (this method is used for 'Area B').

To carry necessary model adjustments, the following operations need to be carried out:

(1) The user needs to click on the 'Options' menu button to open the respective window.
(2) For the dose module corresponding to 'Area A' (preselected in the left column of window) the 'Effective dose rate outdoors calculated from ambient dose rates' option needs to be chosen (see Fig. I-11).
(3) For the dose module corresponding to 'Area B', the 'Effective dose rate outdoors calculated from air and soil concentrations' option needs to be selected.

I-4.4. 'Time series' menu positions

In the exercise currently under consideration, there is no need to make any inputs or adjustments in 'Time series' menu position.

I-4.5. 'Parameters' menu position

The next task is to define various model parameters. To do so, the 'Parameters' window needs to be opened by clicking on the respective button in the main menu. To the left of the screen, the 'Parameters' window displays all parameters needed by the model (see Fig. I-12).

In the upper right part of the window, information on the parameter which is currently selected can be seen. The user needs to click on the 'Information' button on the right side to view parameter units and other relevant information.

In the bottom right part of the window, the 'Data' table is displayed, where the user can view and edit the parameter value. For some parameters, the default values can be used, but for some it may be desirable to use values specific to the current study, and these need to be entered. When inputting data, the user needs to be careful with parameter units.

The controls in the left bottom corner of the window below the parameter list can be used to search for specific parameters. The 'Category' drop down list allows the user to display only parameters of a specific category. The 'Subsystem' drop down list allows the user to display parameters only for a specific subsystem/module. (In this case, these are 'Dose from work on the Area A', 'Dose from worn on the Area B', 'Total Dose', and 'Constants' block where various constants used in the model, such as dose conversion coefficients, inhalation rate, etc. are compiled.)

Before proceeding with entering parameter values, parameter units for some model parameters need to be converted (see below).

I-4.5.1. Conversion of units for time of exposure of the reference person

The NORMALYSA model for Exercise 1 requires as an input parameter time of exposure of the reference person expressed as 'Fraction of the year that the reference person stays in a specific receptor'.

Initially, time of exposure was provided as a percentage of 'working time' (see Section I-2.3). Therefore, this parameter needs to be recalculated to the required unit.
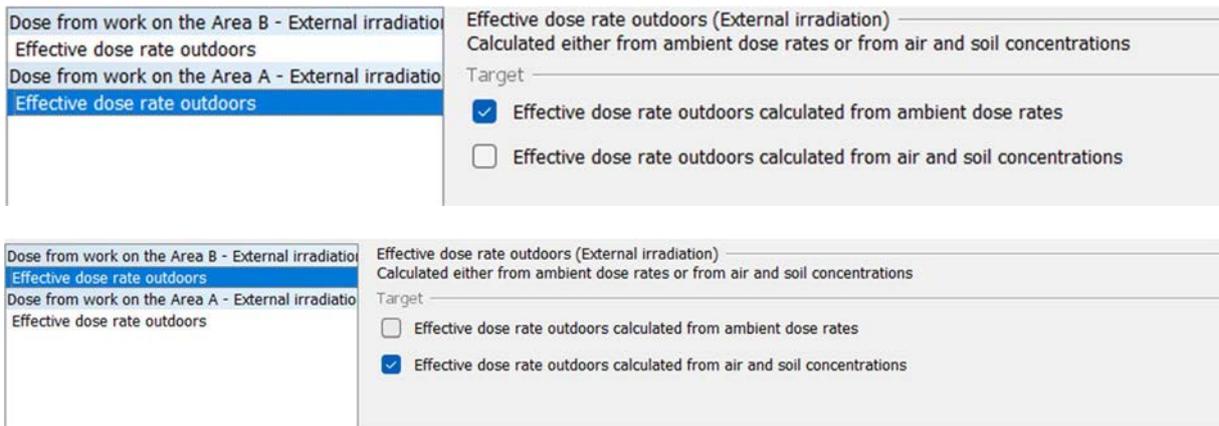
FIG. I-11. Specifying modelling options for calculating the 'Effective dose rate outdoors' parameter.
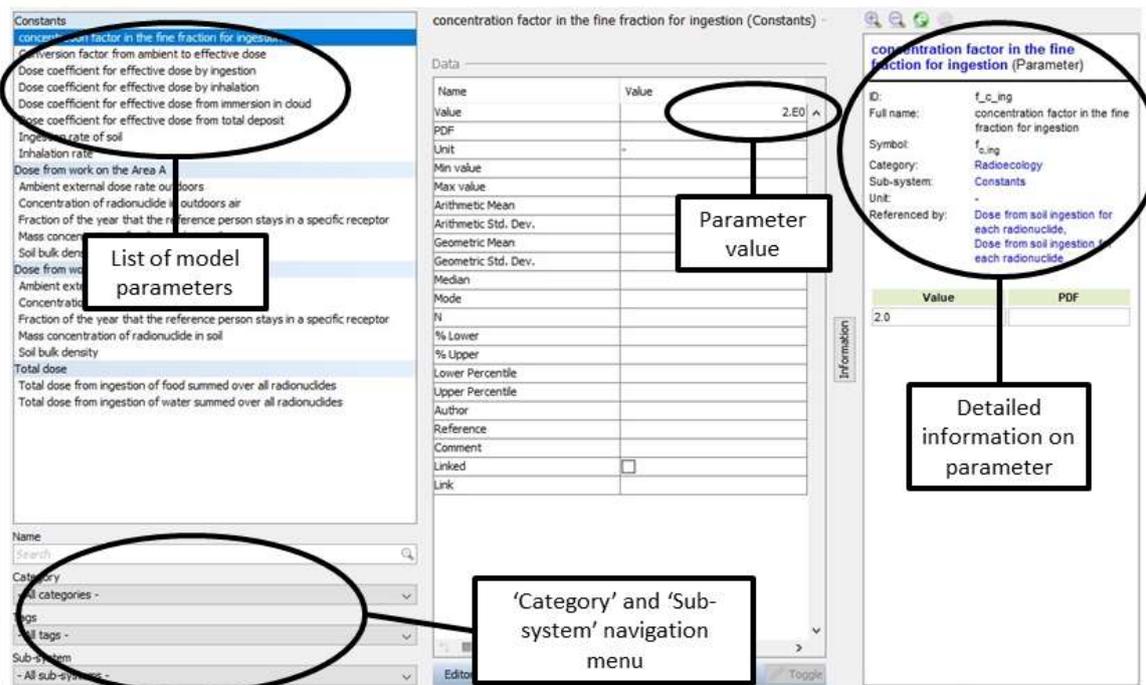
FIG. I-12. 'Parameters' window.

The following formula is used to recalculate the time of exposure from percentage of working time ($Time_{work,percent}$) to the time value expressed as a fraction of year ($Time_{fraction.year}$):

$$Time_{fraction.year} = (Time_{work,percent}/100\% \times N_{work.days.year})/N_{total.year}$$

$N_{work.days.year}$ = 250 days is the number of working days per year, and $N_{total.year}$ = 365.25 days is the total number of days per year.

For 'Area A', the resulting parameter value is:

$$Time_{fraction.year} [Area\ A] = (20\%/100\% \times 250\ \text{days})/365.25\ \text{days} = 0.14$$

For 'Area B', this parameter is calculated as follows:

$$Time_{fraction.year} [Area\ B] = (10\%/100\% \times 250\ \text{days})/365.25\ \text{days} = 0.07$$

I-4.5.2.   Data input for Exercise 1

In order to conduct Exercise 1, the user can take the following steps for each of the parameter sets listed below:

— Select the required subsystem/module ('Dose from work on the Area A' or 'Dose from worn on the Area B');
— Select one by one each parameter in the list;
— Enter the required parameter value(s).

All required parameter values are provided in Section I-2 of this exercise. For convenience, these parameters are repeated below in Tables I-3 and I-4. Attention needs to be paid to the different units used.

TABLE I-3. INPUT PARAMETER VALUES FOR SUBSYSTEM 'DOSE FROM WORK ON THE AREA A'

Name		Value	Unit
Ambient external dose rate outdoors		1.2E-7	Sv/h
Fraction of the year that the reference person stays in a specific receptor		0.14	Unitless
Concentration of radionuclide in outdoors air	Cs-137	4E-5	Bq/m³
	Sr-90	1.5E-5	
Mass concentration of radionuclide in soil	Cs-137	1000	Bq/kg
	Sr-90	500	

TABLE I-4. INPUT PARAMETER VALUES FOR SUBSYSTEM 'DOSE FROM WORK ON THE AREA B'

Name		Value	Unit
Fraction of the year that the reference person stays in a specific receptor		0.07	Unitless
Concentration of radionuclide in outdoors air	Cs-137	1.5E-4	Bq/m³
	Sr-90	7.5E-5	
Mass concentration of radionuclide in soil	Cs-137	3000	Bq/kg
	Sr-90	1500	

I-4.6.   'Simulation' menu position

Once the user has composed the NORMALYSA model and has defined the input parameters, it is possible to perform a simulation.

The simulation window can be opened by clicking on the 'Simulation' button in the menu. This window allows the adjustment and change of simulation settings prior to eventually carrying out the simulation.

A table shown in the bottom part of the window displays any errors and/or warnings (if present), e.g. if a value of some parameter is missing (i.e. is not defined) in the model. A simulation cannot be started if any errors are shown in this table.

I-4.6.1.   Adjusting the list of model outputs

In order to adjust the list of NORMALYSA model outputs that will be included in the list of modelling results upon completion of the simulation, the user needs to follow the steps given below which are also applicable if, as in this case, the user is interested in a larger list of model outputs compared to the default list of output parameters:

(1)   The user needs to click on the 'Simulation Settings' submenu to the left, and choose the 'Outputs' tab in the 'Edit Simulation Settings' window which appears. The window will be opened listing in the right subwindow model outputs. The left subwindow lists all other available model parameters. Output parameters are grouped according to respective subsystems.
(2)   The user can then click the '<<' button to clear the right window.
(3)   The 'Dose from work on the Area A' subsystem can then be chosen and the '>' button clicked (see Fig. I-13).
(4)   In order to include to the output parameter list 'Dose from work on the Area B' and 'Total Dose' subsystems outputs, Step 3 needs to be repeated.
(5)   The user needs to then click the 'OK' button in the bottom of window.

I-4.6.2.   Running the model

In order to perform the simulation, the user needs to click on either of the 'Run' buttons (shown in Fig. I-14).
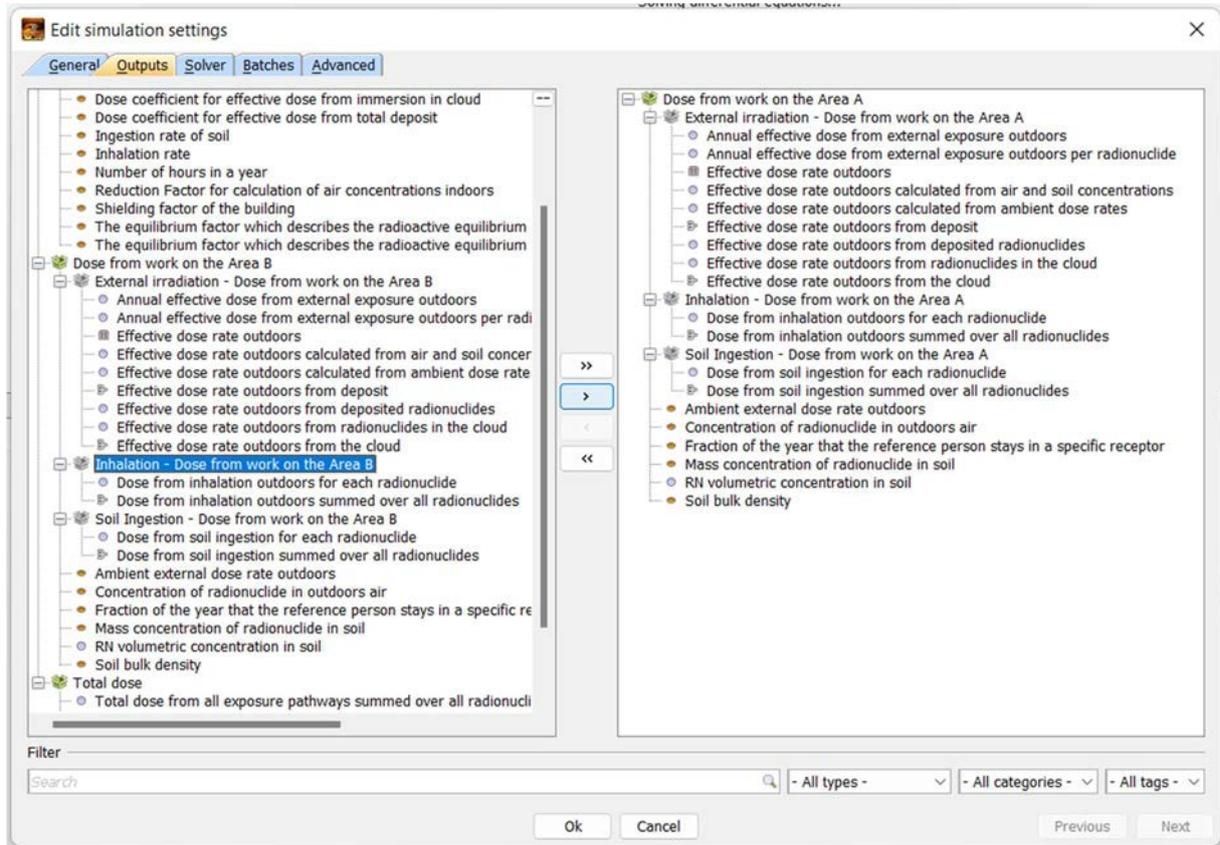
FIG. I-13. Adjusting the list of NORMALYSA model outputs.
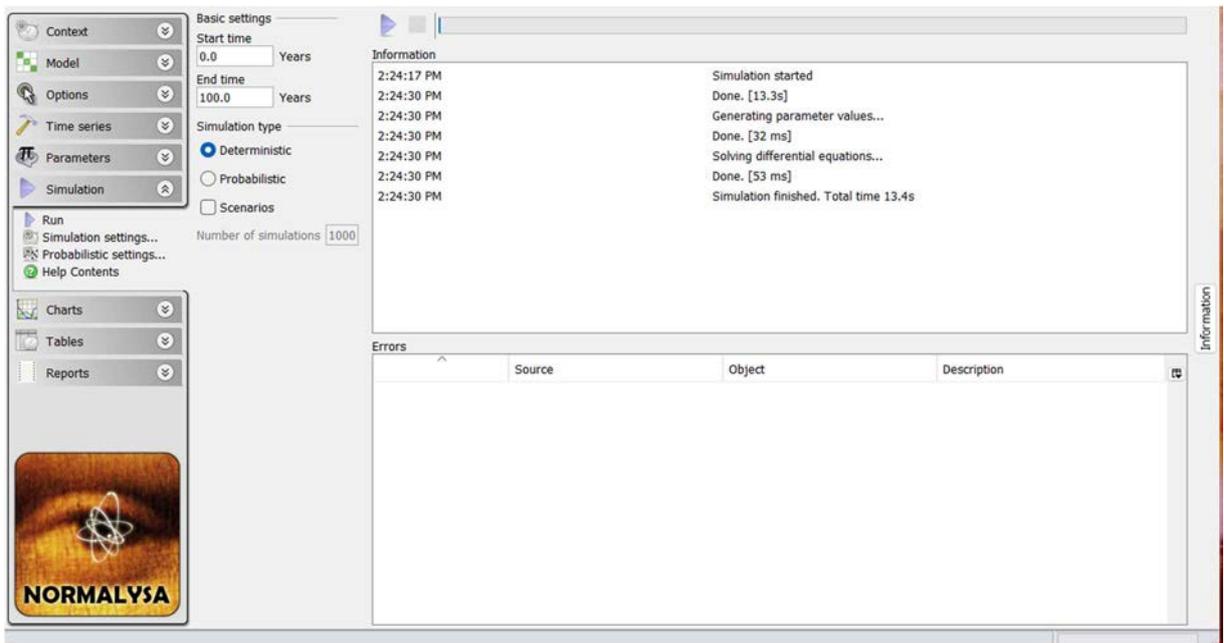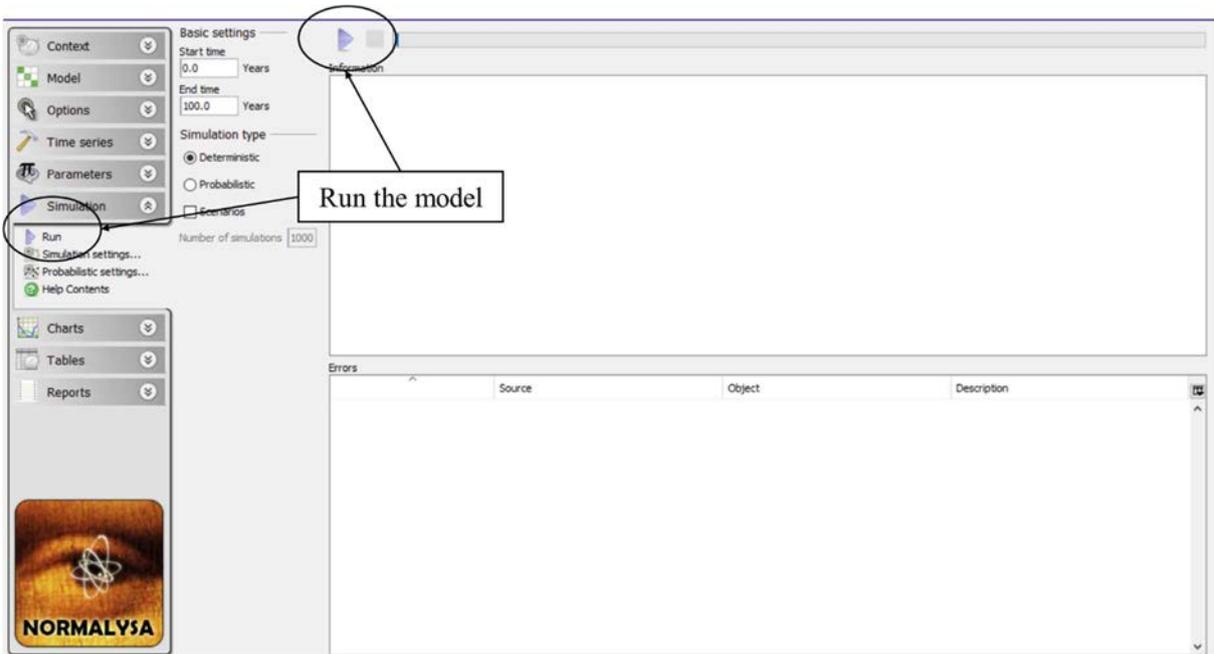
FIG. I-14. Running the NORMAYSA model.

