User’s manual

HYDROGEOCHEM -NORMALYSA

Description of Program Module Libraries, Mathematical Models and Parameters

EXECUTIVE SUMMARY

This report presents the user manual for HGC - NORMALYSA - software consisting of NORMALYSA integrated with HYDROGEOCHEM from the Taiwan Central University (HGC TPC).

The HGC TPC code has been widely applied in simulations of releases of radionuclides from uranium tailings and contaminated lands. To enhance the practical application of the code, an interface with the NORMALYSA Tool has been developed, that allows performing dose calculation using outputs generated from simulations with HGC TPC.

The NORMALYSA (NORM And LegacY Site Assessment) 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, etc.) and to estimate resulting radiation exposure doses to humans. The NORMALYSA software was developed by Facilia AB (Bromma, Sweden) with the support of the International Atomic Energy Agency (IAEA).

The NORMALYSA tool consists of a Simulator program engine, which is integrated with a set of program modules organized in five main libraries: ‘Sources’, ‘Cover Layers’, ‘Transports’, ‘Receptors’ and ‘Doses’. Specific modelling cases can be constructed by selecting need modules and setting up data exchanges between these modules.

HGC - NORMALYSA, allows running NORMALYSA models using as input values of radionuclide concentrations in groundwater and radionuclide fluxes obtained from simulations of reactive transport with HGC TPC. This way an integrated tool has been attained that can be used for assessments of radiological impacts from contaminated lands and surface deposits of waste, such as uranium tailings.

HGC-NORMALYSA functions as follows: From simulations with HGC TPC time series of radionuclide concentrations and fluxes in different points at the interface between the contaminated groundwater and target environments of interest is obtained. The values for different points in space are then postprocessed to obtain input data required by the models available in NORMALYSA for the different target environments.

First, the report describes overall architecture and functionality of HGC – NORMALYSA.

Next chapters, that are focused on main module libraries, provide detailed descriptions of specific of individual models included to this library.

The Appendix to the report contains a compilation of radioecological and dose assessment parameters used by various NORMALYSA modules.

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1. INTRODUCTION

This report presents the user manual for HGC - NORMALYSA - software consisting of NORMALYSA integrated with HYDROGEOCHEM from the Taiwan Central University (HGC TPC).

The HGC TPC code has been widely applied in simulations of releases of radionuclides from uranium tailings and contaminated lands. To enhance the practical application of the code, an interface with the NORMALYSA Tool has been developed, that allows performing dose calculation using outputs generated from simulations with HGC TPC.

The NORMALYSA (NORM And LegacY Site Assessment) 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, etc.), and to estimate resulting radiation exposure doses to humans.

The NORMALYSA software 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) in 2013-2016 in the frame of IAEA MODARIA project (Modelling and Data for Radiological Impact Assessments) Work Group 3 (NORM and Radioactively Contaminated Legacy Sites) activities.

The NORMALYSA software tool is based on the Ecolego 6 (http://ecolego.facilia.se/ecolego/) software [Avila et al., 2005]. 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).

The NORMALYSA tool consists of a Simulator program engine, which is integrated with a set of program modules organized in five main libraries: ‘Sources’, ‘Cover Layers’, ‘Transports’, ‘Receptors’ and ‘Doses’. Specific modelling cases can be constructed by selecting need modules and setting up data exchanges between these modules.

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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 in the following main libraries: ‘Sources’ and ‘Cover Layers’, ‘Transports’, ‘Receptors’, ‘Doses’ (FIG. 1).

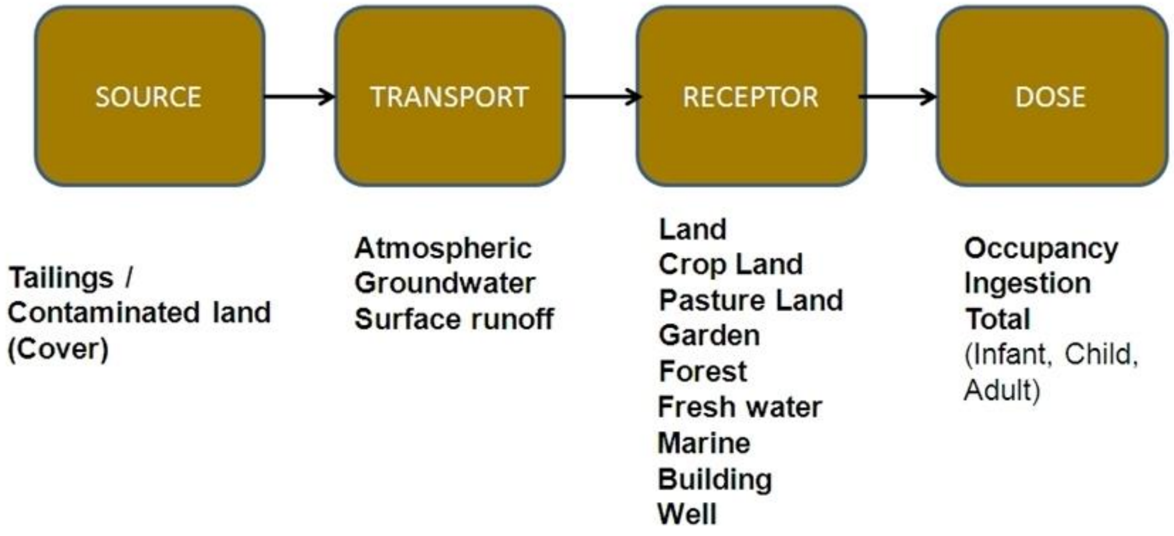

FIG. 1 Conceptual schematization of "source -> impact" analysis in NORMALYSA software tool.

The software architecture of NORMALYSA allows easily configuring 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 next section for more detail on user interface).

NORMALYSA tool is currently based on relatively simple environmental transport and exposure assessment models. NORMALYSA uses several models that have been used in safety assessment of radioactive waste disposal facilities performed by Swedish Nuclear Fuel and Waste Management Company (SKB) [SKB, 1999, 2006]. For some of the radionuclide migration and transfer process NORMALYSA uses models recommended by the IAEA [2001, 2004a-b, 2009, 2010]. The discussed models can be especially useful in early stages of safety assessment, as well as for conservative radionuclide transport and dose assessment analyses (e.g., for getting 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 the reputable parameter compilations (e.g., [IAEA, 2009, 2010; SKB, 2010a-b, 2013]).

The following blocks have been added to the NORMALYSA library to allow for the coupling with HYDROGEOCHEM:

- HGC processed fluxes.

  This block can be used if the HGC TPC simulation and postprocessing has previously been performed (outside of HGC-NORMALYSA. The block reads the results from the postprocessing and produces the inputs required by the HGC-NORMALYSA models. The user must provide the link to one external file: Result file from postprocessing (*.dat). The block produces the following outputs for one target environment: area of the target environment and time series of radionuclide net fluxes at the interface with the target environment.

- HGC processed concentrations.

  This block can be used if the HGC TPC simulation and postprocessing has previously been performed (outside of HGC-NORMALYSA. The block reads the results from the postprocessing and produces the inputs required by the HGC-NORMALYSA models. The user must provide the link to one external file: Result file from postprocessing (*.dat). The block produces the following outputs for one target environment: time series of radionuclide concentrations at the interface with the target environment.

2.2.USER INTEFACE AND FUNCTIONALITY

2.2.1. Software user interface

As already mentioned, NORMALYSA consists of the Simulator and of a set of module libraries (see previous paragraph).

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

Simulator supports classical “Interaction Matrix” interface and graphical “Block-Scheme” interface. Example of the “Interaction Matrix” interface is shown at FIG. 2.

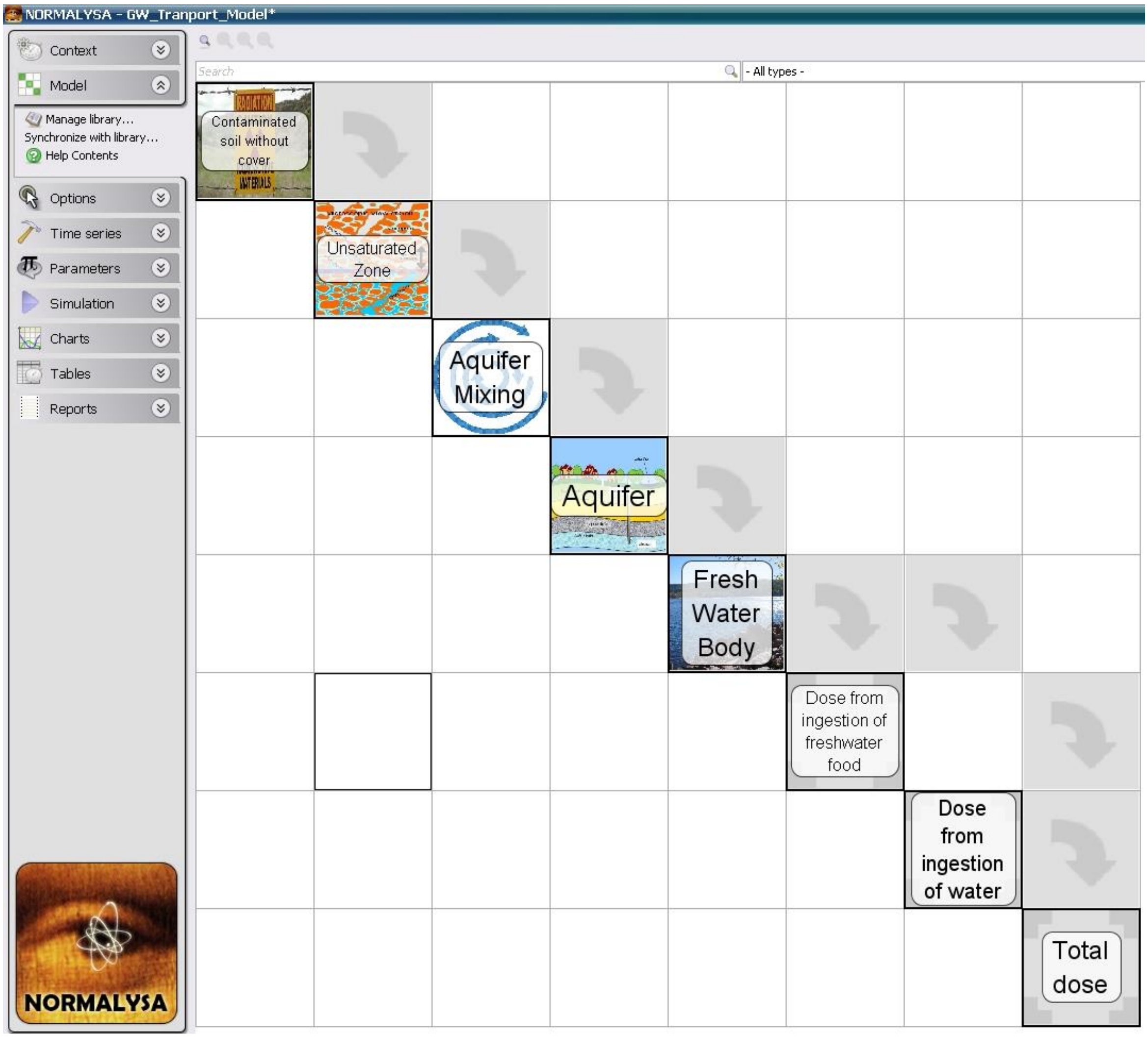

FIG. 2 Interface of NORMALYSA software tool in "Interaction Matrix" format for an example problem describing radionuclide transport in "Contaminated Site – Groundwater – Surface Water" system.

This interface allows easily:

- selecting needed program modules from libraries,
- “connecting models”, that is setting data exchanges between these modules,
- specifying input parameters,
- running the assembled model, and
- examining outputs and analyzing simulation results (table and/or graph formats).

The interface of the Simulator module allows for choosing between English, Spanish and Russian languages.

2.2.2. Functionality

The NORMALYSA Simulator includes the simulation capabilities and functionality inherent to Ecolego 6 modeling platform. This includes:

- built-in radionuclide database (see Section 2.3.1 for the list of radionuclides),
- powerful numerical solvers for ordinary differential equations (ODE-s), which are used to mathematically describe radionuclide transport and transfer process,
- capabilities for probabilistic simulation and sensitivity analyses,
- output data processing capabilities, including graphical presentation of modeling results, and
- report generation options.

2.2.3. List of radionuclides

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

^{238}U decay series (^{238}U → ^{234}U → ^{230}Th → ^{226}Ra → ^{210}Pb → ^{210}Po),

^{238}Pu decay series (^{238}Pu → ^{234}U → ^{230}Th → ^{226}Ra → ^{210}Pb → ^{210}Po

^{232}Th decay series (^{232}Th → ^{228}Ra → ^{228}Th),

^{235}U decay series (^{235}U → ^{231}Pa → ^{227}Ac),

^{222}Rn,

^{137}Cs and ^{90}Sr.

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

User has an option also to add additional radionuclides to the model. However, in this case user will need to specify values of all relevant radionuclide-specific radiecological parameters for NORMALYSA modules used.

2.3.MODULE LIBRARIES (OVERVIEW)

NORMALYSA includes five module libraries describing different components (elements) of the modeled system in accordance with the “source -> impact” analysis schematization shown at FIG. 1. Brief overview of these module libraries is presented below. Detailed descriptions of various libraries and individual modules (and respective radiecological models) included to these libraries is presented in the subsequent chapters of this report.

2.3.1. Sources

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

The source-term modules included to 'Sources' library are described in Table 1. Detailed description of this library and individual modules is provided in Section 3.

Table 1 Description of modules in 'Sources' library.

Module	**Description**
Tailings without cover	This module is designed to describe radionuclide fluxes to subsurface environment and /or radon exhalation to atmosphere from the uranium mill tailings site. The source term is modeled as a single compartment. The radionuclide leaching from soil is described using model of Baes and Sharp [1983]. Radon exhalation to atmosphere is modeled using diffusion model described in [IAEA, 2013] (see Section 3.2 for more detail)
Contaminated land without cover	This module describes radionuclide fluxes to subsurface environment and /or radon exhalation to 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 radioactive contaminant to atmosphere and/or groundwater or surface water body (see Section 3.3 for more detail)

2.3.2. Cover layers

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

Table 2 Description of modules in 'Cover layers' library.

Module	**Description**
Cover Layer	Module allows simulating soil covers over the source in order to calculate resulting radon exhalation rate and concentration in air above the cover, as well as the external dose rate. Radon exhalation to atmosphere is modeled using diffusion model described in [IAEA, 2013]. External dose calculations are

	based on methodology described in [Kamboj et al., 1998] (see Section 4.2 for more detail)
House Slab	This module allows simulating the effect of the house slab residing on contaminated soil layer on radon diffusive flux to house and external dose rate above the slab. It implements models similar to “Cover layer” module described above (see Section 4.2 for more detail)

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. Detailed description of this library and individual modules is provided in Section 5.

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 radionuclide transport process in the subsurface. The modeled radionuclide transport mechanisms include advection, dispersion and retardation due to sorption (Kd model). Radionuclide transfers due to advection and dispersion process in groundwater are modelled using the approach described in [IAEA, 2004, Annex C] (see Sections 5.2 and 5.3 for more detail)
Unsaturated zone	This module simulates 1D vertical radionuclide transport in the unsaturated zone. The modeled radionuclide transport mechanisms include advection, dispersion and retardation due to sorption (Kd model). Radionuclide transfers due to advection and dispersion process are modelled using the approach described in [IAEA, 2004, Annex C] (see Section 5.4 for more detail)
Surface Runoff	This module simulates radionuclide mobilization and transport in surface runoff from the soil of 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 [Bulgakov et al., 1999]. Radionuclide concentrations in runoff water and adsorbed on suspended particles are calculated using the equilibrium Kd-based sorption models, while the soil erosion process is described using empirical coefficient (see Section 5.5 for more detail)
Atmosphere SR-19	This module simulates atmospheric dispersion of contaminant from the point source using Gaussian plume atmospheric dispersion model described in [IAEA, 2001] (see Section 0 for more detail)
Atmosphere chronic	This module calculates 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

	(that shall 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)

2.3.4. Receptors

The 'Receptors' library includes modules for calculation of radionuclide transfer and redistribution process in different types of receptor environments, such as different types of lands (crop lands, pasture lands, forests, uncultivated lands etc.), buildings, surface water bodies (lakes and rivers), and near-shore (coastal) marine environment. These modules are essentially based on radioecological models that have been developed and used by SKB in safety assessment of radioactive waste disposal facilities [SKB, 1999, 2006]. The respective receptor modules are described in Table 4. Detailed description of this library and individual modules is provided in Section 6.

Table 4 Description of modules in 'Receptors' library

Module	**Description**
Land	This module simulates the contaminated land where exposure of 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. The implemented radiecological model dynamically simulates vertical distribution of radionuclides in soil profile (consisting of "top" and "deep" zone compartments), and it accounts for losses from the soil through erosion, bio-turbation (using diffusion-type transfer models) and leaching processes [SKB, 1999]. The model calculates the concentration of radionuclides in soil, as well as concentration of radionuclides in outdoor air due to resuspension from soil (see Section 6.1 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 [IAEA, 2010]. 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, bio-turbation and leaching processes [SKB, 1999] (see Section 6.1 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 can 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 6.4 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

Module	**Description**
	model is generally similar to the ‘cropland’ model described above, while it also accounts for radionuclide transfers to the livestock due to ingestion of contaminated forage and water using the transfer factor approach (see Section 6.2 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 soil profile (consisting of “top” and “deep” zone compartments) and radionuclide concentrations in the tree (leaves, tree wood, understory, litter compartments) and forest food species (berries, mushrooms and game animals) [SKB, 2006]. 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 6.5 for more detail)
Freshwater body	The module covers exposure pathways associated with utilizing of the water body (lakes, rivers and streams) as a source of drinking water, as a source of aquatic foods, as well as for recreational activities such as swimming and boating. The water body can 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 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 transfer factor approach). The implemented model is based on ‘LAKE’ model described in [SKB, 1999] (see Section 6.8 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 model dynamically simulates distribution of radionuclides in abiotic media such as water (“inner” sea compartment), suspended particulate matter and sediments (“top” and “deep” sediment compartments) and biotic media (fish and other edible sea organisms; using transfer factor approach). The model implemented in NORMALYSA is based on ‘COAST’ model described in [SKB, 1999] (see Section 6.9 for more detail)
House	This module is used for assessment of indoor air concentrations of radionuclides (including radon). Radionuclides enter house due to exchange with outdoor air. Radon enters house due to diffusion through basement slab, and its concentration is calculate using mathematical expression accounting for inflow from basement (by diffusive flux) and ventilation by outdoor air (see Section 6.6 for more detail)
Well	This module calculates radionuclide concentration in the groundwater extracted by well. It employs simple mixing model for contaminated groundwater migrating from the source (e.g., output of “Aquifer” transport module) and non-

Module	**Description**
	contaminated groundwater with “background” concentration (see Section 6.7 for more detail)

2.3.5. Doses

A set of modules included to ‘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 modeler has also 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/day). The reference persons can belong to different age groups: adults, children (10 year olds) and infants (1 year olds). 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 [EPA, 1993]. Dose coefficients for internal exposure through inhalation and ingestion pathways are based on ICRP Publication no.72 [ICRP, 1995b].

Detailed description of this library and individual modules is provided in Section 7.

Table 5 Main exposure pathways considered for the different receptor environments.

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 terrestrial food									
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 to water).

Table 6 Description of modules and sub-libraries 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 remarks to 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 MODEL IN HGC-NORMALYSA

Setting up and running a model in HGC-NORMALYSA includes seven main steps shown in FIG. 3. The HGC-NORMALYSA simulator module uses a simple and intuitive GUI that is generally similar to the interface of Ecolego 6 (http://ecolego.facilia.se/ecolego/) software. The main steps to run a simulation are briefly explained below.

2.4.1. Setting of assessment context

In this step, the Ecolego project file is created defining the simulation case. In particular, user specifies the name of the project file, and selects radionuclides to be included to the simulation case. User can also input additional radionuclides (to those listed in Section 2.2.3).

Modeler also has a possibility to activate or de-activate specific index lists relevant to modeled case such as, for example, ‘Reference persons’, ‘Age groups’ or specific food types included to simulation, etc.

User can also manage here specific interface options, such as language of software interface and some other options.

2.4.2. Defining the model

This is the key step in setting up the modeling case, where user sets up the radioecological model. For composing the model, the Simulator supports classical Ecolego “Interaction Matrix” interface and graphical “Block-Scheme” interface (see FIG. 2).

The radiecological model can be composed from modules included to libraries described in Section 2.3. User selects modules needed for his modeling case and sets up data exchanges between modules.

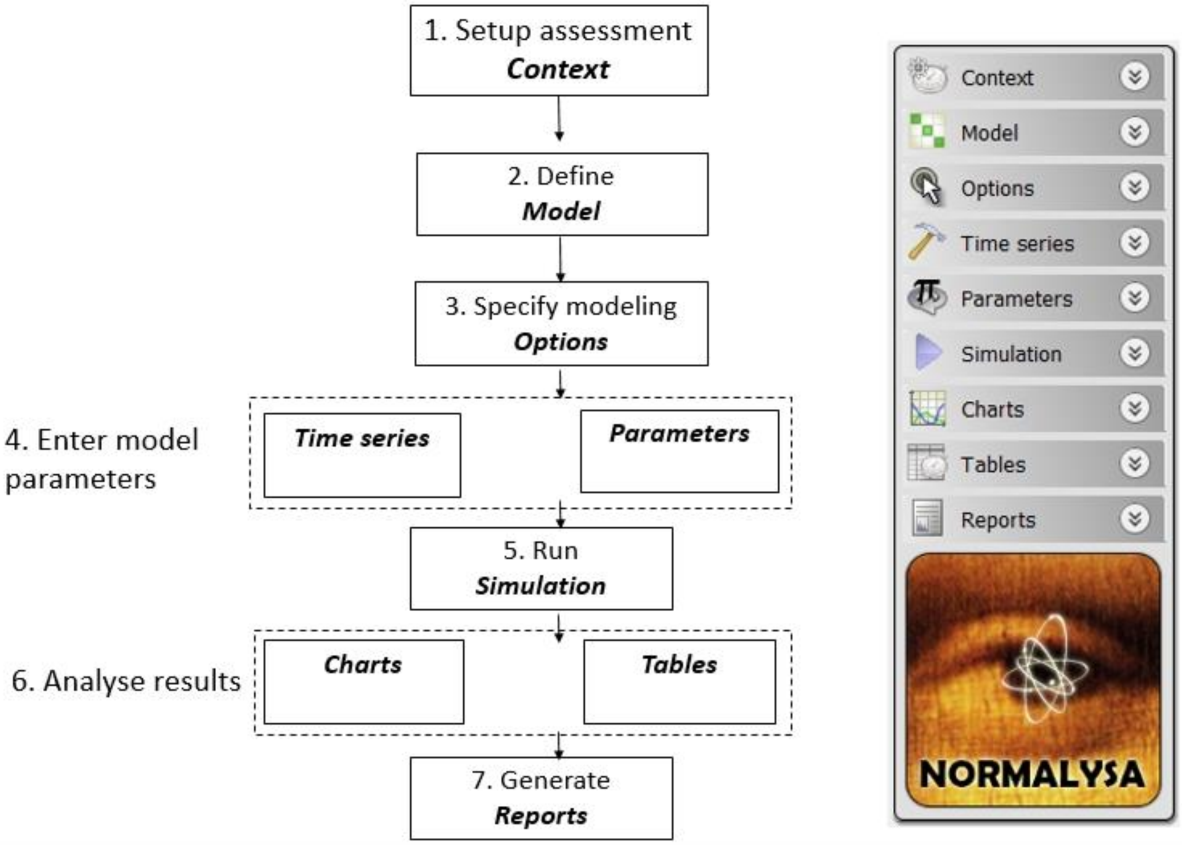

FIG. 3 Seven steps for performing assessment using NORMALYSA software tool.

2.4.3. Specifying modeling options

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

For example, modeler can specify whether dose calculations will employ predetermined radionuclide concentrations in soil (e.g., based on monitoring data), or these will be modelled dynamically using 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 parameter values are detailed along with references below in the report in sections describing module libraries.

User has possibility to modify all model parameters. Some of these need not to be necessarily changed (for example, radionuclide Kd values for soil, or dose coefficients for dose assessment simulations). However, almost any model includes site-specific and/or modeling case specific parameters that will be need to be specified by user.

The Simulator menu includes two menu items for input of model parameter values: ‘Time series’ and ‘Parameters’.

The ‘Time series’ menu allows entering in table format those input parameters of the model that are time-dependent (if any).

The ‘Parameters’ menu allows to enter parameters representing individual values as well as parameters depending of index lists (e.g., radionuclides, or age categories of reference persons, etc.).

User has possibility to carry out parameter export / import operations using Excel file format (similarly to Ecolego 6 functionality).

2.4.5. Running the simulation

This menu allows user to set up simulation options (e.g., starting and ending times, etc.), and eventually to run the model. User can activate here the index list related to ‘Scenarios’.

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

2.4.6. Analyzing results

The Simulator menu includes two menu items for analyzing simulation results: ‘Charts’ and ‘Tables’. These menu items allow modeler to view data either in chart or table format. Various table / chart options are available by means of respective menus, that are generally similar to those provided by Ecolego 6 user interface. Simulation data can be exported to Excel format.

2.4.7. Generating reports

This menu allows to generate automatically modeling 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 user interface of NORMALYSA Simulator can be obtained from context sensitive ‘Help Content’ menu.

3. ‘SOURCES’ MODULE LIBRARY

3.1.GENERAL DESCRIPTION OF LIBRARY

The ‘Sources’ library includes modules for calculation of radionuclides releases to atmosphere and groundwater from contaminated object (source-tem) such as uranium mill tailings and contaminated land.

The library includes three modules: ‘Tailings Without Cover’, ‘Contaminated Soil Without Cover’ and ‘Chronic Release’ (see Table 1).

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

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

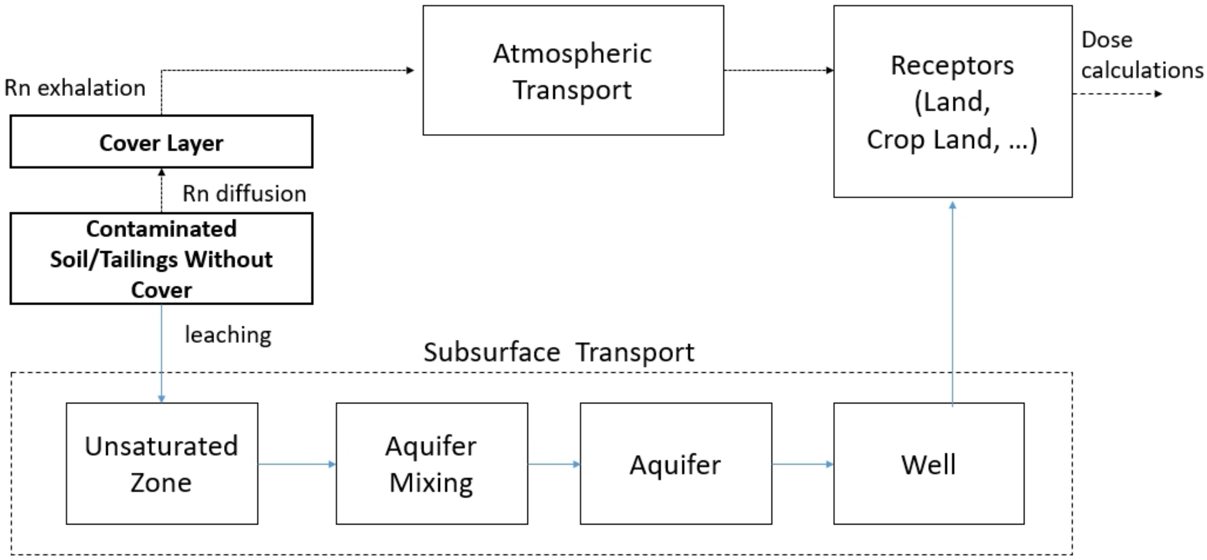

FIG. 4 Combined used of Source Term modules along with transport and receptor modules of NORMALYSA library.

3.2.‘TAILINGS WTHOUT COVER’ AND ‘CONTAMINATED SOIL WITHOUT COVER’ MODULES

3.2.1. Module description

3.2.1.1.General description

In this section ‘Tailings Without Cover’ and ‘Contaminated Soil Without Cover’ modules are described.

Both modules implement similar mathematical models for radionuclides 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 Rn-222 diffusion in waste material and exhalation to atmosphere) (FIG. 4). These modules have similar organization and same notation of main model variables and parameters.

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

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

Estimated Rn-222 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 Soil Without Cover’ modules assumes 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 (FIG. 5).

Hydraulic leaching process

For radionuclide leaching from contaminated soil by infiltrating atmospheric water, modules use the model described in [Baes and Sharp, 1983]. This models 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 (here Kd is sorption distribution coefficient). Mathematical equations of the model are described in Section 3.2.2.

The discussed source term modules 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).

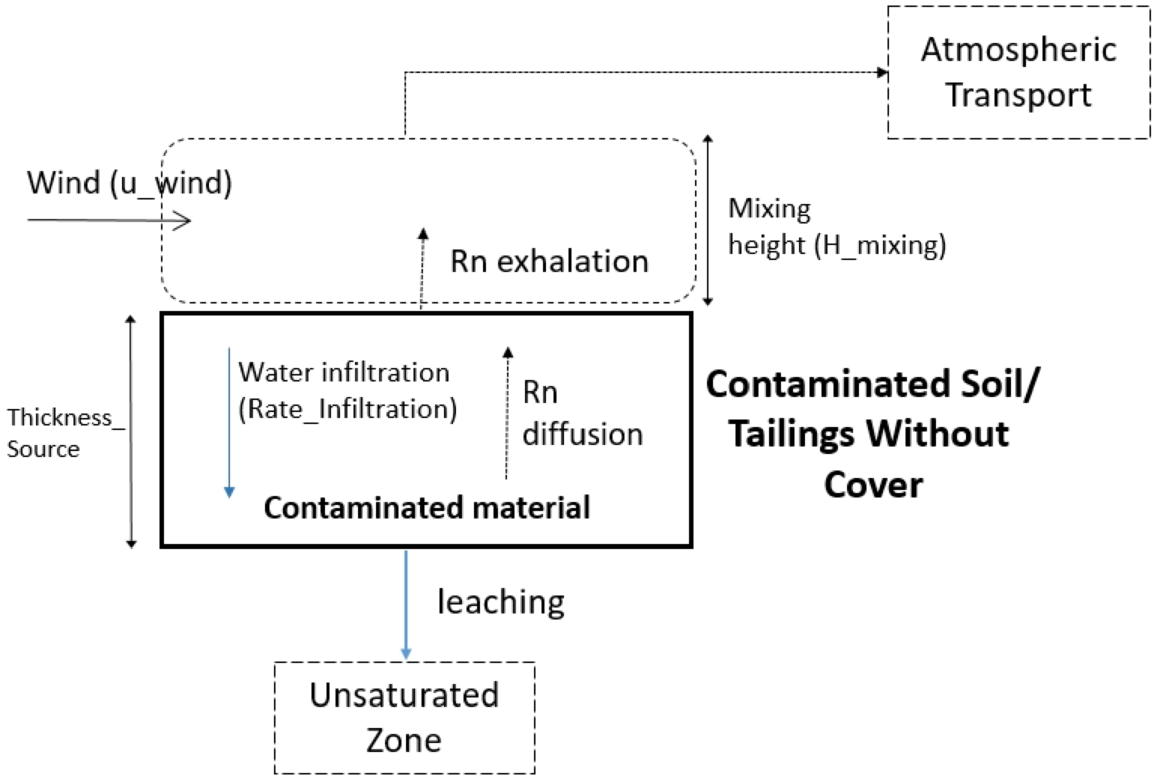

FIG. 5 Conceptual model of 'Contaminated Soil / Tailing without Cover' Modules.

Radon diffusion and exhalation from waste material

For radon (Rn-222) exhalation from waste material, the diffusion model from the [IAEA, 2013; p. 41] is used. This model assumes that the contaminated soil/waste layer thickness is much greater than the radon diffusion length.

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

Radon concentration in air above the contaminated soil layer is calculated using the atmospheric mixing model described in [Yu et al., 2001; p.C-9].

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

- The annual average Rn 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 Rn-222 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 open atmosphere. Once in the open atmosphere, emanated radon is influenced by the dynamics of the wind, which remove part of radon. Radon emanation from soil and radon removing 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

The 'Tailings Without Cover' and 'Contaminated Soil Without Cover' modules first of 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 be used also to calculate exposure of a person present immediately at the contaminated site (Table 7).

Table 7. Potential coupled modules from NORMALYSA library for 'Tailings Without Cover' and 'Contaminated Soil Without Cover' modules.

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

3.2.2. Mathematical model

3.2.2.1.Mass balance equation for the source term compartment

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

$$\frac{dSource}{dt} = Infiltration - Source \times Leaching - \lambda \times Source + \qquad \text{Eq. (1)}$$

$$\sum_{p \in P} Br_p \times \lambda \times Source$$

Where

Infiltration = mass transfer by infiltration (inflow) to the contaminated source (soil) layer (Bq/day).

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

The two last right hand side terms in Eq. (1) describe radioactive decay and ingrowth of radionuclides.

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

$$Infiltration = c_{\inf iltration}\, rate_{\inf iltration}\, area_{Source}$$

Where

$C_{infiltration}$ = radionuclide concentration in water infiltrating to the contaminated material (soil) layer (Bq/m^3),

$Rate_{infiltration}$ = infiltration rate to contaminated site (m/day),

$area_{source}$ = area of contaminated site (m^2).

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

The radionuclide mass transfer coefficient from containated source (soil) layer due to leaching is given by [Baes and Sharp, 1983; IAEA, 2004b]:

$$leaching = \frac{rate_{\inf iltration}}{moisture_{source} \times Thickness_{Source} \times Ret_{Source}}$$

Where

$moisture_{source}$ = is moisture content in source (soil) material (unitless),

$Thickness_{Source}$ = thickness of the contaminated material (soil) layer (see FIG. 5) (m),

Ret_{source} = is retardation coefficient due to radionuclide sorption on source (soil) materials (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{source} = 1 + \frac{rho_{source}}{moisture_{source}} \times Kd_{source}$$

Where

Rho_{source} = density of source (soil) material (kg.DW/m^3),

Kd_{source} = 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)

Radionuclide concentration in source (soil) material (C_{source}, Bq/kg) is calculated dynamically as:

$$C_{Source} = {}^{Source}\!/_{(area_{source} \cdot Thickness_{source} \cdot rho_{source})}$$

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

$$C_{water,pore,out} = \frac{C_{iwaste} \times rho_{source}}{moisture_{source} \times Ret_{Source}}$$

3.2.2.4. Radionuclide flux in outflowing pore water ($Flux_{out,gw}$, Bq/day)

$$Flux_{out,gw} = c_{water,pore,out} \times rate_{\mathrm{inf}\,iltration} \times area_{Source}$$

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

$$Rate_{release,atm} = Radon_{flux,out} \times area_{source}$$

Where

$Radon_{flux,out}$= radon emission rate from the source per unit area (Bq/(m^2.s)).

Radon emission rate from the source ($Radon_{flux,out}$, $Bq/(m^2.s)$)

Radon emission (exhalation) from the source is given by formula [IAEA, 2013; p. 41]:

$$Radon_{flux,out} = rho_{source} \times C_{source}[Ra - 226] \times coeff_{eman} \times$$

$$\sqrt{\lambda_{Rn} \times D_{radon,source}} \times tanh\left({}^{Thickness_{source}}\!/_{\sqrt{D_{radon,source}/\lambda_{Rn}}}\right)$$

Where

$Coeff_{eman}$ = Rn emanation coefficient from source (soil) layer (unitless),

$D_{radon,source}$ = diffusion coefficient of Rn in the source (soil) layer (m^2/s),

λ_{Rn} = radon decay constant (1/s).

3.2.2.6.Radon concentration in outdoor air above the source ($Radon_{conc,air}$, *Bq/m^3*)

Radon concentration in outdoor air above the source is given by formula [Yu et al., 2001]:

$$Radon_{conc,air} = Rn_{flux,out} \times F_{a0} \times (1 - \exp\left(-\lambda_{Rn} \times \frac{0.5 \times length_{eff}}{U_{wind}}\right)) \qquad Eq.(2)$$

$$\times \frac{1}{\lambda_{Rn} \times H_{mixing}}$$

Where

F_{a0} = outdoor area factor (unitless),

$length_{eff}$ = “effective length” of contaminated site (m),

U_{wind} = average wind speed (annual)(m/s),

H_{mixing} = mixing height for radionuclides above the source (m).

