UK Health Security Agency

Assessment of dose rates to Biota in PC-CREAM 08

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Executive Summary

A new module has been developed for the PC-CREAM 08® radiological impact assessment software that implements the ICRP system for protection of the environment. A framework for this system was first described in Publication 91 (ICRP, 2003) and in the 2007 Recommendations of ICRP (ICRP, 2007) the system of radiological protection was extended to include protection of the environment more explicitly. The concepts were further developed in ICRP Publications 108, 114, 124 and 136 (ICRP, 2008; ICRP, 2009; ICRP, 2014; ICRP, 2017) and are endorsed by the basic safety standards of the IAEA (IAEA, 2014b) and Euratom Directive (2013/59/Euratom) (Council of the European Union, 2014).

This report describes the methodology for calculating absorbed dose rates to non-human biota in PC-CREAM 08, which was developed on the basis of guidance from ICRP and other organisations. Throughout this report non-human biota are referred to simply as biota which also encompasses the term ‘wildlife’ which is generally used by the IAEA in reference to environmental protection. The PC-CREAM 08 methodology allows the user to assess doses to biota that inhabit terrestrial, riverine and marine environments. Biota can be defined by the user or selected from the ICRP set of reference animals and plants. The key parameters used to define biota are occupancy factors for different environments, radionuclide concentration ratios and internal and external dose coefficients.

It is important to ensure that a radiological impact assessment adopts a consistent approach for biota and humans. This does not mean calculation of the same endpoints but that the required endpoints are calculated using similar assumptions, models and input data such that the level of confidence in the results is consistent. If this is not the case then the process to optimise the management of environmental discharges as required by the system of radiological protection may be compromised. Therefore, within PC-CREAM 08 the dispersion of radionuclides in atmospheric and aquatic environments is calculated for both biota and human dose assessments using the same models and the configuration of these models and the input data used are similar or the same. However, for biota it is often the aim of an assessment to determine the radiological impact of a release at the population level and the average dose to multiple biota inhabiting a particular region is required. The compartmental models used to model dispersion in aquatic environments can be used to calculate average doses. For atmospheric dispersion, additional functionality has been added to the program to enable average model results, such as activity concentrations in air and on the ground, to be calculated for a defined region.

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Report version 1.1

Contents

1 Introduction

This report describes a new module developed for the software program PC-CREAM 08® that implements the system for protection of the environment developed by the International Commission on Radiological Protection (ICRP).

In its latest recommendations, Publication 103 (ICRP, 2007), ICRP introduced an explicit requirement to demonstrate that the environment is protected, with the aim of “preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species or the health and status of natural habitats, communities and ecosystems”. This was a change to previous recommendations in which it was implicitly assumed that by protecting humans the environment would also be protected. The requirement to protect the environment as well as people is also included in the basic safety standards of the EU (Council of the European Union, 2014) and the IAEA (IAEA, 2014b). The latter state that “international trends show an increasing awareness of the vulnerability of the environment… and the need to be able to demonstrate (rather than to assume) that the environment is being protected”.

2 The ICRP system of environmental protection

A framework for the protection of the environment from ionising radiation was first described by ICRP in its Publication 91 (ICRP, 2003); in the 2007 Recommendations of ICRP, Publication 103 (ICRP, 2007), the system of radiological protection was extended to include protection of the environment more explicitly. ICRP Publication 103 considered that a framework for the protection of the environment should be based on establishing the relationships between exposures, doses and effects and that such a framework should be based on a scientific system similar to that developed for human protection. ICRP also argued that the extreme diversity of animal and plant species means that a pragmatic approach to environmental protection should be adopted and therefore recommended that this could best be achieved by the creation of a set of Reference Animals and Plants to represent particular types of fauna and flora.

The concept of Reference Animals and Plants (RAPs) was developed further in ICRP Publication 108 (ICRP, 2008a). Each RAP is intended to represent a particular type of organism and provides a benchmark for the calculation of doses to biota. In Publication 108 the characteristics of 12 RAPs were described and datasets of dose conversion factors, in terms of absorbed dose rate per unit activity concentration in biota, were derived. In addition, the effects of radiation on biota were reviewed and levels of potentially harmful exposure identified in a set of Derived Consideration Reference Levels (DCRLs) which were presented for each RAP. The DCRLs are given in terms of absorbed dose rate and are designed to help optimise the level of effort that might be expended on environmental protection.