I-4.7. Viewing simulation results

Simulation results can be viewed either as charts or tables by using the respective buttons of the main menu. Some calculation end points, such as total annual effective dose and doses per exposure pathway, can be viewed directly in NORMALYSA.

For some other calculation end points, such as doses per Area A and Area B and doses per radionuclides for Area B, the 'raw' output results of NORMALYSA need to be exported first to a MS Excel spreadsheet and additional calculations then need to be performed in the MS Excel spreadsheet itself.

I-4.7.1.   Viewing simulation results in NORMALYSA (table format)

In order to view results of the calculation in table format, the respective window can be opened by clicking the 'Tables' button in the main menu located to the left of the screen (see Fig. I-15).

The available simulation results are listed in a subwindow immediately to the right of the main menu. Similarly to the 'Parameters' window, the controls below this subwindow can be used to search and filter out the required contents from the list of outputs. The results are grouped in 'folders' where the root folder has as a name, the date and time of simulation.

To create a table, the user can either click an output parameter in the displayed tree of simulation results with the left mouse button or right click in the 'Quick View' window to the right. The specific type of table can then be selected from the pop up menu that appears.

In order to create a table showing the results of the calculation of the total dose, the following steps have to be taken:

(1)   By clicking '+' icons in the displayed tree of simulation results in the left column of model outputs, the user needs to open the root folder and the 'Total Dose' subfolder within it;
(2)   The 'Total dose from all exposure pathways summed over all radionuclides' in 'Total Dose' subfolder then needs to be chosen. A table will now be displayed in the 'Quick View' window to the right showing the total dose for the reference person ('Worker'). This is the total annual effective dose to the reference person received in both work Areas A and B through the external exposure, soil ingestion and inhalation pathways.
(3)   Listed in the outputs for the 'Total Dose' subsystem the total dose received for each exposure pathway can also be seen. It is also possible for the user to click on the different simulation outputs of the 'Total Dose' subsystem to investigate the dose contribution for each pathway.
(4)   Investigation of simulation outputs can be continued by viewing calculation results for a specific work area (i.e. by selecting in the list of outputs subsystems 'Dose from work in Area A' and/or 'Dose from work in Area B'). When selecting the option to view a parameter that is dependent on radionuclides, it is also possible to select specific radionuclides in respective index list (see Fig. I-16).

For example, it may be noted that for subsystem 'Dose from work in Area B' estimated from soil concentration 'Effective dose rate outdoors from deposit' is 2.98×10^{-7} µSv/h. Moreover, the calculated dose rate is higher compared to the ambient dose rate in Area A due to higher ^{137}Cs concentration in soil of Area B.
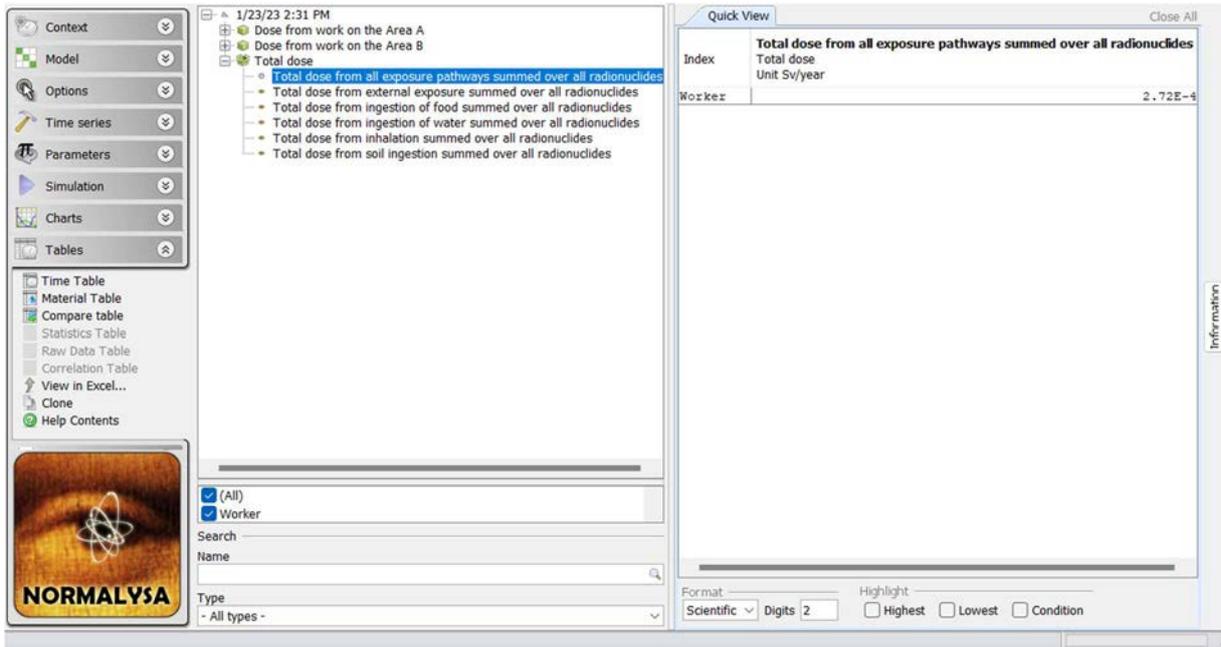
FIG. I-15. Viewing simulation results for Exercise 1 in table format ('Total dose from all exposure pathways over all radionuclides').
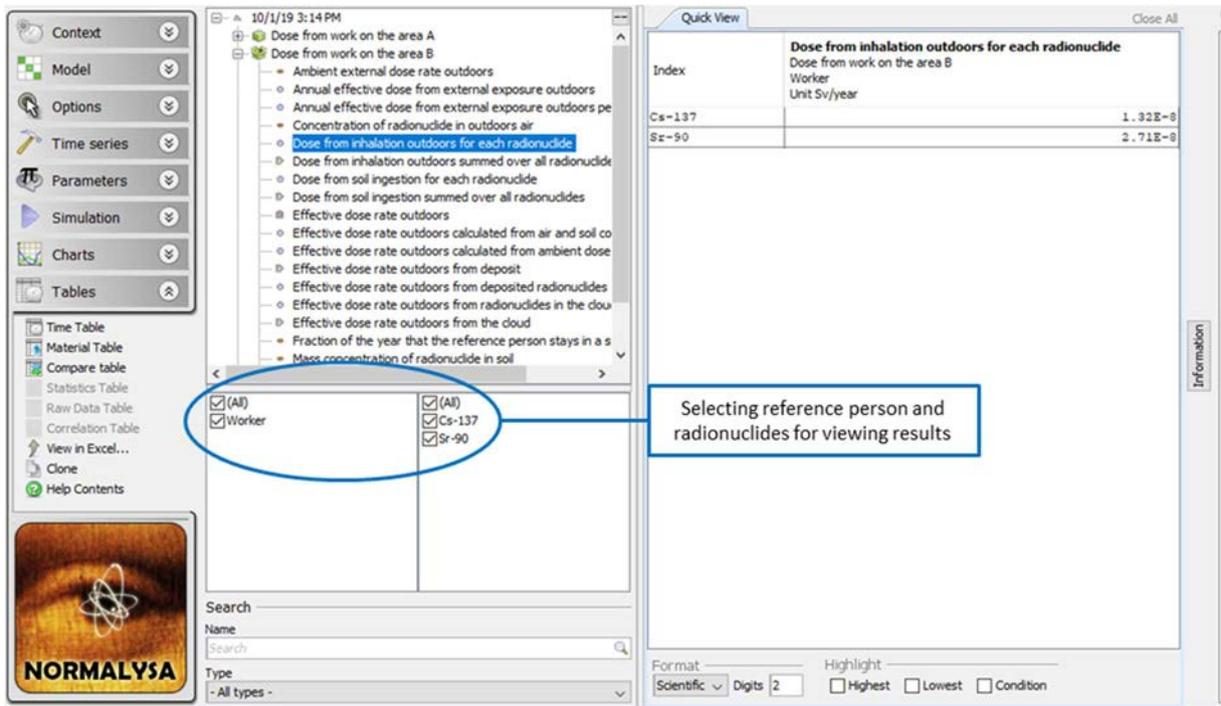
FIG. I-16. Viewing results of dose calculations for Exercise 1 for specific radionuclides.

I-4.7.2. Exporting simulation results to a MS Excel spreadsheet and carrying out additional calculations

Calculating total doses per Area A and B

Some of the required calculation end points (see Section I-1.3) cannot be obtained directly from NORMALYSA output. It is therefore necessary to firstly export NORMALYSA outputs to MS Excel and to then perform additional spreadsheet calculations on these outputs.

In order to calculate total doses (by reference person) received separately in Area A and in Area B, the following parameters need to be extracted, for both areas, from the list of available outputs: 'Dose from soil ingestion summed over all radionuclides', 'Dose from inhalation outdoors summed over all radionuclides' and 'Annual effective dose from external exposure outdoors'.

The following steps need to be taken by the user to accomplish the above task:

(1) The user needs to choose from the previously listed outputs for the respective subsystems from the tree with simulation results, as required. The 'Ctrl' key on the keyboard can be used for multiple choices (see Fig. I-17).
(2) The 'View in Excel' button can then be clicked in the submenu of the main 'Tables' menu in the left column. The MS Excel file will be opened and will include the chosen output parameters.
(3) The user can then perform the required calculations on the simulation results to calculate the total doses (summed on all pathways) for both Areas A and B. The 'Dose from soil ingestion summed over all radionuclides', 'Dose from inhalation outdoors summed over all radionuclides' and 'Annual effective dose from external exposure outdoors' for Area A in opened MS Excel sheet can then be summed up and then the steps repeated for Area B.

Calculating doses per radionuclide (for Area B)

In order to obtain dose per radionuclide (^{90}Sr and ^{137}Cs) summed over all pathways for the 'Area B', the following parameters are of interest: 'Annual effective dose from external exposure outdoors per radionuclide', 'Dose from inhalation outdoors for each radionuclide' and 'Dose from ingestion of soil for each radionuclide' for the respective subsystem.

The user needs to take the following steps to accomplish the above mentioned task:

(1) The required output parameters need to be chosen from the tree with simulation results.
(2) The user needs to ensure that both ^{90}Sr and ^{137}Cs are selected (see Fig. I-18).
(3) Steps 2–3 described in the previous exercise then need to be taken.
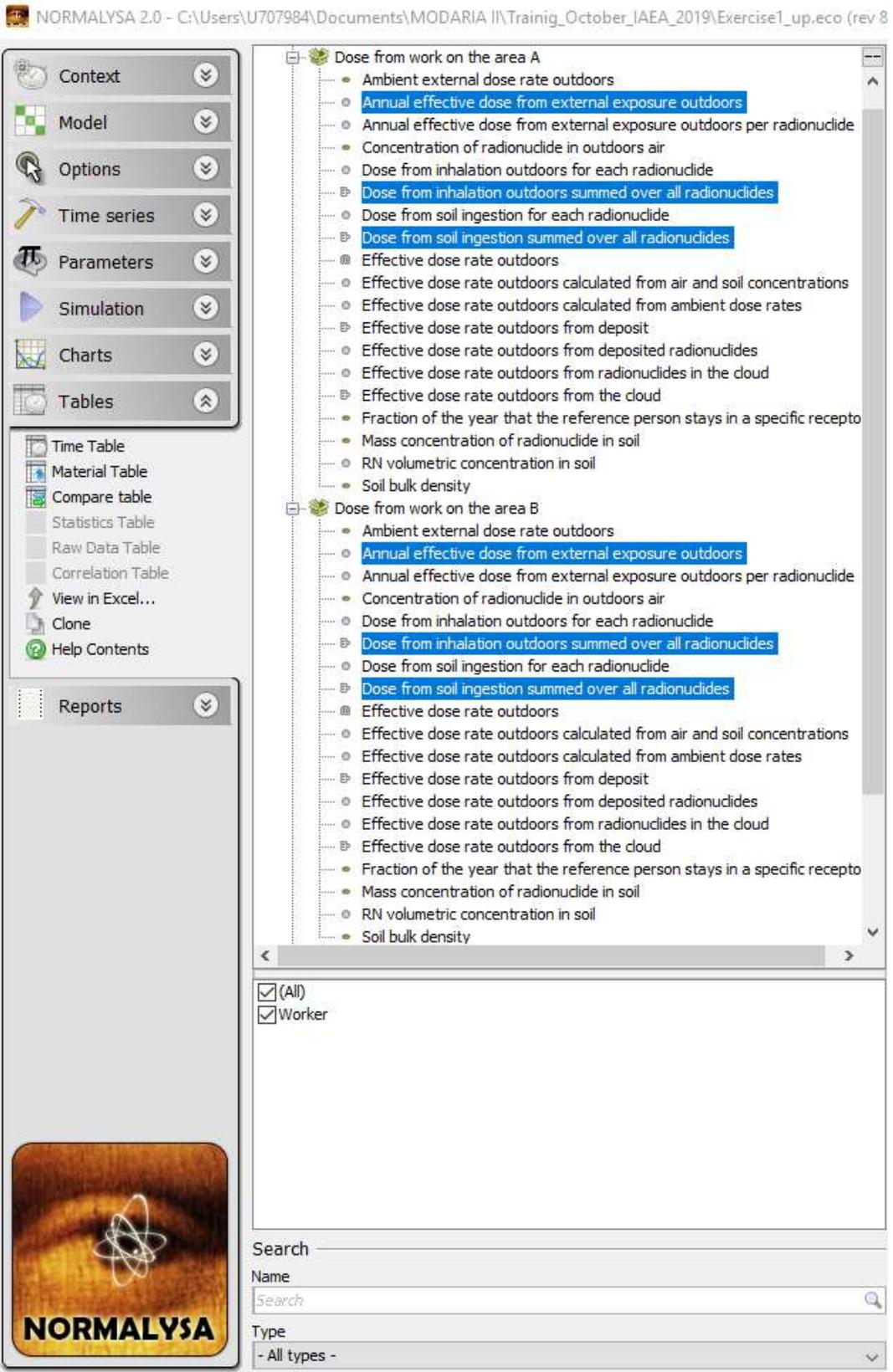
FIG. I-17. Selecting the needed intermediate dose calculations results for export to MS Excel to calculate 'Dose per area' end point.
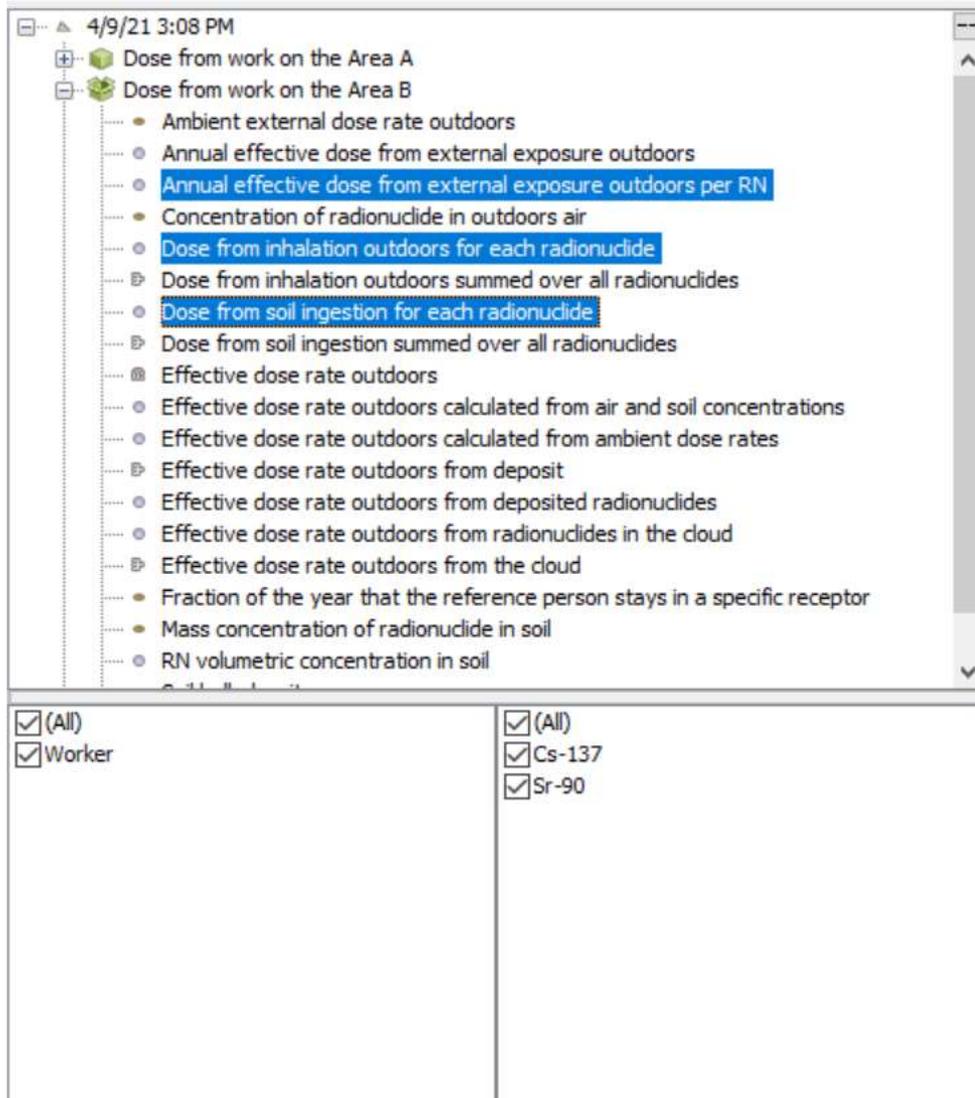
FIG. I-18. Selecting the needed intermediate dose calculations results for export to MS Excel to calculate 'Dose per radionuclide (Area B)' end point.

I-5. RESULTS OF THE EXERCISE

This section lists simulation results in table format which may be utilized for exercise cross-checking purposes.

I-5.1. Total annual effective dose

The total dose summed up over all pathways and all radionuclides needs to be 2.72×10^{-4} Sv/year.

I-5.2. Doses for different exposure pathways

Doses for different exposure pathways summed over all radionuclides are shown in Table I-5, where it can be seen that the main exposure pathway is external exposure.

I-5.3.   Doses per Area A and Area B

Doses per Area A and per Area B summed up over all pathways and radionuclides are shown in Table I-6. The total dose from occupancy outdoors is higher in Area B compared to Area A due to higher radionuclide activity concentration (in particular ^{137}Cs) in the topsoil layer.

I-5.4.   Doses per radionuclide in Area B

Doses formed by ^{137}Cs and ^{90}Sr through all exposure pathways in Area B are shown in Table I-7, where it can be seen that dose is dominated by ^{137}Cs, as this radionuclide contributes mostly to the external exposure pathway, which is the dominant pathway.