Here the “effective length” of contaminated site is calculated as:

$$length_{eff} = \sqrt{area_{source}}$$

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

$$F_{a0} = \begin{cases} \frac{area_{source}}{100}, for\ area_{source} < 100\ m^{\ 2}, \\ 1.0\ \ for\ area_{source} > 100\ m^{\ 2} \end{cases}$$

It is also taken into account in calculations that the ratio

$$CF_{ratio} = Radon_{conc,air}/Radon_{flux,out}$$

is bounded by the value 500 s/m [Yu et al., 2001]. Therefore if calculations using Eq.(2) yield value CF_{ratio} >500 m/s, then the following corrected value is used for outdoor Radon concentration:

$$Radon_{conc,air} = Rn_{flux,out} \times 500.$$

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/day)	Infiltration recharge rate to the source material (soil)	1.37E-04	Site specific parameter
Kd_source (m^3/kg.DW)	Sorption distribution coefficient (radionuclide specific) of source material (soil)	Table I- 1 (Appendix I)	[IAEA, 2010; Table 14]

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	[IAEA, 2013]
D_radon_source (m^2/s)	Radon diffusion coefficient in source (soil) material	1.3E-6	[IAEA, 2013]
H_mixing (m)	Mixing height of radionuclides above the source	2	[Yu et al., 2001]
U_wind (m/s)	Average wind speed	2	Site specific parameter

3.2.4. Output parameters

The output parameters of the described above source term module 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 out-flowing from the source term modules	Can be used to calculate further radionuclide transport in the underlying unsaturated zone and/or aquifer (see Table 7)
Flux_out (Bq/day)	Radioactive contaminant flux from the source term modules	Can be 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)	Can be 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	Can be 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	Can be used to estimate doses from the external irradiation for a person exposed to radioactivity at the site

3.3.‘CHRONIC RELEASE’ MODULE

3.3.1. Module description

3.3.1.1.General description

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

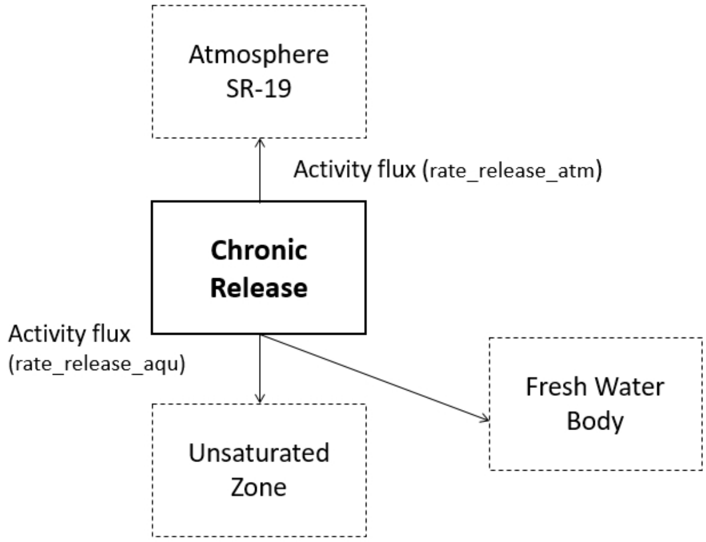

FIG. 6 Conceptual model of the ‘Chronic Release’ module.

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 following modules	
‘Atmosphere SR-19’	Radionuclide flux to the atmosphere (Bq/s) from contaminated site
‘Unsaturated Zone’, ‘Aquifer Mixing’, ‘Aquifer’	Radioactive contaminant activity flux to subsurface (Bq/day) in infiltrating water
‘Fresh water Body’, ‘Marine’	Radioactive contaminant activity flux (Bq/day) to surface water body

3.3.2. Mathematical model

As already mentioned, modeler 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/day)	Radioactive contaminant flux from the source term to aquatic environment	0	Can be 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	Can be used to calculate further radon dispersion in the atmosphere (see Table 12)

4. ‘COVER LAYERS’ MODULE LIBRARY

4.1.GENERAL DESCRIPTION OF LIBRARY

The ‘Cover Layers’ library includes modules for simulating soil covers over the source in order 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: ‘Cover Layer’ and ‘House Slab’. The ‘Cover Layer’ module allows simulating a soil cover on top the uranium mill tailings, and it calculates 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 contaminated soil layer on the radon diffusive flux to house and external dose rate above the slab. Detailed descriptions of these modules are provided below.

4.2. ‘COVER LAYER’ AND ‘HOUSE SLAB’ MODULES

4.2.1. Module description

4.2.1.1.General description

The objectives of ‘Cover Layer’ and ‘House Slab’ modules are to model respectively cover layer of soil (i.e., engineered barrier) or house slab (basement) on top of the source term of radioactivity (such as ‘Tailings without Cover’ or ‘Contaminated Soil without Cover’ modules discussed in the previous section of this report) (FIG. 7).

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

- Radon (Rn-222) release rate to atmosphere and concentration in the atmosphere above the contaminated site, and
- Dose rate on the surface of the contaminated site covered by 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 multi-layer soil cover with varying physical

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

Below the conceptual, 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 listed above remark).

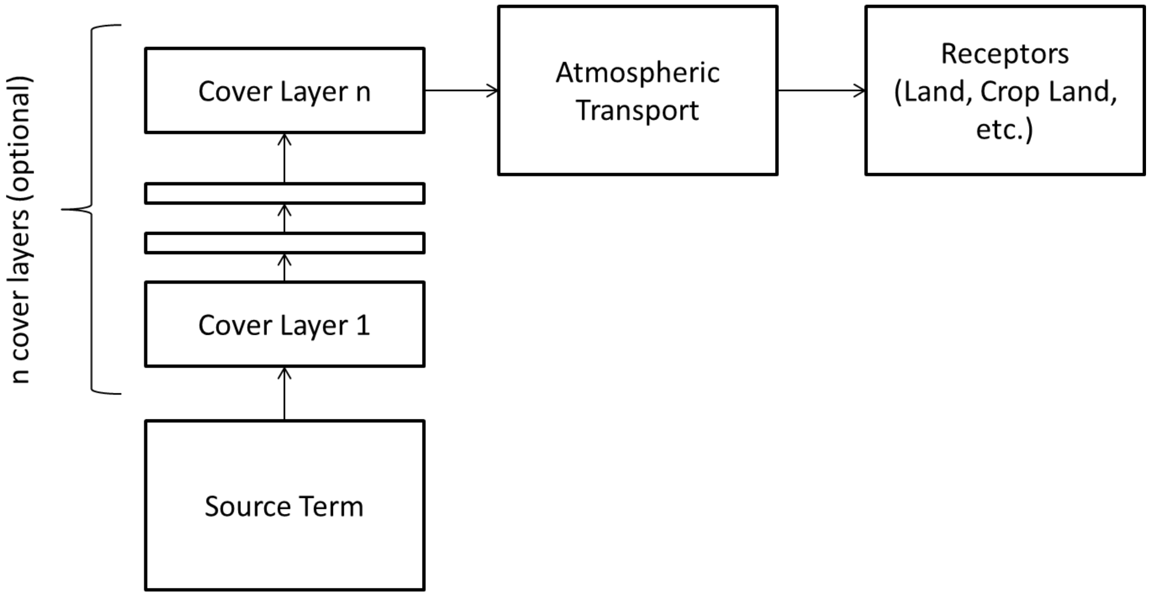

FIG. 7 Scheme illustrating application of 'Cover Layer' module for modelling atmospheric releases from source term of radioactivity.

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 it physical properties and parameters.

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

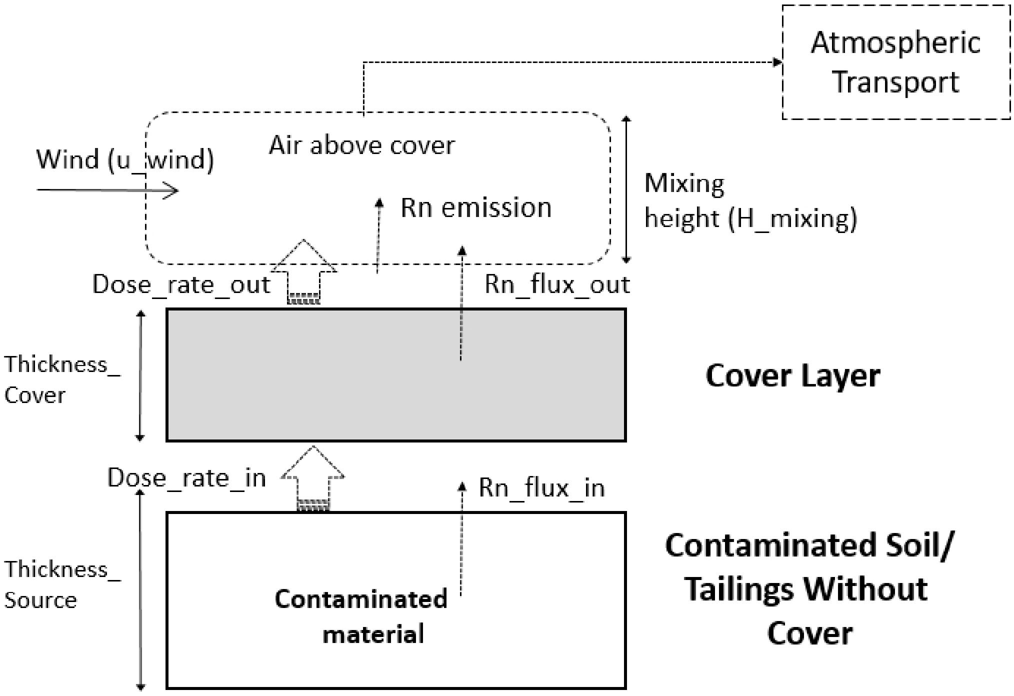

FIG. 8 Conceptual model of 'Cover Layer' module.

For modelling impact of soil cover on radon release rate to atmosphere the model is used that is described in [IAEA, 2013; p.43].

Radon concentration in air above the soil cover is calculated using the atmospheric mixing model described in [Yu et al., 2001; p.C-9]. The underlying assumptions are discussed in Section 3.2.1.2.

To calculate dose rate from contaminated site covered by one or several cover layers, the approach is used described in [Kamboj et al., 1998].

4.2.1.3.Potential coupled modules

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

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 soil without Cover', 'Tailings Without Cover'; previous 'Cover Layer' module	Radon (Rn-222) flux to atmosphere (Bq/day) 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 (Rn-222) flux to atmosphere (Bq/s) from contaminated site
'Dose from Occupancy Outdoors'	Effective dose rate outdoors (Sv/h), concentration of Rn-222 in outdoor air (Bq/m^3)
'Cover Layer' (next module)	Radon (Rn-222) flux to atmosphere (Bq/s) from contaminated site; effective dose rate from contaminated material per radionuclide (Sv/h)

4.2.2. Mathematical model

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

$$Rate_{release,atm} = Radon_{flux,out} \times area_{source}$$

Where

$Radon_{flux,out}$ = radon emission rate from the cover layer per unit area (Bq/(m^2.s)).

Radon emission rate from the cover layer (Radon_flux_out, Bq/(m²^2.s))

Radon emission (exhalation) from the cover layer (*Radon_flux_out*, *Bq/(m^2.s)*) is given by formula [IAEA, 2013; p. 43]:

$$Radon\_flux\_out = Radon\_flux\_in \times exp\left(-thickness\_cover \times \sqrt{\frac{\lambda_{Rn}}{D_{cover}}}\right)$$

Where

Radon_flux_in = radon emission rate to cover layer from the source of radioactivity or previous cover layer (Bq/(m^2.s)),

Thickness_cover = tickness of cover layer (m),

D_{cover} = diffusion coefficient of Rn in the cover layer (m^2/s),

λ_{Rn} = radon decay constant (1/s).

4.2.2.2. Radon concentration in outdoor air above the cover layer (*Radon$_{conc,air}$*, *Bq/m^3*)

Radon concentration in outdoor air above the cover layer is given by formula [Yu et al., 2001]:

$$Radon_{conc,air} = Rn_{flux,out} \times F_{a0} \times (1 - \exp\left(-\lambda_{Rn} \times \frac{0.5 \times length_{eff}}{U_{wind}}\right)) \times \frac{1}{\lambda_{Rn} \times H_{mixing}} \qquad Eq.(\,3)$$

Where

F_{a0} = outdoor area factor (unitless),

$Length_{eff}$ = “effective length” of contaminated site (m),

U_{wind} = average wind speed (annual)(m/sec),

H_{mixing} = mixing height for radionuclides above the source (m).

Here the “effective length” of contaminated site is calculated as:

$$length_{eff} = \sqrt{area_{source}}$$

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

$$F_{a0} = \begin{cases} \frac{area_{source}}{100}, for\ area_{source} < 100\ m^{\,2}, \\ 1.0\ \ for\ area_{source} > 100\ m^{\,2} \end{cases}$$

It is also taken into account in calculations that the ratio

$$CF_{ratio} = Radon_{conc,air}/Radon_{flux,out}$$

is bounded by the value 500 sec/m [Yu et al., 2001]. Therefore if calculations using Eq.(3) yield value CF_{ratio} >500 m/s, then the following corrected value is used for outdoor Radon concentration:

$$Radon_{conc,air} = Rn_{flux,out} \times 500.$$

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

$$doseRate_{eff,out} = \sum_i doseRate\_eff\_out\_RN_i$$

Where

$doseRate\_eff\_out\_RN_i$ = dose rate formed by radionuclide *'i'* (Sv/h).

Dose rate formed by radionuclide 'i' (doseRate_eff_out_RN$_i$, Sv/h)

$$doseRate\_eff\_out\_RN_i = doseRate\_eff\_out\_RN\_in_i \times Factor\_Cover_{dept}$$

Where

$doseRate\_eff\_out\_RN\_in_i$ = dose rate formed by radionuclide 'i' before attenuation by cover (Sv/h),

$Factor\_Cover_{depth}$ = 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 thickness and density of cover material is given by the following formula [Kamboj et al., 1998]:

$$Factor\_cover_{deptih,i} = \left(A_i \times \exp\left(-0.1 \times K_{A,i} \times rho_{cover_{eff}} \times Thickness_{cover_{out}}\right)\right) \times$$

$$\left(1.0 - \exp\left(-0.1 \times K_{A,i} \times rho_{source} \times Thickness_{source}\right)\right) + \left(B_i \times \exp\left(-0.1 \times K_{B,i} \times rho_{cover_{eff}} \times Thickness_{cover_{out}}\right)\right) \times$$

$$(1.0 - \exp(-0.1 \times K_{B,i} \times rho_{source} \times Thickness_{source}))$$

Where

rho_source = density of source term layer (Bq/kg.DW),

rho_cover_eff = effective cover density, calculate as the sum of cover densities weighted by cover thicknesses (kg.DW/m^3),

Thickness_source = thickness of source term layer (m),

Thickness_cover_out = total thickness of covers (m),

A_i , B_i, = tabulated fitted radionuclide-specific parameters for calculating cover correction factors (unitless) (provided in [Kamboj et al., 1998]),

$K_{A,i}$, $K_{B,i}$ = tabulated fitted radionuclide-specific parameters for calculating cover correction factors (g/cm^2) (provided in [Kamboj et al., 1998]).

Here

rho_cover_eff = *rhoXthickness_out* / *Thickness_cover_out.*

Where

rhoXthickness_out = cumulative sum of products of density cover times cover thickness for all cover layers ($kg.DW/m^2$).

The last parameter is defined as:

rhoXthickness_out = *rhoXthickness_in* + *rho_cover* × *Thickness_cover*,

Where

rhoXthickness_in = product of density cover times cover thickness for previous layer(s) (input parameter to be provided by modeler) ($kg.DW/m^2$).

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

Abbreviation and unit	**Full name**	**Default value**	**Reference**
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	[IAEA, 2013]
H_mixing (m)	Mixing height of radionuclides above the cover layer	2	[Yu et al., 2001]
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)	Can be 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	Can be 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	Can be 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 LIBRARY

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

Modules ‘Aquifer Mixing’, ‘Aquifer’, and ‘Unsaturated Zone’ are designed for modeling groundwater transport. Modules ‘Atmosphere SR-19’ and ‘Atmosphere Chronic’ simulate radionuclide transport in the atmosphere. The ‘Surface runoff’ module simulates radionuclide transport from 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 radionuclide migration process in subsurface environment.

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

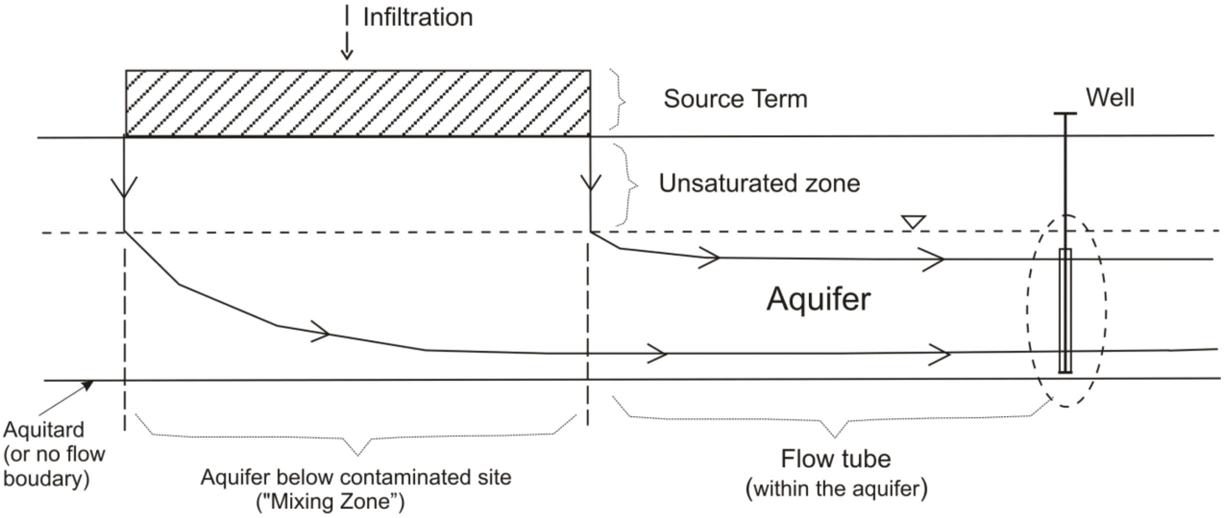

FIG. 9 Schematization of groundwater transport calculations in NORMALYSA.

The subsurface environment is schematized in the following compartments:

- ‘Unsaturated Zone’, where vertical radionuclide migration is assumed to occur from the source of migration towards 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, and

- ‘Aquifer’ zone, where radionuclide transport occurs sub-horizontally in groundwater flow towards the relevant receptor point (e.g., well or surface water body).

The respective representation of the transport process by compartmental model is presented at FIG. 10.

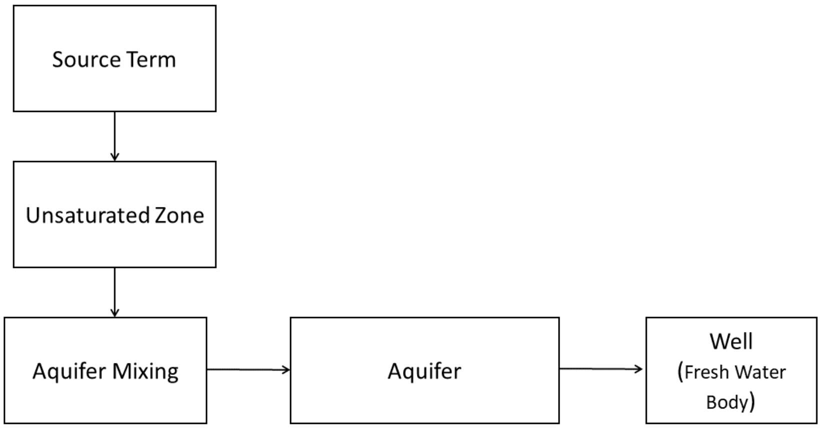

FIG. 10 Compartmental model for groundwater transport from contaminated site using NORMALYSA modules (arrows show data exchanges between modules).

Detailed descriptions of individual modules from ‘Transports’ library are provided below.

5.2. ‘AQUIFER MIXING’ MODULE

5.2.1. Module description

5.2.1.1.General description

The ‘Aquifer Mixing’ module simulates the section of groundwater aquifer situated immediately below the contaminated site (FIG. 9). This module usually receives contaminant input from the Source of 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 radionuclide migration and saturated zone of geological deposits (i.e., aquifer) (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 contaminated topsoil layer due to leaching by atmospheric precipitations;

- Contaminants originating from direct application of liquid effluents on topsoil (e.g. direct application of sludge originating from sewage treatment plants, fertilizers, etc.).

The output of the ‘Aquifer Mixing’ module usually serves an input to the ‘Aquifer’ module simulating radionuclide transport in groundwater in horizontal direction towards receptor points of interest (e.g., ‘Well’ or ‘Fresh Water Body’ module(s)) (see FIG. 10).

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 (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 known layer inventory and equilibrium Kd sorption model using corresponding partitioning equation.

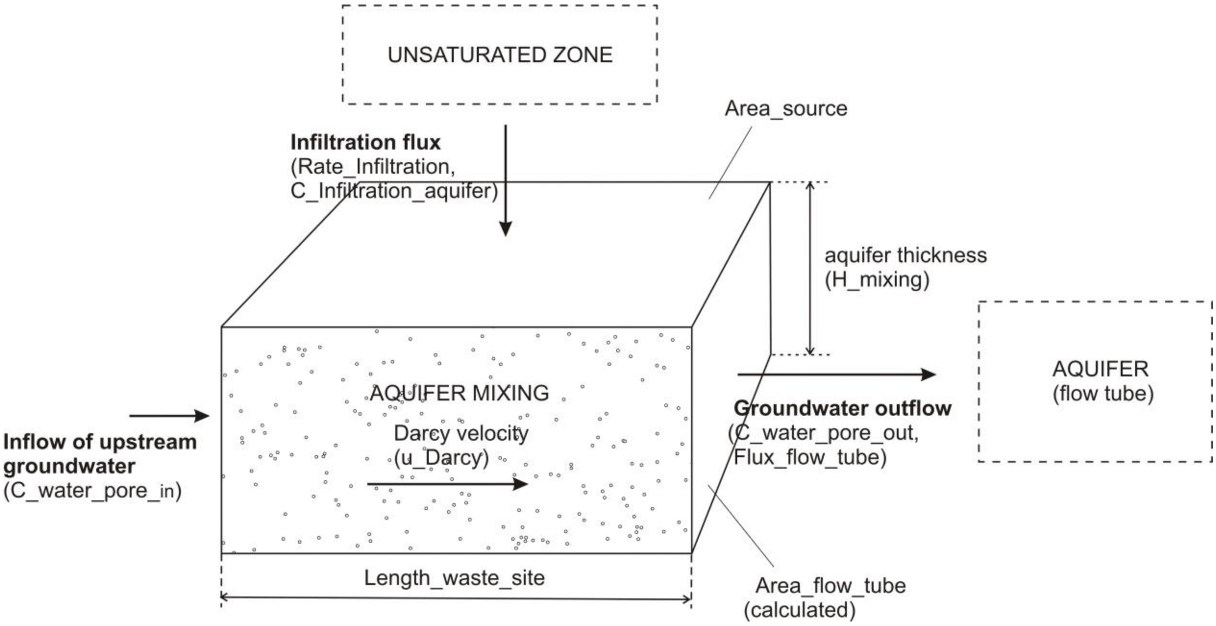

FIG. 11 Conceptual model of the ‘Aquifer Mixing’ compartment.

The inputs of radioactive contaminant(s) into the ‘Aquifer Mixing’ system can 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 infiltration mechanism are needed to be defined by user in the coupled external Source model (possibly coupled with modules simulating intermediate transfers such as ‘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 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 following modules	
Source Term models (‘Tailings without cover’, ‘Contaminated land’), ‘Unsaturated Zone’	Radioactive contaminant concentration (Bq/m^3) or activity flux (Bq/day) in infiltrating water
Outputs from module can be used by following modules	
‘Aquifer’, ‘Well’, ‘Fresh Water Body’	Radioactive contaminant concentration (Bq/m^3) or activity fluxes (Bq/day) in outflow water

5.2.2. Mathematical model

5.2.2.1.Mass balance equation for aquifer compartment

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

$$\frac{dAM}{dt} = Inflow + Infiltration - advection_{gw\_out} \times AM - \lambda \times AM + \sum\nolimits_{\mathrm{P} \in \mathrm{Pi}} \mathrm{Br}_{\mathrm{p}} \times \lambda \times AM \qquad \textit{Eq.(4)}$$

Where

Infiltration = mass transfer by vertical infiltration to ‘Aquifer Mixing’ cell (Bq/day),

Inflow = mass transfer by horizontal inflow to ‘Aquifer Mixing’ cell (Bq/day),

$Advection_{gw\_out}$ = mass transfer coefficient by advective transport from cell (1/day)

The two last right hand side terms in Eq.(4) describe radioactive decay and ingrowth of radionuclides.

Mass transfer by infiltration (Infiltration, Bq/day)

$$Infiltration = area_{source} \times c_{\mathrm{inf}\,iltration} \times rate_{\mathrm{inf}\,iltration}$$

Where

$area_{source}$ = area of ‘Aquifer Mixing’ cell (same as the area source of contamination to aquifer) (m^2),

$C_{infiltration}$ = radionuclide concentration in water infiltrating to the aquifer (Bq/m^3),

$Rate_{infiltration}$ = infiltration rate to the aquifer (m/day).

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

$$Inflow = c_{water\ pore\,in}(u_{Darcy} \times area_{flow\_tube} - area_{source} \times rate_{\inf iltration})$$

Where

u_{Darcy} = groundwater Darcy velocity in the aquifer (m/day),

$area_{flow\_tube}$ = cross-sectional area of the flow tube (m^2),

C_{water_porein} = radionuclide concentration in groundwater entering the aquifer compartment from upstream direction (m^2).

Here parameter $area_{flow\_tube}$ is calculated as follows:

$$area_{flow\_tube} = h_{mixing} \times width_{waste\_site}$$

Where

h_{mixing} = aquifer mixing zone (flow tube) thickness (see FIG. 11) (m),

$width_{waste\_site}$ = width of waste site (m).

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

$$width_{waste\_site} = \frac{area_{source}}{length_{waste\_site}}$$

Where

$length_{waste\_site}$ = length of the contaminated site along the groundwater flow direction (see FIG. 11) (m).

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

The mass transfer coefficient by advection in the aquifer is calculated as follows [IAEA, 2004b, Annex C]:

$$advection_{gw\,out} = \frac{u_{Darcy}}{porosity_{aquifer} \times length_{waste\_site} \times Ret_{aquifer}}$$

Where

$porosity_{aquifer}$ = is aquifer porosity (unitless),

$Ret_{aquifer}$ = is radionuclide retardation coefficient due to radionuclide sorption on aquifer materials (unitless).

Retardation coefficient in the aquifer ($Ret_{aquifer}$, 1/day)

$$Ret_{aquifer} = 1 + \frac{rho_{aquifer}}{porosity_{aquifer}} \times Kd_{aquifer}$$

Where

$rho_{aquifer}$ = density of soil in the aquifer (kg/m^3),

$Kd_{aquifer}$ = sorption distribution coefficient for the aquifer sediments with respect to radionuclides (radionuclide-dependent) (m^3/kg).

5.2.2.2.Radionuclide concentration in groundwater ($C\__{water\_pore\_out}$, Bq/m^3)

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

$$c_{water\_pore\_out} = \frac{AM}{area_{source} \times h_{mixing}} \times \frac{1}{porosity_{aquifer} \times Ret_{aquifer}} \qquad Eq.(5)$$

5.2.2.3.Activity flux in water from compartment ($Flux_{flow\_tube}$, Bq/day)

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

$$Flux_{flow\_tube} = u_{Darcy} \times area_{flow\_tube} \times c_{water\_pore\_out} \qquad Eq.(6)$$

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/day)	Infiltration rate to the aquifer	8.21E-04	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

Abbreviation and unit	**Full name**	**Default value**	**Reference**
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/day)	Darcy velocity in the aquifer	2.74E-02	Site specific parameter
Kd_aquifer ($m^3/kg.DW$)	Sorption distribution coefficient (radionuclide specific)	Table I- 1 (Appendix I)	[IAEA, 2010; Table 14*]

Remark: * - mean Kd value for 'all soils'

5.2.4. Output parameters

The main output parameter of the ‘Aquifer Mixing’ module is radionuclide concentration in outflowing groundwater from compartment (see Eq.(5)). Module calculates also activity flux from compartment (see Eq.(6)).

Table 22. Output parameters of ‘Aquifer Mixing’ module

Abbreviation and unit	**Full name**	**Purpose**
c_water_pore_out (Bq/m^3)	Radioactive contaminant concentration in the porous solutions out-flowing from the ‘Aquifer Mixing’ cell	Can be used to calculate doses from contaminated groundwater. Can be used to calculate further radionuclide transport in the ‘Aquifer’, ‘Well’ or ‘Fresh water body’ modules (see Table 19)
Flux_flow_tube (Bq/day)	Radioactive contaminant flux from the ‘Aquifer Mixing’ cell (integral over aquifer cross-section)	Can be used to calculate activity inputs to the ‘Aquifer’, ‘Well’ or ‘Fresh water body’ modules (see Table 19)

5.3.‘AQUIFER’ MODULE

5.3.1. Module description

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 block-scheme at FIG. 10). Alternatively, this module can receive inputs from the upstream ‘Aquifer’ module. (Several consecutive ‘Aquifer’ modules can be used aquifer with spatially varying physical or geochemical properties or varying initial contamination conditions).

The output of the ‘Aquifer’ module usually serves 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 (FIG. 12).

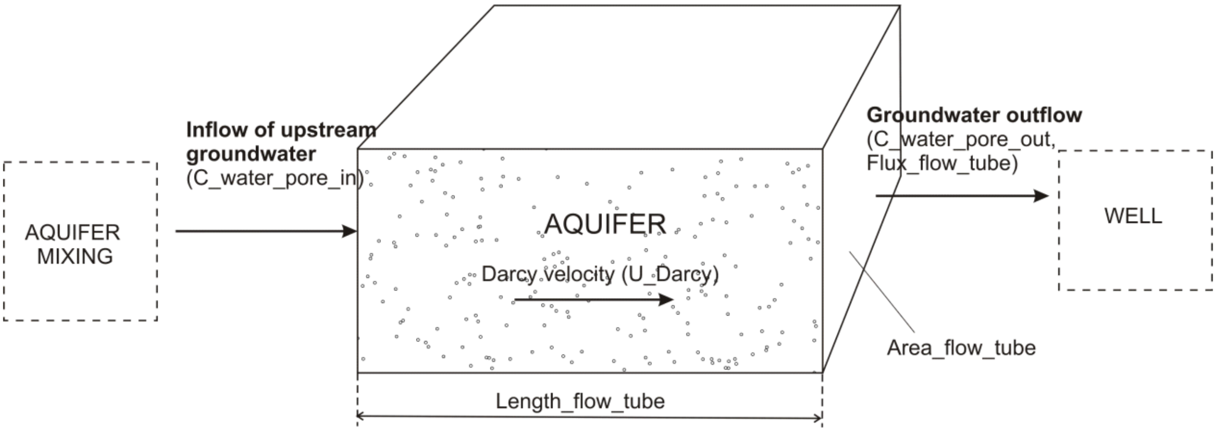

FIG. 12 Conceptual model of the 'Aquifer' module.

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 include: 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 (here Kd is sorption distribution coefficient).

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 advection and dispersion process following the approach described in [IAEA, 2004b, Annex C]. The respective schematization is represented in FIG. 13. The model expressions operate total radionuclide inventories in each transport cell. Then radioactive contaminant concentrations in pore water and soil matrix can be calculated for each transport cell based on known cell inventory and 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 need number of cell compartments using Ecolego 6 'Transport' block.

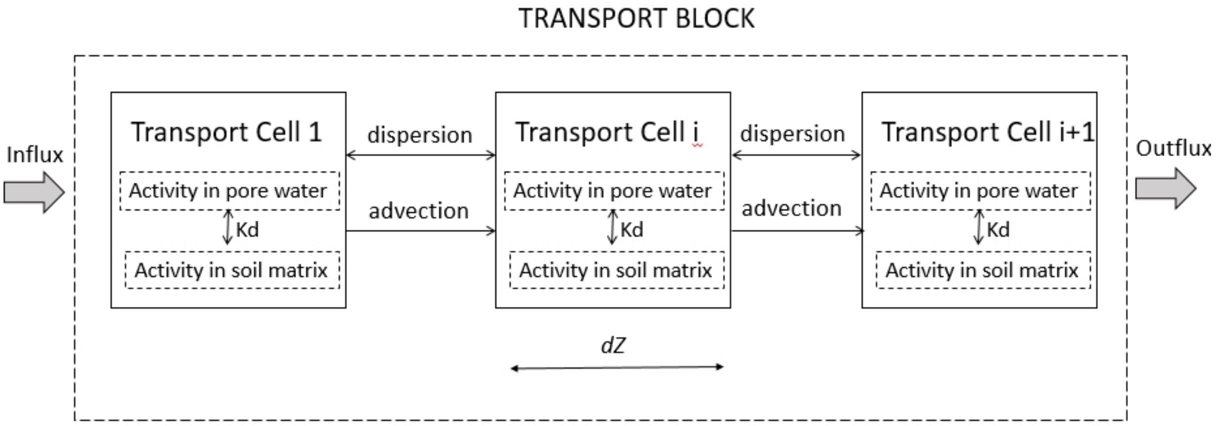

FIG. 13 Representation of the modelled aquifer system by a sequence of individual transport cells using Ecolego 'Transport' block.

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/day) 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/day) in outflow water

5.3.2. Mathematical model

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:

$$\frac{dTransp\_Cell_i}{dt} = advection_{aquifer} \times Transp\_Cell_{i-1} - advection_{aquifer} \times Transp\_Cell_i$$
$$- dispersion_{aq\_forward} \times Transp\_Cell_i - dispersion_{aq\_back} \times Transp\_Cell_i +$$
$$dispersion_{aq\_back} \times Transp\_Cell_{i+1} + dispersion_{aq\_forward} \times Transp\_Cell_{i-1}$$
$$- \lambda \times Transp\_Cell_i + \sum_{p \in P} Br_p \times \lambda \times Transp\_Cell_i \qquad \text{Eq. (7)}$$

Where

$advection_{aquifer}$ = mass transfer coefficient by advective transport (1/day),

$dispersion_{aq\_forward}$ = mass transfer coefficient by forward dispersive transport (1/day),

$dispersion_{aq\_back}$ = mass transfer coefficient by backward dispersive transport (1/day).

The two last right hand side terms in Eq. (7) describe radioactive decay and ingrowth of radionuclides.

Here mass transfer coefficients are calculated as follows [IAEA, 2004b, Appendix C].

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

$$advection_{aquifer} = \frac{u_{Darcy}}{porosity_{aquifer} \times dz \times Ret_{aquifer}} \qquad \text{Eq.(8)}$$

Where

u_{Darcy} = groundwater Darcy velocity in the aquifer (m/day),

$porosity_{aquifer}$ = is aquifer porosity (unitless),

dZ = horizontal size of transport cell in the aquifer (m),

$Ret_{aquifer}$ = is retardation coefficient due to radionuclide sorption on aquifer materials (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{aquifer} = 1 + \frac{rho_{aquifer}}{porosity_{aquifer}} \times Kd_{aquifer}$$

Where

$rho_{aquifer}$ = density of soil in the aquifer (kg/m^3),

$Kd_{aquifer}$ = 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/day)

$$dispersion_{aq\_forward} = \frac{dispersivity_{aq} \times u_{Darcy}}{porosity_{aquifer} \times dz^2 \times Ret_{aquifer}}$$

Where

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

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

5.3.2.2.Mass balance equation for the 1-st Transport Cell in the aquifer

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

$$\frac{dTransp\_Cell_1}{dt} = Infiltration - dispersion_{aq\_forward} \times Transp\_Cell_1 +$$
$$dispersion_{aq\_back} \times Transp\_Cell_2 - advection_{aquifer} \times Transp\_Cell_1$$
$$- \lambda \times Transp\_Cell_1 + \sum\nolimits_{p \in P} Br_p \times \lambda \times Transp\_Cell_1$$

Where

$Infiltration$ = mass transfer by infiltration (inflow) to the first 'Aquifer' cell (Bq/day).

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

$$Infiltration = c_{water\_pore\_in}\, u_{Darcy}\, area_{flow\_tube}$$

Where

$C_{water\_pore\_in}$ = radionuclide concentration in water infiltrating (inflowing) to the aquifer (Bq/m^3),

$area_{flow\_tube}$ = 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:

$$\frac{dTransp\_Cell_N}{dt} = advection_{aquifer} \times Transp\_Cell_{N-1} - advection_{aquifer} \times Transp\_Cell_N$$
$$- dispersion_{aq\_forward} \times Transp\_Cell_N - dispersion_{aq\_back} \times Transp\_Cell_N +$$
$$+ dispersion_{aq\_forward} \times Transp\_Cell_{N-1} - \lambda \times Transp\_Cell_N + \sum\nolimits_{p \in P} Br_p \times \lambda \times Transp\_Cell_N$$

5.3.2.4.Calculation of dispersivity parameter for aquifer transport

Following the recommendation of [Walton, 1988; IAEA, 2004b] dispersivity parameter for aquifer transport ($dispersivity_{aq}$) is calculated as 10% of the linear scale of transport problem:

$$dispersivity_{aq} = 0.1 \times length_{flow\_tube}$$

Where

$length_{flow\_tube}$ = 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.(8)) 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 (e.g., [Kinzelbach, 1986], p.267)

$$D_{num} = \frac{U_{Darcy} \times dZ}{2} \qquad \textit{Eq. (9)}$$

The above formula shows that numerical dispersion is proportional to the size of compartment *dZ*.