ICRP Publication 108 did not contain the dataset of concentration ratios that relate activity concentrations in biota to activity concentrations in the environment, needed to assess dose rates from radionuclide uptake. In Publication 114 (ICRP, 2009) ICRP presented element and RAP dependent concentration ratios which could be used with measured or modelled environmental activity concentrations and dose conversion factors to calculate dose rates to the RAPs.

In Publication 136 (ICRP, 2017) the dose conversion factors were replaced by a more comprehensive dataset of dose coefficients which are based on the more recent nuclear decay data of Publication 107 (ICRP, 2008b).

Finally, guidance on the application of ICRP recommendations is provided in ICRP Publication 124 (ICRP, 2014) which addresses the protection of the environment under different exposure conditions and provides a mechanism for including protection of the environment in the optimisation process.

ICRP stresses that it is important to ensure that an integrated and consistent assessment approach is adopted for both biota and humans to ensure that risks to biota and humans are not considered in isolation. An integrated approach should ensure that although different endpoints are being calculated, ie absorbed dose rate for biota and committed effective dose for humans, they are evaluated to the same or similar levels of accuracy using the same or similar modelling techniques and input data.

In following the ICRP system of environmental protection PC-CREAM 08 provides an integrated dose assessment tool where a consistent set of dispersion models and input data are used to evaluate the radiological impact of routine gaseous and liquid discharges on biota and humans.

3 Characterization of biota

The system for protection of the environment developed by ICRP focuses on non-human biota in natural habitats, referred to in ICRP Publication 124 as simply ‘biota’ (ICRP, 2014). ICRP considers that an assessment of the radiological impact on humans provides adequate protection to domesticated animals and plants (ICRP, 2008a). IAEA, on the other hand, uses the term ‘wildlife’ as this is more consistent with other areas of environmental protection. The term ‘wildlife’ is defined as “living species that are not domesticated and which exist in natural habitats” (IAEA, 2014a). In the remainder of this document the term ‘biota’ will be used for consistency with the ICRP methodology.

The methodology used in PC-CREAM 08 for the assessment of dose to biota is based on the ICRP system [or framework] for protection of the environment; consequently, PC-CREAM 08 makes use of the ICRP concepts of reference animals and plants (RAPs) and representative organisms (ROs). These are discussed in more detail below.

3.1 Reference Animals and Plants (RAPs)

In ICRP Publication 108 a RAP is defined as: “…a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism” (ICRP, 2008a). RAPs are intended to be typical of terrestrial, freshwater and marine environments throughout the world but ICRP note that, because of a lack of data on other biota, they are essentially representative of temperate regions (ICRP, 2008a).

RAPs were defined with the following considerations in mind:

a. the amount of radiobiological information available for them;

b. their amenability to future research in order to obtain missing data;

c. their likelihood of being exposed to radiation from a range of radionuclides (taking into account bio-accumulation, nature of their surroundings, overall life span, life cycle, and general biology);

d. their radiosensitivity and potential dose-effect response;

e. whether they are recognisable to the public.

The characteristics of the RAPs and the types of animals and plants they represent are summarised in Table 1.

Table 1 Summary of characteristics of Reference Animals and Plants (ICRP, 2008a)