I-6.   EXERCISE FOR INDEPENDENT WORK

To calculate the total annual effective dose to the reference individual through all pathways, it is assumed that the individual spends 25% of their working time in Area A, and 5% of their working time in Area B. This can be done by following the instructions given previously, but ensuring that the new information is input accordingly.

TABLE I-5. ANNUAL EFFECTIVE DOSES PER PATHWAY SUMMED OVER ALL RADIONUCLIDE FOR EXERCISE 1

Pathways	Dose, Sv/year
Soil ingestion	5.70E-07
Inhalation outdoors	1.77E-08
External exposure outdoors	2.71E-04

TABLE I-6. DOSES PER AREA A AND PER AREA B CALCULATED IN EXERCISE 1

Area	Dose, Sv/year
Area A	8.86E-05
Area B	1.83E-04

TABLE I-7. DOSES FORMED BY ^{137}CS AND ^{90}SR IN AREA B CALCULATED IN EXERCISE 1

Radionuclide	Dose, Sv/year
Cs-137	1.82E-04
Sr-90	1.44E-06

NORMALYSA TRAINING MATERIAL, EXERCISE 2: RADIONUCLIDE TRANSPORT TO GROUNDWATER FROM A URANIUM TAILING SITE

II-1. GENERAL DESCRIPTION OF THE PROBLEM

In this exercise, NORMALYSA is used to calculate transport of radionuclides in groundwater to a well situated downstream from a uranium tailing site. It is assumed that the well is used as a source of drinking water by the reference individual (shown in Fig. II-1).

II-1.1. Contamination source term

The contaminant source term is the uranium mill tailing site. The area of the tailing site is 40 000 m^2 (X=200 m × Y=200 m; here X and Y are coordinate axes along and perpendicular to groundwater flow direction). The body of tailing contains ^{238}U, ^{234}U and its progenies, ^{230}Th, ^{226}Ra, ^{210}Po and ^{210}Pb. The thickness of the waste body is 8 m and the tailing body is separated from the underlying sandy aquifer by a 2 m thick unsaturated zone of soil. The thickness of the saturated zone in the aquifer is 10 m. It is assumed that at the beginning of the simulation the unsaturated soil zone and aquifer immediately below the tailing site are contaminated due to the radionuclide leaching from the tailing body by infiltrating meteoric waters.

II-1.2. Reference person and exposure scenario

The modelled scenario considers radionuclide migration in the groundwater aquifer from the uranium tailing site to the well which is situated 200 m downstream from the site. Radionuclides from the tailing body infiltrate the unsaturated zone and aquifer and are transported by horizontal groundwater flow towards the well located downstream.

The groundwater from well is occasionally used as a source of drinking water by the reference individual (adult) and it is assumed that the well provides 25% of the yearly drinking water consumption to the reference individual.
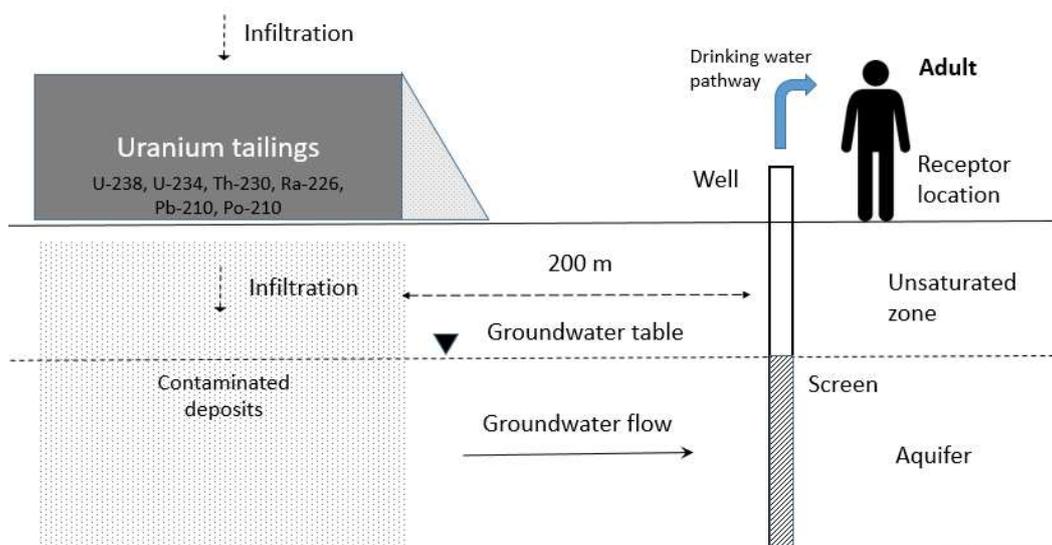
FIG. II-1. Scheme illustrating radionuclide transport in groundwater from the uranium tailing.

II-1.3. Calculations end points

The calculation end points are as follows:

— Radionuclide concentrations in the well;
— Annual effective dose received by the reference individual through the drinking water pathway.

The calculations will be performed at the time scale of 1000 years and the calculation results will be provided with the time step of 100 years.

II-2. INPUT DATA

The input data include characteristics of radioactivity source (term) uranium tailing (see Tables II-1 and II-2), parameters of the unsaturated zone (shown in Tables II-3 and II-4), parameters of the aquifer (given in Tables II-5 and II-6) and habits of the reference person, i.e. adult (shown in Table II-7).

TABLE II-1. PARAMETERS OF URANIUM TAILINGS SITE

Parameter	Value	Unit
Waste site area	40 000	m^2
Length of the site	200	m
Width of the site	200	m
Thickness of waste layer	8	m
Waste bulk density	1600	kg/m^3
Waste moisture content	0.15	unitless
Infiltration recharge rate	0.2	m/year

TABLE II-2. RADIONUCLIDE SPECIFIC PARAMETERS OF THE TAILING BODY

Radionuclide	Initial specific activity of radionuclides in waste, Bq/kg	Waste Kd, m^3/kg
U-238	2500	0.005
U-234	2500	0.005
Ra-226	14 000	6.3
Th-230	12 700	10
Po-210	21 000	2.5
Pb-210	17 000	3.5

TABLE II-3. PARAMETERS OF THE UNSATURATED ZONE

Parameter	Value	Unit
Thickness of the unsaturated zone	2	m
Moisture content	0.15	unitless
Soil bulk density	2000	kg/m^3

TABLE II-4. RADIONUCLIDE SPECIFIC PARAMETERS OF THE UNSATURATED ZONE

Radionuclide	Initial specific activity of soil, Bq/kg	Unsaturated zone soil Kd, m³/kg
U-238	500	0.003
U-234	500	0.003
Th-230	510	3
Ra-226	435	0.2
Po-210	900	0.1
Pb-210	2200	0.5

TABLE II-5. PARAMETERS OF THE AQUIFER

Parameter	Value	Unit
Thickness of the aquifer	10	m
Groundwater flow Darcy velocity	10	m/year
Porosity	0.3	unitless
Aquifer material bulk density	1600	kg/m³

TABLE II-6. RADIONUCLIDE SPECIFIC PARAMETERS OF THE AQUIFER

Radionuclide	Aquifer material Kd, Bq/m³	Initial radionuclide concentration in groundwater (below the tailing), Bq/m³
U-238	0.01	2000
U-234	0.01	2000
Ra-226	0.2	200
Th-230	3	0
Po-210	0.1	0
Pb-210	0.5	0

TABLE II-7. HABITS OF THE REFERENCE INDIVIDUAL (ADULT)

Parameter	Value	Unit
Fractional contribution of water from the well to total ingestion of water	0.25	unitless
Ingestion rate of water	0.37	m³/year

II-3. GENERAL DESCRIPTION OF THE IMPLEMENTATION OF THE PROBLEM IN NORMALYSA

In this section, detailed descriptions of the module used, the NORMALYSA model structure, and data exchanges between modules and general description of modelling steps are provided.

II-3.1. Modules used

In this exercise, the following NORMALYSA modules will be used:

— The 'Tailing without cover' module from the 'Sources' library to model the radionuclide source term for radionuclide transport in groundwater;

— The 'Unsaturated zone' module from the 'Transports' library to model vertical radionuclide transport in the unsaturated soil zone below the tailing from the source (uranium tailing) towards the aquifer;

— The 'Aquifer mixing' module from the 'Transports' library to model the aquifer zone immediately below the contaminated site where vertical infiltration activity flux from the unsaturated zone mixes with the horizontal groundwater flow in the aquifer;

— The 'Aquifer' module from the 'Transports' library to model the horizontal radionuclide transport in the aquifer from the uranium tailing site to the well location;

— The 'Well' module from the 'Receptors' library to model radionuclide concentrations in a well extracting groundwater from the aquifer;

— The 'Dose from ingestion of water' module from the 'Doses' ⇒ 'Doses from ingestion of different food types' library to calculate doses to the reference individual from the drinking water pathway.

The zone of contaminated geological deposits immediately below the uranium tailing is modelled by means of assigning non-zero values of initial radionuclide concentrations in soil (or water) at the beginning of the simulation to the 'Unsaturated zone' and 'Aquifer mixing' modules.

II-3.2. NORMALYSA model structure and data exchanges between modules

The structure of the NORMALYSA model for Exercise 2 is shown in the form of the block scheme illustrated in Fig. II-2.

II-3.3. General description of modelling steps

In order to solve the problem described above using NORMALYSA, the modeller needs to follow the general sequence of steps shown in Sections II-4.1 to II-4.6 . This is accomplished by going through different positions of the NORMALYSA main menu (shown to the left in the main software interface window).

The rationale of each NORMALYSA menu position (and respective modelling step) is briefly explained in the following Sections II-3.3.1 to II-3.3.8.

II-3.3.1. Setting the assessment context ('Context')

In this step, the NORMALYSA project file is created by defining the simulation case. In particular, the user specifies the name of the project file and selects the radionuclides to be included to the simulation case.

The modeller also has the possibility of activating or deactivating specific index lists relevant to the modeled case such as, e.g. 'Exposed groups', included in the simulation.

The user can also manage specific interface options, such as the language of the software interface, as well as other options.

II-3.3.2. Defining the model ('Model')

This is the key step in setting up the modelling case, where the user sets up the radioecological model. For composing the model, the Simulator supports a classic 'Interaction Matrix' interface and graphical 'Block Scheme' ('Graph') interface.

The radioecological model can be composed from modules included in libraries. The user selects the particular modules needed for the current modelling case and sets up data exchanges between modules.
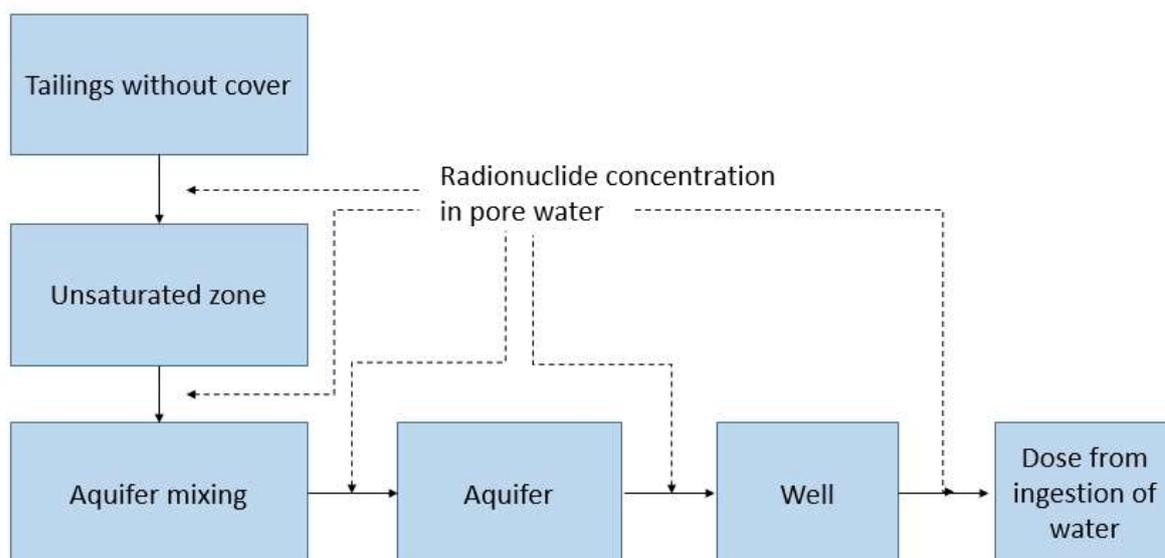
FIG. II-2. NORMALYSA model structure for Exercise 2.

II-3.3.3. *Specifying modelling options ('Options')*

In this step, the user specifies particular modelling options which are available in relevant modules used to setup the radioecological model.

II-3.3.4. *Specifying time dependent input parameters in table format ('Time Series')*

In the case that the model includes time dependent input parameters which need to be specified in table format, input of such parameters is carried out in this menu position.

II-3.3.5. *Entering model parameters ('Parameters')*

In this menu, the user has the possibility to modify all model parameters.

The NORMALYSA modules are supplied with the default values of all model parameters. Some of these do not necessarily need to be changed (e.g. dose coefficients for dose assessment calculations). However, almost any model includes site specific and/or modelling case specific parameters that will need to be specified by the user.

II-3.3.6. *Running the simulation ('Simulation')*

This menu allows the user to set up simulation options (e.g. start and end times, specifying output parameters), and eventually to run the model.

II-3.3.7. *Analyzing results ('Tables' and 'Charts')*

The Simulator menu includes two menu items for analyzing simulation results, i.e. 'Charts' and 'Tables'. These menu items allow the modeller to view data either in chart or table format. Simulation data can be also exported into MS Excel file format.

II-3.3.8.   Generating reports ('Reports')

This menu allows the automatic generation of a modelling report describing the simulation case, model used, input parameters and simulation results. The report can be printed or exported into PDF format.

Additional information on the user interface of the NORMALYSA Simulator can be obtained from context sensitive 'Help Contents' menus.

The following provides a detailed explanation of how to perform modelling operations for a respective exercise for each step specified above (i.e. for the main menu positions).

II-4. DETAILED DESCRIPTION OF COMPOSING AND RUNNING THE MODEL IN NORMALYSA

In this section, detailed descriptions of the 'Context' menu position, 'Model' menu button, 'Options' and 'Time series' menu positions, 'Parameters' menu position, 'Simulation' menu position and viewing simulation results are provided.

II-4.1.   'Context' menu position

The user starts by defining the 'context' for the modelling case, which includes defining the model name and selecting the list of radionuclides to be included in the simulation. By default, the 'Context' window is shown in NORMALYSA when the tool is opened.

(1)   The user needs to click on the 'New' button in the context menu to create a new model file. The 'Edit' button then needs to be pressed to gain access to the model description field.
The model needs to be given a name (in this instance 'Exercise 2'), and the user needs to fill in their name in the 'Author' field (optional) and a short description of the exercise typed into the 'Description' field (optional).
(2)   In the context menu, the user needs to click the 'Save As' button, then name and save the model file to an appropriate location on their computer.

List of 'Contaminants' (radionuclides) is shown on the right hand side of the 'Context' window. When a new model is created, all radionuclides and decay chains are enabled by default.

For the purposes of Exercise 2, the whole ^{238}U decay chain needs to be included in the model. In order to do this, the user needs to firstly disable all radionuclides in the 'Nuclides' window and then select ^{238}U (its whole decay chain will be selected automatically) (shown in Fig. II-3).

II-4.2.   'Model' menu button

The next step is the assemble the model. In this menu position, the model will be created by using the module libraries and 'connectors' to exchange output and input data between different modules.

The user needs to click on the 'Model' button in the menu to open the model window. NORMALYSA provides two means to visualize the model, i.e. either as a box diagram (graph) or as an interaction matrix. The user can toggle between these two modes at any time by clicking on the tabs in the upper right corner of the 'Model' window. The 'Matrix' button is located next to the 'Graph' button (which is selected by default), which can be clicked on to select the 'matrix view'.
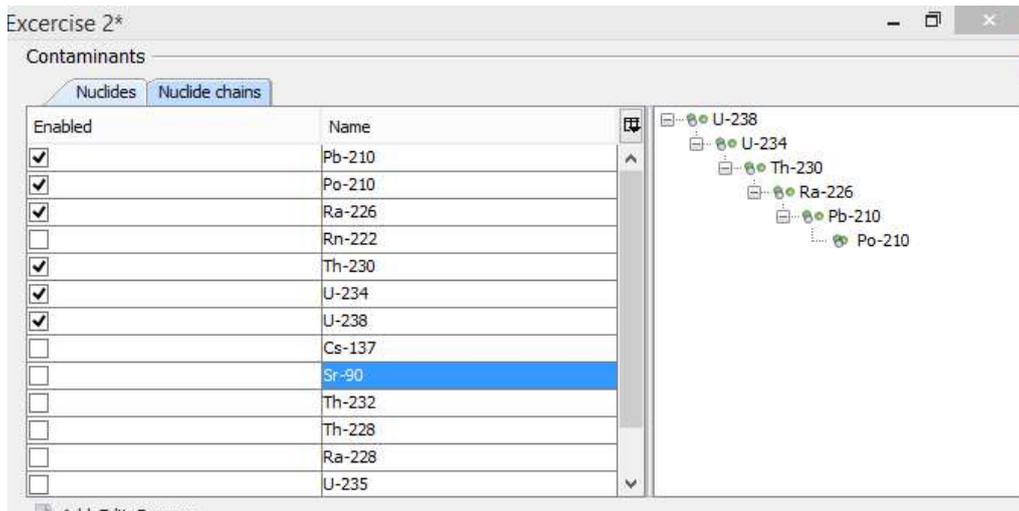
FIG. II-3. 'Contaminants' window with selected radionuclides for Exercise 2.

The following steps provide details of how to compose the NORMALYSA model for Exercise 2 using the modules from respective libraries:

(1) The user needs to right click on an empty diagonal element in the matrix and choose 'Get from the library...' (or 'Add…') from the pop up menu that appears.
(To add more empty diagonal elements to the matrix, the user can right click with the mouse on a diagonal element and choose 'Insert Above' or 'Insert Below'.)

(2) In the list of modules, the 'Tailing without cover' module needs to be selected from the 'Sources' folder. A short description of the selected model is available in the 'Description' field of 'Library' window.

(3) The user needs to click 'OK' and the selected module needs to now be visible as a 'box' on the model area.

(4) The user can also right click in the matrix to choose either 'Insert Above' or 'Insert Below' to add new diagonal elements.

(5) Steps 1–4 above can be repeated to insert on the diagonal of the matrix the 'Unsaturated Zone' module from 'Transports' library.

(6) Steps 1–4 can also be repeated to insert on the diagonal of the matrix the 'Aquifer Mixing' module from 'Transports' library.