The true dispersion coefficient in transport equation is given by the formula

$$D_{true} = dispersivity_{aq} \times U_{Darcy} \qquad \textit{Eq.(10)}$$

To ensure accurate approximation of advective-dispersive transport the following condition should hold:

$$D_{num} << D_{true} \qquad \textit{Eq. (11)}$$

Or, substituting to Eq. (11) expressions Eq. (9) and Eq.(10):

$dZ << 2 \times dispersivity_{aq}$.

In particular, our 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 needed number of transport compartments (N):

$dZ = dispersion_{accuracy} \times 2 \times dispersivity_{aq}$,

Where

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

It should be noted that too small value of $dispersion_{accuracy}$ parameter may result in too small *dZ*, and respectively too large number of transport cells and long calculation times.

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

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

$$dZ = \frac{Length_{f\ low\_tube}}{N_{Transp}}$$

Here notation [a] stands for nearest integer to real number 'a' towards zero.

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

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

$$c_{water\_pore\_out} = \frac{Transp\_Cell_N}{area_{flow\_tube} \times dZ} \times \frac{1}{porosity_{aquifer} \times Ret_{aquifer}} \qquad \text{Eq. (12)}$$

5.3.2.7.Activity flux in water from 'Aquifer' module (Flux$_{flow\_tube}$, Bq/day)

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

$$Flux_{flow\_tube} = u_{Darcy} \times area_{flow\_tube} \times c_{water\_pore\_out} \qquad \text{Eq. (13)}$$

5.3.3. Input parameters

Table 24. Input parameters related to initial contamination and radiological loads for 'Aquifer' module

Abbreviation and unit	Full name	Default value	Reference
c_water_pore_in (Bq/m^3)	Concentration of the radioactive contaminant in groundwater inflowing to the aquifer	0	Site specific parameter
c0_gw_aquifer (Bq/m^3)	Initial contamination of groundwater in the aquifer by radionuclides	0	Site specific parameter

Table 25. Input parameters of '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/day)	Darcy velocity in the aquifer	2.74E-02	Site specific parameter
Kd_aquifer (m^3/kg.DW)	Sorption distribution coefficient (radionuclide specific)	Table I- 1 (Appendix I)	[IAEA, 2010; Table 14]

5.3.4. Output parameters

The main output parameter of the 'Aquifer' module is radionuclide concentration in outflowing groundwater from compartment (see Eq. (12)). Module calculates also activity flux from system (see Eq. (13)).

Table 26. Output parameters of 'Aquifer' module

Abbreviation and unit	Full name	Purpose
c_water_pore_out (Bq/m^3)	Radioactive contaminant concentration in the groundwater out-flowing from the 'Aquifer' module	Can be used to calculate doses from contaminated groundwater. Can be used to calculate further radionuclide transport in the 'Well', 'Fresh water body' etc. modules (see Table 23)
Flux_flow_tube (Bq/day)	Radioactive contaminant flux from the 'Aquifer' module	Can be used to calculate activity inputs to the 'Fresh water body' etc. modules (see Table 23)

5.4.‘UNSATURATED ZONE’ MODULE

5.4.1. Module description

5.4.1.1. General description

The goal of the ‘Unsaturated Zone’ module is to dynamically simulate 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 Soil Without Cover’ modules; see block-scheme at FIG. 10).

The output of the ‘Unsaturated Zone’ module (radionuclide concentration and/or flux in outflowing pore water) usually serves 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 (FIG. 14).

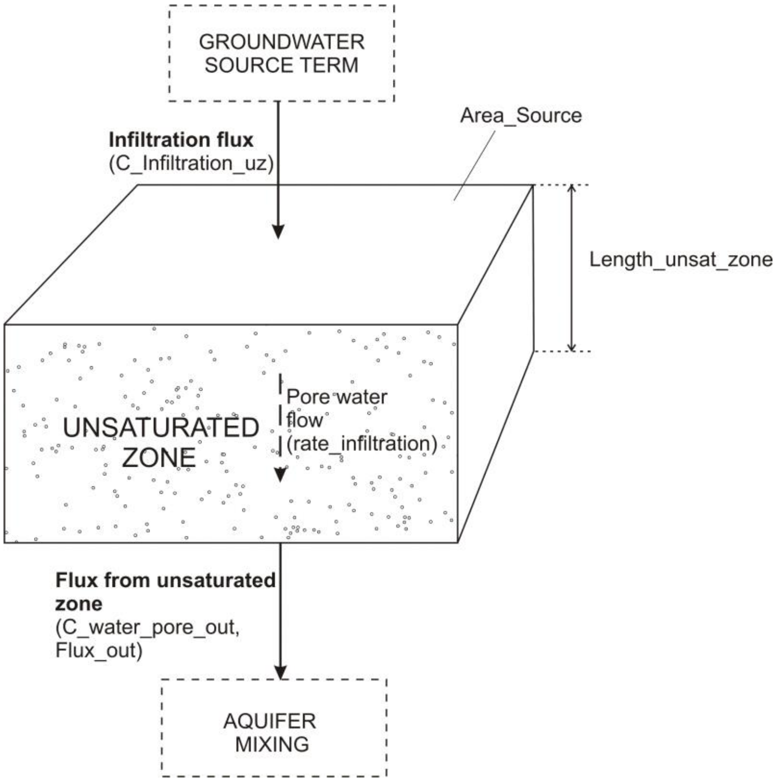

FIG. 14 Conceptual model of the ‘Unsaturated Zone’ Module.

For the unsaturated zone systems showing significant variations in their properties in vertical direction, it is recommended to subdivide these latter in 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 unsaturated zone occurs in vertical (downward) direction (see FIG. 14). The transport process taken into account by the module include: 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 (here Kd is sorption distribution coefficient).

The ‘Unsaturated Zone’ module simulates radionuclide transfer processes in soil profile dynamically, however it is assumed that radionuclide transport in soil occurs under the steady-state infiltration flow conditions (i.e., that infiltration flow velocity in 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 advection and dispersion process following the approach described in [IAEA, 2004b; Annex C].

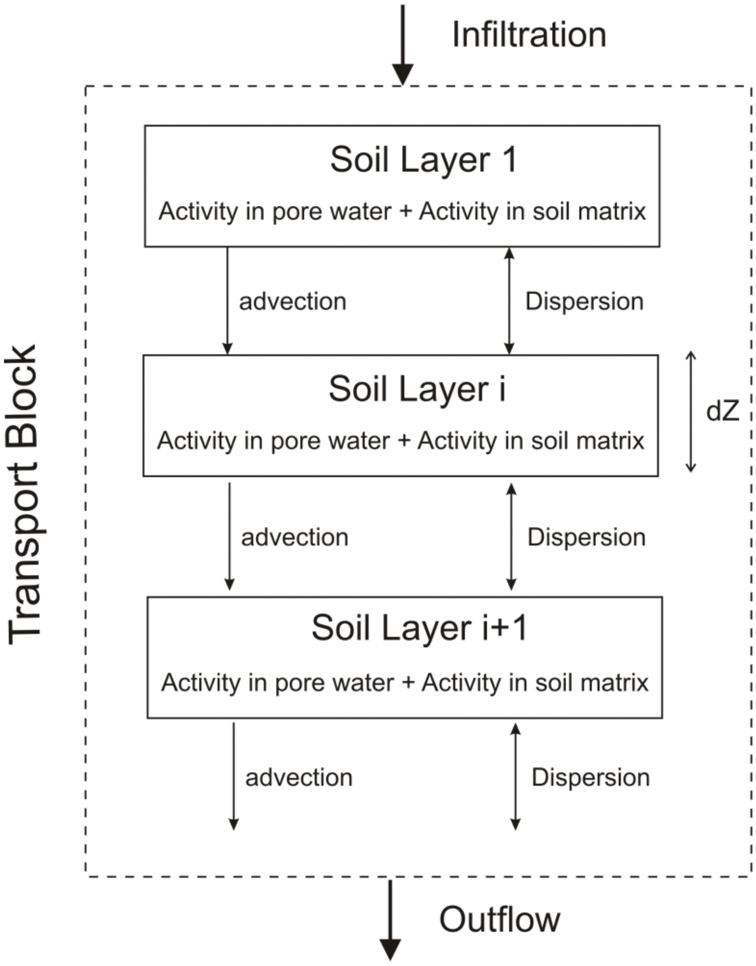

FIG. 15 Representation of the modelled unsaturated zone by a sequence of individual soil layers using Ecolego ‘Transport’ block.

The number and size of layers (cells) is determined automatically based on specified accuracy requirements. The program generates the need number of cell compartments using Ecolego 6

‘Transport’ block. This approach is similar to the radionuclide transport modeling 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 user in the coupled Source module. The contaminant input is defined by specifying two parameters: 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 modeled) by outflow (i.e., contaminant movement by advective outflow).;

- Radioactive decay of contaminant in the unsaturated zone media.

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 following modules	
‘Contaminated Soil Without Cover’, ‘Tailings Without Cover’	Radioactive contaminant concentration (Bq/m^3) or activity flux (Bq/day) in infiltrating water
Outputs from module can be used by following modules	
‘Aquifer Mixing’, ‘Aquifer’	Radioactive contaminant concentration (Bq/m^3) or activity fluxes (Bq/day) in outflow water

5.4.2. Mathematical model

5.4.2.1. Mass balance equation for unsaturated soil system

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

$$\frac{dSoil\_Layer_i}{dt} = advection_{uz} \times Soil\_Layer_{i-1} - advection_{uz} \times Soil\_Layer_i$$
$$- dispersion_{uz\_back} \times Soil\_Layer_i - dispersion_{uz\_forward} \times Soil\_Layer_i +$$
$$dispersion_{uz\_back} \times Soil\_Layer_{i+1} + dispersion_{uz\_forward} \times Soil\_Layer_{i-1}$$
$$- \lambda \times Soil\_Layer_i + \sum\nolimits_{p \in P} Br_p \times \lambda \times Soil\_Layer_i \qquad Eq.\ (14)$$

Where

Advection$_{uz}$ = mass transfer coefficient by advective transport (1/day),

Dispersion$_{uz\_forward}$ = mass transfer coefficient by forward dispersive transport (1/day),

Dispersion$_{uz\_back}$ = mass transfer coefficient by backward dispersive transport (1/day).

The two last right hand side terms in Eq. (14) describe radioactive decay and ingrowth of radionuclides.

Here mass transfer coefficients are calculated as follows [IAEA, 2004b, Appendix C].

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

$$advection_{uz} = \frac{rate_{\inf iltration}}{moisture_{uns\_zone} \times dZ \times Ret_{uns\_zone}}$$

Where

rate$_{infiltration}$ = soil moisture infiltration rate to the unsaturated zone (m/day),

moisture$_{uns\_zone}$ = is moisture content in the unsaturated zone (unitless),

dZ = vertical size of transport layer in the unsaturated zone generated by Ecolego 'Transport' block (see FIG. 15) (m),

Ret$_{uns\_zone}$ = is retardation coefficient due to radionuclide sorption on soil (unitless).

The retardation coefficient is calculated as follows:

$$Ret_{aquifer} = 1 + \frac{rho_{uns\_zone}}{moisture_{uns\_zone}} \times Kd_{unsat\_zone}$$

Where

rho$_{uns\_zone}$ = density of soil in the unsaturated zone (kg/m^3),

Kd$_{unsat\_zone}$ = sorption distribution coefficient of soil in unsaturated zone with respect to radionuclides (radionuclide-specific) (m^3/kg).

Mass transfer coefficient by dispersive transport ($dispersion_{uz\_forward}$, 1/day)

$$dispersion_{uz\_forward} = \frac{dispersivity_{uz} \times rate_{infiltration}}{moisture_{uns\_zone} \times dZ^2 \times Ret_{uns\_zone}}$$

Where

$dispersivity_{uz}$ = dispersivity parameter for solute transport in the unsaturated zone (m).

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

5.4.2.2. Mass balance equation for the 1-st Soil Layer in the unsaturated zone

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

$$\begin{aligned}\frac{dSoil\_Layer_1}{dt} &= Infiltration - dispersion_{uz\_forward} \times Soil\_Layer_1 + \\ & dispersion_{uz\_back} \times Soil\_Layer_2 - advection_{uz} \times Soil\_Layer_1 \\ & - \lambda \times Soil\_Layer_1 + \sum\nolimits_{p \in P} Br_p \times \lambda \times Soil\_Layer_1\end{aligned}$$

Where

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

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

$$Infiltration = c_{infiltration}\, rate_{infiltration}\, area_{source}$$

Where

$C_{infiltration}$ = radionuclide concentration in water infiltrating to the unsaturated zone system (Bq/m^3),

$area_{source}$ = surface area of the modeled unsaturated zone system (underlying contaminant source) (m^2).

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

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

$$\begin{aligned}\frac{dSoil\_Layer_N}{dt} &= advection_{uz} \times Soil\_Layer_{N-1} - advection_{uz} \times Soil\_Layer_N \\ & - dispersion_{uz\_forward} \times Soil\_Layer_N - dispersion_{uz\_back} \times Soil\_Layer_N + \\ & + dispersion_{uz\_forward} \times Soil\_Layer_{N-1} - \lambda \times Soil\_Layer_N + \sum\nolimits_{p \in P} Br_p \times \lambda \times Soil\_Layer_N\end{aligned}$$

5.4.2.4. *Calculation of dispersivity parameter for the unsaturated zone*

Following the recommendation of [Walton, 1988; IAEA, 2004] dispersivity parameter for unsaturated zone transport ($dispersivity_{uz}$) is calculated as 10% of the linear scale of transport problem:

$$dispersivity_{aq} = 0.1 \times length_{unsat\_zone}$$

Where

$Length_{unsat\_zone}$ = 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 transfers calculations in the unsaturated zone are 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 Ecolego 'Transport' block is calculated as

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

$$dZ = \frac{Length_{unsat\_zone}}{N_{Transp}}$$

Here notation [a] stands for nearest integer to real number 'a' towards zero.

5.4.2.6. *Radionuclide concentration in outflowing pore water for 'Unsaturated Zone' module ($C_{water\_pore\_out}$, Bq/m^3)*

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

$$c_{water\_pore\_out} = \frac{Soil\_Layer_N}{area_{source} \times dZ} \times \frac{1}{moisture_{uns\_zone} \times Ret_{uns\_zone}} \qquad \text{Eq. (15)}$$

5.4.2.7. *Activity flux in water from 'Unsaturated Zone' module ($Flux_{flow\_tube}$, Bq/day)*

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

$$Flux_{out} = rate_{infiltration} \times area_{source} \times c_{water\_pore\_out} \qquad \text{Eq. (16)}$$

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)	42000	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/day)	Infiltration recharge rate to the unsaturated zone	1.37E-04	Site specific parameter
Kd_unsat_zone (m^3/kg.DW)	Sorption distribution coefficient (radionuclide specific)	Table I- 1 (Appendix I)	[IAEA, 2010; Table 14]
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 radionuclide concentration in outflowing pore water from the modelled system (see Eq. (15)). Module calculates also activity flux from system (see Eq. (16)).

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 out-flowing from the 'Unsaturated Zone' module	Can be used to calculate further radionuclide transport in the underlying unsaturated zone or aquifer (see Table 27)
Flux_out (Bq/day)	Radioactive contaminant flux from the 'Unsaturated Zone' module	Can be used to calculate further radionuclide transport in the underlying unsaturated zone or aquifer (see Table 27)

5.5.‘SURFACE RUNOFF’ MODULE

5.5.1. Module description

5.5.1.1. General description

The goal of the ‘Surface Runoff’ module is to dynamically simulate transport of radioactive contaminants from the contaminated watershed soils by surface runoff mechanism to ‘Fresh Water Body’ receptor. The contamination of watershed can be formed, for example, by the atmospheric deposition of radionuclides.

The mathematical model for radionuclide leaching from contaminated watershed soil is based on “exchangeable soil layer” concept described in [Bulgakov et al., 1990, 1999]. It is assumed that radionuclide interaction between runoff water and soil in contaminated watershed occurs in the top “exchangeable soil layer” of a relatively small (e.g., centimeter scale) thickness.

The model for radionuclide redistribution in watershed soil profile takes into account input of radionuclides to 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.

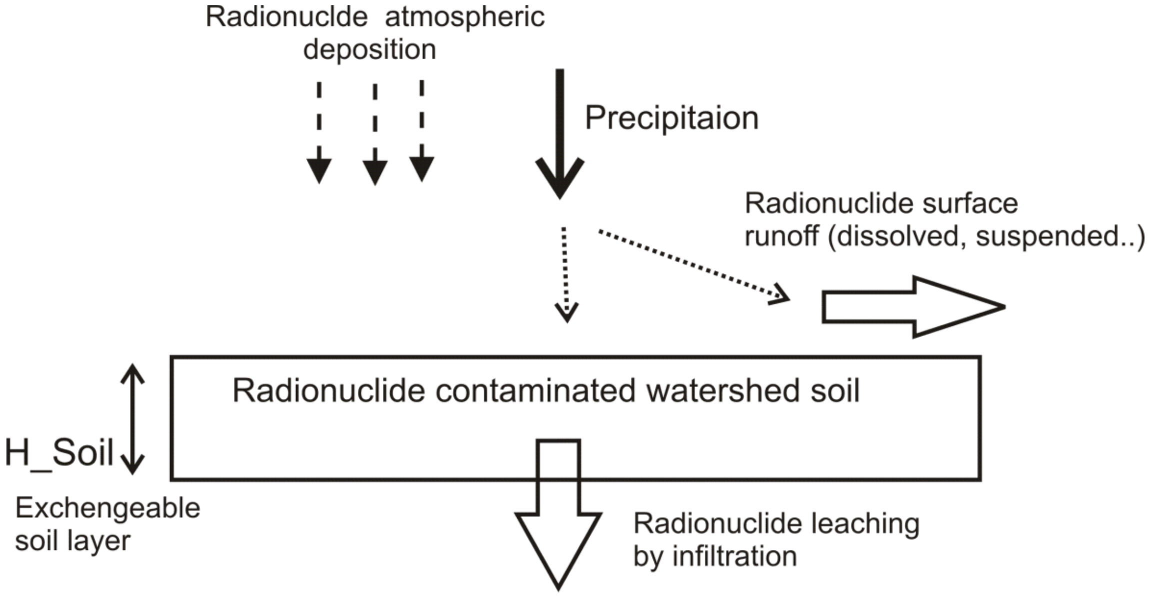

FIG. 16 Illustrative scheme for ‘Surface Runoff’ module.

Water runoff and radionuclide transport process 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), Kd-s (sorption distribution coefficients), etc.

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

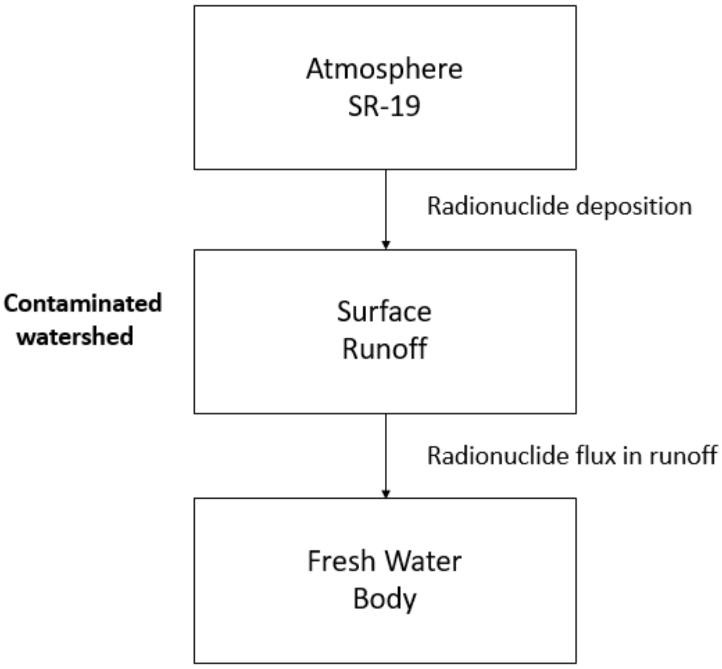

FIG. 17 Data exchanges of 'Surface Runoff' module with other NORMALYSA modules.

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 watershed soil presumably interacting with surface runoff. Then radioactive contaminant concentrations in runoff water and contaminant concentrations adsorbed on suspended particles in surface runoff water are calculated based on known inventory of the "exchangeable soil layer" compartment and equilibrium Kd-based sorption models describing radionuclide partitioning between the liquid and solid phases (FIG. 18).

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

- It is assumed that 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).

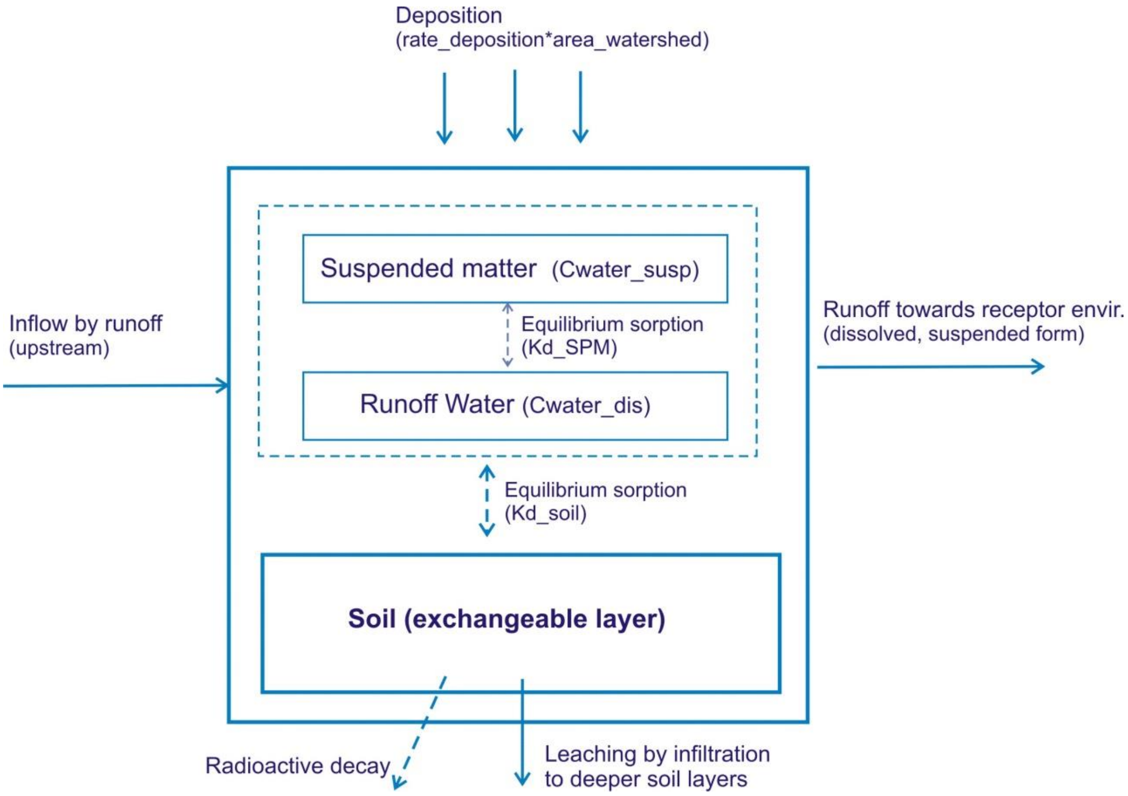

FIG. 18 Conceptual model of the 'Surface Runoff' module.

The inputs of radioactive contaminant(s) to the 'Surface Runoff' (i.e., contaminated watershed soil) compartment can 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.

Modeler can specify also initial contamination of watershed soil.

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

- 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.

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•d)) 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/day) from contaminated watershed entering surface water body

5.5.2. Mathematical model

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:

$$\frac{dSoil}{dt} = + Runoff_{upstream} + Deposition \quad - TC_{Runoff} \times Soil - TC_{Infiltration} \times Soil - \lambda \times .Soil + \sum_{p \in P} Br_p \times \lambda \times Soil \qquad \text{Eq. (17)}$$

Where

Deposition = mass transfer by deposition from atmosphere to watershed soil (Bq/day),

$Runoff_{upstream}$ = mass transfer by runoff from the upstream watershed compartment (Bq/day),

TC_{Runoff} = Mass transfer coefficient by surface runoff water (1/day),

$TC_{Infiltration}$ = mass transfer coefficient due to infiltration of water to soil profile (1/day).

The two last right hand side terms in Eq. (17) describe 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/day)

$$Deposition = rate_{dep} \times area_{watershed}$$

Where

$rate_{dep}$ = radionuclide deposition rate from the atmosphere (Bq/(m^2 • d)),

$area_{watershed}$ = area of watershed (m^2).

Mass transfer by runoff from the upstream watershed compartment (Runoff_upstream, Bq/day)

$$Runoff_{upstream} = Flux_{runoff\_upstream}$$

Where

$Flux_{runoff\_upstream}$ = flux of the radioactive contaminant in surface runoff from upstream watershed areas (specified by modeler) (Bq/day).

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

$$TC_{runoff} = \frac{Flux\_water_{runoff} \times (1 + 0.001 \times K_{d\_SPM} \times C_{SPM})}{K_{d\_soil} \times rho_{soil} \times \mathrm{V}_{soil}}$$

Where

$Flux\_water_{runoff}$ = rate of surface water runoff from the watershed (m^3/day),

Kd_{soil} = Sorption distribution coefficient for watershed soil (m^3 /kg.DW),

rho_{soil} = dry density of watershed soil (kg.DW/m^3),

V_{soil} = soil volume in the exchangeable layer for the whole watershed (m^3),

Kd_{SPM} = sorption distribution coefficient for suspended particles in runoff water (m^3/kg),

C_{SPM} = concentration of suspended soil particles in runoff water (g.DW/m^3).

Here rate of surface water runoff from the watershed soil is calculated as follows:

$$Flux_{water\_runoff} = rate_{prec} \times coeff_{runoff} \times area_{watershed}$$

Where

$rate_{prec}$ = meteoric water precipitation rate (m/day),

$coeff_{runoff}$ = surface runoff coefficient (unitless).

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

$$V_{soil} = area_{watershed} \times h_{soil}$$

Where

h_{soil} = thickness of the exchangeable layer of watershed soil (m).

Mass transfer coefficient by infiltration water flow (TC_Infiltration, 1/day)

$$TC_{\inf iltration} = \frac{rate_{prec} \times coeff_{infiltration}}{soil\_moisture \times h_{soil} \times Ret_{soil}}$$

Where

$coeff_{infiltration}$ = Infiltration coefficient - fraction of precipitation that infiltrates to soil profile (unitless),

$soil\_moisture$ = soil moisture content (unitless),

Ret_{soil} = radionuclide retardation factor for soil (unitless).

Here soil radionuclide retardation coefficient is calculated as follows:

$$Ret_{soil} = 1 + \frac{rho_{soil}}{Soil\_moisture} \times Kd_{soil} .$$

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

$$c_{soil} = \frac{Soil}{rho_{soil} \times V_{soil}}$$

5.5.2.3. Radionuclide concentration in surface runoff

Radioactive contaminant concentration in the surface runoff in dissolved form (C_water_dis, Bq/m³)

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

Radioactive contaminant concentration in the surface runoff in suspended form (c_water_susp, Bq/m³)

$$c_{water\_susp} = c_{water\_dis} \times 0.001 \times K_{d\_SPM} \times C_{SPM}$$

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/day)

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

Where

$Flux_{ruoff\_diss}$ = radioactive contaminant flux in dissolved form (Bq/day),

$Flux_{ruoff\_susp}$ = radioactive contaminant flux in suspended form (Bq/day).

Radioactive contaminant flux from watershed by surface runoff in dissolved phase (Flux_runoff_diss, Bq/day)

$$Flux_{runoff\_diss} = c_{water\_diss} \times Flux_{water\_runooff}$$

Radioactive contaminant flux from watershed by surface runoff in suspended phase (Flux_runoff_susp, Bq/day)

$$Flux_{runoff\_susp} = c_{water\_susp} \times Flux_{water\_runooff}$$

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 exchangeable layer (initial value)	0	Site specific parameter
rate_dep (Bq/(m^2 •d))	Radionuclide deposition rate from the atmosphere	0	Site specific parameter
Flux_runoff_upstream (Bq/day)	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	10000	Site specific parameter
H_soil (m)	Thickness of exchangeable soil layer	0.01	[Bulgakov et al., 1990]
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/day)	Precipitation rate	1.64E-03	Site specific parameter
Coeff_runoff (unitless)	Runoff coefficient (fraction of precipitation that goes to surface runoff)	0.1	Site specific parameter

Abbreviation and unit	**Full name**	**Default value**	**Reference**
Coeff_infiltration (unitless)	infiltration coefficient (fraction of precipitation that infiltrates 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 I- 1 (Appendix I)	[IAEA, 2010; Table 14*]
Kd_SPM (m^3/kg.DW)	Sorption distribution coefficient of suspended particles in surface runoff (radionuclide specific)	Table 34	[IAEA, 2010; Table 14**]

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 [IAEA, 2010; Table 14].*

Radionuclide	**Kd, m^3/kg.DW**
Ac	1.7E+00
Cs	3.7E-01
Pa	2.0E+00
Pb	1.3E+01
Po	2.10E-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

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) 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/m^3)	Radioactive contaminant concentration in the surface runoff (dissolved phase)	Calculation of contaminant inputs (loads) to 'Fresh Water Body' receptor
C_water_susp (Bq/m^3)	Radioactive contaminant concentration in the surface runoff (in suspended phase)	Same as above
Flux_runoff_diss (Bq/day)	Radioactive contaminant flux from watershed by surface runoff in dissolved phase	Same as above
Flux_runoff_susp (Bq/day)	Radioactive contaminant flux from watershed by surface runoff in suspended phase	Same as above
Flux_runoff_total (Bq/day)	Total radioactive contaminant flux from the watershed by surface runoff	Same as above

5.6.'ATMOSPHERE SR-19' MODULE

5.6.1. Module description

5.6.1.1. General description

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

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 [IAEA, 2001].

The 'Atmosphere SR-19' module implements the Gaussian plume model to simulate the atmospheric dispersion of long-term atmospheric releases, that is described in [IAEA, 2001]. This model is widely accepted for use in radiological assessment activities. The model is considered to be most appropriate for representing the dispersion of either continuous or long term intermittent releases within a distance of a few kilometres of the source (FIG. 19).

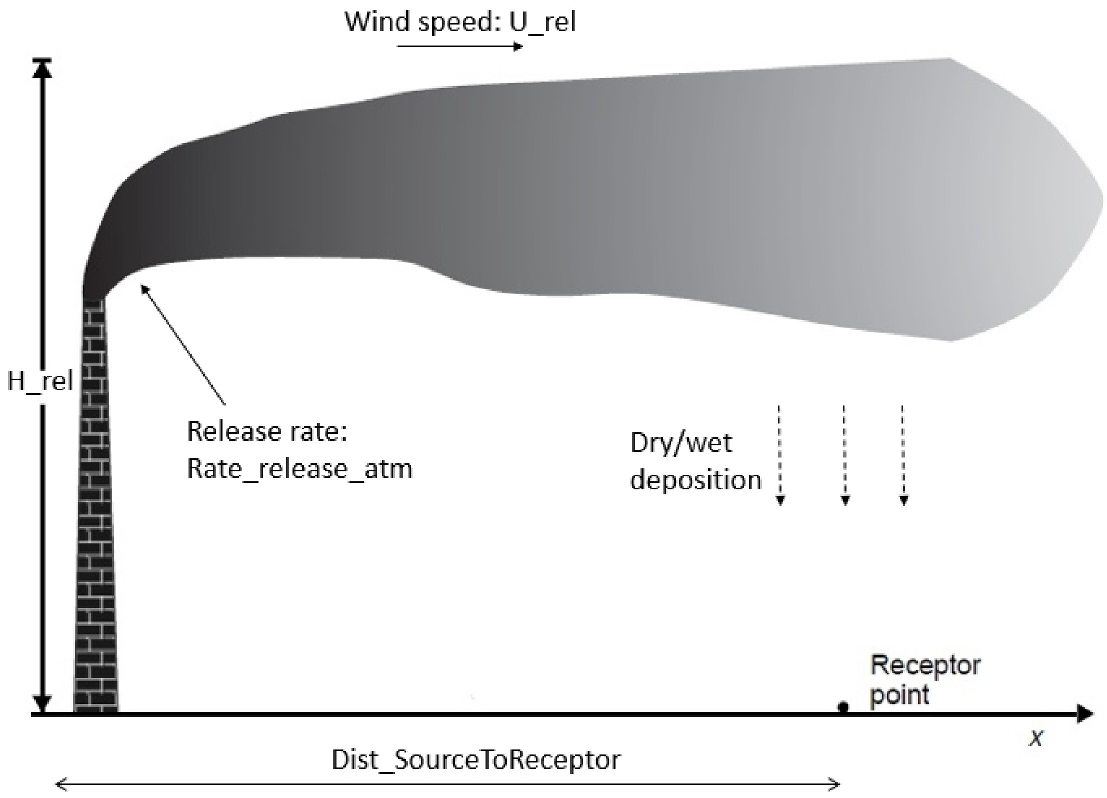

FIG. 19. Conceptual model of radioactive contaminant atmospheric dispersion from the point source.

The Gaussian plume model implemented in '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 [IAEA, 2001; Annex V] 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 contaminated site as a point source.

The presented below model expressions 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 user in the coupled external Source model (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 'Doses' library (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 Soil 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.d)) to receptor
'Dose from Occupancy Outdoors'	Radioactive contaminant concentrations in the air (Bq/m^3)

5.6.2. Mathematical model

5.6.2.1.Ground level radionuclide concentration in the air (C_air_atm, Bq/m^3)

Ground level radionuclide concentration in the air at receptor (*C_air_atm*, Bq/m^3) is calculated as follows [IAEA, 2001]:

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

Where:

Rate_rel_atm = the annual average release rate for radionuclide from the source (Bq/s),

Diff_factor = the Gaussian diffusion factor appropriate for the height of release and the downwind distance being considered (1/m^2),

U_rel = the geometric mean of the wind speed at the height of release representative of one year (m/s),

Freq_wind = 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)

$$Diff\_factor = \frac{12}{\sqrt{2 \times \pi^3}} \times \frac{exp\left[-\left({H_{rel}}^2/(2 \times Sigma_Z^2)\right)\right]}{Dist\_sourceToReceptor \times Sigma_Z}$$

Where:

H_rel = height of release (see FIG. 19) (m),

Dist_sourceToReceptor = distance from the source of release to receptor (m),

Sigma_Z = the vertical diffusion parameter (m).

Vertical diffusion parameter (Sigma_Z, m)

$$Sigma\_Z = \begin{cases} 0.06 \times dist_{SourceToReceptor} \Big/ \sqrt{1 + 0.0015 \times dist_{SourceToReceptor}}\ ;\ for\ h_{rel} < 46m \\ (0.215 \times dist\_SourceToReceptor)^{0.885}\ ;\ for\ 46m \leq h\_rel < 80m \\ (0.265 \times dist_{SourceToReceptor})^{0.818};for\ h\_rel \geq 80m \end{cases}$$

5.6.2.2.*Radionuclide deposition rate at receptor location* (*Rate_dep, Bq/(m^2.d)*)

$$rate\_dep = C\_air\_atm \times u\_tot\_dep$$

Where

u_tot_dep = total deposition velocity (m/day).

Here

$$u\_tot\_dep = u\_wet\_dep + u\_dry$$

Where

u_wet_dep = wet deposition velocity (m/day),

u_dry = 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_rel_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 receptor point	1000	Site specific parameter
U_rel (m)	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/daya)	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/m^3)	Radioactive contaminant concentrations in the air	Calculation of doses by inhalation pathway at receptor point
Rate_dep (Bq/(m^2.d))	Radioactive contaminant deposition rates to ground surface	Calculation of contaminant inputs (loads) to receptor modules (see Table 36)

5.7. ‘ATMOSPHERE CHRONIC’ MODULE

5.7.1. Module description

5.7.1.1. General description

The ‘Atmosphere Chronic’ module is designed to calculate atmospheric dispersion of radioactive contaminant from the chronic (steady state) source of atmospheric contamination to the receptor point based on calculations results 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 shall be evaluated using an external model. These values are scaled with the actual release rate from the source, that is specified by modeler 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 atmospheric transport module discussed in previous paragraph, the inputs (release rates) of radioactive contaminant(s) for the ‘Atmosphere Chronic’ module need to be defined by user in the coupled external Source model. The outputs of the ‘Atmosphere Chronic’ can 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 ‘Doses’ library (see Table 36).