Description	Family	Characteristics of Reference Animal or Plant
Large terrestrial mammal	Deer (Cervidae)	Large woodland deer, life span of 15 years, female produces one calf per year for an average of 10 years, gestation period 250 days.
Small terrestrial mammal	Rat (Muridae)	Night feeder, rests in a burrow during the day, lives in a colony, life expectancy 2 years, breeding occurs from age 100 days, average seven pups per litter for seven litters, gestation period 24 days.
Aquatic bird	Duck (Anatidae)	Dabbling duck, life span 11 years, breeding occurs from age 1 year, female produces 10 eggs at 1-day intervals, incubation takes 30 days, nestlings fledge at 60 days.
Amphibian	Frog (Ranidae)	Lives in temperate freshwater ecosystem, spends non-breeding time out of water and hibernates in mud over winter for 16 weeks, carnivorous, life span 10 years, breeding occurs from 3 years, lays ~3000 eggs in clumps of around 400 eggs every spring in shallow water, tadpoles emerge after 10 days and metamorphosis to froglet complete 100 days after hatching.
Freshwater fish	Trout (Salmonidae)	Pelagic (i.e. lives in water column). Lives in 'soft' water, life span 6 years, breeding occurs from age 4 years, spawns around 1500 eggs each year in late autumn for 2 years, eggs hatch at 100 days.
Marine fish	Flatfish (Pleuronectidae)	Benthic (i.e. bottom feeder). Lives in shallow marine water, life span 10 years, breeding occurs from 4 years, female spawns around 300000 eggs each year, eggs hatch in 15 days, larvae fully metamorphosed into adult form at 50 days.
Terrestrial insect	Bee (Apidea)	Typical social bee, male bees die after mating with a queen (i.e. in first year), worker bee life span 100 days, queen life span 4 years, breeding occurs from age 1 year, queen lays 200000 eggs per year (600000 in a lifetime), eggs hatch after 4 days, larvae pupate after 6 days and emerge as adults after 20 days, some develop into young queens, some worker bees also lay unfertilised eggs that mature into males.
Marine crustacean	Crab (Cancridae)	Reasonably large temperate water crab, moult annually, life span 15 years, males mature at 5 years & females at 10, female produces 1 million fertilised eggs in late autumn that are retained by the female as a clutch for 6 months before larvae are released into the water column, larvae settle on bottom after further 60 days.
Terrestrial annelid	Earthworm (Lumbricidae)	Typical member of Lumbricidae, life span 4 years, breeding occurs from 10 weeks, produce 5 cocoons per week which hatch after 4 weeks.

Description	Family	Characteristics of Reference Animal or Plant
Large terrestrial plant	Pine Tree (Pinacea)	Large tree growing in temperate region, life span 200 years, reproductive maturity at 10 years, young trees grow at 1 m per year, produces ovoid cones that take 18 months to mature.
Small terrestrial plant	Wild Grass (Poaceae)	'Barley type' wild grass, flowering spikelet on a stalk above the ground, perennial.
Seaweed	Brown Seaweed (Fucaceae)	Cyclosporean brown seaweed, covered with sea water for 75% of the time, dries out and is covered by silt remaining 25% of the time, life span 5 years, adult plant is diploid sporophyte and reproduces annually.

3.2 Representative Organisms (ROs)

The Representative Organisms (ROs) are analogous to the concept of the representative person for human dose assessments. The ROs should be typical of the ecosystem under consideration and should be representative of populations of individual organisms that are more highly exposed. Consideration of populations is necessary because it is the aim of environmental protection to ensure that populations of biota remain viable (ICRP, 2007). In many cases, the ROs may be suitably represented by one or more RAPs. However, if this is not the case then user defined ROs can be set up in PC-CREAM 08. To do this the user must decide which habitats the RO is exposed to, provide occupancy factors for each habitat and also provide dose coefficients and concentration factors.

4 Assessing dose rates to biota

In PC-CREAM 08 the following steps are taken to assess the exposure of biota to ionising radiation:

a. identify the representative organisms for the ecosystem under consideration;

b. use dispersion models to calculate activity concentrations in the environmental media to which organisms will be exposed;

c. apply concentration ratios to determine activity concentrations in biota from uptake of radionuclides in the surrounding environment,

d. apply dose coefficients to calculate internal and external dose rates to biota.

Each step is discussed below and examples of the dose rate calculations carried out in PC-CREAM 08 are given in Section 4.7.

4.1 Selecting suitable organisms

The selection of representative organisms (ROs) is based on a review of the flora and fauna that inhabit the region of interest. As with the assessment of doses to humans, the relevant exposure pathways must be identified in order to evaluate dose rates to each RO. In PC-CREAM 08 the exposure pathways are limited to a predefined set relevant to the 12 RAPs and radionuclide concentration ratios and dose coefficients are provided for each RAP.

Therefore, where a RO can be based on a RAP all relevant input data are readily available for the elements and radionuclides considered in ICRP Publication 114 (ICRP, 2009) and Publication 136 (ICRP, 2017), respectively.