(7) Steps 1–4 above can also be repeated to insert on the diagonal of the matrix the 'Aquifer' module from 'Transports' library.

(8) Steps 1–4 above can be repeated to insert on the diagonal of the matrix the 'Well' module from 'Receptors' library.

(9) Steps 1–4 above can also be repeated to insert on the diagonal of the matrix the 'Dose from ingestion of water' module from 'Doses' / 'Doses from ingestion of different food types' library.

The next task is to connect individual modules in between each other using 'connector' blocks to exchange data:

(1) To create a new 'connector' block, the user can right click on the off diagonal element of the matrix window projected (horizontally, vertically) on diagonal blocks that need to be connected, and choose 'Connector' from the pop up menu (see Fig. II-4).

(2) The user needs to repeat the process of connecting modules until the model looks like the one illustrated in Fig. II-5.
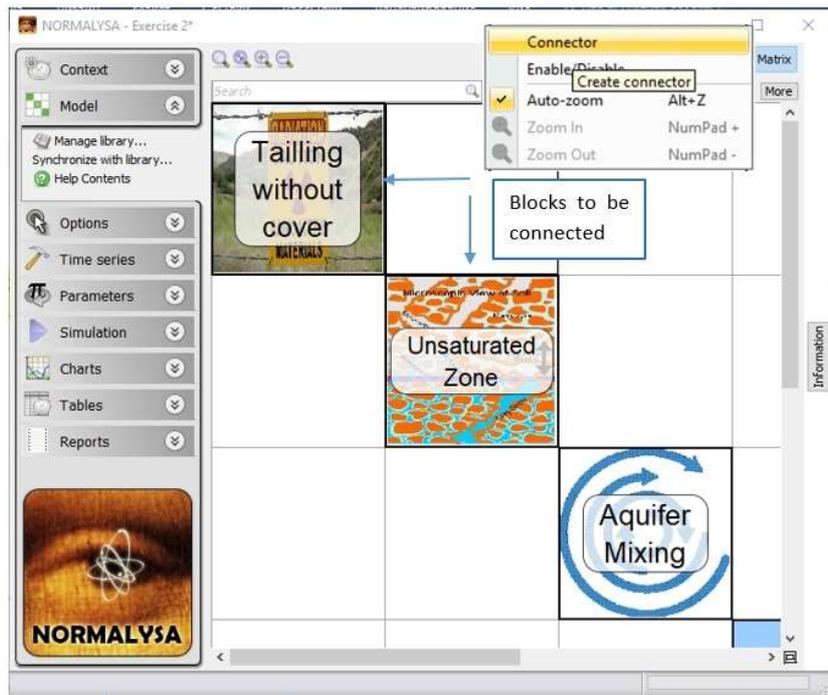
FIG. II-4. Connecting modules using 'connector' blocks for data exchanges.
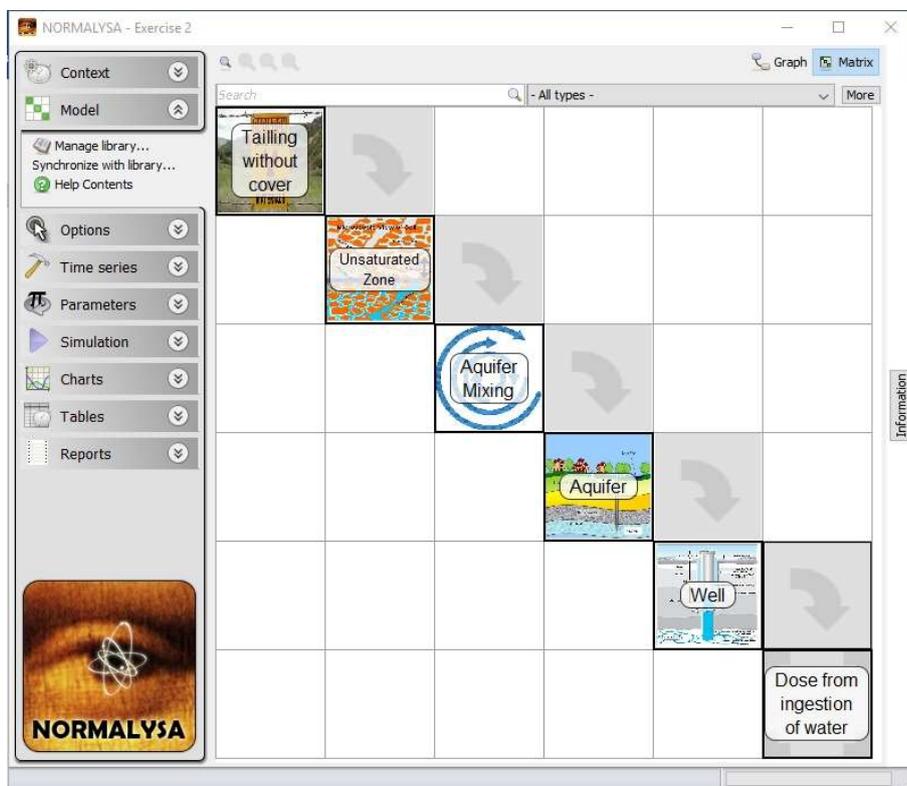
FIG. II-5. Full model for Exercise 2 including main modules and 'connectors' in 'Matrix' view.
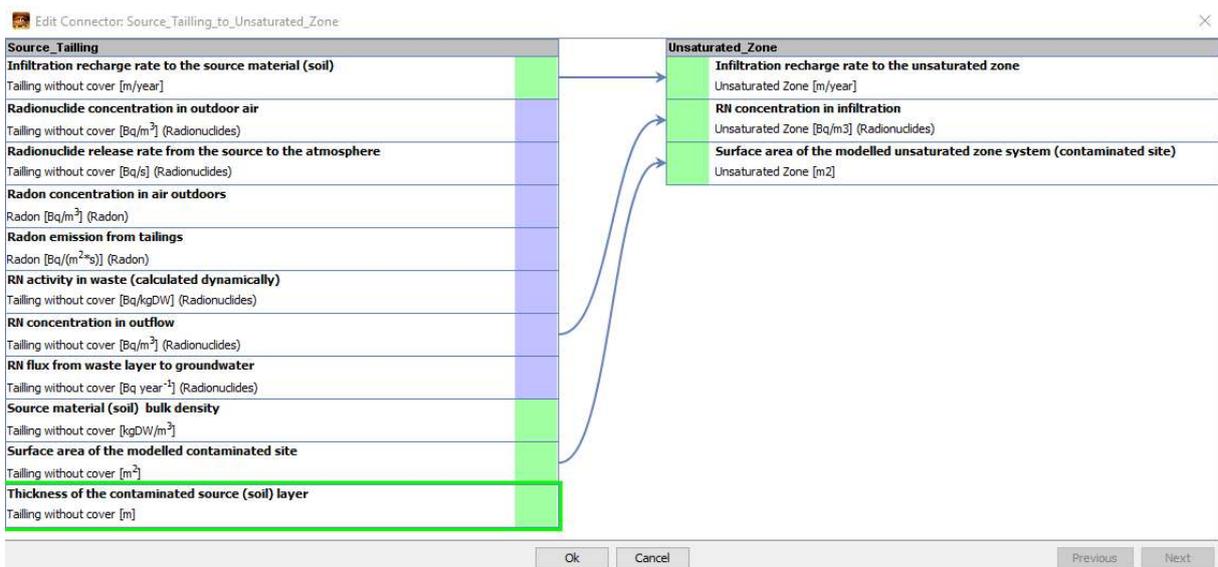
FIG. II-6. Using 'Edit Connector' window to set up data exchanges between modules.

The next task is to tune the 'connector' blocks to set proper data exchanges between modules. This process is described below:

(1) The user needs to double click on the 'connector' block between the 'Tailings without cover' and 'Unsaturated Zone' modules. The 'Edit Connector' window will be opened allowing the user to set up data exchanges between these modules (shown in Fig. II-6). The left column of the window lists output parameters of the 'Tailings without cover' module, while the right column lists the input parameters of the 'Unsaturated zone' module. The user needs to match 'output – input' parameter pairs between these two columns. The specific parameter can be selected by right clicking the particular table cell, and selecting the required parameter from the drop down list that appears.

(2) The user needs to connect the following 'output (left column) – input (right column)' parameter pairs;

> *'RN concentration in outflow'* and *'RN concentration in infiltration'*;
> *'Infiltration recharge rate to source material (soil)'* and *'Infiltration recharge rate to the unsaturated zone'*;
> *'Surface area of the modelled contaminated site'* and *'Surface area of the modelled unsaturated zone system (contaminated site)'*.

Connected parameters need to have same units.
Similar operations can be repeated for the 'connector' block between the 'Unsaturated Zone' and 'Aquifer mixing' modules as follows:

(3) For these modules the user needs to connect the following 'output (left column) – input (right column)' parameter pairs:

> *'RN concentration in outflow'* and *'RN concentration in infiltration'*;
> *'Infiltration recharge rate to the unsaturated zone'* and *'Infiltration recharge rate to the unsaturated zone'*;
> *'Surface area of the modelled unsaturated zone system (contaminated site)'* and *'Surface area of the modelled unsaturated zone system (contaminated site)'*.

(4) The user needs to repeat similar operations for the 'connector' block between 'Aquifer mixing' module and 'Aquifer' module.

(5)   For these last modules the user needs to connect the following 'output (left column) – input (right column)' parameter pairs:

> *'RN concentration in groundwater'* and *'RN concentration in inflowing groundwater'*;
> *'Darcy velocity in the aquifer'* and *'Darcy velocity in the aquifer'*;
> *'Sorption distribution coefficient (radionuclide specific)'* and *'Sorption distribution coefficient (radionuclide specific)'*;
> *'flow tube area'* and *'Aquifer (flow tube) cross-section area'*;

The user needs to not connect the following parameters: 'Initial RN concentration in groundwater' because these parameters need to have different values for these two modules.

(6)   The user needs to repeat similar operations for the 'connector' block between the 'Aquifer' and 'Well' modules.

(7)   For these last modules, the user needs to connect the following 'output (left column) – input (right column)' parameter pair:

> *'RN concentration in outflow GW'* and *'Radionuclide concentration in groundwater originating from the contaminated site'*;

(8)   Finally, the user is able to perform similar operations for the 'connector' block between the 'Well' and 'Dose from ingestion of water' modules.

(9)   For these last modules, the user needs to connect the following 'output (left column) – input (right column)' parameter pair:

> *'RN concentration in water'* and *'Concentration of radionuclide in water'*.

With the steps described above, the setup of the NORMALYSA model structure and data exchanges is complete.

When the NORMALYSA model is created using one or other combination of modules, a set of different 'Indices' (or 'index lists') required by these modules is added automatically to the 'Context' window.

Subsequent to setting up the model, the following provides reiteration of the use of the 'Context' window.

II-4.2.1.   Defining the 'Exposed Groups' index list

To review the 'index lists' included to the model, the user needs to click on the 'Context' button in the main menu on the left side to reopen the respective window. The 'Context' window displays list of 'Indices' in the bottom right corner.

The user needs to browse through the respective tabs to see which index lists have been added to the NORMALYSA model. Two 'index lists' can be seen, i.e. 'Exposed Groups' and 'Age Groups'. By default, all available entries in the index lists are selected (activated).

With regard to the current case (Exercise 2), it is necessary to use the 'Exposed Groups' index list to define the age characteristics of the reference persons considered in this exercise:

(1)   The user needs to click on the 'Exposed Groups' tab.
(2)   The existing group needs to then be renamed from 'Reference person 1' to 'Adult site visitor'. By default, this reference person belongs to the 'Age Group' category 'Adults'. On this occasion, this last setting needs not to be changed.
(3)   All other remaining reference persons need to be deselected.

The result of the adjustments made to the 'Exposed Groups' index list are illustrated in Fig. II-7.
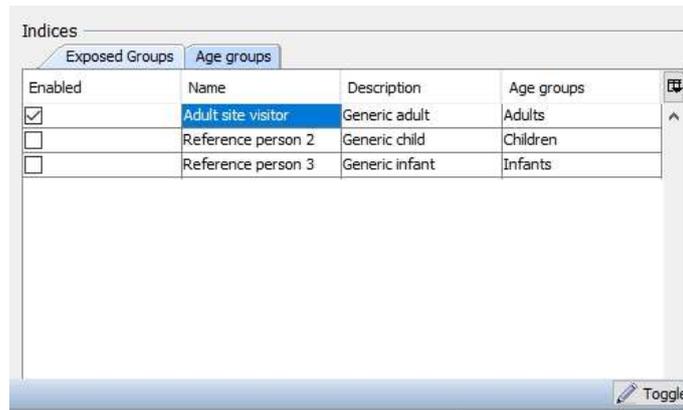
FIG. II-7. Defining the 'Exposed Groups' index list.

The 'Age groups' index list cannot be changed in NORMALYSA and only respective age groups from this list can be assigned to the reference persons listed in the 'Exposed Groups' window.

II-4.3. 'Options' and 'Time series' menu positions

During Exercise 2, there is no need to make any inputs or adjustments in the 'Options' and 'Time series' menu positions.

II-4.4. 'Parameters' menu position

The next task is to define various model parameters. To do so, the user needs to open the 'Parameters' window by clicking on the respective button in the main menu.

All parameters required by the model are displayed to the left of the 'Parameters' window.

Information on the parameter which is currently selected is displayed in the upper right part of the window. The user needs to click on the 'Information' button located in the upper right corner to view parameter units and other relevant information.

The 'Data' table is displayed in the bottom right part of the window, where parameter values can be viewed and edited. For some parameters the user can utilize the default values, but for others the user may wish to use values specific to the respective study, and these need to be entered. Care needs to be taken with regard to the parameter unit selection.

To search for specific parameters the user can use the controls located in the left bottom corner of the window below the parameter list. The 'Category' drop down list allows the user to display only parameters of a specific category. The 'Subsystem' drop down list allows the user to display parameters only for a specific subsystem/module. (With regard to Exercise 2, these are 'Tailing without cover', 'Unsaturated zone', 'Aquifer mixing', 'Aquifer' and 'Dose from ingestion of water' and the 'Constants' block where various constants used in the model, such as dose conversion coefficients, inhalation rate, etc. are compiled.)

II-4.4.1.   Data input for Exercise 2

For each of the parameter sets listed below, the user needs to take the following steps:

— Select the required subsystem/module ('Tailing without cover', 'Unsaturated zone', 'Aquifer mixing', 'Aquifer', 'Well' or 'Dose from ingestion of water');

— Select one by one each parameter in the list;

— Enter the required parameter value(s).

All required parameter values are provided in Section II-2 of this exercise. For convenience, these parameters are repeated below in Tables II-8–II-16 in accordance with the respective subsystems. If a particular parameter is not explicitly listed in these tables, the default value of this parameter does not need to be changed in NORMALYSA.

TABLE II-8. INPUT PARAMETER VALUES FOR SUBSYSTEM 'TAILING WITHOUT COVER'

Parameter	Value	Unit
Infiltration recharge rate to the source material (soil)	0.2	m/year
Soil moisture content in the source material (soil)	0.15	unitless
Source material (soil) bulk density	1600	kg/m^3
Surface area of the modelled contaminated site	40 000	m^2
Thickness of the contaminated source (soil) layer	8	m

TABLE II-9. INPUT PARAMETER VALUES FOR SUBSYSTEM 'TAILING WITHOUT COVER' THAT ARE RADIONUCLIDE SPECIFIC

Radionuclide	Initial concentration of the radionuclide in the source soil (waste), Bq/kg	Sorption distribution coefficient (radionuclide specific) of source material (soil), $m^3/kgDW$
Pb-210	17 000	3.5
Po-210	21 000	2.5
Ra-226	14 000	6.3
Th-230	12 700	10
U-234	2500	0.005
U-238	2500	0.005

TABLE II-10. INPUT PARAMETER VALUES FOR SUBSYSTEM 'UNSATURATED ZONE'

Parameter	Value	Unit
Length (depth) of the modelled unsaturated zone system	2	m
Soil bulk density	2000	kg/m^3
Soil moisture content in the unsaturated zone	0.15	unitless

TABLE II-11. INPUT PARAMETER VALUES FOR SUBSYSTEM 'UNSATURATED ZONE' THAT ARE RADIONUCLIDE SPECIFIC

Radionuclide	Initial specific activity of soil, Bq/kg	Sorption distribution coefficient for the Unsaturated zone, m^3/kg
Pb-210	2200	0.5
Po-210	900	0.1
Ra-226	435	0.2
Th-230	510	3
U-234	500	0.003
U-238	500	0.003

TABLE II-12. INPUT PARAMETER VALUES FOR SUBSYSTEM 'AQUIFER MIXING'

Parameter	Value	Unit
Aquifer material bulk density	1600	kg/m^3
Aquifer mixing thickness	10	m
Aquifer porosity	0.3	unitless
Darcy velocity in the aquifer	10	m/year
Length of the modelled aquifer system	200	m

TABLE II-13. INPUT PARAMETER VALUES FOR SUBSYSTEM 'AQUIFER MIXING' THAT ARE RADIONUCLIDE SPECIFIC

Radionuclide	Sorption distribution coefficient (radionuclide specific), Bq/m^3	Initial radionuclide concentration in groundwater, Bq/m^3
Pb-210	0.5	0
Po-210	0.1	0
Ra-226	0.2	200
Th-230	3	0
U-234	0.01	350 000
U-238	0.01	350 000

TABLE II-14. INPUT PARAMETER VALUES FOR SUBSYSTEM 'AQUIFER'

Parameter	Value	Unit
Aquifer material bulk density	1600	kg/m^3
Aquifer porosity	0.3	unitless
Length of the modelled aquifer system	200	m

TABLE II-15. INPUT PARAMETER VALUES FOR SUBSYSTEM 'WELL'

Parameter	Value	Unit
Well debit fraction formed by contaminated groundwater originating from the contaminated site	1.0	unitless

TABLE II-16. INPUT PARAMETER VALUES FOR SUBSYSTEM 'CONSTANTS'

Parameter	Value	Unit
Ingestion rate of water (Exposed group: '*Adult site visitor*')	0.37	m^3/year

TABLE II-17. INPUT PARAMETER VALUES FOR SUBSYSTEM 'DOSE FROM INGESTION OF WATER'

Parameter	Value	Unit
Fractional contribution of water from the freshwater body receptor to the total ingestion of water (Exposed group: '*Adult site visitor*')	0.25	unitless

II-4.5. 'Simulation' menu position

Once the user has composed the NORMALYSA model and the input parameters have been defined, it is possible to perform a simulation.

The user needs to open the simulation window by clicking on the 'Simulation' button in the menu. This window allows the user to adjust/change simulation settings and eventually to perform the simulation.