5.7.2. Mathematical model

5.7.2.1.Radionuclide concentrations in the outdoor atmospheric air at receptor point (C_air_atm, Bq/m^3)

$C\_air\_atm = Rate\_release\_atm \times C\_air\_atm\_norm \times CorrFactor\_decay$

Where

Rate_release_atm = radionuclide release rate at source (Bq/day),

C_air_atm_norm = normalized radionuclide concentration in the atmospheric air obtained from simulations with an external atmospheric dispersion model for continuous unit releases (1 Bq/day) of radionuclides (d/m^3),

CorrFactor_decay = correction factor for decay and ingrowth during the atmospheric transport from the source to the receptor (unitless).

Here

$CorrFactor\_decay = \exp(-\lambda \times (dist\_SourceToReceptor/u\_wind))$

Where

dist_SourceToReceptor = distance from the source of atmospheric release to receptor (m), *u_wind* = average yearly wind speed in direction from release source to receptor (m/s),

λ = radionuclide-specific radioactive decay constant (1/s).

5.7.2.2. Radionuclide deposition rates at receptor point (*Rate_dep, Bq/(m*^{2}*.d)*)

$Rate\_dep = Rate\_release\_atm \times Rate\_dep\_norm \times CorrFactor\_decay$

Where

Rate_dep_norm = normalized rate of deposition obtained from simulations with an external atmospheric dispersion model assuming continuous unit (1 Bq/day) release rates (1/m^2).

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_rel_atm (Bq/day)	The annual average release rate for radionuclide from the source	0	Site specific parameter
C_air_atm_norm (m^3/day)	Normalized radionuclide concentration in the atmospheric air obtained from simulations with an external atmospheric dispersion model for continuous unit releases (1 Bq/day) of radionuclides	0	
Rate_dep_norm (1/m^2)	Normalized rate of deposition obtained from simulations with an external atmospheric dispersion model assuming continuous unit (1 Bq/day) release rates		

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 receptor point	1000	Site specific parameter
U_wind (m)	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/m^3)	Radioactive contaminant concentrations in the air	Calculation of doses by inhalation pathway at receptor point
Rate_dep ($Bq/(m^2.d)$)	Radioactive contaminant deposition rates to ground surface	Providing contaminant inputs (loads) to receptor modules

6. ‘RECEPTORS’ MODULE LIBRARY

6.1.GENERAL DESCRIPTION OF LIBRARY

The ‘Receptors’ library includes modules for calculation of radionuclides transfers and redistribution in different types of receptor environments, such as different types of lands (crop lands, pasture lands, forests, uncultivated lands, etc.), buildings, surface water (lakes and rivers), and near-shore marine environment (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 etc.) are usually calculated using the modules from ‘Transports’ library described in the previous chapter.

The receptor modules presented below are essentially based on dynamic radioecological models that have been developed and used by SKB in safety assessment of radioactive waste disposal facilities (e.g., [SKB, 1999, 2006]).

The discussed modules usually provide both radionuclide concentrations in the abiotic media (e.g., soil, water, air) and in various foodstuffs associated with respective receptor environment (e.g., agricultural plants for ‘Cropland’, mushrooms, berries and game for ‘Forest module’, etc.).

Detailed descriptions of individual modules are presented below.

6.1. ‘CROPLAND’ MODULE

6.1.1. Module description

6.1.1.1.General description

The ‘Cropland’ module is designed to assess exposure pathways associated with 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 crop irrigation model described in [SKB, 1999]. 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. 20). Same mathematical model for radionuclide transfers in soil profile is used in ‘Pasture land’, ‘Garden’ and ‘Land’ modules.

Remark: The module provides an option for user to specify radionuclide concentration in soil (e.g., based on monitoring data). In this case fixed in time soil concentration values specified by modeler are used to calculate radionuclide concentrations in crops.

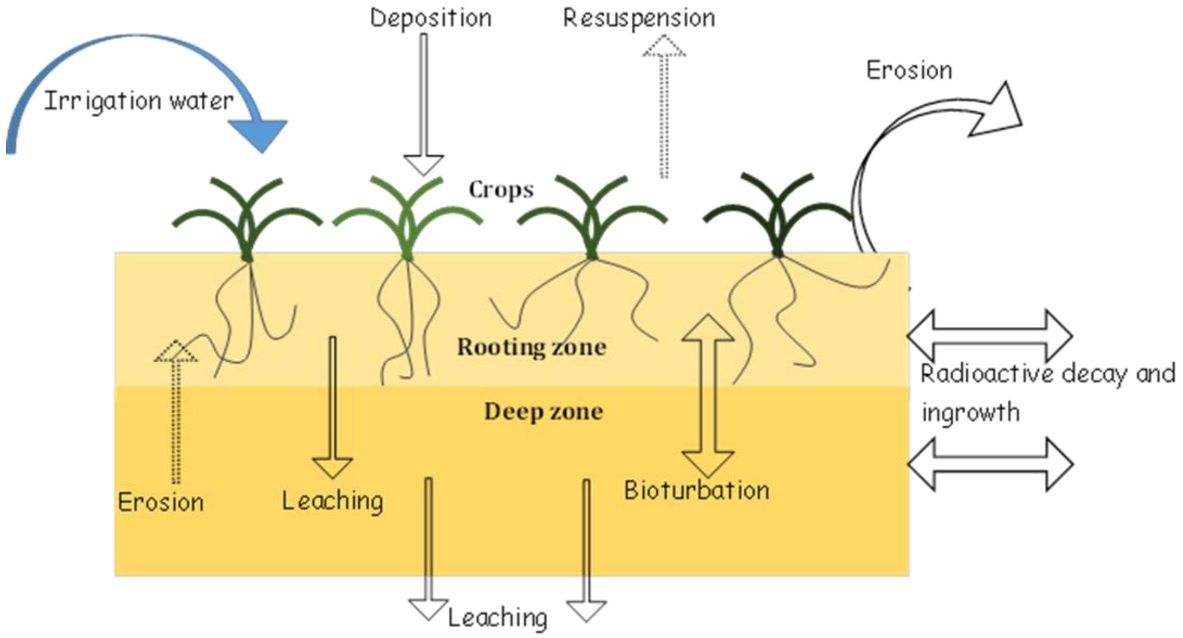

FIG. 20 Illustrative scheme of the 'Cropland' module. Exchanges between media, loadings and losses are shown by arrows.

6.1.1.2.Conceptual model

The conceptual model of the 'Cropland' is illustrated in FIG. 21.

The 'Cropland' model includes the following media.

Soil is subdivided into two compartments:

- Soil 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 considered 'Cropland' and are part of the human diet.

Air: This media is defined as the outdoor air in the 'Cropland' area.

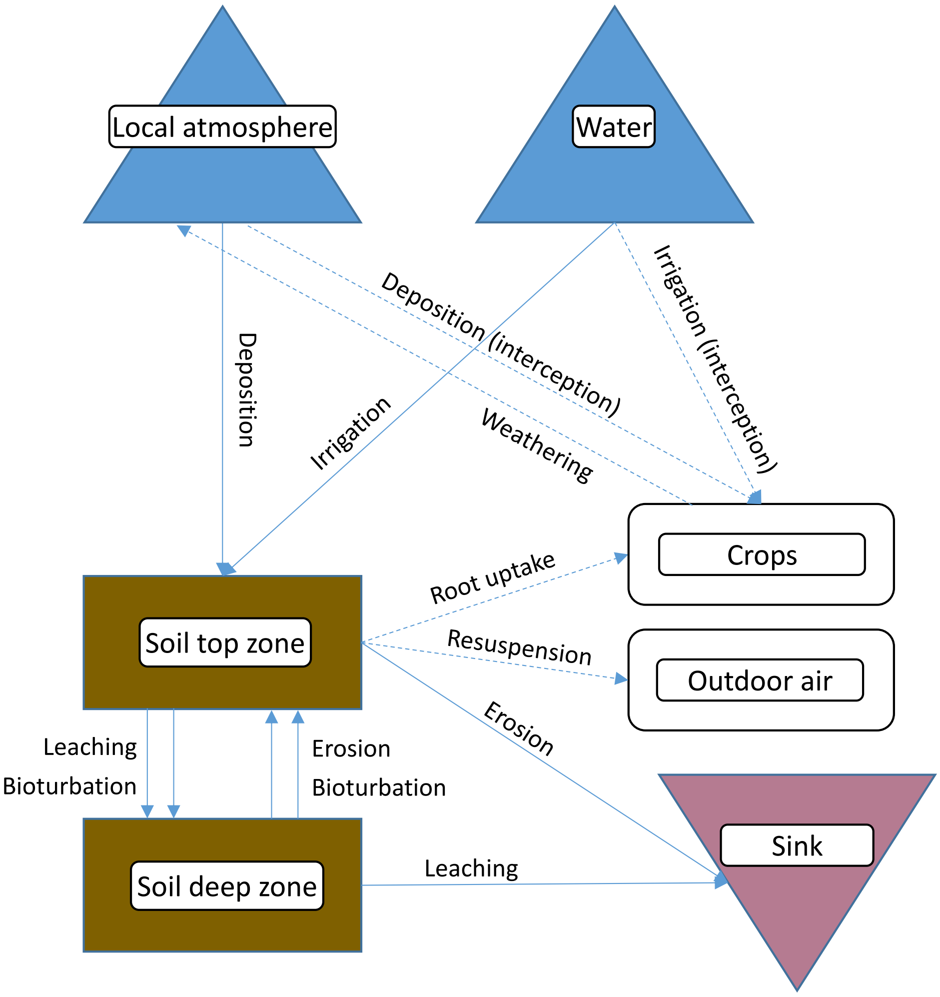

FIG. 21 Conceptual model of the 'Cropland' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

The inputs of radionuclides into the modelled 'Cropland' system can 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 can 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 can occur through the following mechanisms, that are modelled as first order rate process:

- Bioturbation (which is modelled as 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 distribution coefficient) [IAEA, 2010].

Radionuclide accumulation in plants is calculated based on radionuclide concentration in top soil (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 Concentration Ratio (or Transfer Coefficients) approach [IAEA, 2001]. Detailed model equations are given below (see Section 6.1.2).

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 ratios 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 “dust load” model parameter.

6.1.1.3.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 ($Bq/m^2 \cdot d$)
‘Fresh water body’, ‘Well’	Radionuclide concentration in irrigation water (Bq/m^3)

Outputs from the module can be used by following modules	
'Dose from ingestion of crops'	Radionuclide concentration in crops (Bq/kg.FW)
'Dose from occupancy outdoors'	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
	Mass radionuclide concentration in soil root zone (Bq/kg.DW)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.1.2. Mathematical model

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

6.1.2.1.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:

$$\frac{dSoil_{RZ}}{dt} = Dep + Irr + Soil_{DZ} \times Erosion_{DZ} + Soil_{DZ} \times bioT_{DZ} - Soil_{RZ} \times Leach_{RZ} - Soil_{RZ} \times Erosion_{RZ} - Soil_{RZ} \times bioT_{RZ} - \lambda \times Soil_{RZ} + \sum_{p \in P} Br_p \times \lambda \times Soil_{RZ}^{p} \qquad \text{Eq.(18)}$$

Where

Dep = total deposition rate of radionuclides from atmosphere on the receptor area (Bq/day),

Irr – = transfer of radionuclide to the receptor area with irrigation water (Bq/day),

$Soil_{DZ}$ = radionuclide inventory in deep zone of soil (Bq),

$Erosion_{DZ}$ = transfer coefficient of radionuclide from deep soil zone to rooting zone to compensate erosion losses from the rooting zone (1/day),

$bioT_{DZ}$ = transfer coefficient of radionuclide from the deep soil to rooting zone due to bioturbation (1/day),

$Leach_{RZ}$ = transfer coefficient of radionuclides from the root zone to deep zone by leaching (1/day),

$Erosion_{RZ}$ = transfer coefficient of radionuclides from the rooting zone due to erosion process (1/day),

$bioT_{RZ}$ = transfer coefficient of radionuclide from the rooting soil to deep zone due to bioturbation (1/day).

The two last right hand side terms in Eq.(18) describe radioactive decay and ingrowth of radionuclides from the parent nuclides in the root zone.

Deposition rate of radionuclides (Dep, Bq/day)

$$Dep = rate_{dep} \times A$$

Where

$rate_{dep}$ = radionuclide deposition per unit area of receptor (Bq/(m^2•d)),

A = area of the receptor (m^2).

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

$$Irr = c_{water,irr} \times rate_{irr,crops} \times A$$

Where

$c_{water,irr}$ = radionuclide concentration in irrigation water (Bq/m^3),

$rate_{irr,crops}$ = irrigation rate for crops (m/day).

Mass transfer coefficient from the deep soil zone to compensate for erosion (Erosion_DZ, 1/day)

$$Erosion_{DZ} = rate_{erosion}/\left(h_{soil,DZ} \times rho_{soil,DZ}\right)$$

Where

$rate_{erosion}$ = erosion rate of soils in the considered receptor (kg.DW/(m^2•d)),

$h_{soil,DZ}$ = height of the deep soil zone (m),

$rho_{soil,DZ}$ = density of the deep zone soil (kg.DW/m^3).

Mass transfer coefficient due to erosion from the soil root zone (Erosion_RZ, 1/day)

$$Erosion_{RZ} = rate_{erosion}/\left(h_{soil,RZ} \times rho_{soil,RZ}\right)$$

Where

$rate_{erosion}$ = erosion rate of soils in the considered receptor (kg.DW/(m^2•d)),

$h_{soil,RZ}$ = height of the rooting soil zone (m),

$rho_{soil,RZ}$ = density of the rooting zone soil (kg.DW/m^3).

Mass transfer coefficient due to bioturbation in the soil deep zone (bioT_DZ, 1/day)

$$bioT_{DZ} = bioT/\left(h_{soil,DZ} \times rho_{soil,DZ}\right)$$

Where

$bioT$ = bioturbation coefficient in the soil (kg.DW/(m^2•d)).

Mass transfer coefficient due to bioturbation in the soil root zone (bioT_RZ, 1/day)

$$bioT_{RZ} = bioT/\left(h_{soil,RZ} \times rho_{soil,RZ}\right)$$

Mass transfer coefficient due to leaching from the soil deep zone (Leach_DZ, 1/day)

$$Leach_{DZ} = \frac{max(\left(rate_{prec} + rate_{irr,crops} - ET_{crops}\right), 0.0)}{\left(h_{soil,DZ} \times porosity_{soil,DZ} \times Ret_{DZ}\right)}$$

Where

$rate_{prec}$ = precipitation rate (m^3/(m^2•d)),

ET_{crops} = evapotranspiration rate (m^3/(m^2•d))

$porosity_{soil,DZ}$ = porosity of the soil deep zone (m^3/m^3)

Ret_{DZ} = retardation factor for the soil deep zone (unitless).

Mass transfer coefficient due to leaching from the soil root zone (Leach_RZ, 1/day)

$$Leach_{RZ} = \frac{max(\left(rate_{prec} + rate_{irr,crops} - ET_{crops}\right), 0.0)}{\left(h_{soil,RZ} \times porosity_{soil,RZ} \times Ret_{RZ}\right)}$$

Where

Ret_{RZ} = retardation factor for the soil rooting zone (unitless).
The equation for calculating the retardation factor in the soil root zone is:

$$Ret_{RZ} = 1.0 + Kd_{soil,RZ} \times rho_{soil,RZ}/porosity_{soil,RZ}$$

Where

$Kd_{soil,RZ}$ = distribution coefficient for the soil rooting 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:

$$\frac{dSoil_{DZ}}{dt} = Soil_{RZ} \times Leach_{RZ} + Soil_{RZ} \times bioT_{RZ} - Soil_{DZ} \times Leach_{DZ} - Soil_{DZ} \times Erosion_{DZ} - Soil_{DZ} \times bioT_{DZ} - \lambda \quad \times Soil_{DZ} + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Soil_{DZ}^{p} \qquad Eq.(19)$$

Where

$Soil_{RZ}$ = radionuclide inventory in root zone of soil (Bq),

$Erosion_{DZ}$ = transfer coefficient of radionuclide from deep soil zone to rooting zone to compensate for erosion process (1/day),

$bioT_{DZ}$ = transfer coefficient of radionuclide from the deep soil to rooting zone due to bioturbation (1/day),

$Leach_{DZ}$ = transfer coefficient of radionuclides from the root zone to deep zone by leaching (1/day),

$Erosion_{RZ}$ = transfer coefficient of radionuclides from the rooting zone due to erosion process (1/day),

$bioT_{RZ}$ = transfer coefficient of radionuclide from the rooting soil to deep zone due to bioturbation (1/day).

The two last right hand side terms in Eq.(19) describe 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:

$$Ret_{DZ} = 1.0 + Kd_{soil,DZ} \times rho_{soil,DZ}/porosity_{soil,DZ}$$

Where

$Kd_{soil,DZ}$ = distribution coefficient for the soil deep zone (m^3 / kg.DW).

6.1.2.2.Radionuclide concentration in soil media

Radionuclide mass concentration in the soil rooting zone ($c_{soil,byCrop,}$, Bq/kg_{DW})

$$c_{soil,byCrop} = Soil_{RZ}/(A \times h_{soil,RZ} \times rho_{soil,RZ}) \qquad Eq.(20)$$

Where

$Soil_{RZ}$ = radionuclide inventory in the soil rooting zone (Bq),

A = area of the receptor (m^2),

$h_{soil,RZ}$ = height of the soil rooting zone (m),

$rho_{soil,RZ}$ = density of the soil rooting zone ($kg.DW/m^3$).

Radionuclide volumetric concentration in soil (c_soil_vol, Bq/m^3)

$$c_{soil,vol} = c_{soil} \times rho_{soil,RZ} \qquad Eq.(21)$$

6.1.2.3. *Radionuclide concentration in outdoor air*

The radionuclide concentration in the outdoor air is calculated as:

$$c_{air,outdoor} = c_{air,resusp} + c_{air,atm} \qquad Eq.(22)$$

Where

$c_{air,res}$ = radionuclide concentration in outdoor air from resuspension (Bq/m^3),

$c_{air,atm}$ = radionuclide concentration in atmospheric air (Bq/m^3) resulting from the radionuclide atmospheric transport from source to receptor.

Radionuclide concentration in outdoor air due to resuspension (c_air,resusp, Bq/m^3)

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

$$c_{air,resusp} = c_{soil} \times c_{dust} \qquad Eq.(23)$$

Where

c_{soil} = radionuclide concentration in the receptor top soil (Bq/kg.DW),

c_{dust} = concentration of dust in atmospheric air (dust load) (kg.DW/m^3).

6.1.2.4. *Radionuclide concentration in crops*

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

$$c_{crops} = c_{root\ uptake} \times \left(1.0 - WC_{crops}\right) \times UnitCorr_{DW,FW} + c_{crops,interc} \qquad Eq.(24)$$

Where

$c_{root\ uptake}$ = radionuclide concentration in the specific crop type due to root uptake (Bq/kg.DW),

WC_{crops} = fractional water content of the crops (unitless),

$UnitCorr_{DW,FW}$ = unit correction factor from dry weight to fresh weight (kg.DW/kg.FW),

$c_{crops,interc}$ = radionuclide concentration in the crop type due to interception from air and irrigation water (Bq/kg.FW).

Radionuclide concentration in cops from root uptake (c_root_uptake, Bq/kg.DW)

Radionuclide concentration in cops from root uptake is calculated by taking the minimum value of two expressions: 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 concentration ratio (CR) [IAEA, 2001]:

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

$$c_{root\ uptake} = min\left(c_{soil,byCrop} \times h_{soil,RZ} \times \frac{rho_{soil,RZ}}{biomass_{crops}}, c_{soil,byCrop} \times CR_{crops}\right)$$

Eq.(25)

Where

$biomass_{crops}$ = biomass of crops (kg.DW/m^2),

CR_{crops} = 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:

$$\mathrm{c_{crops,interc}} = \frac{\mathrm{c_{water,irr}} \times \mathrm{rate_{irr,crops}} \times \mathrm{factor_{interc,crops}} \times \left(1.0 - \exp\left(-\left(\frac{\ln(2)}{\mathrm{T_{weath}}} + \lambda_{\mathrm{decay,days}}\right) \times \mathrm{T_{irr,crops}}\right)\right)}{\left(\frac{\ln(2.0)}{\mathrm{T_{weath}}} + \lambda_{\mathrm{decay,days}}\right)} + \frac{\mathrm{rate_{dep}} \times \mathrm{factor_{interc,crops}} \times \left(1.0 - \exp\left(-\left(\frac{\ln(2)}{\mathrm{T_{weath}}} + \lambda_{\mathrm{decay,days}}\right) \times \mathrm{T_{exp,crops}}\right)\right)}{\left(\frac{\ln(2.0)}{\mathrm{T_{weath}}} + \lambda_{\mathrm{decay,days}}\right)}$$

Eq.(26)

Where

$factor_{interc,crops}$= mass interception factor for crops (m^2/kg.FW),

T_{weath} = weathering half-time (d),

$\lambda_{decay,days}$ = radionuclide decay constant (1/day),

$T_{irr,crops}$ = time period that crops are irrigated (d),

$T_{exp,crops}$ = crops exposure period i.e. the number of days that crops have above ground parts and as a result are exposed to radionuclide deposition (d).

6.1.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial conditions for soil compartments are zero (Table 44), however modelers shall adapt these values according to their specific modeling 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/$m^{3)}$	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/(m^2 •d))	Deposition rate	0	Site specific parameter
c_water_irr (Bq/m^3)	Concentration of radionuclides in irrigation water	0	Site specific parameter

Remark: * - 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 carried out (see Section 6.1.1.1).

Input parameters related to contaminated land geometry and physico-chemical properties of soils are provided in Table I- 2.

Table 45. Input parameters related to agricultural crops

Abbreviation and Unit	**Name**	**Default value**	**Reference**
ET_crops (m^3/(m^2•d))	Evapotranspiration rate	0	
biomass_crops (kg.DW/m^2)	Biomass of crops	See Table 46	[POSIVA, 2012;Table 17-9]
CR_crops (kg.DW/kg.DW)	Concentration ratio for crops	See Table 47	[IAEA, 2010; SKB, 2013]
factor_interc_crops (m^2/kg.FW)	Mass interception factor	See Table 46	[IAEA, 2001; Table VII]
rate_irr_crops (m^3/(m^2•d))	Irrigation rate for crops	See Table 46	[Brundell et al., 2008; SKB, 2012]
T_exp_crops (d)	Crop exposure period	See Table 46	[Andersson , 2013]
T_irr_crops (d)	Time period of irrigation of crops	See Table 46	[IAEA 2001; Table VIII]
T_weath (d)	Weathering half time	22.4	[IAEA, 2010]
WC_crops (unitless)	Fractional water content of the crops	See Table 46	[IAEA, 2009]

*Table 46. Default values of parameters related to crops **

Abbreviation and Unit	**Cereals**	**Leafy vegetables**	**Legumes**	**Roots**
ET_crops ($m^3/(m^2•d)$)	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 ($m^3/(m^2•d)$)	3.34E-04	1.34E-04	3.34E-04	3.34E-04
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	9.2E-1	1.2E-1	8.7E-1

Remark: * - see Table 45 for literature sources for parameter values

Table 47. Default values of concentration ratios (CRs) describing radionuclide transfer to crops, kg/kg [IAEA, 2010; SKB, 2013]

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

6.1.4. Output Parameters

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

Other calculated parameters are radionuclide concentrations in soil and air, that can be used for calculating doses to persons exposed to radioactivity at 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	Can be used to calculate doses from ingestion of crops
c_soil_byCrops (Bq/kg.DW)	Mass radionuclide concentration in soil	Can be used to calculate doses from radionuclides deposited to soil
c_soil (Bq/m^3)	Volumetric radionuclide concentration in soil	Can be used to calculate doses from radionuclides deposited to soi
c_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Can be used to calculate doses from radionuclides in air

6.2.'PASTURE LAND' MODULE

6.2.1. Module description

6.2.1.1.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 simulates dynamically the vertical distribution of radionuclides in the soil of pastureland, the concentrations in fodder and in livestock products (meat and milk).

The mathematical model of radionuclide transfers in pastureland soil is same as for 'Cropland' module (see Section 6.1), and it is based on crop irrigation model described in [SKB, 1999]. 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).

Module calculates radionuclide concentrations in livestock (meat, milk) resulting from cattle grazing on contaminated pasture. It can also account for ingestion by cattle of contaminated water.

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

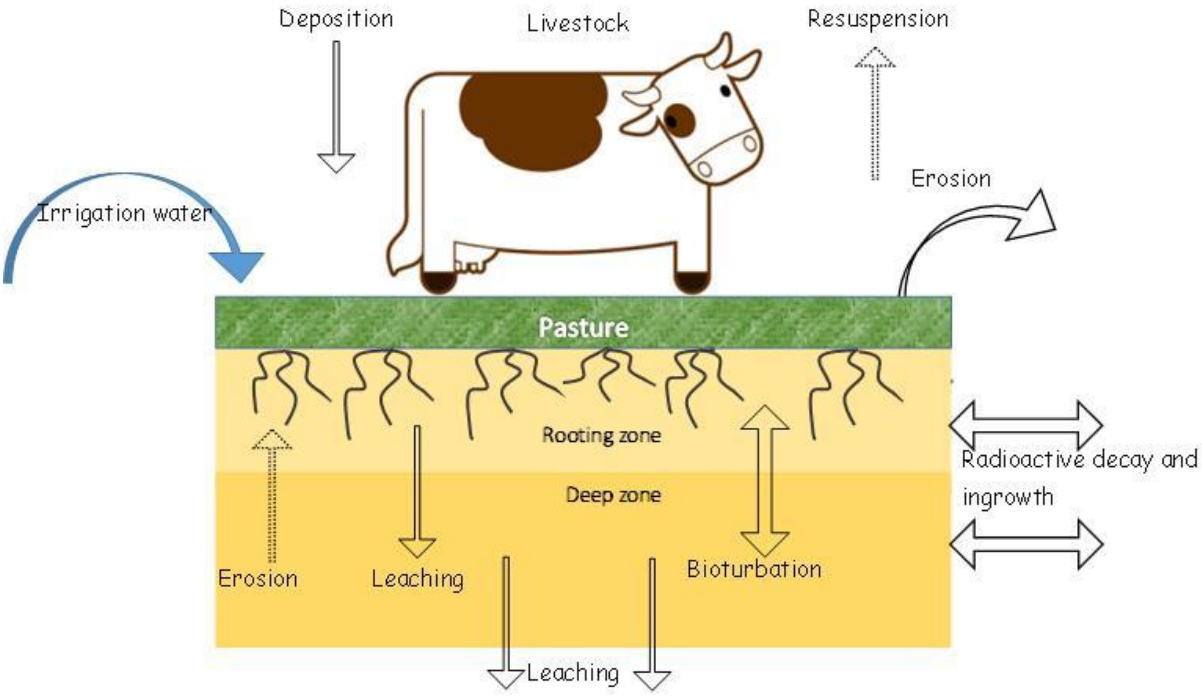

FIG. 22 Illustrative scheme of the 'Pasture land' module. Exchanges between media, loadings and losses are shown by arrows.

6.2.1.2.Conceptual model

The conceptual model of the 'Pasture land' is illustrated in FIG. 23.

The 'Pasture land' model includes the following media.

Soil is subdivided into two compartments:

- Soil root zone: This media is defined as the top soil layer hosting most of the active roots of the fodder pants. 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 the humans (e.g. milk and meat).

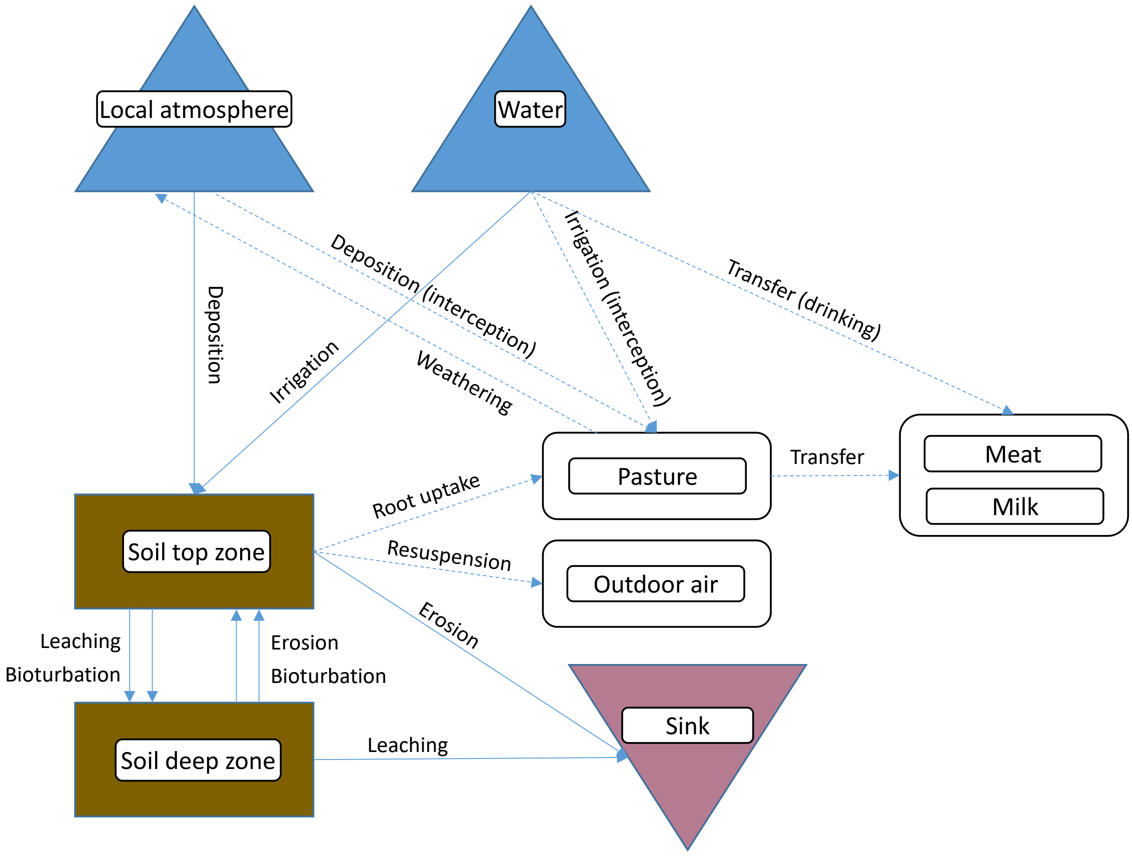

FIG. 23 Conceptual model of the 'Pastureland' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

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

- Irrigation water coming from another receptor (e.g. a river or the 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 can 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 can occur through the following mechanisms, that are modelled as first order rate process:

- Bioturbation (which is modelled as 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 distribution coefficient) [IAEA, 2010].

Radionuclide accumulation in fodder is calculated based on radionuclide concentration in top soil (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 Concentration Ratio (or Transfer Coefficients) approach [IAEA, 2001]. Detailed model equations are given below (See 6.2.2).

Model takes into account the following types of livestock products:

- “beef”,
- “sheep”, and
- “cow milk”.

These livestock products have specific values of relevant radioecological parameters such as the transfer factors? Ingestion rates of fodder, etc. (see 6.2.3)

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 “dust load” model parameter.

6.2.1.3.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/m^2•d)
‘Fresh water body’, ‘Well’	Radionuclide concentration in irrigation water and drinking water (Bq/ m^3)
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)
‘Dose from occupancy outdoors’	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
	Mass radionuclide concentration in soil root zone (Bq/ kg.DW)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.2.2. Mathematical model

6.2.2.1.Mass balance equation for soil media

Radionuclide transfers in soil are described by mathematical model that is similar to the model for ‘Cropland’ receptor decribed in Sections 6.1.2.1- 6.1.2.2 (Eq.(18) -Eq.(19)).

6.2.2.2. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air are calculated using equations described in Section 6.1.2.3 (Eq.(22) - Eq.(23)).

6.2.2.3. Radionuclide concentration in pasture (fodder)

Radionuclide concentrations in pasture (fodder) are calculated using model that is similar to the model radionuclides concentration in agricultural crops for ‘Cropland’ module described in Section 6.1.2.4 (Eq.(24)- Eq.(26)).

6.2.2.4. Radionuclide concentration in milk and meat

Radionuclide concentration in meat (c_meat, Bq/kg)

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

$$\begin{aligned} c_{meat} = {} & TF_{meat} \\ & \times \left(c_{pasture} \times rate_{ing.past,meat} \times f_{grazing} \right. \\ & + c_{water,drink,animals} \times rate_{ing.water,meat} \\ & \left. + c_{soil,calc} \times rate_{ing.soil,meat} \times f_{grazing}\right) \end{aligned}$$

Where

TF_{meat} = transfer factor to livestock meat ((Bq/kg.FW)/(Bq/day)),

$c_{pasture}$ = radionuclide concentration in fodder (Bq/kg.DW),

$rate_{ing.past,meat}$ = cattle type specific ingestion rate of pasture by cattle designated for meat production (meat animals) (kg.DW/day),

$c_{water,drink,animals}$ = radionuclide concentration in drinking water of cattle (Bq/m^3),

$rate_{ing.water,meat}$ = cattle type specific ingestion rate of water by meat animals (m^3/day),

$rate_{ing.soil,meat}$ = cattle type specific ingestion rate of soil by meat animals (kg.DW/day),

$f_{grazing}$ = fraction of a year during which 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 to the other activity transfers pathways.

Radionuclide concentration in milk (c_milk, Bq/L)

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

$$c_{milk} = TF_{milk} \times \left(c_{pasture} \times rate_{ing,past,milk} + c_{water,drink,animals} \times rate_{ing,water,milk} + c_{soil} \times rate_{ing,soil,milk} \times f_{grazing}\right)$$

Where

TF_{milk} = transfer factor to milk(d/L),

$rate_{ing.past,milk}$ = cattle type specific ingestion rate of pasture by cattle designated for milk production (milk animals) (kg.DW/day),

$rate_{ing.water,milk}$ = cattle type specific ingestion rate of water by meat animals (m^3/day),

$rate_{ing.soil,milk}$ = cattle type specific ingestion rate of soil by meat animals (kg.DW/day),

$f_{grazing}$ = fraction of a year during which milk animals are grazing pasture (unitless).

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 (Table 50), however modelers shall adapt these values according to their specific modeling case.

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/m^3)	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/m^2 •day)	Deposition rate	0	Site specific parameter
c_water_irr (Bq/m^3)	Concentration of radionuclides in irrigation water	0	Site specific parameter

Abbreviation and unit	**Full name**	**Default value**	**Reference**
c_water_drink_animals (Bq/m^3)	Concentration of radionuclides in drinking water	0	Site specific parameter

Remark: * - 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 carried out (see Section 6.2.1.1).

Input parameters related to contaminated land geometry and physico-chemical properties of soils are provided in Table I- 2.

Table 51. Input parameters related to pasture

Abbreviation and Unit	**Name**	**Default value**	**Reference**
ET_pasture ($m^3/(m^2 \bullet day)$)	Evapotranspiration rate	0	Site specific parameter
CR_pasture (kg.DW/kg.DW)	Concentration ratio for pasture	See Table 52	[IAEA, 2010]
factor_interc_pasture (m^2/kg.FW)	Mass interception factor	3	[IAEA, 2001, Table VII]
rate_irr_pasture	Irrigation rate for pasture	0.131	[Brundell et al., 2008, SCB, 2012]
T_exp_pasture (day)	Pasture exposure period	30	[IAEA, 2001, Table VIII]
T_irr_pasture (day)	The number of days that vegetation is exposed to irrigation	7.5	[IAEA, 2001, Table VIII]
T_weath (day)	Weathering half time	22.4	[IAEA, 2010]
biomass_pasture (kg.DW/m^2)	Biomass of pasture	0.33	[POSIVA, 2012,Table 17-9]
WC_pasture (unitless)	Fractional water content of the pasture	7.6E-1	[IAEA, 2009]

Table 52. Default values of concentration ratios (CRs) describing radionuclide transfer to pasture, kg.DW/kg.DW [IAEA, 2010]

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/day)	The ingestion rates of pasture by meat producing animals.	See Table 54	[Andersson, 2008]
rate_ing_past_milk (kg.DW/day)	The ingestion rates of pasture by milk producing animals.	9.1	[Andersson, 2008]
rate_ing_soil_meat (kg.DW/day)	The ingestion rates of soil by meat producing animals	See Table 54	[SKB, 2008; Andersson, 2008]
rate_ing_soil_milk (kg.DW/day)	The ingestion rates of soil by meat producing animals	0.6	[SKB, 2008]
rate_ing_water_meat (m^3/day)	The ingestion rates of water by meat producing animals	See Table 54	[SKB, 2008; Andersson, 2008]
rate_ing_water_milk (m^3/day)	The ingestion rates of water by meat producing animals	0.04	[SKB, 2008]
f_grazing (unitless)	The fraction of the year during which meat producing animals are grazing the pasture.	0.25	[SKB, 2008]
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	[IAEA, 2010; SKB, 2013]
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	[IAEA, 2010; SKB, 2013]

Table 54. Default values of cattle ingestion rates [SKB, 2008; Andersson, 2008]

Abbreviation and Unit	**Beef**	**Sheep**
rate_ing_past_meat (kg.DW/day)	11.4	3
rate_ing_water_meat (m^3/day)	0.06	0.01
rate_ing_soil_meat (kg.DW/day)	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

Remark: * literature sources for parameter values are listed in Table 53.