For the purpose of screening assessments, ROs can be assumed to consist solely of RAPs. For more detailed assessments, there are inevitably situations where ROs do not map directly to a RAP, in which case ROs can be defined by the user potentially drawing on other sources of information. For example, concentration ratios are available in IAEA publication TRS 479 (IAEA, 2014a) for organisms that have been categorised into broad groups such as ‘birds’ and ’mammals’. The total number of broad groups listed is 14 for terrestrial wildlife, 13 for freshwater wildlife and 13 for marine and brackish water wildlife. Where data exists, the broad groups are divided into subcategories e.g. ‘birds: carnivorous’ or ‘mammals: omnivorous’.

4.2 Calculation of representative environmental activity concentrations

Since the main aim of the ICRP system of environmental protection is to protect populations of biota rather than individuals the environmental activity concentrations used in an assessment of doses to biota should represent the average concentrations to which the population as a whole is exposed. In the biota module of PC-CREAM 08, the user has the option to select the region over which to calculate the average activity concentrations. For discharges to the aquatic environment this region will be determined by the size of the relevant compartment of the models used. For discharges to the atmosphere, the region occupied by the biota population can be defined using the coordinates of a polar grid centred on the discharge point. For generic assessments, guidance on the selection of appropriately sized regions is given in IAEA publication GSG-10 (IAEA, 2018) which states that typically regions of between about 100 to 400 km^2 located around the discharge point should be considered. GSG-10 (IAEA, 2018) notes that, under normal operation, the highest environmental activity concentrations are expected to be found in this region and consequently doses are unlikely to be underestimated.

The period of exposure should also be taken into consideration when calculating environmental activity concentrations for biota dose assessments. ICRP 108 (ICRP, 2008a) acknowledged that radiosensitivity can vary depending on the life-cycle stages of an organism in which case the period of exposure would apply to the duration of the life-cycle stage. For organisms that live for short periods of time, eg a few days, the period of exposure might be the life span of the organism. In its publications ICRP used time frames of hours and days when compiling data for the calculation of dose rates such that these would be applicable over the time periods of interest. PC-CREAM 08 calculates annual average activity concentrations in environmental media and hence dose rates to biota are also based on annual average concentrations. Consequently, environmental conditions, such as meteorology, which regularly coincide with a particular life-cycle stage of an organism, for example juvenile forms generally exist during the spring months in the northern hemisphere, are not explicitly considered in PC-CREAM 08. The time frame of exposure also impacts on how radioactive progeny are handled and this is discussed further in Section 4.4.

4.2.1 Calculation of activity concentrations from atmospheric discharges

In PC-CREAM 08 the source term for atmospheric discharges is defined using an annual discharge rate (Bq y^{-1}) for each radionuclide considered. Radionuclides are selected from a comprehensive list based on ICRP 38 (ICRP, 1983). Subsequent atmospheric dispersion, deposition and transport through soil are modelled using the PLUME and GRANIS models in the same way as is done for human dose assessments. The PLUME results used as input to a biota dose assessment are activity concentrations in air and deposition rates. These are calculated for the sectors and distance bands of a polar grid (Figure 1). The GRANIS results used are soil concentrations per unit deposition rate for soil depths of 0 to 15 cm and 0 to 30 cm.

The biota module allows the user to select the PLUME and GRANIS runs to be used in the biota dose assessment. It also allows the region occupied by the biota in the terrestrial environment to be defined. The default region is a circle of radius 6 km (~ 100 km^2) centred on the discharge point. However, a user defined region can be set up instead, for example, to represent an area of special scientific interest that is occupied by protected or endangered species. The user defined region consists of target areas each of which can be defined by selecting two distances and two angles. Figure 1 shows the 8 sectors of a polar grid and a region highlighted in green. The green region can be approximated by two target areas; one that lies between 8 and 10 km and 2.5 and 22.5 degrees from north and another which lies between 5 and 10 km and 22.5 to 62.5 degrees. The PC-CREAM 08 biota module uses this information and selects PLUME results for the appropriate sectors and distance bands to calculate the area weighted average activity concentration and deposition rate for the entire highlighted area. The biota module then combines the average deposition rate with soil concentrations per unit deposition rate from GRANIS to calculate average activity concentrations in soil for the highlighted area.