The table in the bottom part of the window will display any errors and/or warnings (if present), e.g. if a value of a parameter is missing (i.e. is not defined) in the model. It is not possible to start a simulation if errors are shown in this table.

Before proceeding to calculations, the user needs to adjust simulation time settings and the list of output parameters.

II-4.5.1. Adjusting the simulation time settings

The user needs to adjust the simulation time to 1000 years, and the time step of the output needs to be set to 100 years.

(1) The user needs to click on the 'Simulation Settings' submenu to the left. The 'General' tab of the 'Edit Simulation Settings' window will appear, that allows the setting of the overall simulation time and output times.
(2) The 'End time' needs to be set to 1000.0 ('Years') (shown in Fig. II-8).
(3) In order to adjust the output times, the 'Remove' button at the right side of the 'Outputs' window needs to be pressed to clear the default value of 'Time series' field.
(4) The user needs to then click on the 'Add' button located on the right side of the 'Outputs' window, 'Linear' type of output needs to bed chosen from the menu that appears, and set the 'N' parameter specifying the number of output times to '11' (see Fig. II-8). The output time step is calculated as ('Start time' – 'End time')/(N-1). The 'OK' button can then be pressed to close the window(s).

The 'Edit Simulation Settings' settings window with the adjusted simulation time/output parameters is shown in Fig. II-9.
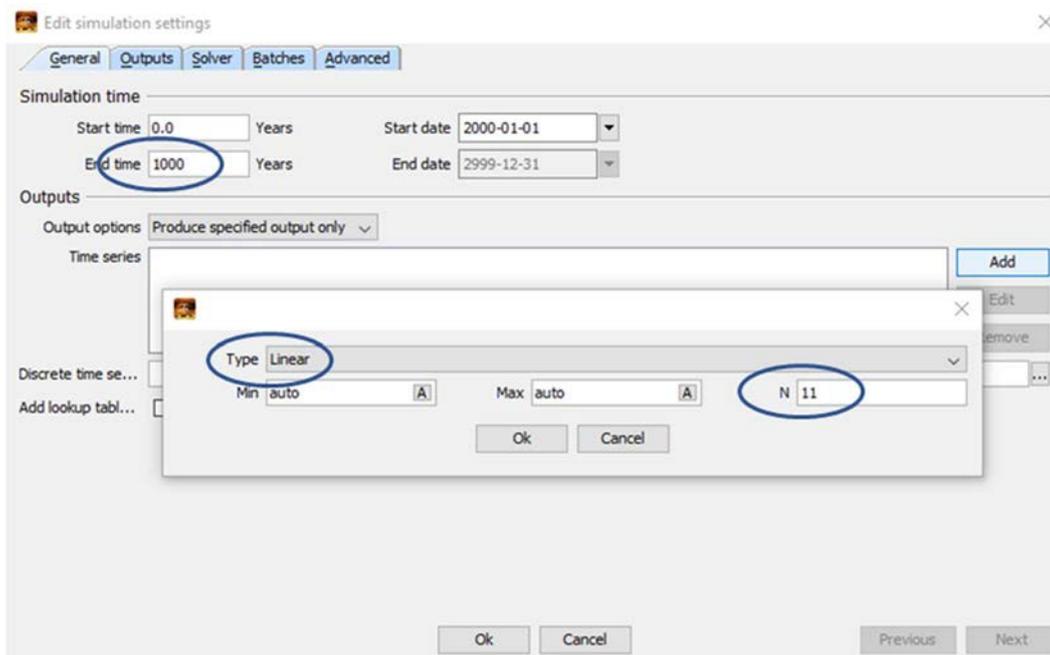
FIG. II-8. Adjusting of the 'Simulation time' and 'Outputs' parameters.
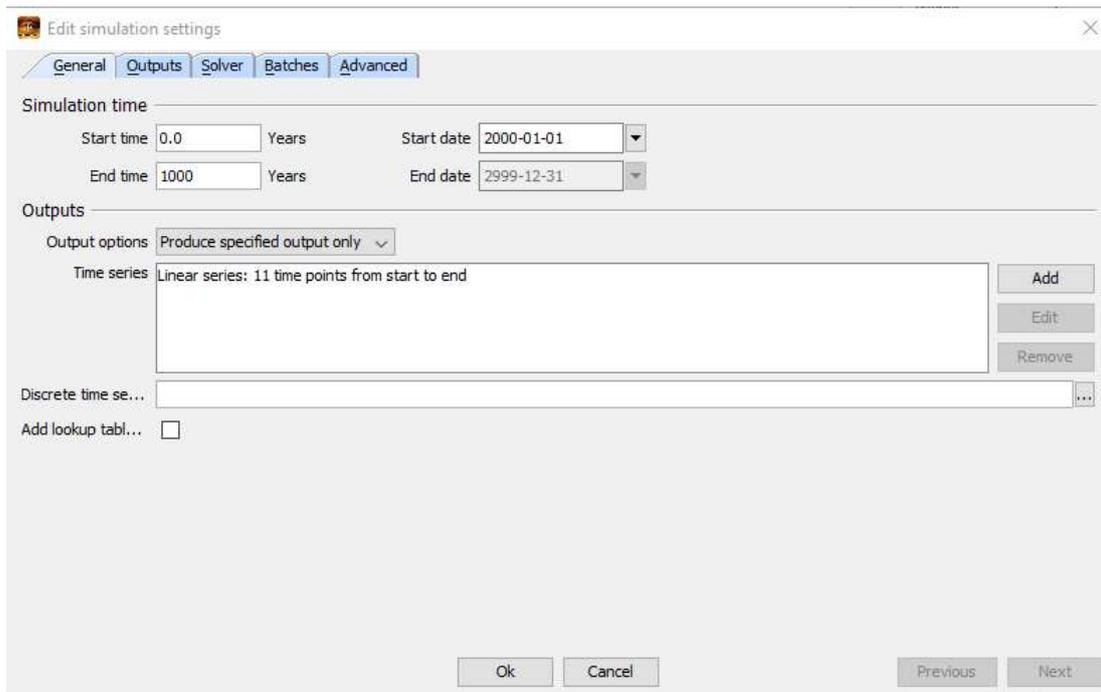
FIG. II-9. The resulting 'Simulation time' and 'Outputs' parameters settings.

II-4.5.2. Adjusting the list of model outputs

In order to adjust the list of NORMALYSA model outputs which will be included to the list of modelling results upon completion of simulation, the following steps need to be followed:

(1) Firstly, the user needs to click on the 'Simulation Settings' submenu to the left, and choose the 'Outputs' tab in the 'Edit Simulation Settings' window that appears. The window opens listing model outputs in the right subwindow. The left subwindow lists all other available model parameters. Output parameters are grouped according to respective subsystems.

(2) To clear the right window, the user needs to click on the '<<' button. Once this window is cleared, the user can select the outputs they are interested in from the respective subsystems.

(3) The user needs to choose the 'Well' subsystem in the left window, select the 'RN concentration in water' parameter, and click the '>' button.

(4) The same operations can be repeated with the following parameters from the 'Dose from ingestion of water' subsystem: 'Dose from ingestion of water for each radionuclide' and 'Dose from ingestion of water summed over all radionuclides'.

(5) The resulting 'Edit Simulation Settings' window with the selected list of output parameters is shown in Fig. II-10.

II-4.5.3. Running the model

In order to perform the simulation, the 'Run' button located in the upper corner has to be clicked.

The 'Information' window will then display information on the progress of the simulation process.
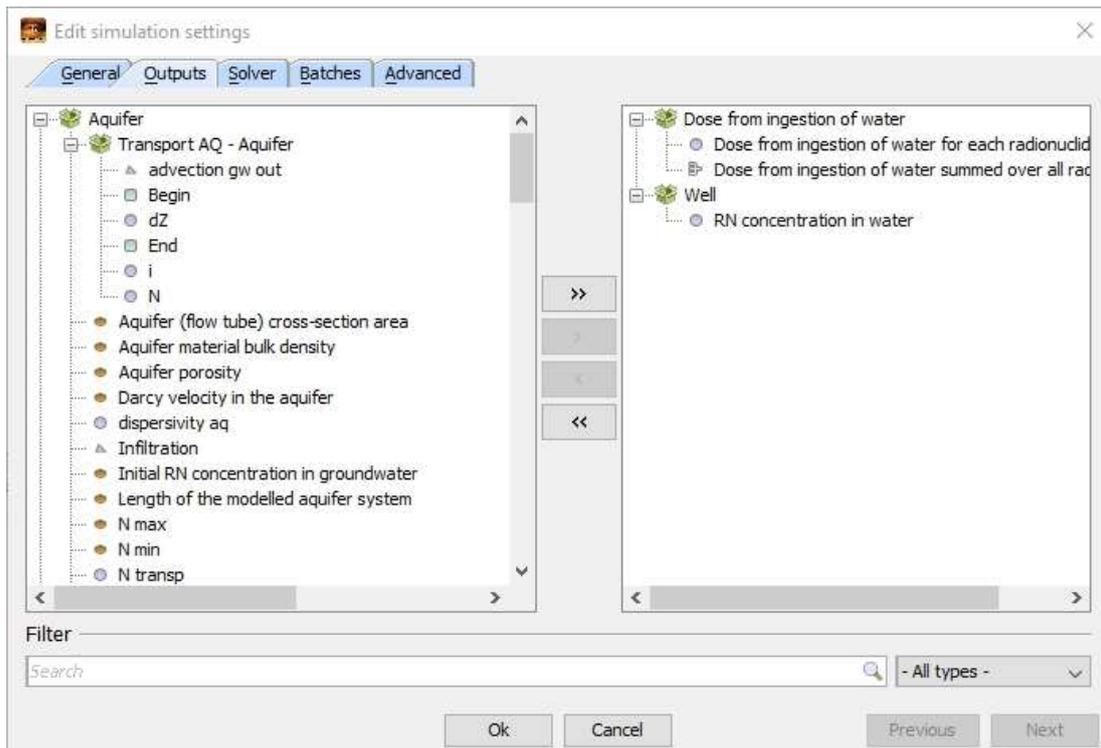
FIG. II-10. 'Edit Simulation Settings' window with selected list of output parameters.

II-4.6.   Viewing simulation results

Simulation results can be viewed either in charts or in tables using the respective buttons of the main menu.

II-4.6.1.   Viewing simulation results in table format

In order to view the results of the calculation in table format, the user needs to open the respective window by clicking on the 'Tables' button in the main menu to the left.

The available simulation results are listed in a subwindow immediately to the right of the main menu. Similar to the 'Parameters' window, the user can use the controls below this window to search and filter out required contents from the list of outputs.

The results are grouped in 'folders' where the root folder has as a name the date and time of the simulation.

To create a timetable for the specific parameter(s) in the 'Quick View' window to the right, the user needs to select the output parameter(s) of interest in the displayed tree of simulation results, using the left mouse button. Several parameters can be selected by pressing and simultaneously holding the 'Ctrl' key on the keyboard. In the case that the selected parameter is dependent on an 'index list' (such as the 'Exposed groups', or 'Nuclides' index list), the required entries of the index lists need to be tagged (the index lists corresponding to selected parameters appear below the window with simulation results).

For example, the following steps need to be taken to display the table with the calculated dose from ingestion of water to reference person considered in this exercise:

(1) Using the left mouse button in the window of simulation results, the user can select the output parameter 'Doses from ingestion of water summed over all radionuclides' inside the 'Dose from ingestion of water' folder.
(2) The 'All' box needs to be tagged (from the index list of exposed groups) which will be displayed immediately below the window with the simulation results.
(3) The time table displaying results of dose calculations for drinking water pathway will be shown in 'Quick View' window (see Fig. II-11).
(4) Adjustments can be made to the format of the numerical values displayed in the respective fields of the 'Format' window that appears immediately below the 'Quick View' window.

Similar operations can be performed to display the simulation results for radionuclide concentrations in groundwater in table format. In order to do so, the following output parameters have to be selected: 'RN concentration in water' ('Well' subsystem), and the 'All' box needs to be tagged in the index list of nuclides that will appear below the window with the simulation results.

II-4.6.2.   Exporting data to Excel

In order to export the table with simulation results to MS Excel, the 'Quick View' window displaying the required table needs to be right clicked and 'View in Excel' chosen from the pop up menu that appears.

II-4.6.3.   Viewing simulation results in graphical (chart) format

To view the results of the calculation in graphical format, the respective window needs to be opened by clicking on the 'Charts' button in the main menu to the left.

The steps required to display charts are generally similar to those for displaying results in table format (see Section II-4.6.1). In order to create a time graph for the specific parameter(s) in the 'Quick View' window to the right, the output parameter(s) of interest have to be selected in the displayed tree of simulation results using the left mouse button. Several parameters can be selected by pressing and simultaneously holding the 'Ctrl' key on the keyboard. In the case that the selected parameter is dependent on an 'index list' (such as the 'Exposed groups', or 'Nuclides' index list), the required entries of the index lists need to be tagged. Some principal adjustments to the style and format of the displayed chart can be made in the respective fields of the 'Plot' window that appears immediately below the 'Quick View' window with the chart.

For example, the following steps need to be taken to display the graph with the calculated radionuclide concentrations in the well water:

(1) Using the left mouse button, the user needs to select in the window of simulation results the output parameter 'RN concentration in water' inside the 'Well' folder.
(2) The 'All' box (in the index lists of radionuclides) which will be displayed immediately below the window with the simulation results needs to be tagged.
(3) The time graph displaying radionuclide concentrations in the well will then be shown in 'Quick View' window.
(4) The user needs to select the 'Bottom' option for legend location in the 'Plot' window below the chart.
(5) The 'Log Y' option below the chart needs to then be elected.

The resulting time graph of radionuclide concentrations in the well is shown in Fig. II-12.
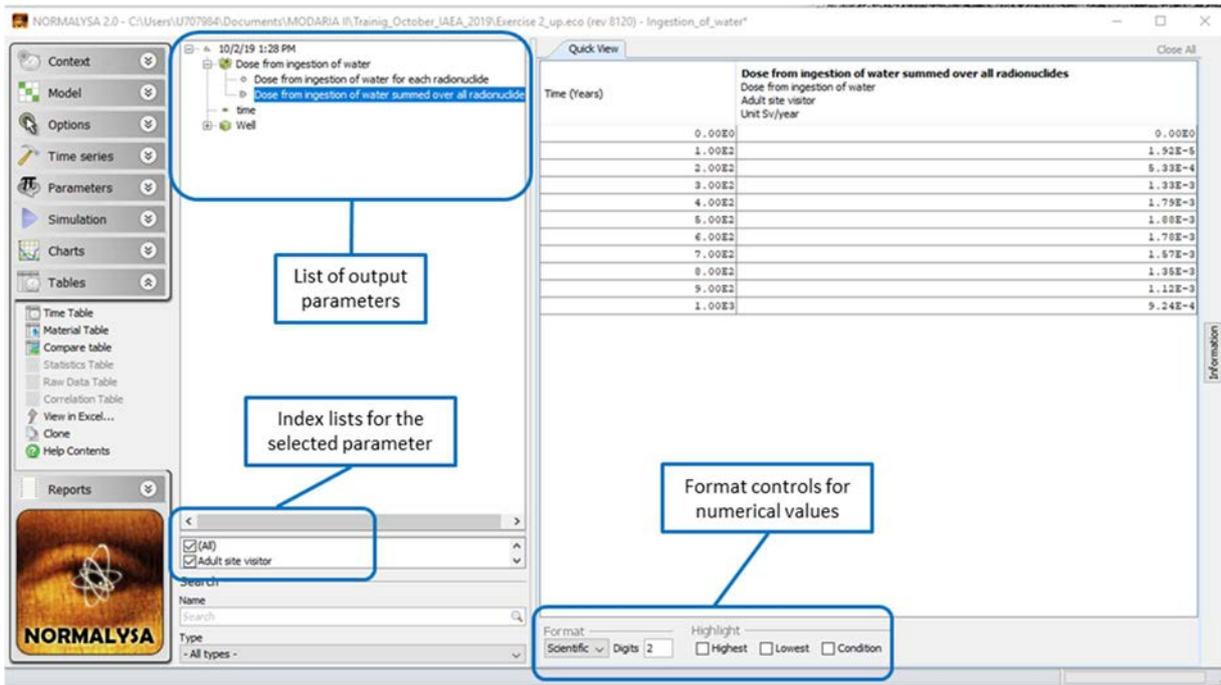
FIG. II-11. Displaying the table with the calculated doses from ingestion of water to reference persons considered in Exercise 2.
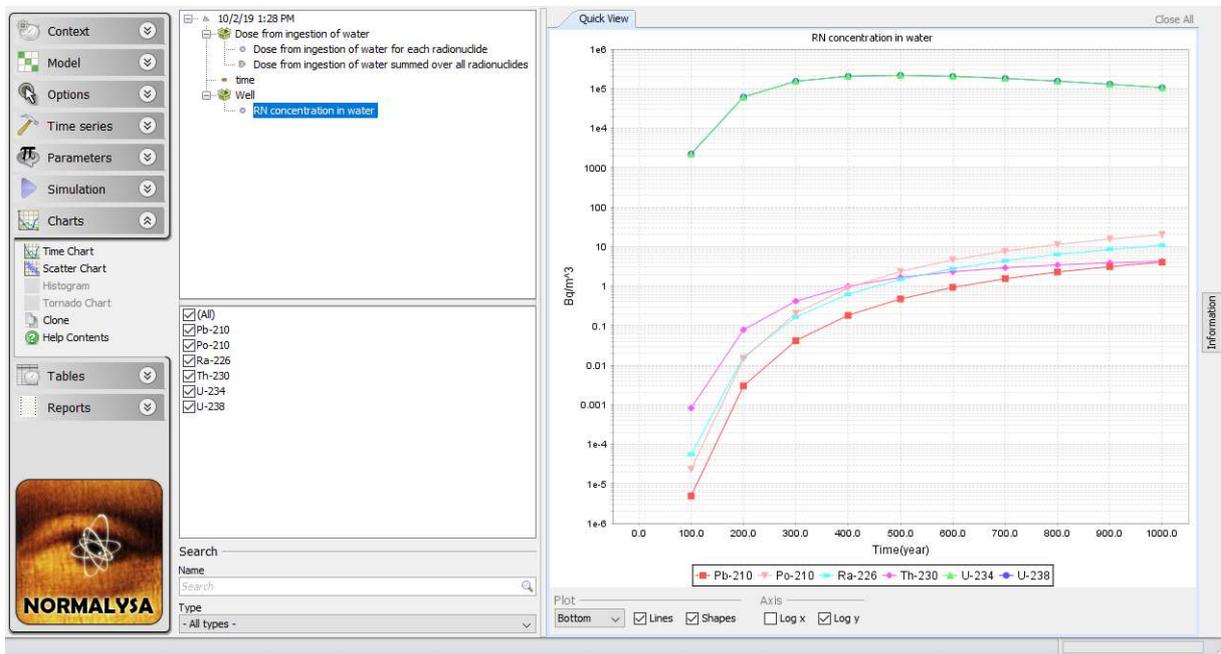
FIG. II-12. Displaying in chart format simulated radionuclide concentrations in the well water for Exercise 2.