6.2.4. Output Parameters

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

Other calculated parameters are radionuclide concentrations in soil and air of pastureland, that can be used for calculating doses to persons exposed to radioactivity at ‘contaminated land (e.g., shepherds).

Table 56. Output parameters of ‘Pasture land’ module

Abbreviation (unit)	**Name**	**Purpose**
c_meat (Bq/kg^{1})	Radionuclide concentration in meat	Can be used to calculate doses from ingestion ofmeat and milk
c_milk (Bq/L)	Radionuclide concentration in milk	Can be used to calculate doses from ingestion ofmeat and milk
c_soil_vol (Bq/kg.DW)	Mass radionuclide concentration in soil	Can be used to calculate doses from radionuclides in the soil
c_soil (Bq/ m^{3})	Radionuclide volumetric concentration in soil	Can be used to calculate doses from radionuclides in the soil
c_air_outdoor (Bq/ m^{3})	Concentration of radionuclides in outdoor air	Can be used to calculate doses from radionuclides in air

6.3.‘LAND’ MODULE

6.3.1. Module description

6.3.1.1.General description

This module simulates the contaminated land where exposure of 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 implemented radioecological model is based on model described in [SKB, 1999] (FIG. 24). This is the same model as for ‘Cropland’ module. The model dynamically simulates vertical distribution of radionuclides in 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, bio-turbation (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

<u>Remark</u>: The module provides an option for user to directly specify radionuclide concentration in soil (e.g., based on monitoring data) for subsequent dose calculations. In this case, dynamic calculations of radionuclide redistribution in soil profile are not carried out.

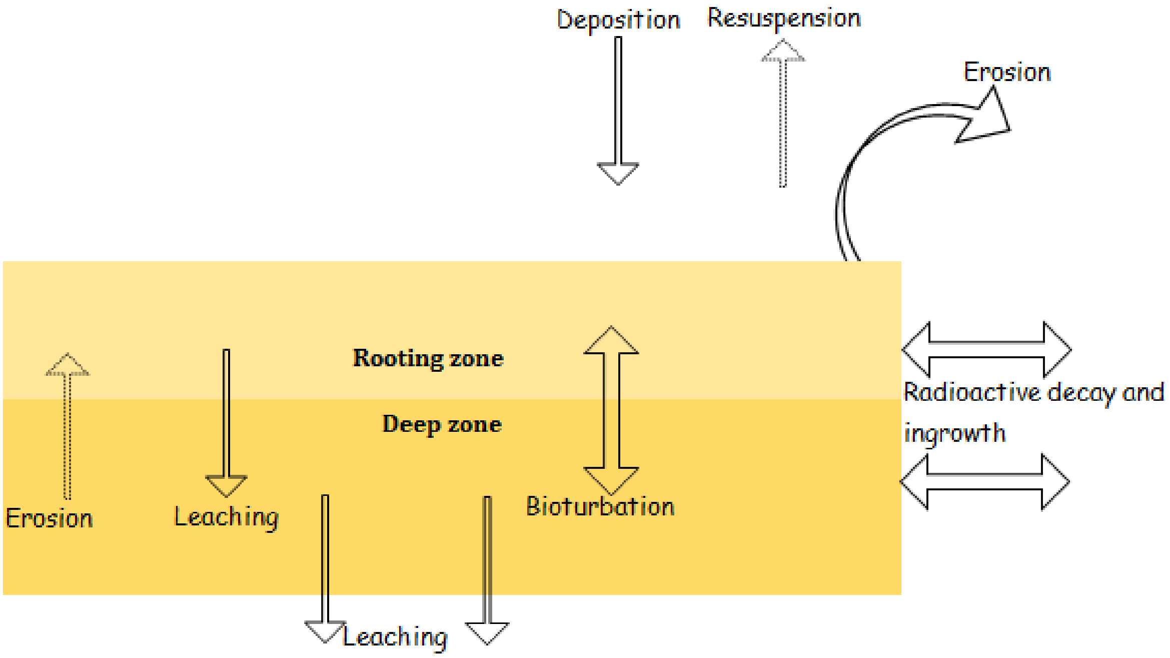

FIG. 24 Illustrative scheme of the ‘Land’ module. Exchanges between media, loadings and losses are shown by arrows.

6.3.1.2.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 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 can occur through the following mechanisms:

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

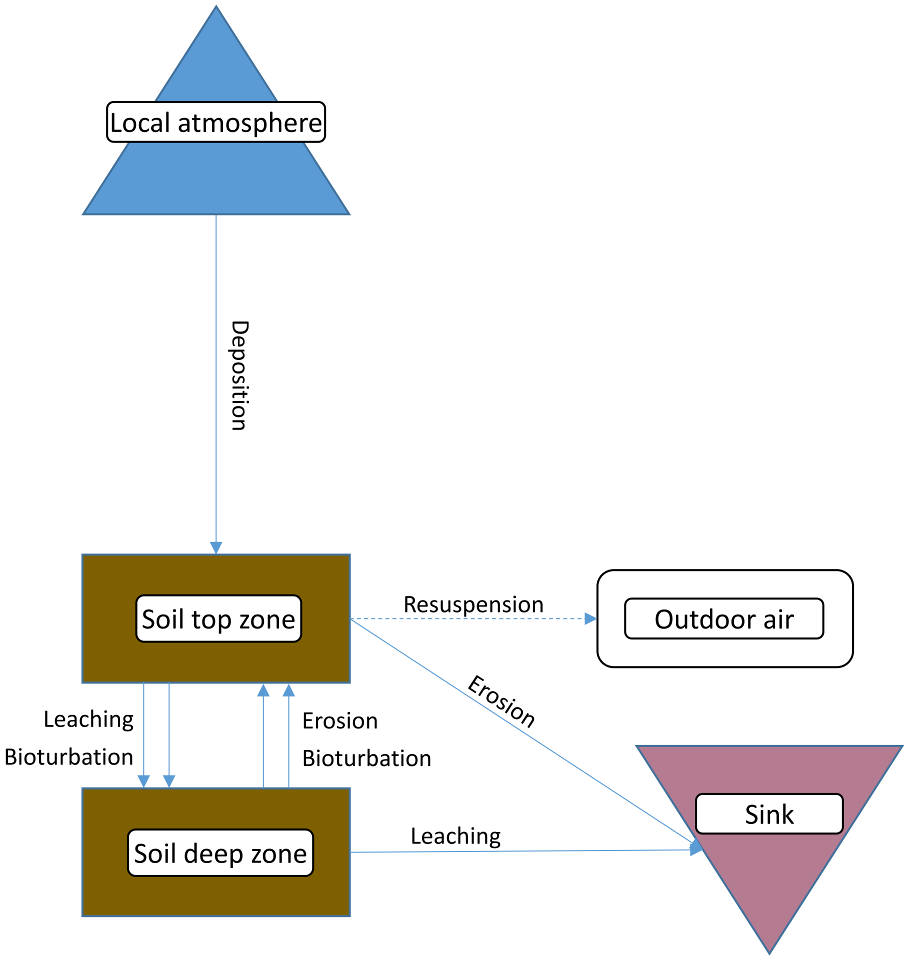

FIG. 25 Conceptual model of the 'Land' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

The potential losses of contaminants from the 'Land' system can 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 can occur through the following mechanisms, that are modelled as first order rate process:

- Bioturbation (which is modelled as 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 distribution coefficient) [IAEA, 2010].

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.

6.3.1.3.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•day)
Outputs from the module can be used by following modules	
‘Dose from occupancy outdoors’	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
	Mass radionuclide concentration in soil root zone (Bq/kg.DW)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.3.2. Mathematical model

6.3.2.1.Mass balance equation for soil media

Radionuclide transfers in soil are described by mathematical model that is similar to the model for 'Cropland' receptor decribed in Section 6.1.2.1- 6.1.2.2 (Eq.(18) -Eq.(19)).
It should be noted that it is assumed that there is no irrigation in 'Land' module, therefore respective terms of the mathematical model related to irrigation are not taken into account.

6.3.2.2. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air are calculated using model that is similar to 'Cropland' module described in Section 6.1.2.3 (Eq.(22) - Eq.(23)).

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 58), however the modellers shall adapt these values according to their specific modelling case.

Input parameters related to contaminated land geometry and physico-chemical properties of soils are provided in Table I- 2.

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 ($Bq/(m^2 \cdot day)$)	Deposition rate	0	Site specific parameter

Remark: * - The *c_soil_meas* value is needed in case radionuclide concentrations in soil calculated based on user-specified soil concentration values. In this case dynamic calculations of radionuclide concentrations in soil profile are not carried out (see 6.3.1.1).

6.3.4. Output Parameters

The main output parameter of ‘Land’ module is radionuclide concentration in the top (root) soil layer. Module also calculates radionuclide concentrations in the air, that can be 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	Can be used to calculate doses from radionuclides deposied on soil
c_soil_vol (Bq/m^3)	Radionuclide volumetric concentration in soil	Can be used to calculate doses from radionuclides deposited on soil
c_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Can be used to calculate doses from radionuclides in the air

6.4.‘GARDEN PLOT’ MODULE

6.4.1. Module description

6.4.1.1.General description

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

The ‘Garden plot’ module simulates 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 same as for ‘Cropland’ module (see Section 6.1), and it is based on crop irrigation model described in [SKB, 1999]. 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).

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

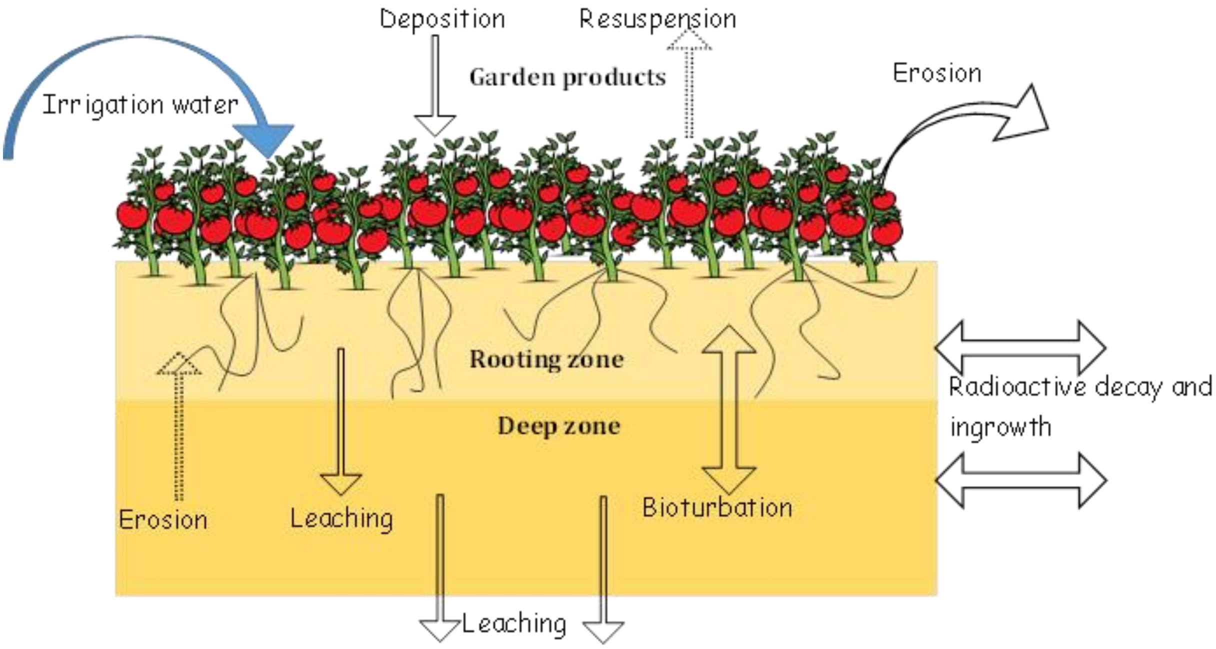

FIG. 26 Illustrative scheme of the 'Garden plot' module. Exchanges between media, loadings and losses are shown by arrows.

6.4.1.2.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 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 considered garden plot and are part of the human diet.

Air: This media is defined as the outdoor air in the garden rea.

The inputs of radionuclides into the modelled 'Garden plot' system can 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 atmosphere in aerosol from and/or dissolved in rainwater;

- Ingrowth of daughter radionuclides due to radioactive decay of their parents.

The potential losses of contaminants from the ‘Garden plot’ system can 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, that are modelled as first order rate process:

- Bioturbation (which is modelled as 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).

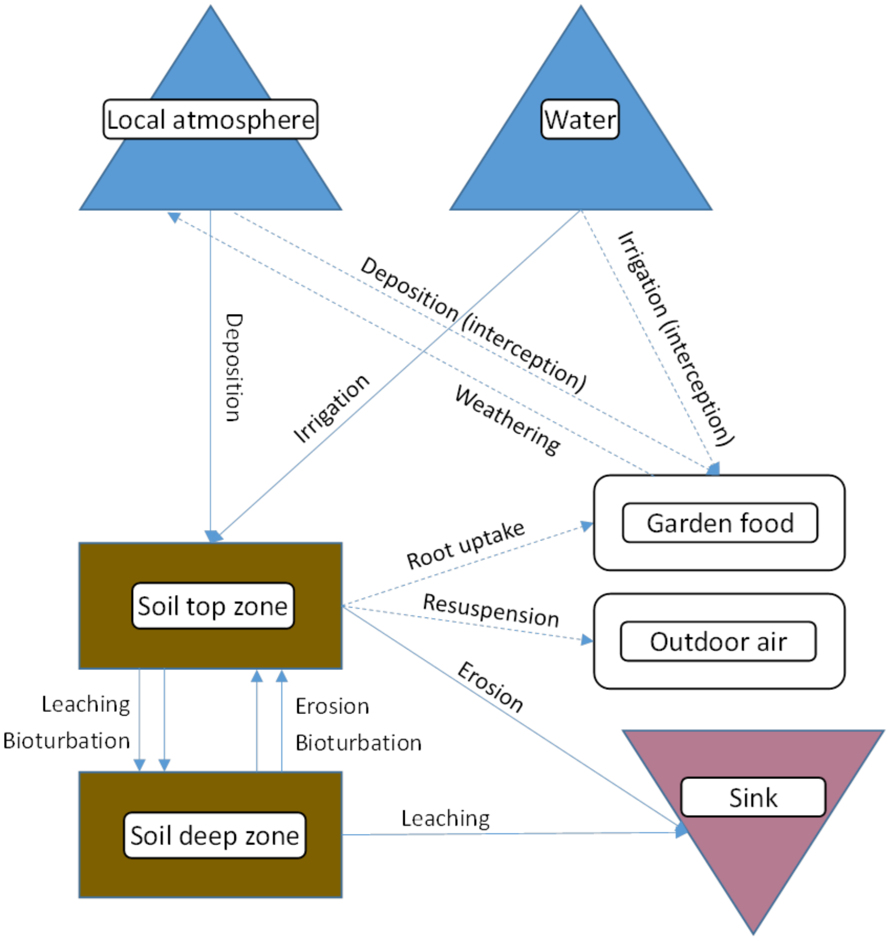

FIG. 27 Conceptual model of the ‘Garden plot’ receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

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 distribution coefficient) [IAEA, 2010].

Radionuclide accumulation in plants is calculated based on radionuclide concentration in top soil (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 Concentration Ratio (or Transfer Coefficients) approach [IAEA, 2001].

Model takes into account four different garden products:

- “legumes”;
- “leafy vegetables”;
- “roots”;
- “fruits”;
- “garden berries”.

These garden products have specific values of relevant radioecological parameters such as concentration ratios values describing radionuclide transfer to garden food from soil, biomass per area values, 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 “dust load” model parameter.

6.4.1.3.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/m^2•day)
‘Fresh water body’, ‘Well’	Radionuclide concentration in irrigation water (Bq/m^3)
Outputs from the module can be used by following modules	
‘Dose from ingestion of garden food’	Radionuclide concentration in garden food (Bq/kg.FW)
‘Dose from occupancy outdoors’	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
	Radionuclide concentration in soil root zone (Bq/kg.DW)

	Concentration of radionuclides in outdoor air (Bq/m^3)

6.4.2. Mathematical model

6.4.2.1.Mass balance equation for soil media

Radionuclide transfers in soil are described by mathematical model that is similar to the model for 'Cropland' receptor decribed in Section 6.1.2.1- 6.1.2.2 (Eq.(18) -Eq.(19)).

6.4.2.2. Radionuclide concentration in outdoor air

Radionuclide concentrations in outdoor air are calculated using equations described in Section 6.1.2.3 (Eq.(22) - Eq.(23)).

6.4.2.3. 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 6.1.2.4 (Eq.(24)- Eq.(26)).

6.4.3. Input parameters

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 (Table 61), however the modellers shall 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 • day))	Deposition rate	0	Site specific parameter
c_water_irr (Bq/m^3)	Concentration of radionuclides in irrigation water	0	Site specific parameter

Remark: * - 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 carried out (see 6.3.1.1).

Input parameters related to contaminated land geometry and physico-chemical properties of soils are provided in Table I- 2.

Table 62. Input parameters related to garden food

Abbreviation and Unit	**Name**	**Default value**	**Reference**
ET_garden_food (m/ day)	Evapotranspiration rate	0	
biomass_garden_food (kg.DW/m^2)	Biomass of garden food	See Table 63	[POSIVA, 2012, Table 17-9]
CR_garden_food (kg.DW/kg.DW)	Concentration ratio for garden food	See Table 64	[IAEA, 2010, SKB, 2013]
factor_interc_garden_food (m^2/kg.FW)	Mass interception factor	See Table 63	[IAEA, 2001; Table VII]
rate_irr_garden_food (m/day)	Irrigation rate for garden food	0	[Brundell et al., 2008; SKB, 2012]
T_exp_garden_food (day)	Garden food exposure period	See Table 63	[Andersson, 2013]
T_irr_garden_food* (day)	Time period of irrigation of garden food	0	[IAEA 2001; Table VIII]
T_weath (day)	Weathering half time	22.4	[IAEA, 2010]
WC_garden_food (unitless)	Fractional water content of the garden food	See Table 63	[IAEA, 2009]

*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 (day)	75	90	75	75	75
WC_garden_food (unitless)	1.2E-1	9.2E-1	8.7E-1	8.5E-1	8.5E-1

Remark: * 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) [IAEA, 2010, SKB, 2013]

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

6.4.4. Output Parameters

The main output parameter of ‘Garden plot’ module is radionuclide concentration in garden food, which can be used for calculating doses from ingestion of garden food. Other calculated parameters are radionuclide concentrations in soil and air of garden plot, that can be used for calculating doses to persons exposed to radioactivity at 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	Can be used to calculate doses from ingestion of garden food
c_soil_byGarden food (Bq/kg.DW)	Mass radionuclide concentration in soil	Can be used to calculate doses from radionuclides in the soil
c_soil (Bq/m^3)	Radionuclide volumetric concentration in soil	Can be used to calculate doses from radionuclides in the soil
c_air_outdoor (Bq/m^3)	Concentration of radionuclides in outdoor air	Can be used to calculate doses from radionuclides in air

6.5. ‘FOREST’ MODULE

6.5.1. Module description

6.5.1.1.General description

The ‘Forest’ module covers exposure pathways relevant for reference person utilizing a forest as a source of food.

Forest module is based on mathematical models of forest ecosystem developed by [SKB, 2006], that dynamically simulates the vertical distribution of radionuclides in soil and radionuclide uptake by tree leaves, tree wood, understory, berries, mushrooms and game (FIG. 28).

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

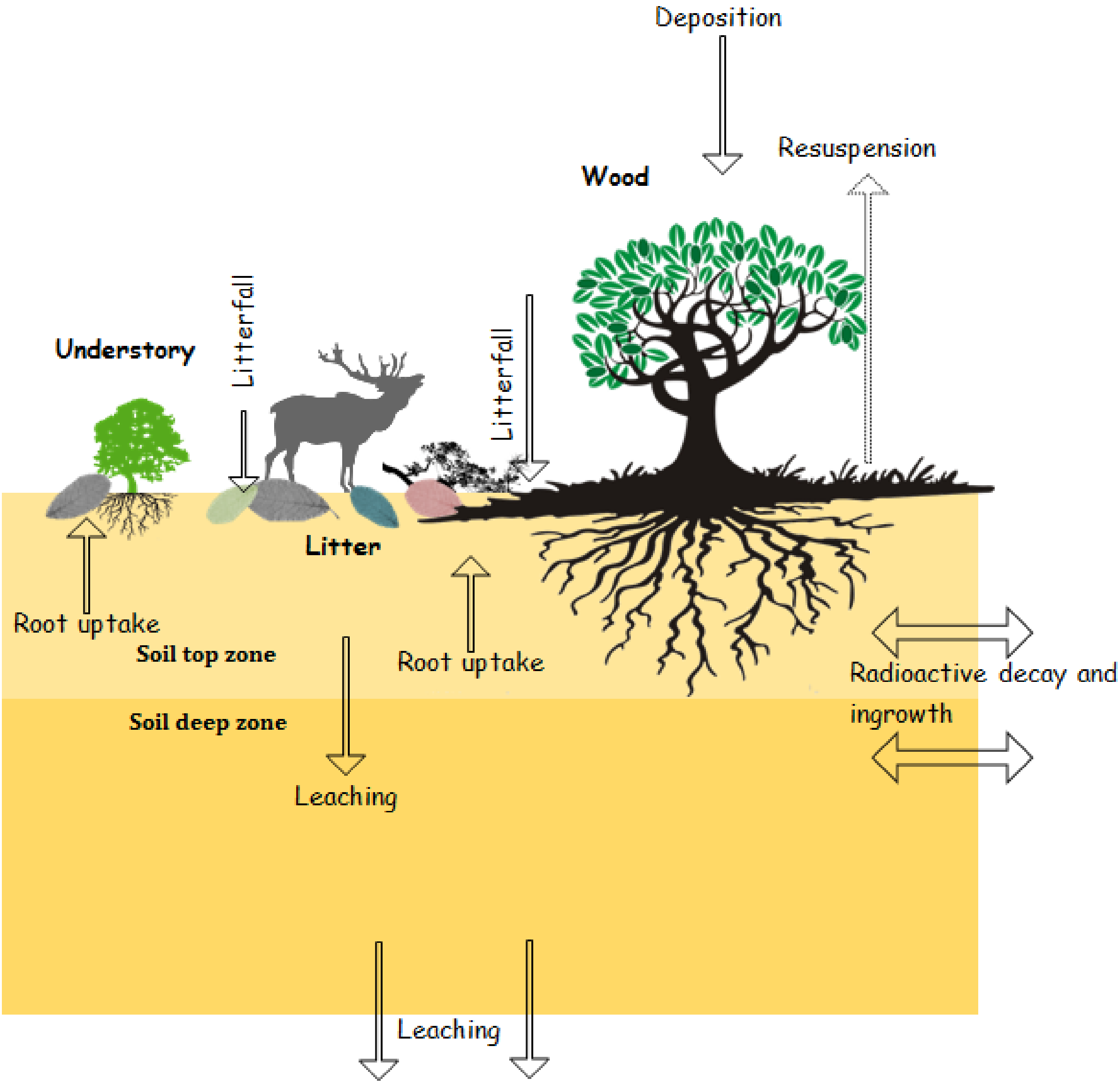

FIG. 28 Illustrative scheme of the 'Forest' module. Exchanges between media, loadings and losses are shown by arrows.

6.5.1.2.Conceptual model

The conceptual model of the 'Forest' module is illustrated in FIG. 29.

The 'Forest' module includes the following compartments.

- Soil 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;
- Understory: 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, dead wood and bark.

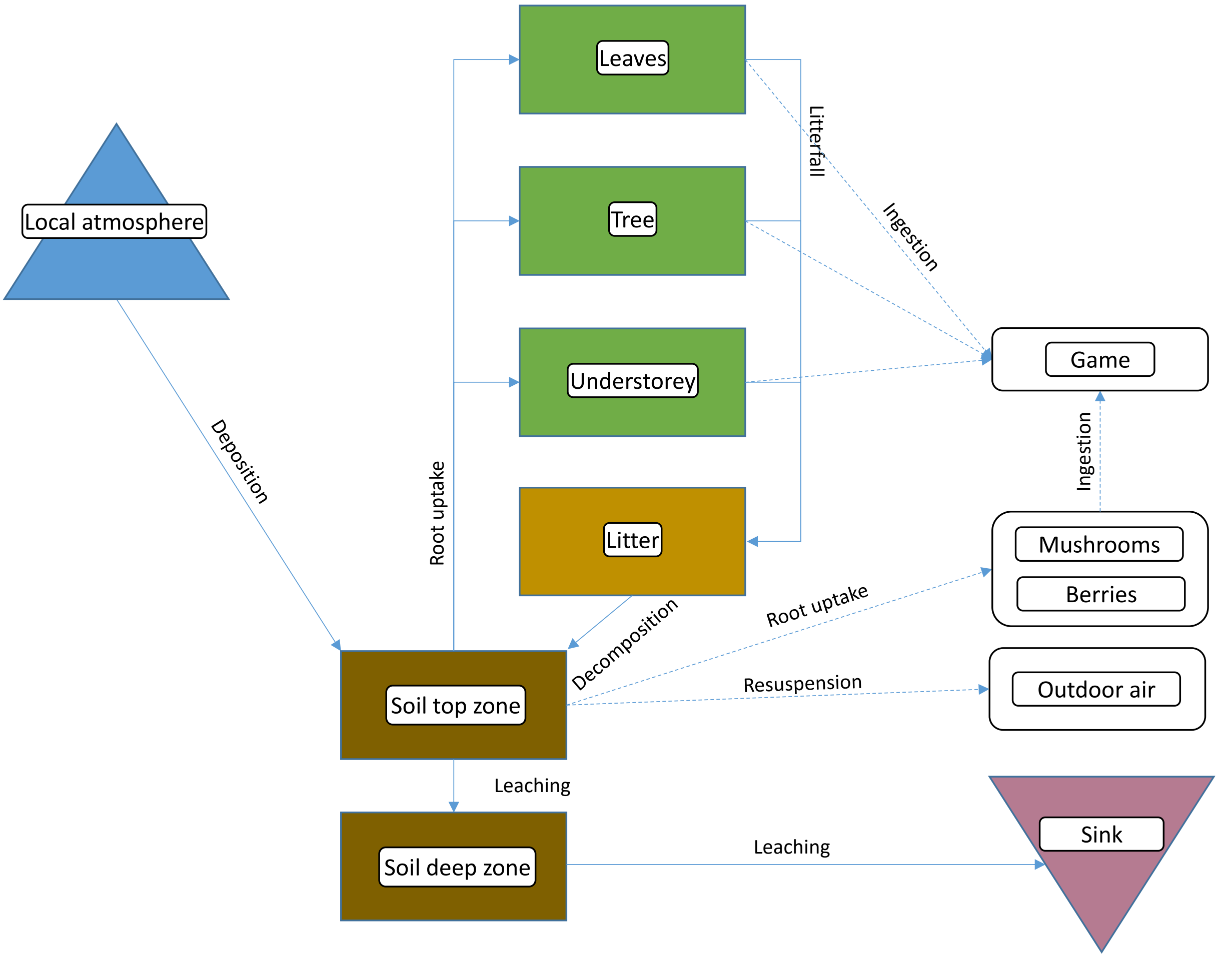

FIG. 29 Conceptual model of the 'Forest' receptor. Transfers represented by dashed lines are modelled non-dynamically (hence do not affect the mass balance).

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

- Deposition of radionuclides (dry and/or wet) from atmosphere in aerosol from 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 can 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 the leaching (i.e., vertical transport of radionuclides dissolved in pore water by moisture flow) that is modelled as first order rate 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 distribution coefficient) [IAEA, 2010].

The considered model describes radionuclides accumulation from soil in wood, leaves, understory, berries and mushrooms using concentration ratio approach [SKB, 2006].

The following radionuclide fluxes that are modelled as 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 leaves 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 by following litter decomposition (FIG. 29).

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

Model takes into account four different forest game/product species:

- “roe deer”;

- “moose”;

- “mushroom”;

- “berries”.

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 “dust load” model parameter.

6.5.1.3.Potential coupled modules

Table 66. Potential coupled modules from NORMALYSA library for 'Forest' 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• day)
Outputs from the module can be used by 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)
'Dose from occupancy outdoors'	Volumetric concentration of radionuclides in the soil root zone (Bq/m^3)
	Radionuclide concentration in soil root zone (Bq/kg.DW)
	Concentration of radionuclides in outdoor air (Bq/m^3)

6.5.2. Mathematical model

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

6.5.2.1.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:

$$\frac{dSoil_{RZ}}{dt} = Dep + Litter \times LitterToSoil + Lichens \times LichensToSoil - Soil_{RZ} \times rootUptake_{wood} - Soil_{RZ} \times rootUptake_{leaves} - Soil_{RZ} \times rootUptake_{understory} - Soil_{RZ} \times Leach_{RZ} - \lambda \times Soil_{RZ} + \sum_{p \in P_i} Br_p \times \lambda \times Soil_{RZ} \qquad Eq.(27)$$

Where

Dep = total deposition of radionuclides from atmosphere on the receptor area (Bq/ day),

Litter – = radionuclide inventory in the litter that lays on top of the soil (Bq), *Lichens* – = radionuclide inventory in the lichens (Bq),

LitterToSoil = transfer rate coefficient of radionuclide from litter to soil due to decomposition process (1/day),

LichensToSoil = transfer coefficient of radionuclide from lichens to soil due to decomposition process (1/day),

$rootUptake_{wood}$ = transfer coefficient of radionuclide from soil to tree wood via root uptake (1/day),

$rootUptake_{leaves}$ = transfer coefficient of radionuclide from soil to tree leaves via root uptake (1/day),

$rootUptake_{understory}$= transfer coefficient of radionuclide from soil to understory via root uptake (1/day).

The two last right hand side terms in Eq.(27) describe radioactive decay and ingrowth of radionuclides from the parent nuclides in the root soil zone.

Deposition of radionuclides (Dep, Bq/ day)

The equation for calculating the deposition of radionuclides is:

$$Dep = rate_{dep} \times A$$

Where

$rate_{dep}$ = radionuclide deposition per unit area of receptor (Bq/(m^2• day)),

A = area of the receptor (m^2).

Transfer rate coefficient of radionuclide from lichens to soil (LichensToSoil, 1/ day)

$$LichensToSoil = rate_{leach,lichens}$$

Where

$rate_{leach,lichens}$= rate of leaching of radionuclides from lichens (1/ day).

Transfer rate coefficient of radionuclide from litter to soil (LitterToSoil, 1/ day)

$$LitterToSoil = rate_{decomp}$$

Where

$rate_{decomp}$ = the decomposition rate of litter (plant matter) in the considered object. (1/ day).

Transfer rate coefficient of radionuclide due to leaching from the soil root zone (Leach_RZ, 1/ day)

$$Leach_{RZ} = \frac{max((rate_{prec} - ET_{forest}), 0.0)}{(h_{soil,RZ} \times porosity_{soil,RZ} \times Ret_{RZ})}$$

Where

$rate_{prec}$ = precipitation rate (m/day),

ET_{forest} = evapotranspiration rate (m/day),

$porosity_{soil,RZ}$ = porosity of the soil rooting zone (unitless),

$h_{soil,RZ}$ = height of the rooting soil zone (m),

Ret_{RZ} = radionuclide retardation factor for the soil rooting zone (unitless).

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

$$Ret_{RZ} = 1.0 + Kd_{soil,RZ} \times rho_{soil,RZ}/porosity_{soil,RZ}$$

Where

$rho_{soil,RZ}$ = density of the rooting zone soil (kg.DW/m^3),

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

The equation for calculating the evapotranspiration rate (ET_{forest}, *m/day*) is:

$$ET_{forest} = rate_{prec} \times factor_{rain,interc} + rate_{transp}$$

Where

$rate_{transp}$ = the transpiration rate of considered vegetation (m/day),

$factor_{rain,interc}$= rain interception factor. (unitless).

Mass transfer coefficient from soil to tree wood due to root uptake (rootUptake_wood, 1/day)

$$rootUptake\_wood = NPP_{wood} \times CR_{wood}/(rho_{soil,RZ} \times h_{soil,RZ})$$

Where

NPP_{wood} = net primary production of wood (kg.DW/(m^2•day))

CR_{wood} = activity concentration ratio for wood (unitless).

Mass transfer coefficient from soil to leaves due to root uptake (rootUptake_leaves, 1/day)

$$rootUptake\_leaves = NPP_{leaves} \times CR_{leaves}/(rho_{soil,RZ} \times h_{soil,RZ})$$

Where

NPP_{leaves} = net primary production of leaves (kg.DW/(m^2•day))

CR_{leaves} = activity concentration ratio for leaves (unitless).

Mass transfer coefficient from soil to understory due to root uptake (rootUptake_understory, 1/day)

$$rootUptake\_understorey = NPP_{understorey} \times CR_{understorey} / \left(rho_{soil,RZ} \times h_{soil,RZ}\right)$$

Where

$NPP_{understorey}$ = net primary production of understorey (kg.DW/(m^2•day))

$CR_{understorey}$ = activity concentration ratio for understorey (unitless).

6.5.2.2.Mass balance equation for lichens (Lichens, Bq)

The mass balance for radionuclides in the 'Lichens' (Bq) media is given by the differential equation:

$$\frac{dLichens}{dt} = Dep_{lichens} - Lichens \times LichensToSoil - \lambda \quad \times Lichens + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Licnens \qquad Eq.(28)$$

Where

$Dep_{lichens}$ = total deposition of radionuclides from atmosphere on the lichens (Bq/day).

The fraction of deposition intercepted by lichens is calculated by the equation:

$$Dep_{lichens} = Dep \times f_{lichens}$$

Where

$f_{lichens}$ = fraction of the total deposition rate that is intercepted by lichens(unitless).

The two last right hand side terms in Eq.(28) describe radioactive decay and ingrowth of radionuclides from the parent nuclides in the lichens.

6.5.2.3.Radionuclide inventory in the deep zone (Soil_DZ, Bq)

The mass balance for the activity of radionuclides in the soil deep zone ($Soil_{DZ}, (Bq)$) is given by the differential equation:

$$\frac{dSoil_{DZ}}{dt} = Soil_{RZ} \times Leach_{RZ} - Soil_{DZ} \times Leach_{DZ} - \lambda \quad \times Soil_{DZ} + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Soil_{DZ} \qquad Eq.(29)$$

Where

$Leach_{DZ}$ = mass transfer coefficient of radionuclides from the deep zone by leaching (1/day).

The two last right hand side terms in Eq.(29) describe 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/day)

The equation for calculating the radionuclide mass transfer coefficient from the soil deep zone through water leaching is:

$$Leach_{DZ} = \frac{max((rate_{prec} - ET_{forest}), 0.0)}{(h_{soil,DZ} \times porosity_{soil,DZ} \times Ret_{DZ})}$$

Where

$porosity_{soil,DZ}$ = porosity of the soil deep zone (unitless),

$h_{soil,DZ}$ = height of the deep soil zone (m),

Ret_{DZ} = 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:

$$Ret_{DZ} = 1.0 + Kd_{soil,DZ} \times rho_{soil,DZ} / porosity_{soil,DZ}$$

Where

$rho_{soil,DZ}$ = density of the deep zone soil (kg.DW/m^3),

$Kd_{soil,DZ}$ = radionuclide distribution coefficient for the soil deep zone (m^3/kg.DW).

6.5.2.4.Radionuclide concentration in soil media

Radionuclide concentrations in soil are calculated using equations that are similar to those described in Section 6.1.2.2 (Eq.(20) - Eq.(21)).

6.5.2.5.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 differential equation:

$$\frac{dLitter}{dt} = Understorey \times UnderstoreyToLitter + Wood \times WoodToLitter + Leaves \times LeavesToLitter - Litter \times LitterToSoil - \lambda \times Litter + \sum_{p \in P_i} Br_p \times \lambda \times Litter$$

Where

$Understorey$ = radionuclide inventory in above ground part of understory plants (Bq),

$Leaves$ = radionuclide inventory in leaves including yearly and older leaves (Bq),

$Wood$ = radionuclide inventory in tree wood including living and dead wood and bark (Bq),

$UnderstoreyToLitter$ = transfer coefficient of radionuclide from above ground part of understory plants to the litter or soil (1/day),

$WoodToLitter$ = transfer coefficient of radionuclide from tree wood including living and dead wood and bark to the litter or soil (1/day),

$LeavesToLitter$ = transfer coefficient of radionuclide from leaves including yearly and older leaves to the litter or soil (1/day).

Mass transfer coefficient from leaves to litter (LeavesToLitter, 1/day)

$$LeavesToLitter = NPP_{leaves}/Biomass_{leaves}$$

Where

$Biomass_{leaves}$ = biomass of leaves (kg.DW/m^2).

Mass transfer coefficient from understory to litter (UnderstoreyToLitter, 1/day)

$$UnderstoreyToLitter = NPP_{understorey}/Biomass_{understorey}$$

Where

$Biomass_{understorey}$ = biomass of understorey (kg.DW/m^2).

Mass transfer coefficient from tree wood to litter (WoodToLitter, 1/day)

$$WoodToLitter = NPP_{wood}/Biomass_{wood}$$

Where

$Biomass_{wood}$ = biomass of wood (kg.DW/m^2).