II-5. RESULTS OF CALCULATIONS

This section lists simulation results in table format which can be utilized for exercise cross-checking purposes.

II-5.1.   Radionuclide concentrations in the well

Simulation results for radionuclide concentrations in the well are shown in Table II-18, where it can be seen that groundwater concentrations (and respectively doses for the drinking water pathway, see below) are dominated by uranium isotopes. Maximum ^{238}U and ^{234}U concentrations in well water reach ~2.2×10^5 Bq/m^3 (220 Bq/L) in 500 years from the beginning of the simulation.

II-5.2.   Dose from ingestion of water

Simulation results for total dose are shown in Table II-19, where it can be seen that the maximum dose to the reference individual due to drinking water from the well is 1.9 mSv/year (in 500 years).

II-6.   EXERCISE FOR INDEPENDENT WORK

The user can include in the list of exposed groups a child (in addition to the adult) and doses to these exposed groups (adult, child) can be calculated assuming fractional contribution of water from well to their yearly drinking water consumption is 50%, and that the distance from the radionuclide source (tailings) to the well is 300 m.

TABLE II-18. SIMULATED RADIONUCLIDE CONCENTRATIONS IN WELL WATER FOR EXERCISE 2

Time, years	Radionuclide concentration, Bq/m^3					
	Pb-210	Po-210	Ra-226	Th-230	U-234	U-238
0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	2.21E+03	2.21E+03
200	0.0	0.0	0.0	0.1	6.14E+04	6.14E+04
300	0.0	0.2	0.2	0.4	1.53E+05	1.53E+05
400	0.2	0.9	0.6	1.0	2.05E+05	2.05E+05
500	0.5	2.4	1.5	1.7	2.17E+05	2.17E+05
600	0.9	4.6	2.8	2.3	2.04E+05	2.04E+05
700	1.5	7.7	4.4	2.9	1.81E+05	1.81E+05
800	2.3	11.4	6.3	3.4	1.55E+05	1.55E+05
900	3.1	15.6	8.5	3.9	1.29E+05	1.29E+05
1000	4.0	20.2	10.9	4.3	1.06E+05	1.06E+05

TABLE II-19. SIMULATED TOTAL DOSE FROM DRINKING WATER PATHWAY IN EXERCISE 2

Time, years	Dose, Sv/year
0	0
100	1.92E-05
200	5.33E-04
300	1.33E-03
400	1.79E-03
500	1.88E-03
600	1.78E-03
700	1.57E-03
800	1.35E-03
900	1.12E-03
1000	9.24E-04

NORMALYSA TRAINING MATERIAL, EXERCISE 3:
CALCULATION OF RADON TRANSPORT IN THE ATMOSPHERE FROM
A URANIUM TAILING SITE AND RESULTING INHALATION DOSES
TO REFERENCE PERSONS

III-1. GENERAL DESCRIPTION OF THE PROBLEM

In this exercise, NORMALYSA is used to calculate inhalation doses to reference persons due to atmospheric dispersion of radon from a uranium tailing site.

III-1.1. Contamination source term (contaminated site)

The source of radioactivity releases to the atmosphere is a uranium mill tailing site containing radionuclides of ^{238}U decay series including ^{226}Ra. The tailings site is not covered by soil cover. The radon gas (^{222}Rn that is the progeny of ^{226}Ra) exhales from the tailings surface and is transported in the atmosphere to the downwind receptor location (shown in Fig. III-1).

III-1.2. Reference persons and exposure scenario

The reference persons for dose calculations are an adult and a child, who are both locals that are exposed to radon through the inhalation pathway.

The exposure of the reference persons occurs at an outdoor location at the distance of 200 m downwind from the tailings site (e.g. in a park area).

The adult is exposed to radon occasionally during a year, while the child spends more time outdoors in the receptor location. Additional details on the exposure scenario are provided in Section III-2.
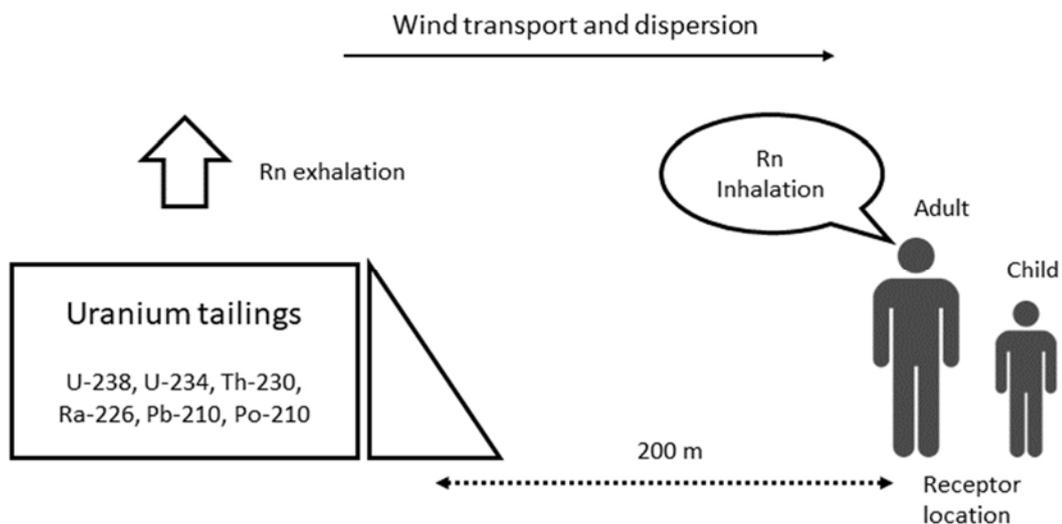
FIG. III-1. Illustrative scheme of atmospheric transport of radon from the uranium tailing site.

III-1.3. Calculation end points

The calculation end points for this exercise are as follows:

— Radon-222 concentration in the air above the source (uranium tailings) and at 200 m downwind at the receptor location;

— Annual effective doses from inhalation of ^{222}Rn received by reference persons for the exposure scenario described above.

The calculations need to be performed at the time scale of 1000 years and the calculation results need to be provided with the time step of 100 years.

III-2. INPUT DATA

The input data include characteristics of radioactivity source – term – uranium tailing site (see Tables III-1 and III-2), parameters of atmospheric transport process (given in Table III-3) and habits of reference persons (shown in Table III-4).

TABLE III-1. PARAMETERS OF THE URANIUM TAILINGS SITE

Parameter	Value	Unit
Waste site area	10 000	m^2
Thickness of waste layer	5	m
Waste moisture content	0.15	unitless
Waste bulk density	2000	kg/m^3
Infiltration recharge rate	0.3	m/year
Average annual wind speed	3	m/s
Radon diffusion coefficient in source (soil) material	0.000002	m^2/s
Radon emanation coefficient from source (soil) material	0.2	unitless

TABLE III-2. SPECIFIC ACTIVITY OF WASTE AND *Kd* VALUES OR DIFFERENT RADIONUCLIDES

Radionuclide	Specific activity in waste, Bq/kg	Sorption distribution coefficient for waste (*Kd*), m^3/kg
U-238	3000	0.1
U-234	3000	0.1
Th-230	15 000	0.5
Ra-226	15 000	0.2
Rn-222	0	0
Po-210	15 000	0.1
Pb-210	15 000	2.0

TABLE III-3. PARAMETERS OF THE ATMOSPHERIC TRANSPORT PROCESS

Parameter	Value	Unit
Distance from the source of release to the receptor point	200	m
The fraction of the time during the year that the wind blows towards the receptor	0.25	unitless
Height of release	0	m
The geometric mean of the wind speed at the height of release (yearly average)	3	m/s
Mixing height for radon above the source	2	m

TABLE III-4. HABITS OF THE REFERENCE PERSONS

Reference person	Duration of exposure to Rn-222
Adult	6 weeks per year, 8 hours per day outdoors
Child	4 hours per day during the whole year

III-3. GENERAL DESCRIPTION OF IMPLEMENTATION OF THE PROBLEM IN NORMALYSA

This section provides detailed descriptions of modules used, model structure and data exchanges between modules and a general description of the modelling steps.

III-3.1. Modules used

In this exercise, the following NORMALYSA modules will be used:

⎯ The 'Tailing without cover' module from 'Sources' library to model radionuclide source term and radon release to the atmosphere;
⎯ The 'Atmosphere SR-19' module from 'Transports' library to model radon dispersion in the atmosphere from the source to the receptor location;
⎯ The 'Dose from occupancy outdoors' module from 'Doses' library to calculate doses to the reference persons from inhalation of radon at the receptor location.

III-3.2. Model structure and data exchanges between modules

The structure of the NORMAYSA model for Exercise 3 is shown in Fig. III-2 in the form of a block scheme.

III-3.3. General description of modelling steps

To solve the problem described above using NORMALYSA, the modeller needs to follow the general sequence of steps. This is accomplished by going through different positions of the NORMALYSA main menu (shown to the left in the main software interface window).

The rationale of each NORMALYSA menu position (and respective modelling step) is briefly explained in the following Sections III-3.3.1 to III-3.3.8.

III-3.3.1. Setting the assessment context ('Context')

In this step, the NORMALYSA project file is created defining the simulation case. In particular, the user specifies the name of the project file, and selects radionuclides to be included in the simulation case.

The modeller also has a possibility to activate or deactivate specific index lists relevant to modelled case such as, e.g. 'Exposed groups', included to simulation. The user can also manage specific interface options , such as the language of the software interface as well as some other options.

III-3.3.2. Defining the model ('Model')

This is the key step in setting up the modelling case, where the user sets up the radioecological model. For composing the model, the Simulator supports a classic 'Interaction Matrix' interface and graphical 'Block Scheme' ('Graph') interface.

The radioecological model can be composed from modules included to libraries. The user selects particular modules needed for the modelling case and sets up data exchanges between modules.
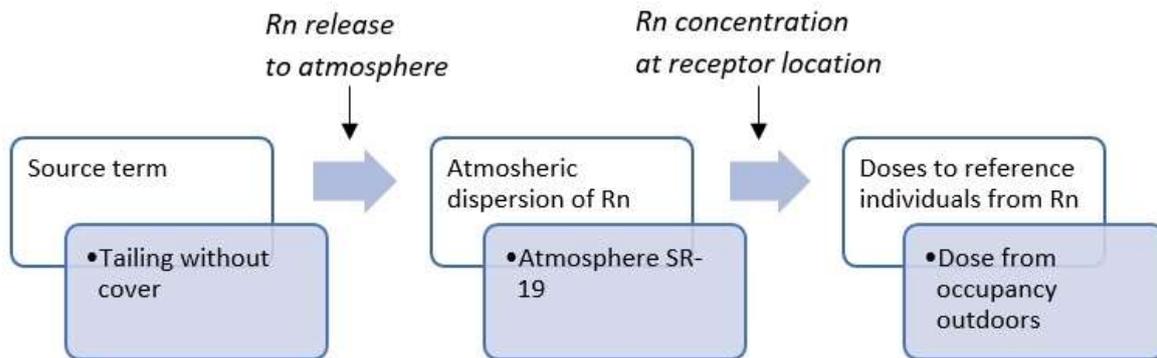
FIG. III-2. NORMALYSA model structure for Exercise 3.

III-3.3.3. Specifying modelling options ('Options')

In this step, the user specifies particular modelling options which are available in the relevant modules used to setup the radioecological model.

III-3.3.4. Specifying time dependent input parameters in table format ('Time Series')

In the case that the model includes time dependent input parameters that need to be specified in table format, input of such parameters is carried out in this menu position.

III-3.3.5. Entering model parameters ('Parameters')

In this menu, the user has the possibility to modify all model parameters.

The NORMALYSA modules are supplied with the default values of all model parameters. Some of these do not necessarily need to be changed (e.g. dose coefficients for dose assessment calculations). However, almost any model includes site specific and/or modelling case specific parameters that will need to be specified by the user.

III-3.3.6. Running the simulation ('Simulation')

This menu allows the user to set up simulation options (e.g. start and end times, specifying output parameters), and eventually to run the model.

III-3.3.7. Analyzing results ('Tables' and 'Charts')

The Simulator menu includes two menu items for analyzing simulation results, i.e. 'Charts' and 'Tables'. These menu items allow the modeller to view data either in chart or table format. Simulation data can also be exported to MS Excel file format.

III-3.3.8. Generating reports ('Reports')

This menu allows the user to automatically generate a modelling report describing the simulation case, model used, input parameters and simulation results. The report can either be printed or exported to PDF format.

Additional information on the user interface of the NORMALYSA Simulator can be obtained from the context sensitive 'Help Content' menu.

Below a detailed explanation is provided of how to perform modelling operations for each of the previously specified steps (i.e. for the main menu positions) for the exercise currently being considered.

III-4. DETAILED DESCRIPTION OF COMPOSING AND RUNNING THE MODEL IN NORMALYSA

As already discussed above, in this exercise the user can gain experience in using the following modules: 'Tailing without cover' from the 'Sources' library' (for the source term for radon release to the atmosphere), 'Atmosphere SR-19' from the 'Transports' library (for radon dispersion in the atmosphere), and the 'Dose from occupancy outdoors' from the 'Doses' library (for dose assessment).

III-4.1. 'Context' menu position

The user starts by defining the 'context' for the modelling case, which includes defining the model name and selecting the list of radionuclides to be included in the simulation.

By default, the 'Context' window is shown in NORMALYSA when the tool is opened.

(1) The user needs to click on the 'New' button in the context menu to create a new model file. The 'Edit' button then needs to be pressed to gain access to the model description field.
The user needs to give the model a name (in this case 'Exercise 3'), fill in their name in the 'Author' field (optional) and type a short description of the exercise in the 'Description' field (optional).
(2) In the context menu, the 'Save As' button needs to be clicked, and the model file needs to be named and saved to an appropriate location on the user's computer.

List of 'Contaminants' (radionuclides) is shown on the right hand side of the 'Context' window. When the user creates a new model, all radionuclides and decay chains are enabled by default.

As ^{222}Rn belongs to the ^{238}U decay chain, the whole radionuclide decay chain needs to be included into the model being considered. In order to do so, all radionuclides in the 'Nuclides' window firstly need to be disabled. Next, the user needs to select ^{238}U (its whole decay chain will be selected automatically) and ^{222}Rn (see Fig. III-3).

III-4.2. Model' menu button

The next step is to assemble the model. In this menu position, the model will be created by using the module libraries and 'connectors' to exchange output and input data between different modules.

The user needs to click on the 'Model' button in the menu to open the model window. NORMALYSA provides two means to visualize the model, i.e. either as a box diagram (graph) or as an interaction matrix. The user is able to toggle between these two modes at any time by clicking on the tabs in the upper right corner of the 'Model' window.

The 'Matrix' button is located next to the 'Graph' button (which is selected by default). The user needs to click on it to select the 'matrix view'.
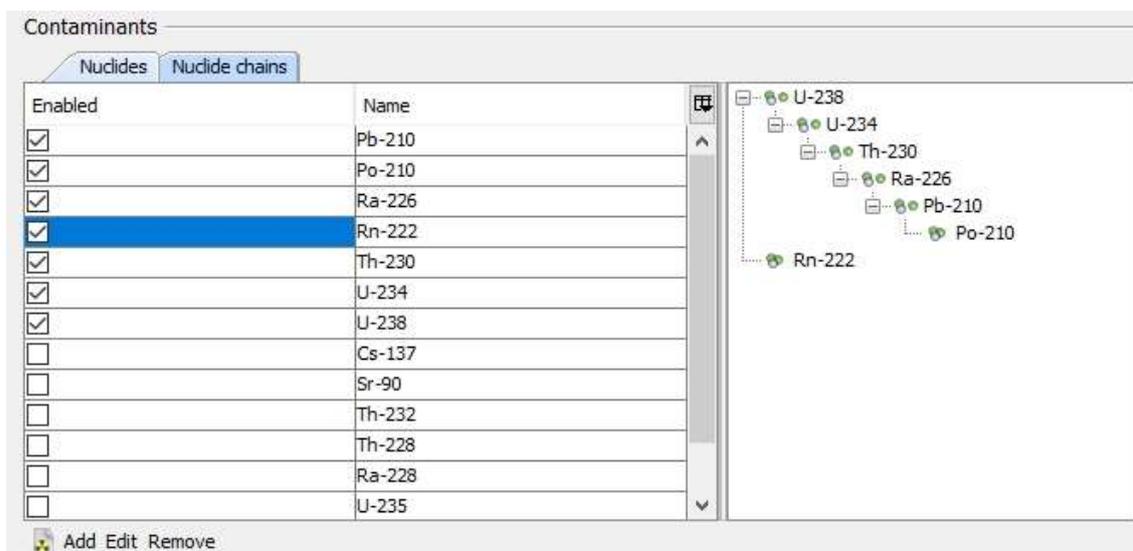
FIG. III-3. 'Contaminants' window with selected radionuclides for Exercise 3.

The following steps can be followed to compose the NORMALYSA model for Exercise 3 using the modules from respective libraries:

(1)   The user needs to right click on an empty diagonal element in the matrix and choose 'Get from the library...' (or 'Add…') from the pop up menu that appears.
(To add additional empty diagonal elements to the matrix, a diagonal element can be right clicked with the mouse and 'Insert Above' or 'Insert Below' can be choosen).

(2)   In the list of modules, the 'Tailing without cover' module needs to be selected from the 'Sources' folder. A short description of the selected model is shown in the 'Description' field of 'Library' window.

(3)   The user needs to click 'OK' and the selected module needs to be visible as a 'box' on the model area.

(4)   The user needs to right click in the matrix and choose 'Insert Above' or 'Insert Below' to add new diagonal elements.

(5)   Steps 1–4 need to be repeated to insert the 'Atmosphere SR-19' module from 'Transports' library on the diagonal of the matrix.

(6)   Steps 1–4 need to be repeated to insert the 'Dose from occupancy outdoors' module from the subfolder 'Doses from occupancy' in 'Doses' library on the diagonal of the matrix.

Next the user needs to connect individual modules in between each other using 'connector' blocks to exchange data. The 'connector' blocks need to be inserted between the 'Tailings without cover' and 'Atmosphere SR-19' modules, and between the 'Atmosphere SR-19' and 'Dose from occupancy outdoors' modules. This is required to allow data exchanges in accordance with the block scheme shown in Fig. III-2.