6.5.2.6. *Mass balance equation for tree leaves (Leaves, Bq)*

The mass balance for radionuclides in the Leaves media is given by the differential equation:

$$\frac{dLeaves}{dt} = Soil_{RZ} \times rootUptake_{leaves} - Leaves \quad \times LeavesToLitter \\ - \lambda \quad \times Leaves \quad + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Leaves$$

6.5.2.7. *Mass balance equation for forest understory (Understorey, Bq)*

The mass balance for radionuclide in the 'Understory' media is given by the differential equation:

$$\frac{dUnderstorey}{dt} \\ = Soil_{RZ} \times rootUptake_{understorey} - Understorey \quad \times UnderstoreyToLitter - \\ - \lambda \quad \times Understorey \quad + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Understorey$$

6.5.2.8. *Mass balance equation for tree wood (Wood, Bq)*

The mass balance for radionuclide in the Wood media is given by the differential equation:

$$\frac{dWood}{dt} = Soil_{RZ} \times rootUptake_{wood} - Wood \quad \times WoodToLitter - \lambda \quad \times Wood \\ + \sum_{p \in P_i} Br_p \quad \times \lambda \quad \times Wood$$

6.5.2.9. *Radionuclide concentrations in forest vegetation compartments*

Radionuclide concentration in leaves (c_leaves, Bq/kg)

$c_{leaves} = Leaves/(Biomass_{leaves} \times A)$

Radionuclide concentration in lichens (C_lichens, Bq/kg)

$c_{lichens} = Lichens/(Biomass_{lichens} \times A)$

Radionuclide concentration in understorey (c_understorey, Bq/kg)

$c_{understorey} = Understorey/(Biomass_{understorey} \times A)$

Radionuclide concentration in wood (c_wood, Bq/kg)

$c_{wood} = Wood/(Biomass_{wood} \times A)$

6.5.2.10. Radionuclide concentrations in forest foods

Radionuclide concentration in berries (c_berries, Bq/kg.FW)

$$c_{berries} = CR_{berries} \times c_{soil} \times (1.0 - WC_{berries}) \times UnitCorr_{DW,FW}$$

Where

$WC_{berries}$ = fractional water content of berries (unitless),

$CR_{berries}$ =concentration ratio coefficient for berries (unitless),

$UnitCorr_{DW,FW}$, =Units correction from DW to FW (kg.DW/kg.FW).

Radionuclide concentration in mushrooms (c_mushroom, Bq/kg.FW)

$$c_{mushroom} = CR_{mushroom} \times c_{soil} \times (1.0 - WC_{mushroom}) \times UnitCorr_{DW,FW}$$

Where

$WC_{mushroom}$ = fractional water content of mushrooms (unitless),

$CR_{mushroom}$ =concentration ratio coefficient for mushrooms (unitless).

Radionuclide concentration in game (c_game, Bq/kg.FW)

$$c_{game} = CR_{game} \times c_{game,diet} \times \left(1.0 - WC_{game}\right) \times UnitCorr_{DW,FW},$$

Where

WC_{game} = fractional water content of game (unitless),

CR_{game} =concentration ratio coefficient for game (unitless).

Here radionuclide concentration in game diet (*c_game_diet*, Bq/kg.FW) are calculated as follows:

$$c_{game,diet} = f_{mushroom,game} \times c_{mushroom}/((1.0 - WC_{mushrooms}) \times UnitCorr_{DW,FW}) + f_{leaves,game} \times c_{leaves} + f_{understorey,game} \times c_{understorey} + f_{wood,game} \times c_{wood} + f_{lichens,game} \times c_{lichens}$$

$f_{mushroom,game}$ =fraction of mushrooms in game diet (unitless),

$f_{leaves,game}$ =fraction of leaves in game diet (unitless),

$f_{understorey,game}$ =fraction of understorey in game diet (unitless),

$f_{wood,game}$ =fraction of wood in game diet (unitless),

$f_{lichens,game}$ =fraction of lichens in game diet (unitless).

6.5.2.11. Radionuclide concentration in outdoor air ($c_{air,outdoor}, Bq/m^3$)

Radionuclide concentrations in outdoor air are calculated using equations that are similar to those described in Section 6.1.2.3 (Eq.(22) - Eq.(23)).

6.5.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation, hence the initial radionuclide concentrations in forest compartments are zero (Table 67), however the modellers shall 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/m$^{3)}$	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/(m^2 •day))	Deposition rate	0	Site specific parameter

Remark: * - 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 carried out (see Section 6.3.1.1).

radionuclide concentrations in soil profile are not carried out (see 6.3.1.1).

Input parameters related to contaminated land geometry and physico-chemical properties of soils are provided in Table I- 2.

Table 68. Input parameters related to plant species

biomass_leaves kg.DW/m^2	Biomass of leaves	0.5	[SKB, 2006; Table 3-2]
biomass_lichens (kg.DW/m^2)	Biomass of lichens	0.5	[SKB, 2006; Table 3-2]
biomass_understorey (kg.DW/m^2)	Biomass of understorey	0.08	[SKB, 2006; Table 3-2]
biomass_wood (kg.DW/m^2)	Biomass of wood	5.1	[SKB, 2006; Table 3-2]
factor_rain_interc (unitless)	Fraction of the rain that is intercepted by the vegetation	0.3	[SKB, 2006; Table 3-4]
rate_leach_lichens (1/day)	Rate of leaching of radionuclides from lichens	5.48E-4	[SKB, 2006]
rate_transp (m/day)	The transpiration rate of considered vegetation. Default values are from (	9.2E-4	[SKB, 2006]
rate_decomp (1/day)	The decomposition rate of litter (plant matter) in the considered object.	2.47E-3	[SKB, 2006]
NPP_leaves (kg.DW/(m^2• day))	The net primary production of tree leaves in forest.	2.19E-4	[SKB, 2006]
NPP_understorey (kg.DW/(m^2• day))	The net primary production of tree wood in forest.	2.19E-4	[SKB, 2006]
NPP_wood (kg.DW/(m^2• day))	The net primary production of tree understorey in forest.	4.93E-4	[SKB, 2006]
f_lichens (unitless)	Fraction of the total deposition rate that is intercepted by lichens.	1	[SKB, 2006]

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	[IAEA, 2010]
CR_mushrooms (unitless)	Concentration ratio for mushrooms	See Table 72	[SKB, 2013]
CR_leaves (unitless)	Concentration ratio for leaves	See Table 72	[SKB, 2013]
CR_understorey (unitless)	Concentration ratio for understorey	See Table 72	[SKB, 2013]
CR_wood (unitless)	Concentration ratio for wood	See Table 72	[SKB, 2013]
CR_game (unitless)	Concentration ratio for game animals	See Table 72	[SKB, 2013]

Table 70. Default values of game diet parameters [SKB, 2006]

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 [SKB, 2013]

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 sepicies**

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

Remark: * literature sources for parameter values are listed in Table 69.

6.5.4. Output Parameters

The main output parameter of ‘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 area (e.g., forestry workers).

Table 73. Output parameters of ‘Forest’ module

Abbreviation (unit)	**Name**	**Purpose**
c_berries (Bq/kg.FW)	Radionuclide concentration in berries	Can be 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

6.6.‘HOUSE’ MODULE

6.6.1. Module description

6.6.1.1.General description

The ‘House’ module is designed to estimate radiation parameters that are required for assessment of indoor exposure. In particular, the objective of ‘House’ module is assessment of indoor air concentrations of radionuclides including radon (Rn-222).

For all radionuclides (except radon) the simple mixing model is used for air concentrations inside house, that is described by '*ReductionFactor*' parameter.

For indoor radon air concentration, the mixing model described in [Bruno, 1983] is used that accounts for radon diffusive flux through the house basement slab from underlying radioactive source, and also takes into account indoor air exchange by ventilation with the outdoor air. The conceptual model of the 'House' receptor (for Rn-222) is illustrated in FIG. 30.

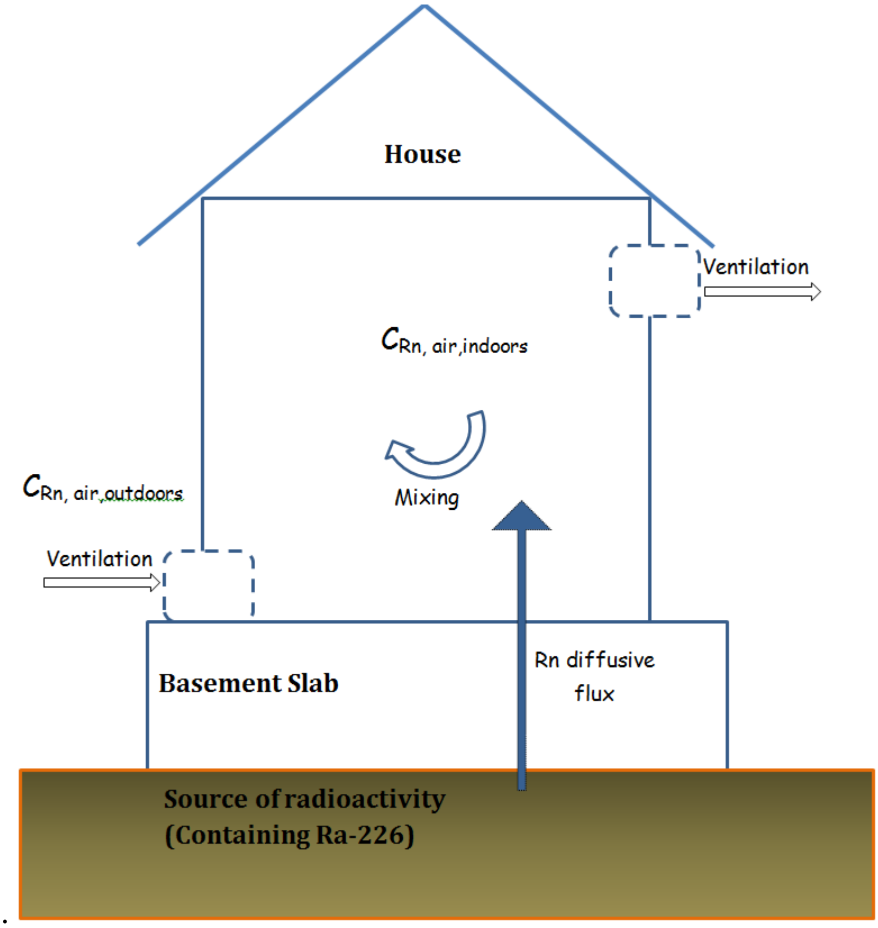

FIG. 30 Conceptual model of Rn-222 mixing indoors for the 'House' receptor.

6.6.1.2.Potential coupled modules

Table 74. Potential coupled modules from NORMALYSA library for 'House' module.

Coupled module	**Description of parameters used as loadings/inputs or outputs**
Inputs to module can be provided by following modules	
'Tailings withut cover', 'Contaminated soil without Cover'with (or without) 'House Slab' modules	Radon concentration in outdoor air (Bq/m^3) Radon flux into the house Bq/(m^2•s)
Outputs from the module can be used by following module	

‘Dose from occulancy indoors’	Concentration of radionuclides and Radon in indoor air (Bq/m^3)

6.6.2. Mathematical model

6.6.2.1.Radionuclide concentration in air

Radionuclide (except Rn-222) concentrations indoors (c_air_indoor, Bq/m^3)

$$c_{air,indoor} = c_{air,outdoor} \times ReductionFactor$$

Where

$c_{air,outdoor}$ = radionuclide concentration in outdoor air (Bq/m^3),

$ReductionFactor$ = parameter determining mixing ratio between indoor and outdoor air concentrations (values between zero and one) (unitless).

Radon (Rn-222) concentration in air indoors (c_air_indoor, Bq/m^3)

Radon concentration in indoor air indoors is calculated as [Bruno, 1983]:

$$c_{air,indoor,Rn} = c_{air,outdoor,Rn} + RadonFlux_{in} \times area/(V \times \left(\frac{rate_{exch}}{SecPerHour} + \frac{\lambda}{SecperYear}\right))$$

Where

$RadonFlux_{in}$ = Radon flux density into the house from the house floor (or through basement slab) (Bq/m^2•sec),

$area$ = area of the house floor (m^2),

V = volume of the house (m^3),

$rate_{exch}$ = exchange rate of air in the house (1/h),

λ = radon decay constant (1/day),

$SecPerHour$ =seconds per hour (sec/h),

$SecPerYear$ =seconds per year (sec/day).

6.6.3. 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/m$^{3)}$	Concentration of radionuclide in outdoor air	0	Site specific parameter
c_air_outdoor_Rn (Bq/m$^{3)}$	Concentration of Radon in outdoor air	0	Site specific parameter
RadonFlux_in (Bq/(m^{2}•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

6.6.4. Output Parameters

Calculated parameters are radionuclide concentrations in indoor air of house, that can be used for calculating doses to persons exposed to radioactivity in ‘House’ receptor.

Table 77. Output parameters of ‘House’ module

Abbreviation (unit)	**Name**	**Purpose**
c_air_indoor (Bq/m^3)	Radionuclide concentration in air indoors	Can be used to calculate doses from occupancy indoors
c_air_indoor_Rn (Bq/m^3)	Radon concentration in air indoors	Can be used to calculate doses from occupancy indoors

6.7. ‘WELL’ MODULE

6.7.1. Module description

6.7.1.1. General description

This module calculates radionuclide concentration in groundwater pumped by a water-well, that can be further used for calculating doses from drinking water pathway or other similar purposes (see below).

This module usually receives input from the modules simulating radionuclide transport in groundwater aquifer (such as ‘Aquifer’ or ‘Aquifer Mixing’ modules; see block-scheme at FIG. 10).

The output of the ‘Well’ module (radionuclide concentration in pumped water) can be used as an input to module from ‘Doses’ library (i.e., ‘Ingestion of water’ module), that calculates doses from drinking water pathway. It can be used also by other receptor modules (e.g., ‘‘Cropland’”, ‘‘Pasture land’’ or ‘Garden Plot’) for contaminant concentrations in irrigation water and/or water for watering cattle.

6.7.1.2. Conceptual model

The module employs 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 well debit is formed by "background" groundwater (FIG. 31).

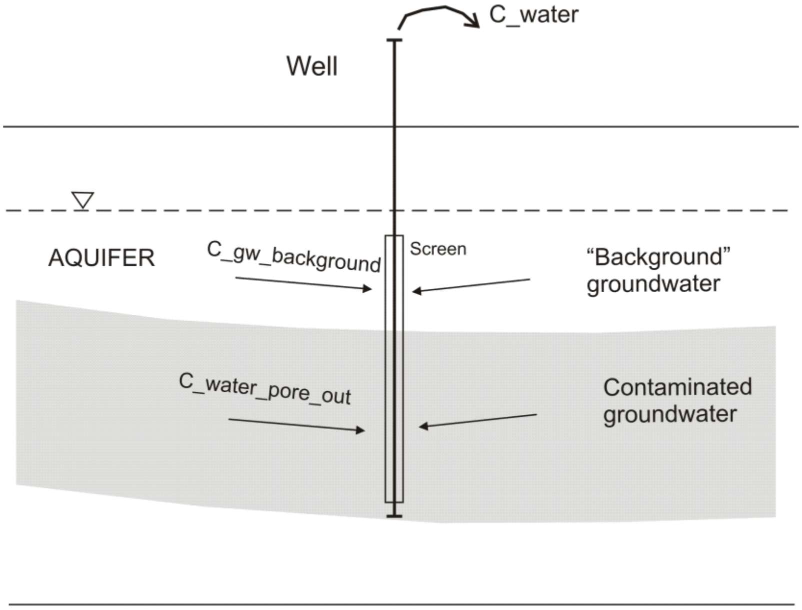

FIG. 31 Conceptual model of 'Well' receptor.

6.7.1.3. *Potential coupled modules*

Table 78. Potential coupled models from 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

6.7.2. Mathematical model

As already discussed, a simple mixing model is employed to calculate radionuclide concentrations in the well water (*C_water*, Bq/m^3) resulting from mixing of contaminated groundwater originating from contaminated site with "background" groundwater:

$$C_{water} = f_{debit\_flowtube} \times C_{water\_pore\_out} + (1 - f_{debit\_flowtube}) \times C_{gw\_background} \qquad \text{Eq. (30)}$$

Where

$f_{debit\_flowtube}$ = well debit fraction formed by contaminated groundwater originating from the contaminated site (unitless),

$C_{water\_pore\_out}$ = radionuclide concentration in groundwater originating from the contaminated site (Bq/m^3),

$C_{gw\_background}$ = radionuclide concentration in "background" groundwater within the aquifer (Bq/m^3).

6.7.3. Input parameters

Table 79. Input parameters for '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

6.7.4. Output parameters

The main output parameter of the 'Well' module is radionuclide concentration in water pumped by well (see Eq. (30)).

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	Can be used to calculate doses from drinking water pathway or used for radionuclide concentrations in water used for irrigation and watering cattle (see Table 78)

6.8. ‘FRESH WATER BODY’ MODULE

6.8.1. Module description

6.8.1.1.General description

The ‘Fresh Water Body’ (FWB) module is designed for assessment of exposure pathways associated with utilizing the modelled surface water reservoir as a source of drinking water and/or food (e.g., fish, etc.) as well as for recreational activities such as swimming and boating

The FWB module is designed to simulate radionuclide transport and fate in lakes, rivers, streams and similar fresh water objects. This module dynamically simulates the distribution of radionuclide both in abiotic media (i.e. surface water, suspended particulate matter and bottom sediments of reservoir) and biotic media (e.g., fish and other edible freshwater organisms) (FIG. 32).

The mathematical model of radionuclide transfers in FWB system is based on ‘Lake’ model described in [SKB, 1999]. The modelled water objects can receive radionuclides by deposition from the atmosphere directly on 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 (upstream water bodies, contaminated groundwater discharge, releases from nuclear facilities etc.).

Remark: The module provides an option for user to specify directly radionuclide concentration in surface water (e.g., based on monitoring data). In this case fixed in time surface water concentration values specified by modeler are used to calculate radionuclide concentrations in freshwater foods.

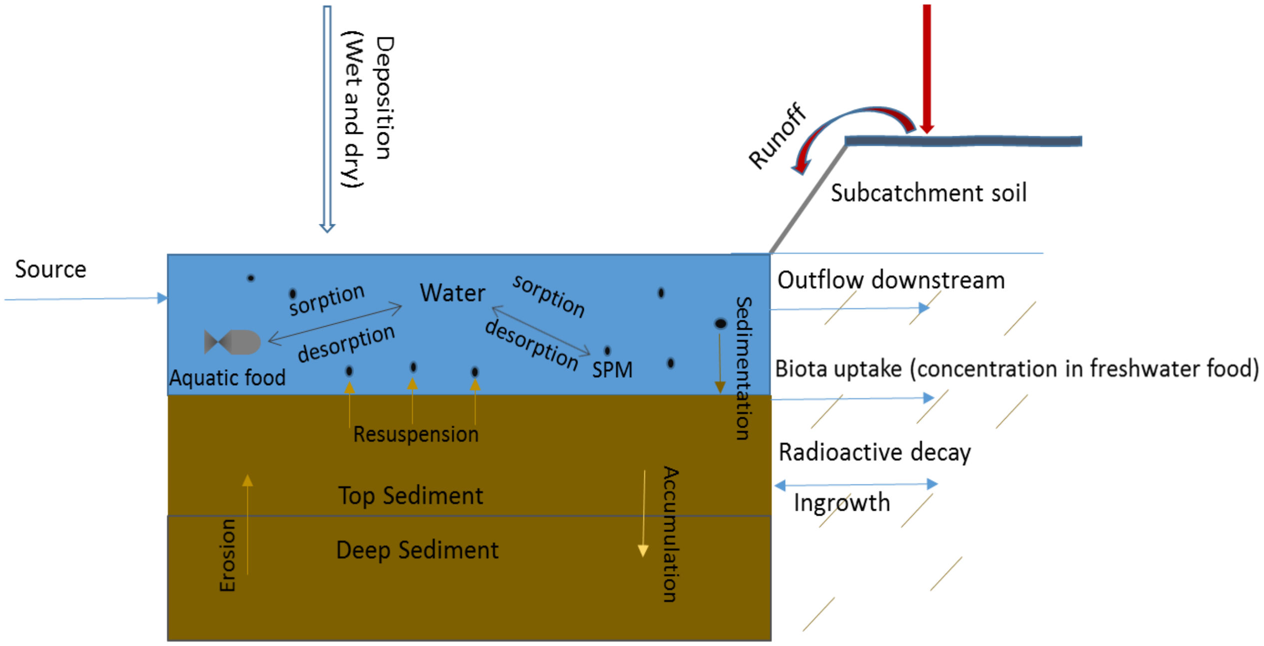

FIG. 32 Scheme illustrating ‘Fresh Water Body’ module.

6.8.1.2.Conceptual model

The conceptual model of the Freshwater Body (FWB) receptor is illustrated in FIG. 33.

The conceptual model includes the following main compartments: ‘Water’ compartment, bottom sediments divided into two compartments – ‘Top Sediment’ and ‘Deep Sediment’, and ‘Sub-catchment’ (i.e., catchment soils of water body that can provide contaminated runoff to ‘Water’ compartment).

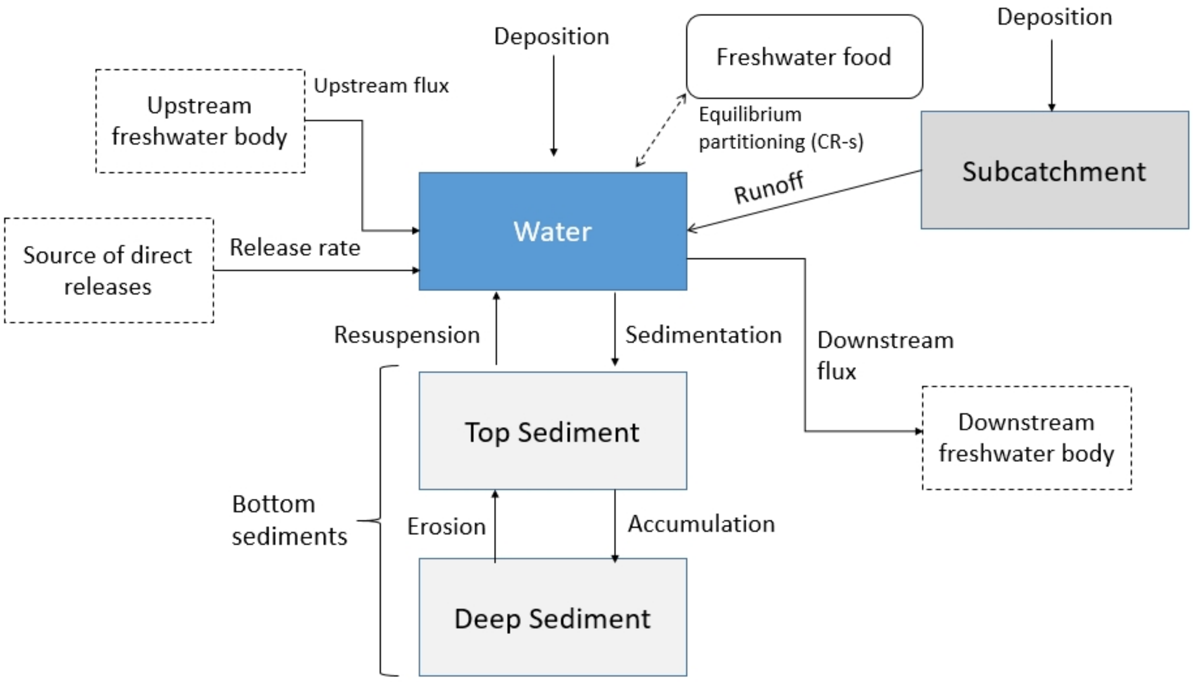

FIG. 33 Conceptual scheme of ‘Fresh water Body’ module.

Exchanges of radionuclides in the solid (sediment, soil) and liquid phases are modelled throughout the module using instantaneous equilibrium reversible sorption model (i.e., Kd model, where Kd is distribution coefficient) [IAEA, 2010].

It is assumed that radionuclide activity stored in ‘Water’ compartment is distributed between activity dissolved in water and activity adsorbed on suspended matter (FIG. 34). Radionuclides dissolved in water and adsorbed on suspended particles are assumed to be in equilibrium described by respective distribution coefficient (Kd_SPM).

The inputs of radionuclides to the ‘modeled FWB system can have the following origins (see FIG. 33):

- Flux of radionuclides from upstream water body in 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 the surface of the FWB;

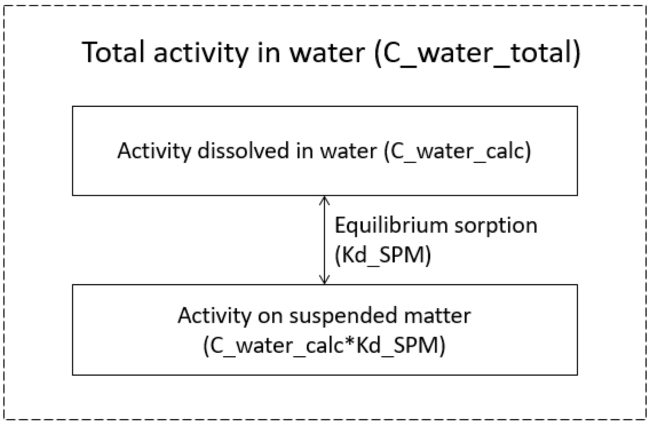

FIG. 34 Partitioning of radionuclide activity in water between dissolved phase and adsorbed on suspended particles.

- Inflow of radionuclides with the contaminated runoff from the sub-catchment 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 ‘Water’ and ‘Top Sediment’ compartment include transfers due sedimentation of suspended particles and process of bottom sediment resuspension to water column. Transfers between ‘Top Sediment’ and ‘Deep Sediment’ include ‘accumulation’ and ‘erosion’ (to compensate for ‘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 ‘Deep Sediment’. More details on these process and their parametrization can be found in [SKB, 1999].

The ‘Sub-catchment’ compartment can receive radionuclides due to atmospheric deposition process. Radionuclide transport in runoff from sub-catchment is modelled as a first order process assuming that radionuclide distribution between the runoff water and contaminated catchment soil is described by Kd-based sorption model (using specific distribution coefficient value, Kd_soil_subcatch).

Radionuclide accumulation in freshwater organisms (e.g., fish, etc.) is calculated based on radionuclide concentration water. Radionuclide transfer to freshwater biota species is modelled using Concentration Ratio (or Transfer Coefficients) approach [IAEA, 2001].

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 ratios 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, etc.).

For water bodies showing significant spatial variations in properties of main compartments mentioned above, it is recommended to subdivide these latter into several sub-models and to couple them which each other as appropriate by means of mass fluxes (e.g., inflowing fluxes from upstream FWB sub-models and outflowing fluxes to downstream sub-models) (see FIG. 33).

6.8.1.3.Potential coupled modules

The 'Fresh Water Body' module can be combined with a large list of other NORMALYSA modules. These latter can be used to specify radiological loads on FWB module (e.g., radionuclide deposition rates from atmosphere, inputs with surface runoff and groundwater, etc.). In its turn the FWB module can provide data on radionuclide concentration in water that can be used by other receptors (e.g., concentrations in irrigation water for 'Cropland' module etc.) or outputs of FWB module (e.g., radionuclide concentrations in water and freshwater foods) can be used directly for dose calculations (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.day))
'Surface Runoff'	Radionuclide release rate (Bq/day) 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/day) from a source of direct release to aquatic object

Coupled model	**Description of parameters used as loadings/inputs or outputs/losses**
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

6.8.2. Mathematical model

6.8.2.1.Mass balance equation for water media (Water, Bq)

$$\frac{dWater}{dt} = Dep + SubCatch \times Outflow_{SubCatch} + TopSediment \times$$

$$\times TC_{res} - Water \times Flux_{WaterToDownstream} + Release - Water \times TC_{sed} - \lambda \times Water + \sum\nolimits_{p \in Pi} Br_p \times \lambda \times Water$$

Where

Dep = radionuclide transfer by deposition from atmosphere on the water surface of FWB (Bq/day),

$SubCatch$ = radionuclide inventory in soil of sub-catchment providing surface runoff to FWB (Bq),

$Outflow_{SubCatch}$ = transfer coefficient for radionuclide transport in surface runoff from sub-catchment (1/day),

$TopSediment$ = radionuclide inventory in top sediment layer (Bq),

TC_{Res} = radionuclide transfer coefficient to water column from top bottom sediment layer by resuspension (1/day),

TC_{Sed} = radionuclide transfer coefficient from water column to top bottom sediment layer by sedimentation (1/day),

$Flux_{WaterToDownstream}$ = radionuclide transfer coefficient from FWB to downstream object by surface water flow 1/day), *Release* = radionuclide transfer to FWB by direct releases (Bq/day).

The two last right hand side terms in equation describe radioactive decay and ingrowth of radionuclides from the parent nuclides in water.

Deposition rate of radionuclides on water surface of FWB (Dep, Bq)

$$Dep = rate_{dep,FWB} \times area_{FWB}$$

Where

$rate_{dep,FWB}$ = radionuclide deposition rate on FWB (Bq/(m^2.day)),

$area_{FWB}$ = area of FWB (m^2).

Transfer coefficient for radionuclide transport in surface runoff ($Outflow_{SubCatch}$, 1/day)

$$Outflow_{subcatch} = runoff/(h_{subcatch} \times porosity_{subcatch} \times Ret_{subcatch})$$

Where

Runoff = the surface runoff expressed as water layer (m/day),

$h_{subcatch}$ = thickness of soil layer in sub-catchment area involved in exchange with surface runoff water (m),

$porosity_{subcatch}$ = porosity of soil in sub-catchment area (unitless),

$Ret_{subcatch}$ = radionuclide sorption retardation coefficient of soil in sub-catchment area (unitless).

Here

$$Ret_{subcatch} = 1.0 + \frac{rho_{subcatch}}{porosity_{subcatch}} \times Kd_{soil,subcatch}$$

Where

$rho_{subcatch}$ = density of soil in sub-catchment area (kg.DW/m^3),

$Kd_{soil,subcatch}$= sorption distribution coefficient of soil in sub-catchment area (m^3/kg.DW).

Transfer coefficient from the top bottom sediment to the water by resuspension (TC_{res}, 1/day)

$$TC_{res} = rate_{res} \times \frac{Kd_{sed}}{h_{sed,top} \times Porosity_{sed,top} \times \left(1.0 + Kd_{sed} \times \frac{rho_{sed,top}}{Porosity_{sed,top}}\right)}$$

Where

$rate_{res}$ = the bottom sediment resuspension (the renewed suspension of a precipitated sediment) rate from top sediment layer in FWB (kg.DW/(m^2.day)),

$h_{sed,top}$ = height (thickness) of the top sediment layer of the FWB; This is considered the bio-turbated layer of the sediment; It is thickness is kept constant in time (m),

$porosity_{sed,top}$ = porosity of the top sediment layer of the FWB (unitless);

$rho_{sed,top}$ = density of the top sediment layer of the FWB (kg.DW/m^3);

Ksed = 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/day)

$$TC_{sed} = rate_{sed} \times Kd_{SPM}/(h_{average}(1.0 + Kd_{SPM} \times c_{SPM})$$

Where

$rate_{sed}$ = 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.day));

$h_{average}$ = average depth of FWB (m),

C_{SPM} = concentration of suspended particulate matter in the FWB water (kg.DW/m^3);

Kd_{SPM} = 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/day)

$$Flux_{WaterToDownStream} = Discharge_{water,downstream}/(area_{FWB} \times h_{average})$$

Where

$Discharge_{water,downstream}$ = surface water flow rate from FWB to the downstream water object (m^3/day

$area_{FWB}$ = surface water area of the FWB (m^2).

6.8.2.2.Mass balance equation for Top Sediment layer (TopSediment, Bq)

$$\frac{dTopSediment}{dt} = Water \times TC_{sed} + DeepSediment \times TC_{erosionSed} -$$
$$- TopSediment \times TC_{res} - TopSediment \times TC_{accumSed}$$
$$- \lambda \times TopSediment + \sum\nolimits_{p \in Pi} Br_p \times \lambda \times TopSediment$$

Where

$DeepSediment$ = radionuclide inventory in deep sediment layer (Bq),

$TC_{erosionSed}$ = radionuclide transfer coefficient from deep sediment layer to top layer account for sediment erosion (as layer thickness stay constant in time) (1/day),

$TC_{accumSed}$ = radionuclide transfer coefficient from top layer to deep sediment layer to account for sedimentation (as layer thickness stay constant in time) (1/day).

The two last right hand side terms in equation describe radioactive decay and ingrowth of radionuclides from the parent nuclides in Top Sediment layer.

Transfer coefficient from the deep sediment to top sediment layer by erosion ($TC_{erosionSed}$, 1/day)

$$TC_{erosionSed} = rate_{res}/(rho_{sed,deep} \times h_{sed,deep})$$

Where

$rho_{sed,deep}$ = density of the deep sediment layer (kg.DW/m^3),

$h_{sed,deep}$ = 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/day)

$$TC_{accumSed} = rate_{sed}/(\rho_{sed,top} \times h_{sed,top})$$

6.8.2.3.Mass balance equation for Deep Sediment layer (DeepSediment, Bq)

$$\frac{dDeepSediment}{dt} = TopSediment \times TC_{accumSed} - DeepSediment \times TC_{erosionSed} - \\ - \lambda \times DeepSediment + \sum_{p \in Pi} Br_p \times \lambda \times DeepSediment$$

All right hand side parameters of the equation already have been defined above.

6.8.2.4.Mass balance equation for Sub-catchment soil

$$\frac{dSubCatch}{dt} = Dep_{SubCatch} - SubCatch \times Outflow_{SubCatch} - \lambda \times SubCatch + \\ \sum_{p \in P} Br_p \times \lambda \times SubCatch$$

Where

$Dep_{SubCatch}$ = radionuclide transfer by deposition from atmosphere on the sub-catchment (Bq/day).

Other parameters of the equation were defined above.

Here

$$Dep_{subcatch} = rate_{dep,subcatch} \times area_{subcatch}.$$

Where

$rate_{dep,subcatch}$ = radionuclide deposition rate from atmosphere on sub-catchment (Bq/(m^2.day)),

$area_{subcacth}$ = area of sub-catchment (m^2).

6.8.2.5. Radionuclide concentration in water of FWB ($C_{water,calc}$, Bq/m^3)

Radionuclide concentration in water in dissolved phase is calculated as:

$$c_{water,calc} = c_{water,total}/(1.0 + Kd_{SPM} \times c_{SPM})$$

Where

$C_{water,total}$ = total radionuclide concentration in water (including radionuclides dissolved in water and those associated with the suspended particles) (Bq/m^3)

Here

$$c_{water,total} = Water/V$$

Where

V = volume of water in FWB (m^3),

that is calculated as

$$V = area_{FWB} \times h_{average}$$

6.8.2.6.Radionuclide concentration in freshwater food ($C_{FreshWaterFood}$, Bq/kg.FW)

$$c_{FreshWaterFood} = c_{water} \times CR_{FreshWaterFood} \times \left(1.0 - WC_{freshwater,food}\right) \times UnitCorr_{DW,FW}$$

Where

$CR_{FreshWaterFood}$ = concentration ratio (radionuclide concentration in aquatic food per element concentration in water) for freshwater food; values are element specific (m^3/kg.DW),

$WC_{freshwater,food}$ = water content in aquatic food (unitless),

$UnitCorr_{DW,FW}$ = units conversion coefficient from DW to FW (kg.DW/kg.FW).

6.8.3. Input parameters

By default, no contamination is assumed at the beginning of the simulation in water bottom sediments and soil of sub-catchment, hence the initial conditions are zero, however modellers shall adapt these values according to their specific cases.

Table 82. Input parameters related to initial contamination and radiological loads on 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 sub-catchment 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 •day))	Deposition rate of radionuclides from air on FWB	0	Site specific parameter
rate_dep_subcatch (Bq/(m^2 •day))	Deposition rate of radionuclides from air on sub-catchment	0	Site specific parameter
rate_rel (Bq/day)	Radionuclide release rate to FWB by direct releases	0	Site specific parameter

Remark: * - 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 radionuclide concentrations in water are not carried out (see Section 6.8.1.1).