(1)   To create a new 'connector' block, the user needs to right click on the off diagonal element of the matrix window projected (horizontally, vertically) on diagonal blocks that need to be connected, and choose 'Connector' from the pop up menu (shown in Fig. III-4).

(2)   The user needs to repeat the process of connecting modules until the model look like the one illustrated in Fig. III-5.
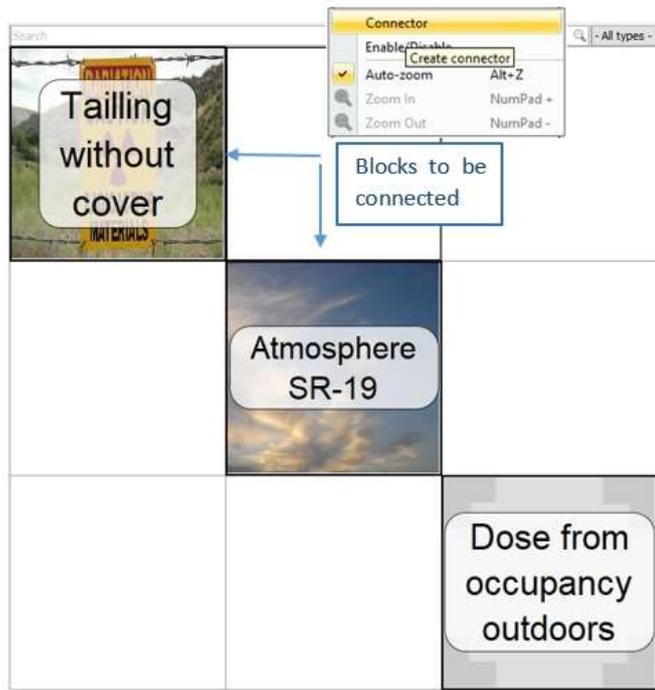
FIG. III-4. Connecting modules using 'connector' blocks for data exchanges.
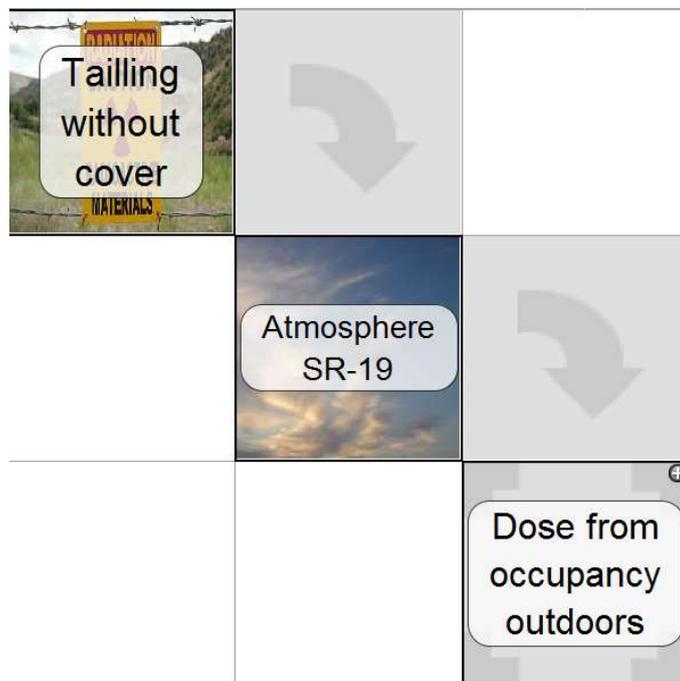
FIG. III-5. Full model for Exercise 3 including main modules and 'connectors' in 'Matrix' view.

The next task is to tune the 'connector' blocks to set proper data exchanges between modules. This process is described below:

(1)   The user needs to double click on the 'connector' block between the 'Tailings without cover' and 'Atmosphere SR-19' modules. The 'Edit Connector' window will be opened allowing the setting up of data exchanges between these modules (see Fig. III-6). The left column of window lists output parameters of the 'Tailings without cover' module, while the right column lists the input parameters of the 'Atmosphere SR-19' module. The user has to match 'output – input' parameter pairs between these two columns and the specific parameters can be selected by right clicking the particular table cell, and selecting the required parameter from the drop down list that appears.

(2)   The user then has to connect the following 'output (left column) – input (right column)' parameter pair: 'Radionuclide release rate from the source to the atmosphere' and 'Release rate at the release point'. Connected parameters need to have the same units.

(3)   Similar operations can be repeated for the 'connector' block between the 'Atmosphere SR-19' module and 'Dose from occupancy outdoors' module.

(4)   For these last modules the user has to connect the following 'output (left column) – input (right column)' parameter pair: 'Ground level air concentration' and 'Concentration of radionuclide in outdoor air'.

With the steps described above the setup of the NORMALYSA model structure and data exchanges is completed.

When the NORMALYSA model is created using one or other combination of modules, a set of different 'Indices' (or 'index lists') required by these modules is added automatically to the 'Context' window.

Subsequent to setting up the model, the following provides reiteration of the use of the 'Context' window.

III-4.2.1.   Defining the 'Exposed Groups' index list

In order to review the 'index lists' included in the model, the user is able to click on the 'Context' button in the main menu on the left side to reopen the respective window. The 'Context' window displays a list of 'Indices' in the bottom right corner.

It is possible to browse through the respective tabs to see which index lists have been added to the NORMALYSA model. Two 'index lists', i.e. 'Exposed Groups' and 'Age Groups' are visible. By default, all available entries in index lists are selected (activated).

In Exercise 3, the modeller will need to use the 'Exposed Groups' index list to define age characteristics of the reference persons considered in this exercise:

(1)   The user needs to click on the 'Exposed Groups' tab;
(2)   The existing group 'Reference person 1' needs to be renamed to 'Adult resident'. By default, this reference person belongs to the 'Age Group' category 'Adults', which needs not to be changed in this case;
(3)   The existing group 'Reference person 2' has to be renamed to 'Child resident'. By default, this reference person belongs to the 'Age Group' category 'Children'. This last setting needs not to be changed;
(4)   The user needs to deselect the remaining reference person.

The result of adjustments of 'Exposed Groups' index list is shown in Fig. III-7.

FIG. III-6. Using 'Edit Connector' window to set up data exchanges between modules.

FIG. III-7. Defining the 'Exposed Groups' index list.

The 'Age groups' index list cannot be changed in NORMALYSA and only respective age groups from this list can be assigned to the reference persons listed in the 'Exposed Groups' window.

III-4.3. Options' and 'Time series' menu positions

In Exercise 3, no inputs or adjustments in 'Options' and 'Time series' menu position need to be made.

III-4.4. 'Parameters' menu position

The next task is to define various model parameters. To do so, the 'Parameters' window needs to be opened by clicking on the respective button in the main menu.

To the left the 'Parameters' window displays all parameters needed by the model.

In the upper right part of the window, information on the parameter that is currently selected can be seen. The user can click on the 'Information' button located in the upper right corner to view parameter units and other relevant information.

The 'Data' table is displayed in the bottom right part of the window, where the parameter value can be viewed and edited. For some parameters the modeller can use the default values, but for some others the user may wish to use values specific to their respective study, and these need to be entered. When data is input manually, care needs to be taken with regard to parameter units.

The modeller can use the controls in the left bottom corner of the window, located below the parameter list, to search for specific parameters. The 'Category' drop down list allows the user

to display only parameters of a specific category. The 'Subsystem' drop down list allows the user to display parameters only for a specific subsystem/module. (In the case of the current exercise these are 'Tailing without cover'/'Tailings without cover – Radon', 'Atmosphere SR-19', 'Dose from occupancy outdoors', and the 'Constants' block where various constants used in the model, e.g. conversion coefficients, inhalation rate, etc. are compiled.)

Before proceeding to entering parameter values, parameter units for some model parameters need to be converted (see below).

III-4.4.1.   Conversion of units for time of exposure of reference persons

The NORMALYSA model for Exercise 3 requires that an input parameter defining the time of exposure of the reference person is expressed as a 'Fraction of the year that the reference person stays in a specific receptor'.

Initially, time of exposure was provided as a number of hours (see Section III-2). Therefore, this parameter needs to be recalculated to the required unit.

For the 'Adult resident', the resulting parameter value is:

$$Time_{fraction.year} \, [Adult \; resident] = (42 \; \text{days/year} \times 8 \; \text{hours/day})/$$
$$(365.25 \; \text{days/year} \times 24 \; \text{hours/day}) = 0.038$$

For the 'Child resident', this parameter is calculated as follows:

$$Time_{fraction.year} \, [Child \; resident] = 4 \; \text{hours} / 24 \; \text{hours} = 0.17$$

III-4.4.2.   Data input for Exercise 3

For each of the parameter sets listed below, the user needs to take the following steps:

— Select the required subsystem/module ('Tailing without cover'/'Tailings without cover – Radon', 'Atmosphere SR-19' or 'Dose from occupancy outdoors');
— One by one, select each parameter in the list;
— Enter the required parameter value(s).

All required parameter values are provided in Section III-2 of this exercise. For convenience, these parameters are repeated in Tables III-5 to III-9 in accordance with the respective subsystems. If a specific parameter is not explicitly listed in the tables below, this indicates that the default value of this parameter needs not to be changed in NORMALYSA.

III-4.5. Simulation' menu position

After the user has composed the NORMALYSA model and has defined input parameters, it is possible to perform a simulation.

The user needs to open the simulation window by clicking on the 'Simulation' button in the menu. This window allows the user to adjust/change simulation settings and eventually to perform the actual simulation.

The table in the bottom part of the window will display any errors and/or warnings (if present), e.g. if a value of some parameter is missing (is not defined) in the model. It is important to note that a simulation cannot be started if errors are shown in this table.

Before proceeding to calculations, the user needs to adjust the simulation time settings and the list of output parameters.

TABLE III-5. INPUT PARAMETER VALUES FOR SUBSYSTEM 'TAILING WITHOUT COVER'

Name	Value	Unit
Average wind speed	3	m/s
Infiltration recharge rate to the source material (soil)	0.3	m/year
Mixing height of radionuclides above the source	2	m
Soil moisture content in the source material (soil)	0.15	unitless
Source material (soil) bulk density	2000	kg/m^3
Surface area of the modelled contaminated site	10 000	m^2
Thickness of waste layer	5	m

TABLE III-6. INPUT PARAMETER VALUES FOR SUBSYSTEM 'TAILING WITHOUT COVER' THAT ARE RADIONUCLIDE SPECIFIC

Radionuclide	Parameter and unit	
	Initial concentration of the radionuclide in the source soil (waste), Bq/kg	Sorption distribution coefficient (radionuclide specific) of source material (soil), m^3/kg
U-238	3000	0.1
U-234	3000	0.1
Th-230	15 000	0.5
Ra-226	15 000	0.2
Rn-222	0	0
Po-210	15 000	0.1
Pb-210	15 000	2.0

TABLE III-7. INPUT PARAMETER VALUES FOR SUBSYSTEM 'TAILING WITHOUT COVER – RADON'

Name	Value	Unit
Radon diffusion coefficient in source (soil) material	0.000002	m^2/s
Radon emanation coefficient from source (soil) material	0.2	unitless

TABLE III-8. INPUT PARAMETER VALUES FOR SUBSYSTEM 'ATMOSPHERE SR-19'

Name	Value	Unit
Distance from the source of release to the receptor point	200	m
Height of release	0	m
The fraction of the time during the year that the wind blows towards the receptor	0.25	unitless
The geometric mean of the wind speed at the height of release (yearly average)	3	m/s

TABLE III-9. INPUT PARAMETER VALUES FOR SUBSYSTEM 'DOSE FROM OCCUPANCY OUTDOORS'

Reference person	Parameter: Fraction of the year that the reference person stays in a specific receptor (unitless)
Adult resident	0.038
Child resident	0.17

III-4.5.1.   Adjusting the simulation time settings

The simulation time needs to be adjusted to 1000 years, and the time step of the output needs to be set to 100 years:

(1)   The 'Simulation Settings' submenu to the left needs to be clicked on. The 'General' tab of the 'Edit Simulation Settings' window will appear, which allows the setting of the overall simulation time and output times.
(2)   The user needs to set the 'End time' to 1000 ('Years') (as shown in Fig. III-8).
(3)   To adjust the output times, the user needs to firstly press the 'Remove' button on the right side of the 'Outputs' window to clear the default value of the 'Time series' field.
(4)   Next, the 'Add' button located on the right side of the 'Outputs' window needs to be pressed and 'Linear' type of output chosen from the menu that appears, and 'N' parameter specifying the number of output times to '11' (see Fig. III-8). The output time step is calculated as ('Start time' – 'End time')/(N-1). The 'OK' button then needs to be pressed to close the window(s).

The 'Edit Simulation Settings' settings window with the adjusted simulation time/output parameters is shown in Fig. III-9.

III-4.5.2.   Adjusting the list of model outputs

Now we will adjust the list of NORMALYSA model outputs that will be included to the list of modelling results upon completion of simulation.

(1)   The user needs to click on the 'Simulation Settings' submenu to the left and choose the 'Outputs' tab from the 'Edit Simulation Settings' window that appears. The window will be opened listing model outputs in the right subwindow and the left subwindow lists all other available model parameters. Output parameters are grouped according to respective subsystems.
(2)   The user needs to click on the '<<' button to clear the right window. Once this window is cleared, tehe user can select the outputs they are interested in from the respective subsystems.
(3)   From the left window the user needs to choose the module 'Tailings without cover', followed by the subtree 'Radon – Tailings without cover', and then the 'Rn concentration in the air' parameter needs to be selected, and the '>' button clicked.
(4)   The user can then repeat the same steps using the following parameters: 'Ground level air concentration' (from the 'Atmosphere SR-19' subsystem) and the 'Dose from inhalation outdoors for each radionuclide' (from the 'Inhalation – Dose from occupancy outdoors' subfolder from the 'Dose from occupancy outdoors' subsystem).
(5)   The resulting 'Edit Simulation Settings' window with the elected list of output parameters is shown in Fig. III-10.

III-4.5.3.   Running the model

The user has to click on the 'Run' button in the upper corner to perform the simulation.

The 'Information' window will display information on the progress of the simulation process.
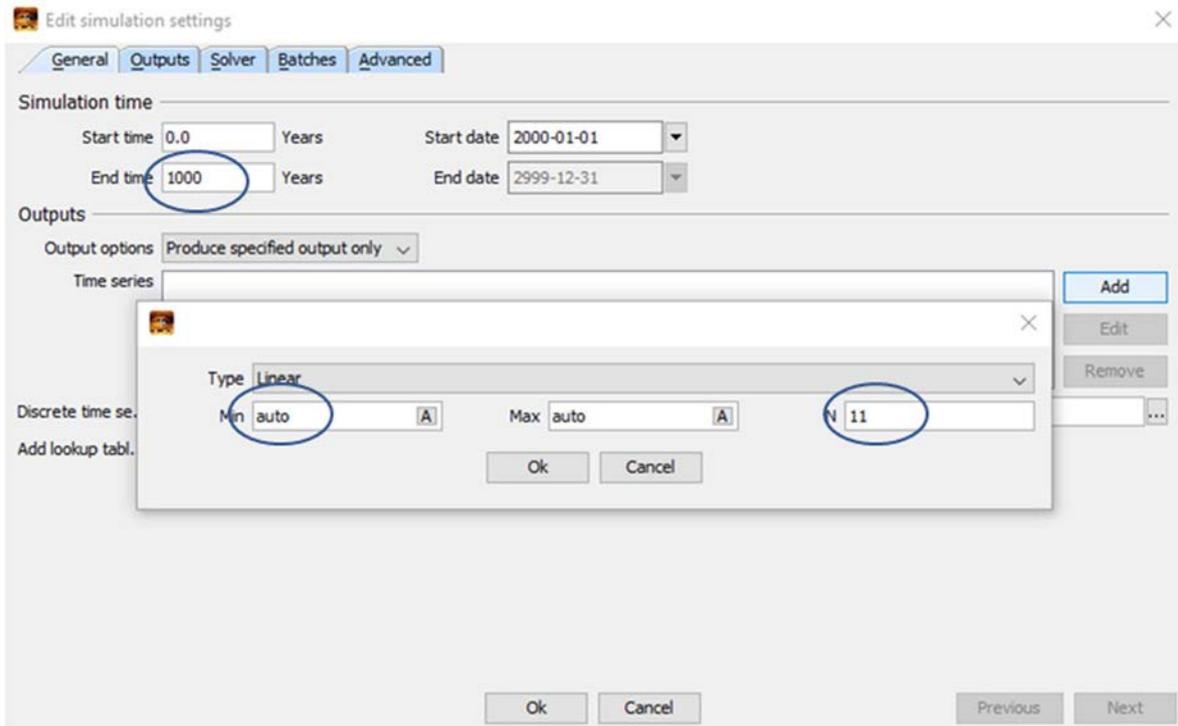
FIG. III-8. Adjusting of the 'Simulation time' and 'Outputs' parameters.
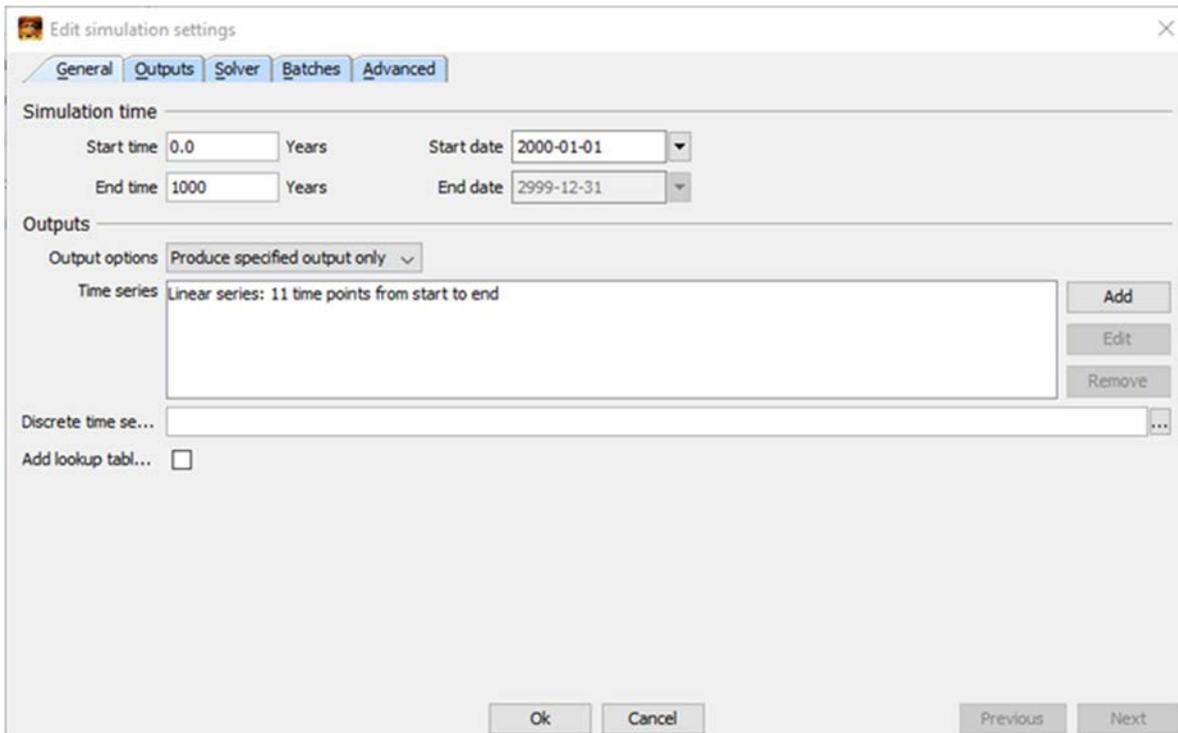
FIG. III-9. The resulting 'Simulation time' and 'Outputs' parameters settings.
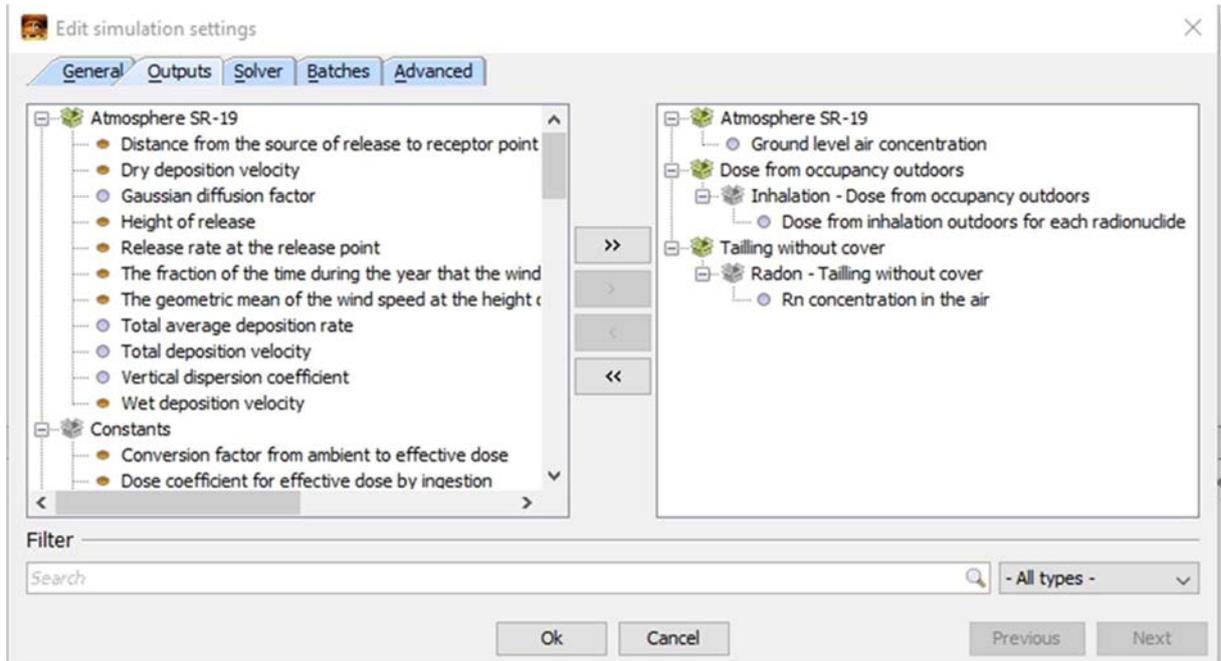
FIG. III-10. 'Edit Simulation Settings' window with selected list of output parameters.

III-4.6. Viewing simulation results

Simulation results can be viewed either in charts or in tables using the respective buttons of the main menu.

III-4.6.1.   Viewing simulation results in table format

In order to view the results of the calculation in table format, the respective window needs to be opened by clicking on the 'Tables' button in the main menu to the left.

The available simulation results are listed in a subwindow immediately to the right of the main menu. Similarly to the 'Parameters' window, the controls below this window can be used to search and filter out the required contents from the list of outputs.

The results are grouped into 'folders' where the root folder has as a name the date and time of simulation.

In order to create a timetable for the specific parameter(s) in the 'Quick View' window to the right, the user needs to select the output parameter(s) of interest in the displayed tree of simulation results using the left mouse button. Several parameters can be selected by pressing and simultaneously holding the 'Ctrl' key on the keyboard. In the case that the selected parameter is dependent on an 'index list' (such as 'Exposed groups', or 'Nuclides' index list), the required entries of the index lists need to be tagged (the index lists corresponding to selected the parameters appear below the window with simulation results).
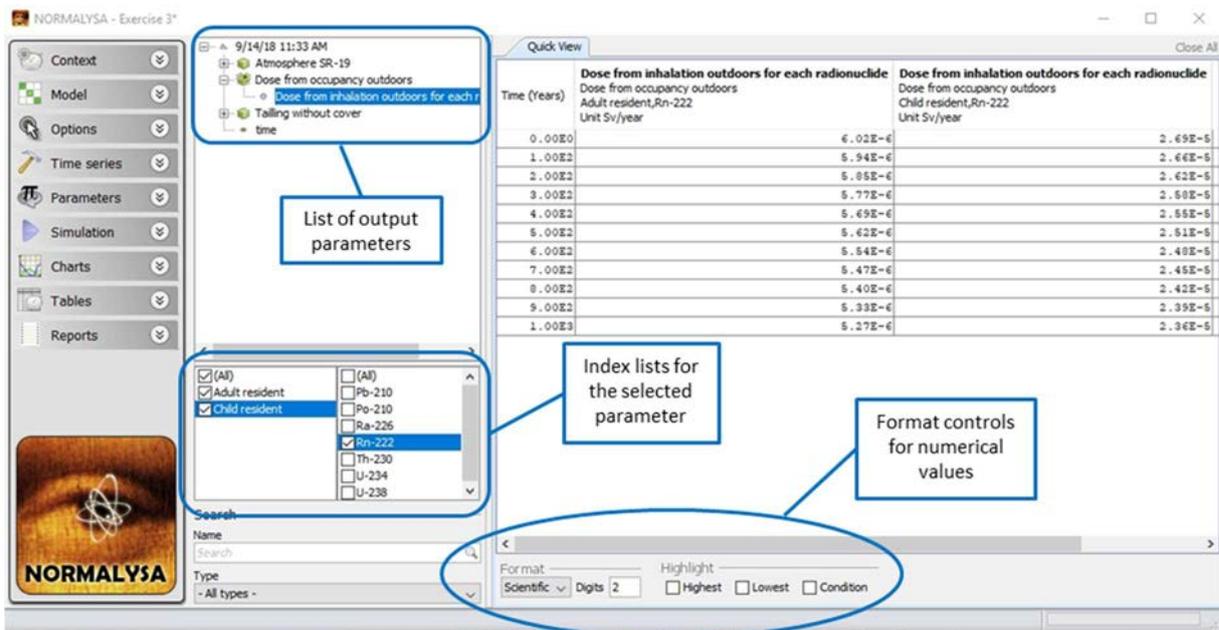
FIG. III-11. Displaying the table with the calculated inhalation doses from radon to reference persons considered in Exercise 3.

For example, the following steps need to be taken to display a table with the calculated inhalation doses from radon to reference persons at the receptor location considered in this exercise:

(1) Using the left mouse button in the window of simulation results the user needs to select the output parameter 'Doses from inhalation of each radionuclide' inside the 'Dose from occupancy' folder.
(2) The modeller then needs to tag 'All' (from the index list of exposed groups) and 'Rn-222' (from the index lists of radionuclides) which will be displayed immediately below the window with the simulation results.
(3) The time table displaying the results of the dose calculations from radon will be shown in the 'Quick View' window (see Fig. III-11).
(4) The user can make adjustments to the format of the numerical values displayed in the respective fields of the 'Format' window that appears immediately below the 'Quick View' window.

Similar steps can be taken to display simulation results in table format for radon concentrations in the air at the source of release and in the receptor point. In order to do so, the following output parameters have to be selected: 'Rn concentration in the air' ('Tailings without cover' subsystem) – for radon concentration above the uranium tailings, and 'Ground level air concentration' ('Atmosphere SR-19' subsystem) – for radon concentration in the air at receptor location. Moreover, the 'Rn-222' radionuclide needs to be tagged in the index list of nuclides.

III-4.6.2. Exporting data to Excel

In order to export a table with simulation results to MS Excel, the user needs to right click the 'Quick View' window displaying the required table and choose 'View in Excel' from the pop up menu that appears.

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III-4.6.3.   Viewing simulation results in graphical (chart) format

To view the results of the calculation in graphical format, the respective window needs to be opened by clicking the 'Charts' button in the main menu to the left.

The steps required to display charts are generally similar to those taken to display the results in table format (see Section III-4.6.1). In order to create a time graph for the specific parameter(s) in the 'Quick View' window to the right, the output parameter(s) of interest have to be selected using the left mouse button in the displayed tree of simulation results. Several parameters can be selected by pressing and simultaneously holding the 'Ctrl' key on the keyboard. In the case that the selected parameter is dependent on an 'index list' (such as 'Exposed groups', or the 'Nuclides' index list), the required entries of the index lists need to be tagged. Some principal adjustments to the style and format of the displayed chart can be made in the respective fields of the 'Plot' window that appears immediately below the 'Quick View' window with the chart.

For example, the following steps need to be taken to display the graph with the calculated radon concentrations in the air at the source of release (uranium tailing) and receptor location considered in this exercise:

(1)   Using the left mouse button in the window of simulation results, the user needs to select the output parameter 'Ground level air concentration' inside the 'Atmosphere SR-19' folder.
(2)   The 'Ctrl' button on keyboard needs to be pressed and held to select the second parameter to be plotted – 'Rn concentration in the air' in the 'Tailing without cover' folder.
(3)   The user needs to then wice tag 'Rn-222' from the index lists of radionuclides that will be displayed immediately below the window with the simulation results.
(4)   The time graph displaying radon concentrations in the selected locations (subsystems) will be shown in the 'Quick View' window.
(5)   Now it is possible for the user to make a number of adjustments to the format of the displayed graph. To do so, the user needs to right click in the graph area and select 'Edit…' from the pop up menu that appears.
(6)   The 'Edit Time Chart' window will then be opened and the user can make the following chart format adjustment in this window: in the 'Legend' field the user has to select the 'Bottom' option from the drop down list to display the chart legend. For the 'Y-axis' set of options, deselect the 'Auto range' and 'Logarithmic' boxes, '0.0' needs to be typed into the value to 'Min' field, and '120.0' into the 'Max' field (see Fig. III-12). The user needs to then press 'OK'.

The resulting time graph of radon concentrations in the air is shown in Fig. III-13.

III-5. RESULTS OF CALCULATIONS

This section provides simulation results in table format for exercise cross-checking purposes.

III-5.1. Radon concentrations in the air

Radon concentrations in the air in the source of release (uranium tailings) and at the downwind receptor location are shown in Table III-10. Radon (^{222}Rn) concentrations in the air decrease in time due to a decrease of the concentration of the parent radionuclide (^{226}Ra) in the body of the tailings. The decrease of ^{226}Ra is due to radioactive decay and the radionuclide leaching to deeper layers by infiltration recharge. Radon concentrations at a 200 m distance from the source decrease by a factor of ~14 compared to the source due to the dispersion process in the air.
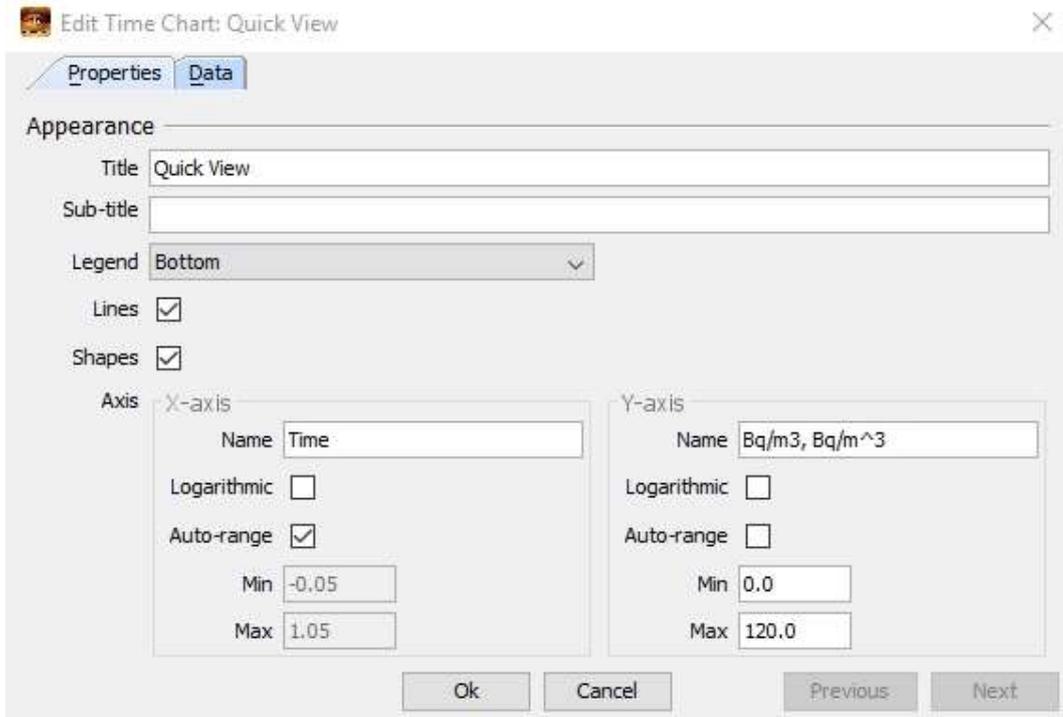
FIG. III-12. Adjustment of the format of the displayed chart with the simulation results (radon concentrations in the air) for Exercise 3.
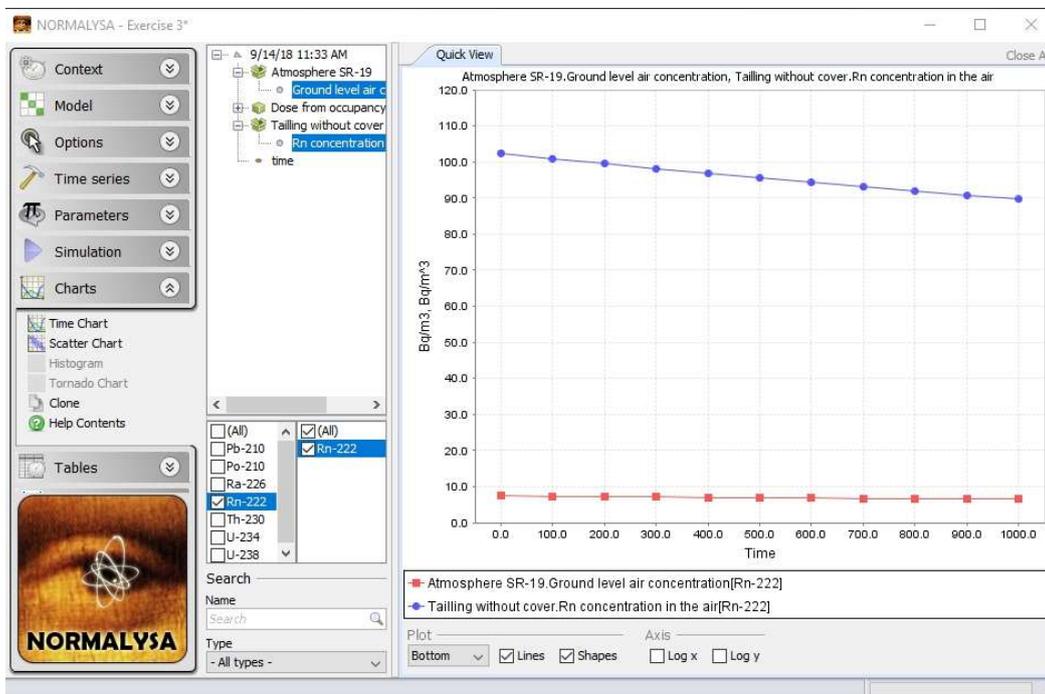
FIG. III-13. Displaying in chart format simulated radon concentrations in the source of release and at receptor location for Exercise 3.

III-5.2. Dose from inhalation of radon

Doses from inhalation of radon for respective reference persons are shown in Table III-11. These doses are generally low. The annual doses to an adult resident are in the µSv range. Doses to a child resident are higher due to a larger time of exposure and are of an order of 20–30 µSv/year. Doses decrease in time following the gradual lowering of radon concentrations in the air.

III-6. EXERCISE FOR INDEPENDENT WORK

In order to estimate how the distance from the source of release influences the inhalation doses from radon, the user can calculate doses to reference persons, assuming the receptor location is situated at 100 m, 300 m and 500 m distance, respectively.

TABLE III-10. SIMULATED RADON CONCENTRATIONS IN THE AIR ABOVE THE SOURCE ('TAILINGS WITHOUT COVER' SUBSYSTEM) AND AT RECEPTOR POINT ('ATMOSPHERE SR-19' SUBSYSTEM), Bq/m^3

Time, years	Radon concentration in the air ('Tailing without cover' subsystem)	Ground level air concentration ('Atmosphere SR-19' subsystem)
0	102.4	7.4
100	100.9	7.3
200	99.5	7.2
300	98.1	7.1
400	96.8	7.0
500	95.5	6.9
600	94.2	6.8
700	93.0	6.7
800	91.9	6.7
900	90.7	6.6
1000	89.6	6.5

TABLE III-11. SIMULATED DOSES TO ADULT AND CHILD RESIDENTS AT RECEPTOR POINT, Sv/year

Time, years	Adult resident	Child resident
0	6.0E-06	2.7E-05
100	5.9E-06	2.7E-05
200	5.9E-06	2.6E-05
300	5.8E-06	2.6E-05
400	5.7E-06	2.5E-05
500	5.6E-06	2.5E-05
600	5.5E-06	2.5E-05
700	5.5E-06	2.4E-05
800	5.4E-06	2.4E-05
900	5.3E-06	2.4E-05
1000	5.3E-06	2.4E-05

ABBREVIATIONS

CR   concentration ratio

DCC   dose conversion coefficient

DW   dry weight

FW   fresh weight

FWB   fresh water body

NORM   naturally occurring radioactive material

SKB   Swedish Nuclear Fuel and Waste Management Company

SPM   suspended particulate matter

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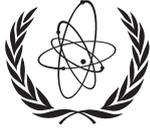
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