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/day)	Water flux from water body upstream (river, lake, etc.)	0	Site specific parameter value needed
C_SPM (kg.DW/m^3)	Concentration of suspended particulate matter in FWB water	0.026	[POSIVA, 2012, Table 10-30]
rate_sed (kg.DW/(m^2.day))	The sedimentation rate of particles in the FWB water	9.55E-3	[POSIVA, 2012, Table 5-11]
Kd_SPM (m^3/kg.DW)	Sorption distribution coefficient for the suspended particulate matter	See Table I-1, Appendix I	[IAEA, 2010; SKB 2013]

Table 84. Input parameters related to bottom sediment geometry and physico-chemical properties

Abbreviation and Unit	**Name**	**Default value**	**Reference**
h_sed_top (m)	Height of the top sediment layer	0.05	[SKB, 2013; Table 2-1]
porosity_sed_top (m^3/m^3)	Porosity of the top sediment layer	0.92	[SKB, 2013; Table 2-1]
rho_sed_top (kg.DW/m^3)	Density of the top sediment layer	179.0	[SKB, 2013; Table 2-1]
h_sed_deep (m)	Height of the deep sediment layer	0.96	[SKB, 2013; Table 2-1]
rho_sed_deep (kg.DW/m^3)	Density of the deep sediment layer	71.7	[SKB, 2013; Table 2-1]
Kd_sed (m^3/kg.DW)	Sorption distribution coefficient for the bottom sediments of FWB	Table 85	[IAEA, 2010; SKB 2013]
rate_res (kg.DW/(m^2.day)	The bottom sediment resuspension rate in FWB	0	Site specific parameter

Table 85. Default radionuclide Kd values for bottom sediments of FWB [IAEA, 2001]

Radionuclide	**Kd, m^3/kg.DW**
Ac	8.80E+01
Cs	9.50E+01
Pa	8.80E+01
Pb	1.40E+02
Po	5.50E+01
Ra	7.40E+01
Sr	1.90E-01
Th	1.90E+02
U	5.00E-01

Table 86. Input parameters related to 'Fresh Water Body' sub-catchment geometry and soil properties

Abbreviation and Unit	**Name**	**Default value**	**Reference**
Area_subcatch (m^2)	Area of sub-catchment	1.5E7	Site specific parameter value needed
h_subcatch (m)	Thickness of soil in sub-catchment area involved in radionuclide exchange process during runoff	0.5	Site specific parameter value needed
runoff (m/day)	Water runoff layer from sub-catchment	0.2	Site specific parameter value needed
porosity_subcatch (m^3/m^3)	Porosity of soil in sub-catchment	5.47E-4	Site specific parameter value needed
rho_subcatch (kg.DW/m^3)	Density of soil in sub-catchment	2115.0	Site specific parameter value needed
Kd_soil_subcatch (m^3/kg.DW)	Sorption distribution coefficient for the soil of sub-catchment	See Table I-1, Appendix I	[IAEA, 2010]

Table 87. Default values of concentration ratios (CRs) describing radionuclide transfer to freshwater food (unitless) [IAEA 2010; SKB 2013]

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 ($WC_{freshater,food}$) (unitless) [IAEA,2009]

Food type	**Fish**	**Cray Fish**	**Mussels**
$WC_{freshater,food}$	0.78	0.78	0.78

6.8.4. Output Parameters

The main output parameters of the ‘Fresh Water Body’ module are radionuclide concentrations in surface water of FWB and radionuclide concentrations in freshwater foods. As discussed in Section 6.8.1.3. these output data can be used by other receptors (e.g., as concentrations in irrigation water etc.) or it can be used directly for dose calculations (Table 89).

Table 89 Output parameters of ‘Fresh Water Body’ module

Abbreviation and unit	**Full name**	**Purpose**
C_water_calc (Bq/m^3)	Radioactive contaminant concentrations in surface water of Fresh Water Body receptor	Can be 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 Fresh Water Body receptor	Can be used to calculate doses from consumption of freshwater foods (see Table 81)
Flux_water_to_dowstream (Bq/day)	Flux with water of radionuclides from the FWB in downstream reservoir	Can be used as input for the next `fresh water body` module.

6.9. ‘MARINE’ MODULE

6.9.1. Module description

6.9.1.1.General description

The ‘Marine’ module allows assessing exposure pathways associated with the use of a sea coastal area as a source of food, as well as with the use of sea for recreational activities such as swimming and boating.

The objective of ‘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 (FIG. 35). The ‘Marine’ module dynamically simulates the distribution of radionuclide in abiotic media (i.e. sea water, suspended particulate matter, and 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 [Lepicard et al., 1998]. The model for radionuclide accumulation in the bech sediment is based on the IAEA SRS no.19 report [IAEA, 2001, p.57].

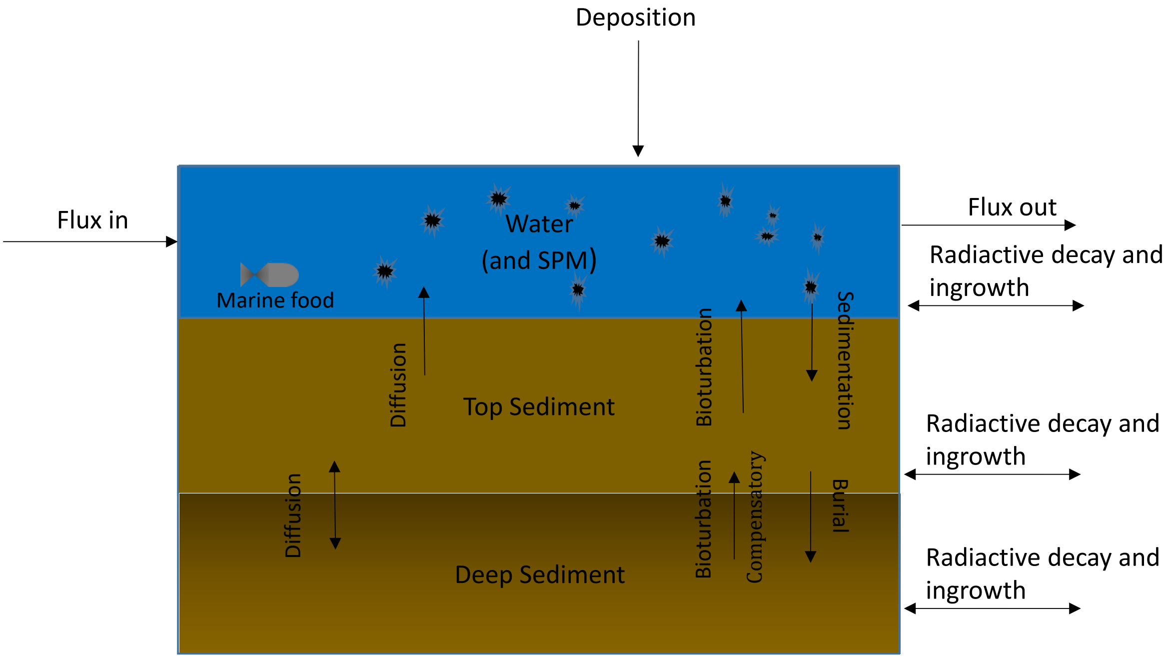

FIG. 35 Scheme illustrating ‘Marine’ module.

Remark: The module provides an option for user to specify directly radionuclide concentration in sea water (e.g., based on monitoring data). In this case fixed in time sea water concentration values specified by modeler are used to calculate radionuclide concentrations in marine food species.

6.9.1.2.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 local sea water (‘Water’) compartment (“inner water compartment”) that can receive direct radionuclide depositions from atmosphere and direct releases of radioactivity from other sources (e.g., liquid releases from nuclear facilities or contaminated groundwater discharge). The area of the local sea compartment is set to the minimum required for sustaining a fish production that is sufficient to feed a small group of individuals. The geometry of 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 (top sediment and deep sediment) defined by the area of the marine compartment and the thicknesses of the sediment layers.

The different compartments in 'Marine' module are assumed to be homogeneous with respect to contamination levels, geochemical properties, etc.

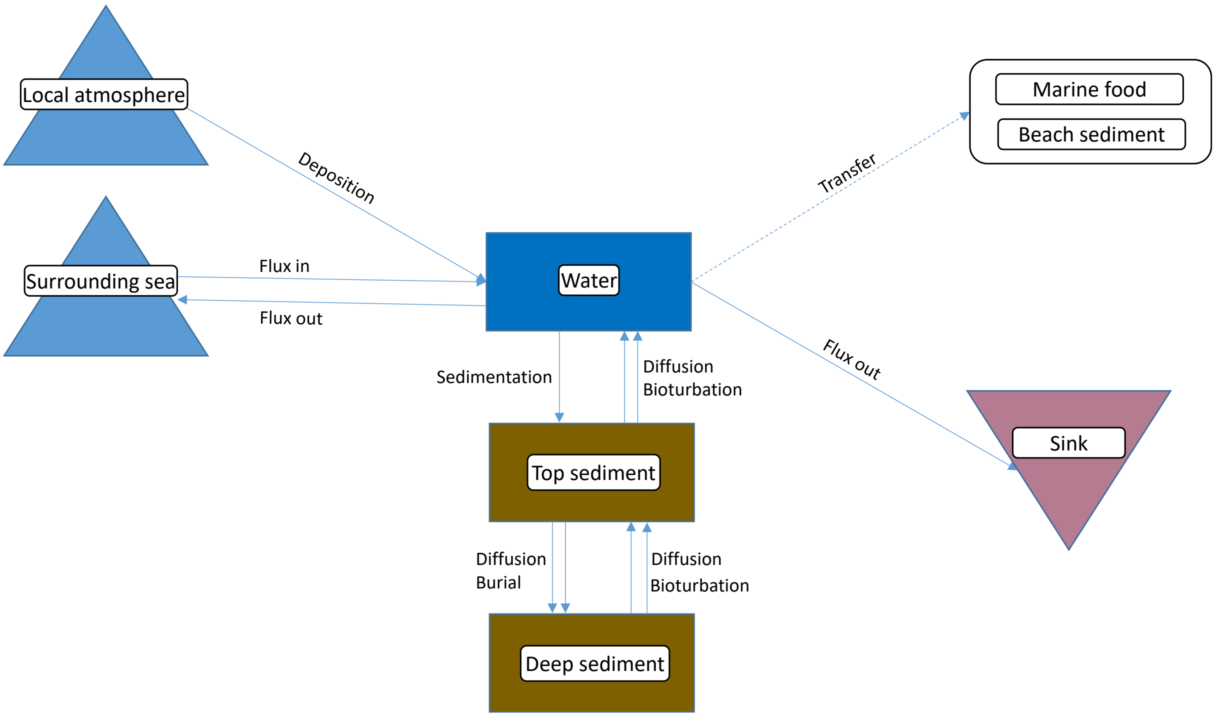

FIG. 36 Conceptual scheme of 'Marine' receptor.

Exchanges of radionuclides in the solid (sediment suspended in water, bottom sediments) and liquid phases are modelled throughout the module using instantaneous equilibrium reversible sorption model (i.e., Kd model, where Kd is distribution coefficient) [IAEA, 2010].

It is assumed that 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 described by respective distribution coefficient (Kd_SPM).

The inputs of radioactive contaminant(s) into the 'Marine' system can have the following origins:

- Contaminant originating from atmospheric deposition on the surface of sea waterbody (total deposition rate, i.e. dry and wet deposition of radionuclides over the water);
- Direct radionuclides release from the source(s) of radioactivity (such as for example industry releases or contaminated groundwater or surface water discharge);

- Contaminant originating from the surrounding sea waterbodies (i.e., inflowing water fluxes)
- Ingrowth of daughter radionuclides from parent radionuclides.;

The potential losses of contaminants from the 'Marine' system can be:

- Out-flux in sea water of radionuclides to adjacent marine areas;
- Radioactive decay.

The discussed exchanges of 'Water' compartment with surrounding marine system (or sub-models) are schematically represented in FIG. 37.

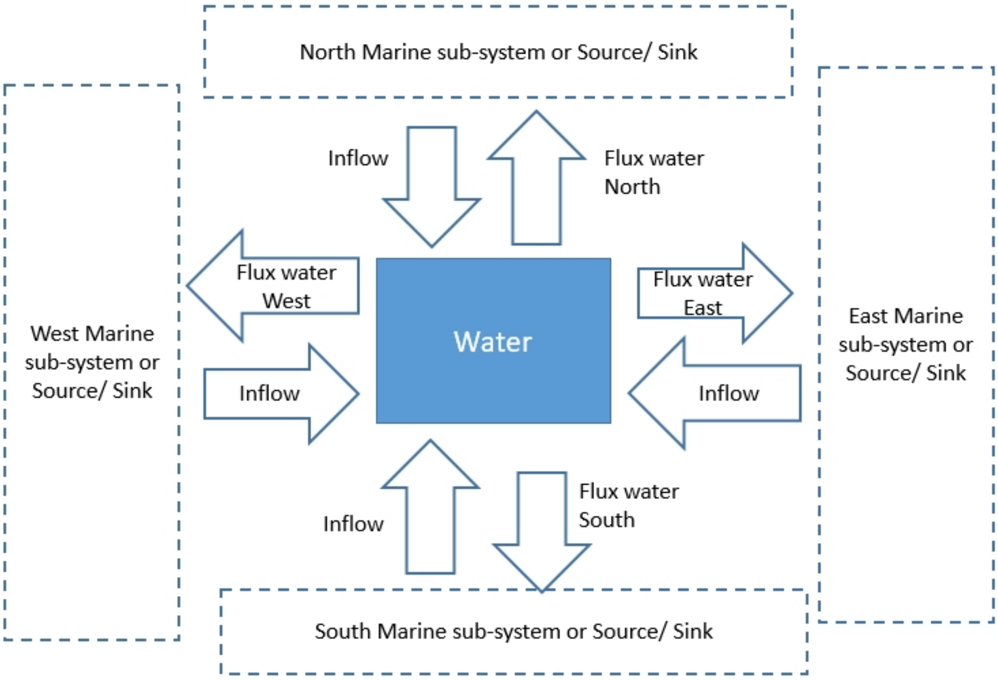

FIG. 37 Schematization of exchanges of 'Water' compartment of 'Marine' system by water fluxes with the surrounding marine environment.

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 radionuclide from bottom sediments (top layer) to the water column. This includes radionuclides contaminant(s) in the sediment solids, as well as radionuclides in the pore water;

- Transfer of radionuclides by diffusion throughout the sediment pore water;

- Exchange between the top layer of the sediment and the water column through bioturbation due to sediment steering by organism 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 grow. This process is modelled as a translocation of radioactive contaminant(s) from top sediment to deeper layers by ‘burial’ processes.

Radionuclide accumulation in aquatic organisms (e.g., fish, etc.) is calculated based on radionuclide concentration water. Radionuclide transfer to marine biota species is modelled using Concentration Ratio (or Transfer Coefficients) approach [IAEA, 2001].

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 water column are accumulating in shore or beach sediment [IAEA, 2001, p.57].

Module takes into account three different types of aquatic food species:

- “fish”;
- “cray fish”;
- “mussels”.

These types of aquatic organisms have specific values of relevant radioecological parameters such as concentration ratios values describing radionuclide transfer from sea water to biota.

Module calculates also accumulation of radioactivity in the sea beach sediments from suspended particles in sea water. The derived activity values can be 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, etc.)

For marine environments showing significant spatial variations in properties of main compartments mentioned above, it is recommended to subdivide these latter into several sub-models 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 sub) (see FIG. 37).

6.9.1.3.Potential coupled modules

The ‘Marine’ module can be combined with a number of other NORMALYSA modules. These latter can be used to specify radiological loads on ‘Marine’ receptor (e.g., radionuclide deposition rates from atmosphere, inputs with surface water and groundwater inflow, etc.). In its turn the ‘Marine’ module can provide data on radionuclide concentrations in sea water, beach sediments and aquatic foods that can be used for dose calculations (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.day))
'Surface Runoff'	Radionuclide release rate (Bq/day) 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' sub-system
'Chronic release'	Radionuclide release rate (Bq/day) 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.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 (swimming, boating, visiting beaches, etc.)
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

6.9.2. Mathematical model

6.9.2.1. Mass balance equation for sea water media (Water, Bq)

$$\frac{dWater}{dt} = Release + Dep + Flux_{in} + TopSediment \times BioturbationToWater + TopSediment \times DiffusionToWater - Water \times SedFromWater - Water \times TC_{out} - \lambda \times Water + \sum_{p \in P_i} Br_p \times \lambda \times Water^p$$

Where

Release = radionuclide transfer to 'Marine' receptor by direct releases (Bq/day),

Dep = radionuclide transfer by deposition from atmosphere on the water surface of 'Marine' receptor (Bq/day),

$Flux_{in}$ = radionuclide transfer to 'Marine' receptor by inflow from other (adjacent) sea water objects (compartments) (Bq/day),

TopSediment = radionuclide inventory in top sediment layer (Bq),

BioturbationToWater = radionuclide transfer coefficient to water column from top bottom sediment layer by bioturbation (1/day),

DiffusionToWater = radionuclide transfer coefficient to water column from top bottom sediment layer by diffusion exchange (1/day),

SedFromWater = radionuclide transfer coefficient from water column to top bottom sediment layer by sedimentation (1/day),

TC_{out} = radionuclide transfer coefficient from 'Marine' receptor to adjacent marine sub-system(s) by sea water flows (1/day).

The two last right hand side terms in equation describe radioactive decay and ingrowth of radionuclides from the parent nuclides in water.

Deposition rate of radionuclides on water surface of 'Marine' receptor (Dep, Bq/day)

$$Dep = rate_{dep} \times area$$

Where

$rate_{dep}$ = radionuclide deposition rate on 'Marine' receptor (Bq/(m^2.day)),

area = area of 'Marine' receptor (m^2).

Radionuclide transfer by direct releases (Release, Bq/day)

$$Release = rate_{rel},$$

Where

$rate_{rel}$ = parameter specifying radionuclide release rate to 'Marine' receptor by direct releases (Bq/day).

Radionuclide transfer by inflow from other sea water objects ($Flux_{in}$, Bq/day)

$$Flux_{in} = FluxIn_{Par},$$

$FluxIn_{Par}$ = parameter specifying radionuclide release rate to 'Marine' receptor by direct inflows of water from adjacent sea boxes (Bq/day).

Radionuclide transfer coefficient from top bottom sediment layer to water by bioturbation (BioturbationToWater, 1/day)

$$BioturbationToWater = (\mathrm{Ret_{sed}} - 1.0)/\mathrm{Ret_{sed}} \times \mathrm{B_k}/(\mathrm{Lt} \times \mathrm{Lt}/2.0)$$

Where

Ret_{sed} = radionuclide retardation factor for bottom sediments (unitless),

B_k = bioturbation coefficient for bottom sediments (m^2/day),

Lt = characteristic length of the top sediment layer (m).

Here

$$\mathrm{Ret_{Sed}} = 1.0 + \left(\frac{rho_{\mathrm{sed,bottom}}}{porosity} \times (1.0 - porosity)\right) \times \mathrm{Kd_{sed}g}$$

Where

$rho_{sed,bottom}$ = density of bottom sediment particles (kg/ m^3),

$porosity$ = porosity of bottom sediments (unitless),

Kd_{sed} = radionuclide distribution coefficient for bottom sediments (m^3/kg).

Transfer coefficient from top sediment layer by diffusion (DiffusionToWater, 1/day)

$$DiffusionToWater = 1.0/\mathrm{Ret_{sed}} \times \mathrm{D_k}/(\mathrm{Lt} \times \mathrm{Lt}/2.0)$$

Here

D_k = diffusion coefficient for bottom sediments (m^2/day),

Other notations are same as in previous formula.

Transfer coefficient from water column to bottom sediment by sedimentation (SedFromWater, 1/day)

$$SedFromWater = \mathrm{Kd_{SPM}} \times \mathrm{rate_{sed}}/(\mathrm{hw} \times (1.0 + \mathrm{Kd_{SPM}} \times \mathrm{c_{SPM}}))$$

Where

Kd_{SPM} = radionuclide distribution coefficient for suspended particles in water column of sea water (m^3/kg).

$rate_{sed}$= sedimentation rate of suspended particles from water column to bottom sediments (kg.DW/(m^2. day)),

hw = dept of water body (m),

C_{SPM} = concentration of suspended particle in sea water (kg/m^3).

Ttransfer coefficient to adjacent marine sub-system(s) by sea water flows (TC_{out}, 1/day)

$$TC_{out} = \frac{Flux_{out}}{Volume}$$

Where

Flux_{out} = sea water flux from 'Marine' receptor (m³/day),

Volume = volume of 'Marine' receptor (m³).

Here sea water flux represents a sum of water fluxes in North, South, West and East directions:

$Fthe\ volume\ lux_{out} = Flux_{Water,North} + Flux_{Water,South} + Flux_{Water,East} + Flux_{Water,West}$

The volume of water in 'Marine' receptor is calculated as:

$Volume = hw \times Area.$

6.9.2.2.Mass balance equation for Top Sediment layer (TopSediment, Bq)

$$\frac{dTopSediment}{dt} = DeepSediment \times DiffusionToTopSed + Water \times SedFromWater + DeepSediment \times BioturbationToTopSed - TopSediment \times BioturbationToWater - TopSediment \times BurialFromTopSed - TopSediment \times DiffusionToWater - TopSediment \times DiffusionToDeepSed - \lambda \times TopSediment + \sum_{p \in P_i} Br_p \times \lambda \times TopSediment^p$$

Where

DeepSediment = radionuclide inventory in deep sediment layer (Bq),

DiffusionToTopSed = radionuclide transfer coefficient from deep sediment layer to top layer by diffusion exchange (1/day),

BioturbationToTopSed = radionuclide transfer coefficient from deep sediment layer to top layer to compensate bioturbation loss from the top layer to water column (1/day),

BurialFromTopSed = radionuclide transfer coefficient from top layer to deep sediment layer to account for deep layer "burial" due to sedimentation (as layer thickness stay constant in time) (1/day),

DiffusionToDeepSed = radionuclide transfer coefficient from top sediment layer to deep layer by diffusion exchange (1/day).

The two last right hand side terms in equation describe radioactive decay and ingrowth of radionuclides from the parent nuclides in 'TopSediment' compartment. Other equation terms and parameters have been already described above.

Transfer coefficient from deep to top sediment layer by diffusion (DiffusionToTopSed, 1/day)

$$DiffusionToTopSed = \frac{1.0}{\mathrm{Ret_{sed}}} \times \mathrm{D_k} / \left(\mathrm{L_m} \times \left(\frac{\mathrm{Lt}}{2.0} + \frac{\mathrm{Lm}}{2.0}\right)\right)$$

Here

Lm = characteristic lenght of the deep sediment layer (m), Other notations are same as in previous formula.

Transfer coefficient from top to deep layer by diffusion (DiffusionToDeepSed, 1/day)

$$\mathrm{DiffusionToDeepSed}=\frac{1.0}{\mathrm{Ret_{sed}}}\times \mathrm{D_k}/\left(\mathrm{L_t}\times\left(\frac{\mathrm{Lt}}{2.0}+\frac{\mathrm{Lm}}{2.0}\right)\right)$$

Radionuclide transfer coefficient from deep to top sediment layer to compensate bioturbation (BioturbationToTopSed, 1/day)

$$BioturbationToTopSed=\frac{1.0}{\mathrm{Ret_{sed}}}\times B_{\mathrm{k}}/\left(\mathrm{L_m}\times\left(\frac{\mathrm{Lt}}{2.0}+\frac{\mathrm{Lm}}{2.0}\right)\right)$$

Transfer coefficient from top layer to deep layer describing "burial" due to sedimentation (BurialFromTopSed, 1/day)

$$\mathrm{Burial\_From\_TopSed}=(\mathrm{Ret_{sed}}-1.0)/\mathrm{Ret_{sed}}\times \mathrm{rate_{sed}}/(\mathrm{Lt}\times(1.0-\mathrm{Porosity})\times \rho_{\mathrm{sed,bottom}})$$

6.9.2.3.Mass balance equation for Deep Sediment layer (DeepSediment, Bq)

$$\frac{dDeepSediment}{dt}=TopSediment^{i}\times BurialFromTopSed$$
$$+TopSediment\quad\times DiffusionToDeepSed\quad-DeepSed\quad\times DiffusionToTopSed$$
$$-DeepSediment\quad\times BioturbationToTopSed-\lambda\quad\times DeepSediment$$
$$+\sum_{p\in P_i}Br_p\quad\times\lambda\quad\times DeepSediment^{p}$$

6.9.2.4.Radionuclide concentration in water of 'Marine' receptor ($C_{water,calc}$, Bq/m^3)

Radionuclide concentration in water in dissolved phase is calculated as:

$$c_{water,calc}=c_{water,total}/(1.0+Kd_{SPM}\times c_{SPM})$$

Where

$C_{water,total}$ = total radionuclide concentration in water (including radionuclides dissolved in water and those associated with the suspended particles) (Bq/m^3).

Here

$$c_{water,total}=\ Water/Volume.$$

6.9.2.5.Radionuclide concentration in marine food ($C_{MarineFood}$, Bq/kg.FW)

$$\mathrm{c_{MarineFood}}=\mathrm{c_{water}}\times \mathrm{CR_{marine,food}}\times\left(1.0-\mathrm{WC_{marine,food}}\right)\times \mathrm{UnitCorr_{DW,FW}}$$

Where

$CR_{MarineFood}$= concentration ratio (radionuclide concentration in aquatic food per element concentration in water) for marine food; values are element specific (m^3/kg.DW),

$WC_{marine,food}$ = water content in aquatic food (unitless),

$UnitCorr_{DW,FW}$ = units conversion coefficient from DW to FW (kg.DW/kg.FW).

6.9.2.6.Radionuclide surface activity concentration in shore/beach sediment ($C_{sed,beach}$, Bq/m²)

$$c_{\mathrm{sed,beach}} = c_{\mathrm{water}} \times Kd_{\mathrm{SPM}} \times rho_{\mathrm{sed,beach}} \times h_{sed,beach} \times \frac{1.0 - \exp(-\lambda \times T_{\mathrm{acc,beach}})}{\lambda \times T_{\mathrm{acc,beach}}}$$

Where

$h_{sed,beach}$ = Thickness of the top layer of the beach sediment (m),

$rho_{sed,beach}$= density of beach sediments (m^3/kg),

$T_{acc,beach}$ = accumulation time for beach sediments (days)

6.9.2.7.Radionuclide flux from 'Marine' receptor ($Flux_{out}$, Bq/day)

$Flux_{out} = Water \times TC_{out}$.

6.9.3. 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 shall adapt these values according to their specific cases.

Table 91. Input parameters related to initial contamination and radiological loads on 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/m³)	Measured radionuclide concentration in water	0	Site specific parameter
rate_dep (Bq/(m² .day))	Deposition rate of radionuclides from air on receptor	0	Site specific parameter
rate_rel (Bq/day)	Radionuclide release rate to receptor by direct releases	0	Site specific parameter
FluxInPar (Bq/day)	Radionuclide influx to receptor by inflow from other (adjacent) sea water objects	0	Site specific parameter

Remark: * - 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 carried out (see Section 6.9.1).

Table 92. Input parameters related to '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/day)	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	[Lepicard at al., 1998]
vel_sed (m/day)	The sedimentation velocity of particles in water to bottom sediments	2.74	[Lepicard at al., 1998]
Kd_SPM (m^3/kg.DW)	Sorption distribution coefficient for the suspended particulate matter	Table 95	[IAEA, 2001; Table VI]

Table 93. Input parameters related to bottom sediment geometry and physico-chemical properties

Abbreviation and Unit	**Name**	**Default value**	**Reference**
Lt (m)	Height of the top sediment layer	0.1	[Lepicard at al., 1998]
Lm (m)	Height of the deep sediment layer	1.9	[Lepicard at al., 1998]
porosity (m^3/m^3)	Porosity of bottom sediment	0.75	[Lepicard at al., 1998]
rho_sed_bottom (kg.DW/m^3)	Density of bottom sediment particles	2600	[Lepicard at al., 1998]
Kd_sed (m^3/kg.DW)	Sorption distribution coefficient for the bottom sediments	Table 95	[IAEA, 2001; Table VI]
D_k (m^2/day)	Solute diffusion coefficient in bottom sediments	8.62E-05	[Lepicard at al., 1998]
B_k (m^2/day)	Bioturbation coefficient in bottom sediments	9.86E-08	[Lepicard at al., 1998]

Table 94. Input parameters related to 'Marine' beach sediment geometry and physico-chemical properties

Abbreviation and Unit	**Name**	**Default value**	**Reference**
h_sed_beach (m)	Thickness of the beach sediment layer	5E-2	[IAEA, 2001]
rho_sed_beach (kg.DW/m^3)	Density of beach sediments	1200	[IAEA, 2001]
T_acc_beach (day)	Accumulation time for beach sediments	0.003	[IAEA, 2001]

Table 95. Default radionuclide Kd values for sediments of 'Marine' environment [IAEA, 2001]

Radionuclide	**Kd, m^3/kg.DW**
Ac	2.00E+03
Cs	3.00E+00
Pa	8.80E+01
Pb	1.00E+03
Po	1.00E+05
Ra	5.00E+00
Sr	1.00E+00
Th	2.00E+03
U	1.00E+00

Table 96. Default values of concentration ratios (CRs) describing radionuclide transfer to marine food (unitless) [IAEA 2001]

Radionuclide	**Fish**	**Cray Fish**	**Mussels**
Ac	5.00E-02	1.00E+00	1.00E+00
Cs	1.00E-01	3.00E-02	3.00E-02
Pa	5.00E-02	5.00E-01	5.00E-01
Pb	2.00E-01	1.00E+00	1.00E+00
Po	2.00E+00	5.00E+01	5.00E+01
Ra	5.00E-01	1.00E+00	1.00E+00
Sr	2.00E-03	2.00E-03	2.00E-03
Th	6.00E-01	1.00E+00	1.00E+00
U	1.00E-03	3.00E-02	3.00E-02

Table 97. Default values of water content of freshwater foods ($WC_{marine,food}$) (unitless) [IAEA,2009]

Food type	**Fish**	**Cray Fish**	**Mussels**
$WC_{freshater,food}$	0.78	0.78	0.78

6.9.4. 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 6.8.1.3. these output data can be used for dose calculations by respective module from ‘Doses’ library (Table 89).

Table 98 Output parameters of ‘Marine’ module

Abbreviation and unit	**Full name**	**Purpose**
C_MarineFood (Bq/kg.FW)	Radioactive contaminant concentrations in sea food of ‘Marine’ receptor	Can be used to calculate doses from consumption of marine foods (see Table 90)
C_water_calc (Bq/m^3)	Radioactive contaminant concentrations in surface water and beach sediment of Marine receptor	Can be used to calculate doses from marine activities (e.g., swimming, boating, visiting beach) (see Table 90)
C_sed_beach (Bq/m^2)	Radioactive contaminant concentrations in beach sediment of Marine receptor	Can be used to calculate doses from visiting beach (see Table 90)
Flux_out (Bq/day)	Radioactive contaminant flux in surface water to adjacent Marine boxes	Can be used to calculate exchanges of radioactivity with the adjacent Marine boxes

7. ‘DOSES’ MODULE LIBRARY

7.1.GENERAL DESCRIPTION OF LIBRARY

A set of modules contained in ‘Doses’ library allows assessment of doses to humans based on radionuclide concentrations in different environmental media (soil, air, water and various foodstuffs) calculated using receptor modules described in previous chapters of this report.

The ‘Dose’ library includes three sub-libraries:

- ‘Doses from occupancy’,
- ‘Ingestion’, and
- ‘Total Dose’.

The first sub-library contains modules that allow calculation of effective doses to reference person exposed to radioactivity in soil, air and water in outdoor environment (i.e., on contaminated land), indoors and in contaminated marine environment.

The second-sub-library includes set of modules for calculating effective internal doses caused by consumption by reference persons of various contaminated foodstuffs related to respective receptor environments (e.g., crops, forest products, aquatic foods etc.).

Eventually the third sub-library includes the ‘Total Dose’ module allowing calculation of the total annual effective dose summed over all relevant radionuclides and exposure pathways that use as input data doses assessed using the first two sub-libraries.

The dose modules allow calculation simultaneously doses to three reference persons: ‘Reference person 1’, ‘Reference person 2’, and ‘‘Reference person 3’.

These reference persons can belong to three different age groups:

- adults,
- children (10 year olds), and
- infants (1 year olds).

The above groups have age-specific radiological and physiological parameters (e.g., dose conversion coefficients for relevant exposure pathways, inhalation rates, etc.)

Different reference persons can be differentiated also by a set of parameters defining their habits influencing exposure patterns (e.g., time passed outdoors in contaminated site, diet habits, etc.).

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 modeler (e.g., based on monitoring data).

Dose coefficients for effective doses from external irradiation from surface deposition and immersion into radioactive cloud and water are based on [EPA, 1993]. Dose coefficients for internal exposure through inhalation and ingestion pathways are based on ICRP Publication no.72 [ICRP, 1995b]. The dose coefficient values for inhalation found in the tables in this report are assumed to be Type S: “Deposited materials that are relatively insoluble in the respiratory tract”, if not specified differently.

Respective dose conversion coefficients (DCC) for various pathways and other parameters for dose assessment (e.g., inhalation rates, ingestion rates etc.) are listed in Appendix I in Table I-3 - Table I- 9.

7.2.‘DOSES FROM OCCUPANCY’ SET OF MODULES

The ‘Doses from Occupancy’ sub-set of modules includes three different modules:

- ‘Dose from occupancy Outdoors’,
- ‘Dose from Occupancy Indoors’, and
- ‘Dose from Marine Activities’.

These modules are described in more detail below.

7.2.1. Doses from occupancy outdoors

7.2.1.1.Module description

The ‘Dose from Occupancy Outdoors’ module is used to calculate the total annual effective dose received by ‘reference person’ during outdoors activities in respective ‘receptor environment’ (radioactively contaminates site).

The following exposure pathway are taken into account:

- external exposure,
- inhalation pathway, and
- dose from inadvertent ingestion of soil.

Radionuclide concentrations in soil and air of 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 modeler (e.g., based on monitoring data).

The external exposure dose rate can be estimated by module based on provided radionuclide concentrations in soil, or modeler can provide measured ambient external dose rate.

7.2.1.2.Potential coupled modules

Table 99. Potential coupled modules from NORMALYSA library for 'Dose from occupancy outdoors' module.

Coupled module	**Description of parameters used as loadings/inputs or outputs**
Inputs to module can be provided by following modules	
'Land', 'Forest', 'Garden', 'Cropland', 'Pastureland'	Volumetric concentration of radionuclides in soil (Bq/m^3) Mass radionuclide concentration in soil (Bq/kg.DW) Concentration of radionuclides in outdoor air (Bq/m^3)
Outputs from module can be used by following modules	
'Total dose'	Dose from external irradiation (Sv/day) Dose from inadvertent soil ingestion (Sv/day) Dose from inhalation (Sv/day)

7.2.1.3.Mathematical equations

The total annual dose from outdoor occupancy in a specific receptor ($Dose_{occup,outdoor}$, Sv/day)

$$Dose_{occup,outdoor} = Dose_{ext,total} + Dose_{inh,outdoor} + Dose_{ing.soil,total}$$

Where

$Dose_{ext,total}$ = dose from external irradiation (Sv/day),

$Dose_{inh,outdoor}$ = dose from inhalation outdoors (Sv/day),

$Dose_{ing.soil,total}$ = dose from inadvertent ingestion of soil (Sv/day).

The annual dose from external exposure ($Dose_{\ ext,total}$, Sv/day)

The annual dose from external exposure (Sv/day) is calculated by:

$$Dose_{\ ext,total} = f_{\ occup,outdoor} \times hoursPerDay \times doseRate_{eff,out}$$

Where

$doseRate_{eff,out}$ = the efficient external dose rate (Sv/h),

$f_{occup,outdoor}$ = the fraction of time that a person is exposed outdoors (unitless),

$hoursPerDay$ = the number of hour in a day (h/day).

Depending of the input data specified by modeller, the efficient external dose rate ($doseRate_{eff,out}$) can be calculated as follows.

In case the known value of ambient external dose rate is specified:

$$doseRate_{eff,out,Eq1} = doseRate_{amb,out} \times Conv_{amb,eff}$$

Where

$doseRate_{amb,out}$ = specified ambient external dose rate outdoors (Sv/h),

$Conv_{amb,eff}$ = conversion factor from ambient to effective dose (unitless).

The second option is calculating efficient external dose rate based on provided radionuclide concentrations in soil and air:

$$doseRate_{eff,out,Eq2} = doseRate_{eff,dep} + doseRate_{eff,imm}$$

Where

$doseRate_{eff,dep}$ = estimated dose rate for external irradiation from the ground (from deposited radionuclides) (Sv/h),

$doseRate_{eff,imm}$ = 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:

$$doseRate_{eff,dep} = \sum_{RN} doseRate_{eff,dep,RN}$$

Where the dose rate for external irradiation from each radionuclide ($doseRate_{eff,dep,RN}$, Sv/h) is calculated by:

$$doseRate_{eff,dep,RN} = c_{soil,vol} \times DCC_{ext,dep}$$

Here

$c_{soil,vol}$ = radionuclide volumetric concentration in soil (provided by the respective receptor module) (Bq/m^3),

$DCC_{ext,dep}$ = is the age group and radionuclide specific dose conversion factor for external irradiation ((Sv•m^3)/(Bq•h)).

The effective dose rate outdoors from immersion in radioactive cloud (doseRate$_{eff,imm}$, Sv/h) is calculated by:

$$doseRate_{eff,imm} = \sum_{RN} doseRate_{eff,imm,RN}$$

Where the dose rate for cloud immersion from each radionuclide ($doseRate_{eff,imm,RN}$, Sv/h) is calculated by:

$$doseRate_{eff,imm,RN} = c_{air,outdoor} \times DCC_{ext,imm}$$

Here

$c_{air,outdoor}$ = radionuclide concentration in outdoor air in a given receptor (Bq/m^3),

$DCC_{ext,imm}$ = age group and radionuclide specific dose conversion factor for external irradiation due to immersion to cloud ((Sv•m^3)/(Bq•h)).

The annual dose from inhalation of radionuclides (except radon) ($Dose_{inh,total}$, Sv/day) is calculated by:

$$Dose_{inh,total} = \sum_{RN} Dose_{inh,RN} + Dose_{inhRn,RN}$$

Where the annual dose from inhalation of each radionuclide ($Dose_{inh,RN}$, Sv/day) is calculated by :

$$Dose_{inh,RN} = f_{occup,outdoor} \times c_{\ air,outdoor} \times rate_{inh} \times f_{c,inh} \times DCC_{inh} \times hoursPerDay$$

Where

$f_{occup,outdoor}$ = fraction of time when the reference person is exposed outdoors (unitless),

$c_{\ air,outdoor}$ = the radionuclide concentration in outdoor air (Bq/m^3),

$rate_{inh}$ = the age group specific inhalation rate (m^3/h),

$f_{c,inh}$ =concentration factor in the fine fraction for inhalation (unitless),

DCC_{inh} = the age group and radionuclide specific inhalation dose coefficient (Sv/Bq).

The annual dose from inhalation of Rn-222 ($Dose_{inh,RN}$, Sv/day) is calculated by:

$$Dose_{inhRn,RN} = f_{occup,outdoor} \times c_{air,outdoor} \times factor_{eq,outdoor} \times DCC_{inh,Rn} \\ \times hoursPerDay,$$

Where

$factor_{eq,outdoor}$ = the equilibrium factor outdoors which describes the radioactive equilibrium between Rn-222 and its short-lived progeny (unitless),

$DCC_{inh,Rn}$ = the age group and Rn-222 specific inhalation dose coefficient (Sv.m^3)/(Bq.h).

The annual dose from inadvertent ingestion of soil ($Dose_{ing,soil,total}$, Sv/day) is calculated by:

$$Dose_{ing,soil,total} = \sum_{RN} Dose_{ing.soil,RN}$$

Where the annual dose from ingestion of soil for each radionuclide ($Dose_{ing,soil,RN}$, Sv/day) is calculated by:

$$Dose_{ing.soil,RN} = f_{occup,outdoor} \times c_{soil} \times f_{c,ing} \times rate_{ing.soil} \times DCC_{ing} \times hoursPerDay$$

Where

c_{soil} = the radionuclide concentration in soil in a given receptor (Bq/kg.DW),

$rate_{ing.soil}$ = the age group specific ingestion rate of soil (kg.DW/h),

$f_{c,ing}$ = concentration factor in the fine fraction for ingestion (unitless),

DCC_{ing} = the age group and radionuclide specific ingestion dose coefficient (Sv/Bq).

7.2.1.4.Input parameters

Table 100. Input parameters related to 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/m^3)	Volumetric concentration of radionuclide in soil	0	Site specific parameter
c_air_outdoor (Bq/m^3)	Concentration of radionuclide in outdoors air	0	Site specific parameter
doseRate_amb_out (Sv/h)	Ambient external dose rate outdoors	0	Site specific parameter
f_c_inh(unitless)	concentration factor in the fine fraction for inhalation	4	[BfS, 2011]
f_c_ing(unitless)	concentration factor in the fine fraction for ingestion	2	[BfS, 2011]
dens_soil (kg.DW/m^3)	Soil bulk density	1600	[EPA, 1993]

Table 101. Parameters related to 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 102. Output parameters of 'Dose from occupancy outdoors' module

Abbreviation (unit)	**Name**
Dose_ext_total (Sv/day)	Annual effective dose from external exposure summed over all radionuclisdes
Dose_ing_soil_total (Sv/day)	Dose from soil ingestion summed over all radionuclides
Dose_inh_total (Sv/day)	Dose from inhalation outdoors summed over all radionuclides summed over all radionuclisdes
Dose_ext_RN (Sv/day)	Annual effective dose from external exposure outdoors for each radionuclide
Dose_ing_soil_RN (Sv/day)	Dose from soil ingestion for each radionuclide
Dose_inh_RN (Sv/day)	Dose from inhalation for each radionuclide

7.2.2. Dose from occupancy indoors

7.2.2.1.Module description

The 'Dose from Occupancy indoors' module is used for calculations of total annual effective dose indoors.

Two exposure pathways are taken into account:

- external exposure,
- inhalation pathway.

External exposure dose rate can be calculated from measured ambient dose rate outdoors (using shielding factor), or from measured effective dose rate indoors (using conversion factor from ambient to effective dose).

- Radionuclide concentrations in indoor air used as input data for dose calculation can be passed from respective 'receptor environment' module, or these can be directly specified by modeler (e.g., based on monitoring data).
- Module can use measured air radionuclide concentration in building, or radionuclide concentration in building can be calculated from air concentration outdoor (using 'ReductionFactor' parameter).

7.2.2.2.Potential coupled modules

Table 103. 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 following modules	
‘House’	Concentration of radionuclides in indoor air (Bq/m^3)
‘Dose from occupancy outdoors’	Concentration of radionuclides in outdoors air (Bq/m^3)
Outputs from module can be used by following modules	
‘Total dose’	Dose from external irradiation (Sv/day) Dose from inhalation (Sv/day)

7.2.2.3.Mathematical equations

The total annual dose from indoor occupancy ($Dose_{occup,indoor}$, Sv/day)

$$Dose_{occup,indoor} = Dose_{ext,total} + Dose_{inh,indoor} \qquad \text{Eq.(31)}$$

Where

$Dose_{ext,total}$ = dose from external irradiation (Sv/day),

$Dose_{inh,indoor}$ = dose from inhalation indoors (Sv/day).

The annual dose from external exposure ($Dose_{\ ext,total}$, Sv/day)

The annual dose from external exposure (Sv/day) is calculated by:

$$Dose_{\ ext,total} = f_{\ occup,indoor} \times hoursPerDay \times doseRate_{eff,indoor}$$

Where

$doseRate_{eff,indoor}$ = the efficient external dose rate (Sv/h),

$f_{occup,indoor}$ = the fraction of time that a person is exposed indoors (unitless),

$hoursPerYear$ = the number of hour in a day (h/day).

Depending of the input data specified by modeller, the efficient external dose rate ($doseRate_{eff,indoor}$) can be calculated as follows.

<u>In case the known value of ambient external dose rate is specified:</u>

$doseRate_{eff,indoor,Eq1} = doseRate_{amb,indoor} \times Conv_{amb,eff},$

Where

$doseRate_{amb,indoor}$ = specified ambient external dose rate indoors (Sv/h),

$Conv_{amb,eff}$ = conversion factor from ambient to effective dose (unitless).

<u>The second option is calculating efficient external dose rate based on effective dose rate outdoor:</u>

$doseRate_{eff,indoor,Eq2} = doseRate_{eff,out} \times ShieldingFactor$

Where

$doseRate_{eff,out}$= is the external dose rate outdoors (Sv/h),

$doseRate_{amb,indoor}$ = the ambient doe rate indoors (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 should be set to 1(unitless),

$Conv_{amb,eff}$ = conversion factor from ambient to effective dose (unitless).

The total dose from inhalation summed over all radionuclides ($Dose_{inh,indoor}$, Sv/day):

$Dose_{inh,indoor} = \sum_{RN} Dose_{inh,RN} + Dose_{inhRn,RN}$

The annual dose from inhalation of air ($Dose_{inh,RN}$, Sv/day)

The annual dose from inhalation of air (Sv/day) for each radionuclide is calculated by:

$Dose_{inh,RN} = f_{occup,indoor} \times c_{air,indoor} \times rate_{inh} \times DCC_{inh} \times hoursPerDay$

Where

$f_{occup,indoor}$ = is fraction of time exposed indoors (unitless),

$c_{air,indoor}$ = is RN 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).

The annual dose from inhalation of Rn-222 ($Dose_{inh,RN}$, Sv/year)

The annual dose from inhalation of Rn-222 is calculated by:

$Dose_{inh,RN} = f_{occup,indoor} \times c_{air,indoor} \times rate_{inh} \times DCC_{inh,Rn} \times hoursPerDay$

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 Rn-222 and its short-lived progeny (unitless),

$DCC_{inh,Rn}$ = is the age group and Rn-222 specific inhalation dose coefficient (Sv•m^3)/(Bq•h).

In case radionuclide concentration indoor ($c_{air,indoor}$) is calculated based on concentration in outdoor air, the following equation is used:

$$c_{air,indoor} = c_{air,outdoor} \times ReductionFactor$$

Where

$c_{\ air,outdoor}$ = is the radionuclide concentration in outdoor air (Bq/m^3),

$ReductionFactor$ = Specified bu modeller ratio between indoor and outdoor air concentrations (values between zero and one) (unitless).

7.2.2.4.Input parameters

Table 104. Input parameters related to 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 indoors air	0	Site specific parameter

Table 105. Parameters specifying habits of reference persons

Abbreviation and Unit	**Name**	**Default value**	**Reference**
f_occup_indoor (unitless)	Fraction of the year that the reference person stays indoor	0.25	Specific for respective reference person parameter

7.2.2.5.Output Parameters

Table 106. Output parameters of 'Dose from occupancy indoors' module

Abbreviation (unit)	**Name**
Dose_ext_total (Sv/day)	Annual effective dose from external exposure summed over all radionuclisdes
Dose_inh_total (Sv/day)	Dose from inhalation outdoors summed over all radionuclides summed over all radionuclides
Dose_ext_RN (Sv/day)	Annual effective dose from external exposure outdoors for each radionuclide
Dose_inh_RN (Sv/day)	Dose from inhalation for each radionuclide

7.2.3. Dose from marine activities

7.2.3.1.Module description

This module is used for calculation of dose from external irradiation during marine activities. Such activities are taken into account: 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 107. 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 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 following modules	
'Total dose'	Dose from external irradiation (Sv/day)

7.2.3.3.Mathematical equations

The total annual dose from marine activities ($\boldsymbol{Dose_{ext,total}, Sv/day}$)

$$Dose_{ext,total} = Dose_{beach,total} + Dose_{boating,total} + Dose_{swimming,total} \qquad Eq.(32)$$

Where

$Dose_{beach,total}$ = is the annual external dose due to external irradiation received during beach occupancy (considering surface deposition) (Sv/day),

$Dose_{boating,total}$ = is the external annual dose for boating (Sv/day),

$Dose_{swimming,total}$ = is the external annual dose from swimming (Sv/day).

$Dose_{beach,total}=\sum_{RN} Dose_{beach,RN}$

$Dose_{boating,total}=\sum_{RN} Dose_{boating,RN}$

$Dose_{swimming,total}=\sum_{RN} Dose_{swimming,RN}$

Where

$Dose_{beach,RN}$ = The annual external dose due to external irradiation received during beach occupancy for each radionuclide(Sv/day),

$Dose_{boating,RN}$ = is the external annual dose for boating for each radionuclide (Sv/day),

$Dose_{swimming,RN}$= is the external annual dose from swimming for each radionuclide (Sv/day).

The annual external dose due to external irradiation received during beach occupancy ($Dose_{beach,RN}$,Sv/day))

The annual dose from external exposure (Sv/day) is calculated by:

$$Dose_{beach,RN} = DCC_{ext,dep,5cm} \times c_{beach} \times f_{beach} \times hoursPerDay$$

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^3)/(Bq•day)).

The external annual dose from swimming ($Dose_{swimming}$, Sv/day)

The external annual dose from swimming $Dose_{swimming}$ (Sv/day) is derived as follows:

$$Dose_{swimming,RN} = DCC_{submersion} \times c_{water,total} \times f_{swimming} \times hoursPerDay$$

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•day)),

$f_{swimming}$ = is the fraction of the year spent swimming on the sea (unitless).

The external annual dose for boating (Dose_boating, Sv/day)

$$Dose_{boating,RN} = 0.5 \times DCC_{submersion} \times c_{water,total} \times f_{boating} \times HoursPerDay$$

Where

$f_{boating}$ = is the fraction of the year spent boating in the sea (unitless).

Here the dose coefficients for water submersion are conservatively used also 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 the equation 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 108. Input parameters related to radiation characteristics of environmental media for the 'Dose from Mrine activities' module

Abbreviation and unit	**Full name**	**Default value**	**Reference**
c_water_total (Bq/m^3)	Concentration of radionuclide in sea water	0	Site specific parameter
c_sed_beach (Bq/m^2)	Radionuclide concentration in beach sediments	0	Site specific parameter

Table 109. Input parameters related to habits of referece persons

Abbreviation and Unit	**Name**	**Default value**	**Reference**
f_boating (unitless)	The fraction of the year spent boating in the sea	0.1	Specific for respective reference person parameter
f_swimming (unitless)	The fraction of the year spent swimming on 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 110. Output parameters of 'Dose from marine activities' module

Abbreviation (unit)	Name
Dose_ext_total (Sv/day)	Anual effective dose from external exposure due marine activities summed over all radionuclides
Dose_ext_RN (Sv/day)	Anual effective dose from external exposure due marine activities for each radionuclide

7.3.'DOSES FROM INGESTION' SET OF MODULES

The 'Doses from ingestion' sub-set 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 freshwater food',
- 'Dose from ingestion of marine water',
- 'Dose from ingestion of milk and meat'.

These modules are described in more detail below.

All modules are used the same mathematical equation for calculation of internal doses for ingestion of various foodstuff given below in Section 7.3.1 (i.e. Eq.(33)). Age depended dose coefficients for effective dose by ingestion is shown in Table I- 5. Ingestion rates for all types of foodstuff for all age groups are shown in Table I- 9.

7.3.1. Mathematical equation

Total dose from ingestion of all foodstuff summed over all radionuclide ($Dose_{ing,foodstuff,total}$, Sv/day) is calculated by:

$$Dose_{ing,foodstuff,total} = \sum_{foodstuff} Dose_{ing,foodstuff}$$

Total dose from ingestion of foodstuff summed over all radionuclides ($Dose_{ing,foodstuff}$, Sv/day) is calculated by:

$$Dose_{ing,foodstuff} = \sum_{RN} Dose_{ing,foodstuff,RN}$$

The dose from ingestion of foodstuff for each radionuclide ($Dose_{ing,foodstuff,RN}$, Sv/day)

$$Dose_{ing,foodstuff,RN} = f_{foodstuff} \times c_{foodstuff} \times rate_{ing,foodstuff} \times DCC_{ing} \qquad \text{Eq.(33)}$$

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/day or kg/day),

DCC_{ing} = is the age group and radionuclide specific ingestion dose coefficient (Sv/Bq).

7.3.2. ‘Dose from ingestion of water‘ module

7.3.2.1.General description

This module calculates dose from ingestion of water to respective reference person.

7.3.2.2.Potential coupled modules

Table 111. Potential coupled modules from 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 following modules	
‘Well’ ‘Freshwater body’	Radionuclide concentration in water (Bq/m^3)
Outputs from module can be used by following modules	
‘Total dose’	Dose from ingestion of water (Sv/day)

7.3.2.3.Input parameters

Table 112. Input parameters related to cocnetration 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 113. Input parameters related to 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 114. Output parameters of 'Dose from ingestion of water' module

Abbreviation (unit)	Name
Dose_ing_water_total (Sv/day)	Dose from water ingestion summed over all radionuclides
Dose_ing_water_RN (Sv/day)	Dose from water ingestion for each radionuclide

7.3.3. 'Dose from ingestion of garden foods' module

7.3.3.1.General description

This module calculates dose from ingestion of foodstuff from contaminated garden (leafy vegetables, legumes, roots, fruits, garden berries) to respective reference person.

7.3.3.2.Potential coupled modules

Table 115. Potential coupled modules from NORMALYSA library for '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 following modules	
'Garden plot'	Radionuclide concentration in garden food (Bq/kg.FW)
Outputs from module can be used by following modules	
'Total dose'	Dose from ingestion of garden foods (Sv/day)

7.3.3.3.Input parameters

Table 116. Input parameters related to concetration 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 117. Input parameters related to 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 respective reference person parameter

7.3.3.4.Output Parameters

Table 118. Output parameters of 'Dose from ingestion of garden foods' module

Abbreviation (unit)	**Name**
Dose_ing_Food_total (Sv/day)	Dose from garden food ingestion summed over all radionuclides and all foodstuff types
Dose_ing_Food_RN (Sv/day)	Dose from ingestion of garden food for each radionuclide summed over all foodstuff types

7.3.4. 'Dose from ingestion of forest food' module

7.3.4.1.General description

This module calculates dose from ingestion of forest food (mushrooms, wild berries, roe-deer and moose) to respective reference person.

7.3.4.2.Potential coupled modules

Table 119. Potential coupled modules from NORMALYSA library for '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 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 following modules	
'Total dose'	Dose from ingestion of food (Sv/day)

7.3.4.3.Input parameters

Table 120. Input parameters related to concetration in foodstuff for '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 121. Input parameters related to habits of 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 122. Output parameters of 'Dose from ingestion of forest foods' module

Abbreviation (unit)	**Name**
Dose_ing_Food_total (Sv/day)	Dose from forest food ingestion summed over all radionuclides and all forest food types
Dose_ing_Food_RN (Sv/day)	Dose from ingestion of forest food for each radionuclide summed over all forest food types

7.3.5. ‘Dose from ingestion of crops‘ module

7.3.5.1.General description

This model derives the doses to respective reference person due to intake of contaminated foodstuff (fruits and vegetables) cultivated in a cropland. Four different types of crops are considered: leafy vegetables, cereals, legumes and roots.

7.3.5.2.Potential coupled modules

Table 123. Potential coupled modules from NORMALYSA library for ‘Dose from ingestion of crops’ module.

Coupled module	**Description of parameters used as loadings/inputs or outputs**
Inputs to module can be provided by following modules	
‘Cropland’	Radionuclide concentration in crops (Bq/kg.FW)
Outputs from module can be used by following modules	
‘Total dose’	Dose from ingestion of crops (Sv/day)

7.3.5.3.Input parameters

Table 124. Input parameters related to concetration in foodstuff ‘Dose from ingestion of crops’

Abbreviation and unit	**Full name**	**Default value**	**Reference**
c_crops (Bq/kg.DW)	Concentration of radionuclide in crops (for respective crop types)	0	Site specific parameter

Table 125. Input parameters related to 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 respective reference person parameter

7.3.5.4.Output Parameters

Table 126. Output parameters of 'Dose from ingestion of crops' module

Abbreviation (unit)	**Name**
Dose_ing_Food_total (Sv/day)	Dose from crops ingestion summed over all radionuclides and all crops types
Dose_ing_Food_RN (Sv/day)	Dose from ingestion e of crops summed over allcrop types for each radionuclid

7.3.6. 'Dose from ingestion of milk and meat' module

7.3.6.1.General description

This module derives the doses to respective reference person due to intake of animal products (milk and meat) from livestock grazing on contaminated pasture lands.

7.3.6.2.Potential coupled modules

Table 127. Potential coupled modules from NORMALYSA library for '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 following modules	
'Pastureland'	Radionuclide concentration in milk and meat (Bq/kg.FW, Bq/L)
Outputs from module can be used by following modules	
'Total dose'	Dose from ingestion of milk and meat (Sv/day)

7.3.6.3.Input parameters

Table 128. 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 129. Input parameters related to habits of refernce 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 respective reference person parameter

7.3.6.4.Output Parameters

Table 130. Output parameters of 'Dose from ingestion of milk and meat' module

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/day)	Dose from milk and meat food ingestion summed over all radionuclides and all meat types
Dose_ing_Food_RN (Sv/day)	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

7.3.7.1.General description

This module derives the doses to respective reference person due to intake of freshwater foods from contaminated river/lake. The aquatic food types considered are: cray fish, mussels and 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 131. Potential coupled modules from NORMALYSA library for '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 following modules	
'Freshwater body'	Radionuclide concentration in freshwater food (Bq/kg.FW)
Outputs from module can be used by following modules	
'Total dose'	Dose from ingestion of freshwater food (Sv/day)

7.3.7.3.Input parameters

For running the ‘Dose from ingestion of freshwater food’ module, the following input parameters must be specified.

Table 132. Input parameters related to concetration 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 133. Input parameters related to habits of reference persons

Abbreviation and Unit	**Name**	**Default value**	**Reference**
f_freshwater_food	Fractional contribution freshwater food from the FWB to the total ingestion of freshwater food	1	Specific for respective reference person parameter

7.3.7.4.Output Parameters

Table 134. Output parameters of ‘Dose from ingestion of freshwater food’ module

Abbreviation (unit)	**Name**
Dose_ing_Food_total (Sv/day)	Dose from freshwater food food ingestion summed over all radionuclides and all food types
Dose_ing_Food_RN (Sv/day)	Dose from ingestion of freshwater food summed over all food types for each radionuclide

7.3.8. ‘Dose from ingestion of marine food‘ module

7.3.8.1.General description

This module derives the doses to respective reference person due to intake of marine food from contaminated sea. The aquatic food types considered are: cray fish, mussels and fish.

7.3.8.2.Potential coupled modules

Table 135. Potential coupled modules from NORMALYSA library for '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 following modules	
'Marine body'	Radionuclide concentration in marine food (Bq/kg.FW)
Outputs from module can be used by following modules	
'Total dose'	Dose from ingestion of marine food (Sv/day)

7.3.8.3.Input parameters

Table 136. Input parameters related to concetration 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 137. Input parameters related to habits of 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 respective reference person parameter

7.3.8.4.Output Parameters

Table 138. Output parameters of 'Dose from ingestion of marine food' module

Abbreviation (unit)	Name
Dose_ing_Food_total (Sv/day)	Dose from marine food food ingestion summed over all radionuclides and all food types
Dose_ing_Food_RN (Sv/day)	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 Total dose to different reference persons defined by modellers by all relevant exposure pathways taking into account contributions from all objects (receptors) and radionuclides.

7.4.2. Potential coupled modules

The inputs to the 'Total dose' module are provided by respective dose modules, that calculates doses from specific receptor for environment through relevant pathways (see Table 139).

Table 139. Potential coupled modules from NORMALYSA library for 'Total dose' module.

Coupled module	Description of parameters used as loadings/inputs
Inputs to module can be provided by 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/day) Dose from ingestion of food summed over all radionuclides (Sv/day) Dose from inadvertent soil ingestion summed over all radionuclides (Sv/day) Dose from ingestion of water summed over all radionuclides (Sv/day) Dose from inhalation summed over all radionuclides (Sv/day)

7.4.3. Mathematical equation

The Total dose ($Dose_{total}, Sv/year$) is calculated by :

$$Dose_{total} = Dose_{ext,total} + Dose_{inh,total} + Dose_{ing,soil,total} + Dose_{ing,water,total} + Dose_{ing,Food,total} \quad)$$

Where

$Dose_{ext,total}$ =is total dose from external exposure (Sv/day),

$Dose_{inh,total}$ = is total dose from inhalation (Sv/day),

$Dose_{ing,soil,total}$ = is total dose from inadvertent soil ingestion Sv/day),

$Dose_{ing,water,total}$ = is total dose from ingestion of water (Sv/day),

$Dose_{ing,Food,total}$ = is total dose from ingestion of food (Sv/day).

7.4.4. Input parameters

For running the 'Total dose' module, the following input parameters must be specified.

Table 140. Input parameters of 'Total Dose module'

Abbreviation and unit	**Full name**	**Default value**
Dose_ext_total (Sv/Bq)	Total dose from external exposure	0
Dose_ing_Food_total (Sv/Bq)	Total dose from ingestion of food	0
Dose_ing_soil_total (Sv/Bq)	Total dose from inadvertent soil ingestion	0
Dose_ing_water_total (Sv/Bq)	Total dose from water ingestion	0
Dose_inh_total (Sv/Bq)	Total dose from inhalation	0

7.4.5. Output Parameters

Table 141. Output parameters of 'Total dose' module

Abbreviation (unit)	**Name**
Total dose (Sv/day)	Total dose from all exposure pathways summed over all radionuclides

APPENDIX I. COMMON RADIOECOLOGICAL AND DOSE ASSESSMENT PARAMETERS USED BY DIFFERENT NORMALYSA MODULES

Table I- 1 Radionuclide distribution coefficients for 'soil' material [IAEA, 2010, Table 14]

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 I- 2 Input parameters related to contaminated land geometry and physico-chemical properties of soils

Abbreviation and Unit	**Name**	**Default value**	**Reference**
Area (m^2)	'Cropland' area	30000	Site specific parameter value needed
c_dust ($kg.DW/ m^3$)	Concentration of dust in atmospheric air	5E-8	[SKB, 2010b; p.349]
h_soil_RZ (m)	Height of the soil rooting zone	0.25	[SKB, 2010b;p.340]
h_soil_DZ (m)	Height of the deep soil zone	0.5	[SKB, 2010b]
porosity_soil_RZ (m^3/m^3)	Porosity of the soil rooting zone	0.36	[SKB, 2013; Table 2-1]
porosity_soil_DZ (m^3/m^3)	Porosity of the deep soil zone	0.21	[SKB, 2013; Table 2-1]
rho_soil_RZ ($kg.DW/m^3$)	Density of the rooting zone soil	1626.0	[SKB, 2013; Table 2-1]
rho_soil_DZ ($kg.DW/m^3$)	Density of the deep zone soil	2115.0	[SKB, 2013; Table 2-1]
rate_erosion ($kg.DW/(m^2 \cdot day)$)	Erosion rate	1.37E-4	[Kirkby et al., 2004]
bioT ($kg.DW/(m^2 \cdot day)$)	Bioturbation coefficient	0.016	[SKB, 2007]
Kd_soil_RZ ($m^3/kg.DW$)	Distribution coefficient for the soil rooting zone	Table I- 1 (Appendix I)	[IAEA, 2010]
Kd_soil_DZ ($m^3/kg.DW$)	Distribution coefficient for the deep soil zone	Table I- 1 (Appendix I)	[IAEA, 2010]
rate_prec $m^3/(m^2 \cdot day)$	The precipitation rate in the considered area	0.00185	[SKB, 2013]

Table I- 3 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	[BfS, 2011]
Factor_eq_outdoor (unitless)	The equilibrium factor which describes the radioactive equilibrium between Rn-222 and its short-lived progeny	0.4	[BfS, 2011]
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 I- 4 Dose coefficient for effective dose from deposition on soil and immersion in cloud, (Sv•m^3)/(Bq•h) [EPA, 1993]

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	1.09E-13	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 I- 5 Dose coefficient for effective dose by ingestion (Age dependent), Sv/Bq [ICRP, 1995b]

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 I- 6 Dose coefficient for effective dose by inhalation (Age dependent),Sv/Bq [ICRP, 1995b]

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 I- 7 Dose coefficient for effective dose by Radon inhalation, (Sv•m^3)/(Bq•h) [BfS, 2011]

Abbreviation and Unit	Name	Default value
DCC_inh_Rn	Dose coefficient for effective dose by Radon inhalation	6.1E-9

Table I- 8 Dose coefficient for effective doses by external irradiation for deposition (for contaminated layer thickness of 5 cm) and immersion in water [EPA, 1993]

Radionuclide	**DCC_ext_dep_5cm,** (Sv•m^2)/(Bq•h) [IAEA, 2003]	**DCC_submersion** (Sv•m^3)/(Bq•h) [EPA, 1993]
Ac-227	1.4E-12	0
Cs-137	2.0E-12	1.99E-13
Pa-231	1.5E-13	0
Pb-210	1.3E-14	0
Po-210	3.0E-17	0
Ra-226	6.0E-12	0
Ra-228	3.3E-12	0
Rn-222	0	0
Sr-90	2.0E-14	3.92E-16
Th-228	5.1E-12	0
Th-230	2.7E-15	0
Th-232	2.0E-15	0
U-234	2.7E-15	0
U-235	6.0E-13	0
U-238	1.1E-13	0

Table I- 9 Parameters describing 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 (m^3/day)	Inhalation rate	9.20E-01	8.30E-01	1.20E-01	[ICRP, 1995b]
rate_ing_water (m^3/day)	Ingestion rate of water	1.64E-03	1.15E-03*	7.12E-04	Based on [IAEA, 2001]
rate_ing_garden_food (kg.FW/day)	Ingestion rate of leafy vegetables	3.09E-01	2.16E-01*	1.53E-01**	Based on [Enghardt et al., 2005]
	Ingestion rate of legumes	1.30E-02	9.09E-03*	6.49E-03**	Based on [Enghardt et al., 2005]
	Ingestion rate of roots	2.11E-01	1.48E-01*	1.04E-01**	Based on [Enghardt et al., 2005]
	Ingestion rate of fruits	1.62E-01	1.13E-01*	8.08E-03**	Based on [Enghardt et al., 2005]
	Ingestion rate of garden berries	6.84E-02	4.79E-02*	3.42E-02**	Based on [Enghardt et al., 2005]
rate_ing_berries (kg.FW/day)	Ingestion rate of berries	0	0	0	This parameter is depended on social habits
rate_ing_mushroom (kg.FW/day)	Ingestion rate of mushrooms	0	0	0	This parameter is depended on social habits
rate_ing_game (kg.FW/day	Roe deer	0	0	0	This parameter is depended on social habits

Parameter	**Name**	**Adults**	**Children**	**Infants**	**Reference**
	Moose	0	0	0	This parameter is depended on social habits
rate_ing_crops (kg.FW/day)	Ingestion rate of legumes	1.30E-02	9.09E-03*	6.49E-03**	Based on [Enghardt et al., 2005]
	Ingestion rate of leafy vegetables	3.09E-01	2.16E-01*	1.53E-01**	Based on [Enghardt et al., 2005]
	Ingestion rate of cereals	4.30E-02	3.01E-02*	2.16E-02**	Based on [Enghardt et al., 2005]
	Ingestion rate of roots	2.11E-01	1.48E-01*	1.04E-01**	Based on [Enghardt et al., 2005]
rate_ing_meat (kg.FW/day)	Ingestion rate of Beef meat	2.74E+00	1.92E-01*	1.10E-01**	Based on [IAEA, 2001]
	Ingestion rate of Sheep meat	0	0	0	This parameter is depended on social habits
rate_ing_milk (L/day)	Ingestion rate of cow milk	6.84E-01	4.79E-01*	8.21E-01	Based on [IAEA, 2001]
rate_ing_marine_food (kg.FW/day)	Ingestion rate of fish	1.37E-01	9.58E-02*	6.84E-02	Based on [IAEA, 2001]
	Ingestion rate of cray fish	0.00E+00	0.00E+00	0.00E+00	This parameter is depended on social habits
	Ingestion rate of mussels	4.11E-02	2.87E-02*	0.00E+00	Based on [IAEA, 2001]
rate_ing_freshwater_food (kg.FW/day)	Ingestion rate of fish	8.21E-02	5.75E-02*	4.11E-02	Based on [IAEA, 2001]
	Ingestion rate of cray fish	0	0	0	This parameter is depended on social habits
	Ingestion rate of mussels	0	0	0	This parameter is depended on social habits
rate_ing_soil (kg.DW/h)	Ingestion rate of soil	5.00E-06	1.00E-05	0	[Yu C., et al., 2001]

*Value for age group ‘Children’ is calculated from the value for age group ‘Adults’ by multiplying by 0.7

** Value for age group ‘Infants’ is calculated from the value for age group ‘Adults’ by multiplying by 0.5

REFERENCES

Andersson K. G., 2013. Work carried out to improve parameterisation of the Rodos DSS for specific use in Sweden, NP-EN 13-32, ver. 1.0, Vattenfall AB, Sweden.

Avila R., et al., 2005. “ECOLEGO - A toolbox for radioecological risk assessment”, Proc. of the Int. Conf. on the Protection from the Effects of Ionizing Radiation, Stockholm 2005, IAEA-CN-109/80, IAEA, Vienna, 229–232.

Baes C.F.III and Sharp, R.D., 1983. A proposal for estimation of soil leaching and leaching constants in assessment models. Journal of Env. Qual., 12, 17-28.

BfS, 2011. Calculation Guide Mining. Calculation Guide for the Determination of Radiation Exposure due to Environmental Radioactivity Resulting from Mining The Federal Office for Radiation Protection (BfS), BfS-SW-09/11, Salzgitter.

Brundell P., et al., 2008. Water use for Irrigation. Report on Grant Agreement No 71301.2006.002-2006.470, Statistiska Centralbyrån, Sweden.

Bruno, R.C., 1989. Sources of indoor radon in houses: A review, Journal of the Air Pollution Control Association, 33, 105-109.

Bulgakov A.A., et al., 1990. Dynamics of long-lived radionuclides wash-off by surface runoff from soil in vicinity of the Chernobyl NPP, Pochvovedenie (Soil Science), N 4, 47-54 (In Russian).

Bulgakov A.A., 1999. Experimental study and prediction of dissolved radionuclide wash-off by surface runoff from non-agricultural watersheds. In: Contaminated Forests: Recent developments in risk identification and future perspectives (Linkov I. and Schell W.R. eds), NATO ASI Series 2- Kluwer Academic Publishers, Dordrecht, 103-112.

Enghardt B. H. et al., 2005. Swedish Nutrition Recommendations Objectified (SNO). Basis for General Advice on Food Consumption for Healthy Adults, National Food Administration, Sweden.

EPA, 1993. External exposure to radionuclides in air water and soil (by Eckerman K. F., Ryman J.C.), Federal Guidance Report No. 12, Office of Radiation and Indoor Air U.S. Environmental Protection Agency (EPA), Washington, DC.

IAEA, 2001. Generic Models for Use in Assessing the Impact of Discharges of radioactive Substances to the Environment. Safety Report Series No.19, International Atomic Energy Agency, Vienna.

IAEA, 2003. Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities, IAEA-TECDOC-1380, International Atomic Energy Agency, Vienna.

IAEA, 2004a. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a co-ordinated research project Volume 1 Review and enhancement of safety assessment approaches and tools, International Atomic Energy Agency, Vienna.

IAEA, 2004b. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a co-ordinated research project Volume 2. Test cases, International Atomic Energy Agency, Vienna.

IAEA, 2009. Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, International Atomic Energy Agency, Vienna.

IAEA, 2010. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments, Technical Reports Series No. 472, International Atomic Energy Agency, Vienna.

IAEA, 2013. Measurement and Calculation of Radon Releases from NORM Residues Technical Reports Series No. 474, International Atomic Energy Agency, Vienna.

ICRP, 1995a. Age-dependent Doses to Members of the Public from Intake of Radionuclides - Part 4 Inhalation Dose Coefficients, ICRP Publication 71, Ann. ICRP 25 (3-4)

ICRP, 1995b. Age-dependent Doses to the Members of the Public from Intake of Radionuclides - Part 5 Compilation of Ingestion and Inhalation Coefficients, ICRP Publication 72, Ann. ICRP 26 (1).

Kamboj S., et al., 1998. External exposure model used in the RESRAD code for various geometries of contaminated soil, ANL/EAD/TM-84, Argonne National Laboratory, IL, USA.

Kinzelbach W., 1986. Groundwater modeling. An introduction with sample programs in BASIC, Elsevier, Amsterdam.

Kirkby M.J., et al., 2004. Pan-European Soil Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. EUR 21176, Office for Official Publications of the European Communities, Luxembourg.

Lepicard, S., Raffestin, D., Rancillac, F., 1998. POSEIDON: a dispersion computer code for assessing radiological impacts in European seawater environment. Radiat. Protect.Dosim., 75 79-83.

NFA, 2012. Riksmaten-vuxna 2010-11. Livsmedels-och näringsintag bland vuxna i Sverige. Diet and nutrient intake among adults (Amcoff E., et al.), National Food Agency, (NFA), Uppsala, Sweden.

Nielsen S. P., et al., 2008. PardNor – PARameters for ingestion Dose models for NORdic areas - Status report for the NKS-B activity 2007 (NKS-232), NKS Secretariat ,Roskilde.

POSIVA, 2012. Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto. POSIVA OY, Eurajoki, Finland.

SKB, 1999. Models for dose assessments. Modules for various biosphere types (Bergström U., et al.), Report TR-99-14, Svensk Kärnbränslehantering AB (SKB), Sweden.

SKB, 2006. Model of the long-term transfer of radionuclides in forests (Avila R., et al.), Report TR-06-08, Svensk Kärnbränslehantering AB (SKB), Stockholm.

SKB, 2007. Bioturbation in different ecosystems at Forsmark and Oskarshamn (Persson T., et al.), Report R-06-123, Svensk Kärnbränslehantering AB(SKB), Sweden.

SKB, 2010a. The marine ecosystems at Forsmark and v SR-Site Biosphere (Aquilonius K. ed), Report TR-10-03, Svensk Kärnbränslehantering AB (SKB), Sweden.

SKB, 2010b. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere (Löfgren A., ed), Report SKB TR-10-01, Svensk Kärnbränslehantering AB (SKB), Sweden.

SKB, 2013. Kd and CR used for transport calculations in the biosphere in SR-PSU (Tröjbom M., et al.), Report R-13-01, Svensk Kärnbränslehantering AB(SKB), Sweden.

Walton, W.C., 1988. Practical Aspects of Groundwater Modelling, 3rd ed., National Water Well Association, Worthington, OH, USA.

Yu C., et al., 2001. User’s Manual for RESRAD Version 6, ANL/EAD-4, Argonne National Laboratory, IL, USA.