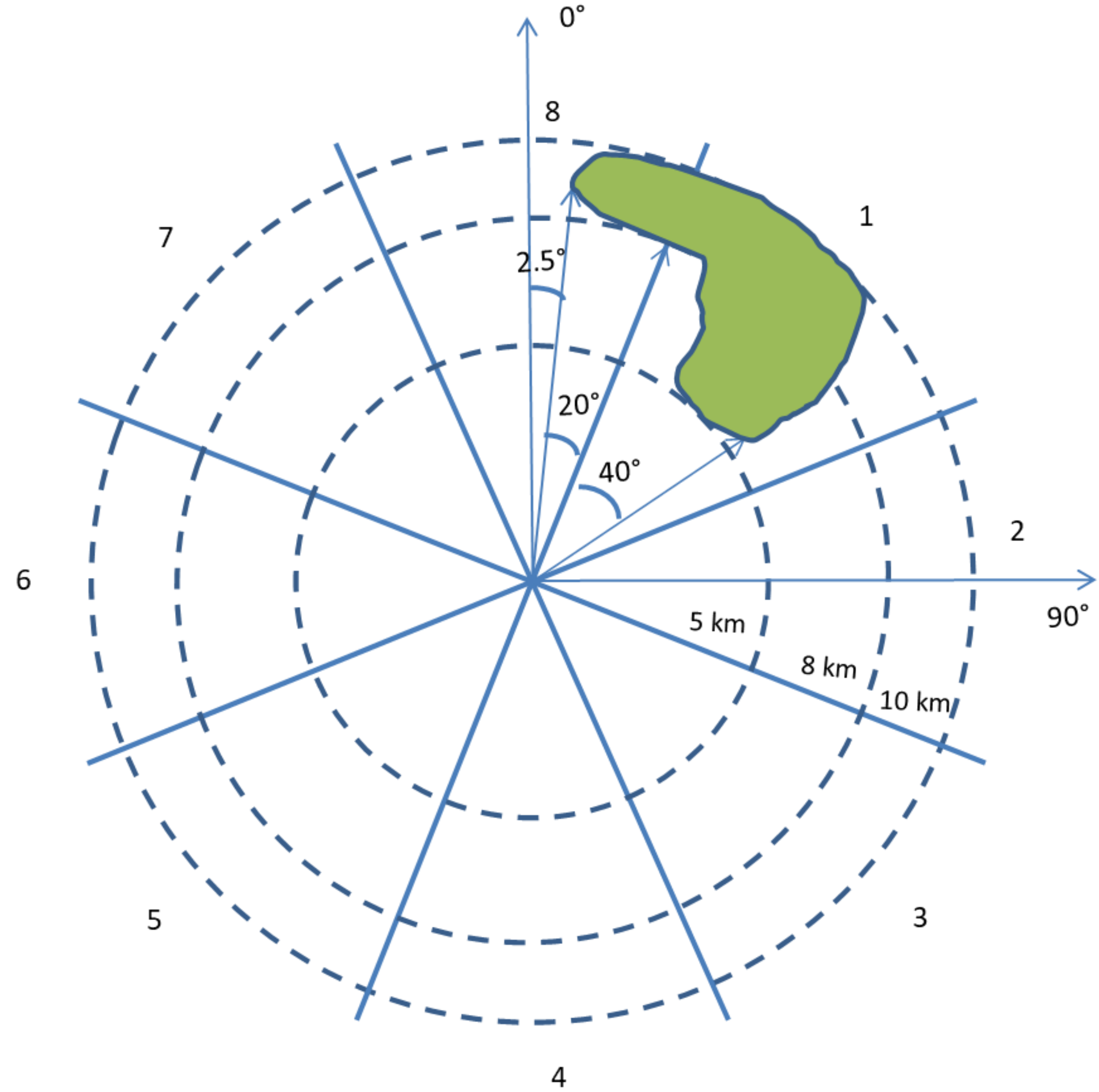

Figure 1 Example target areas considered in atmospheric release assessment

4.2.2 Calculation of activity concentrations from discharges to a river

Discharges to rivers and subsequent dispersion are modelled in the same way for biota as they are for humans. The source term is expressed as the annual discharge rate (Bq y^{-1}) of each radionuclide considered and dispersion is modelled using the PC-CREAM 08 Dynamic River model. This is a compartmental model in which the compartments represent river sections of similar physical characteristics and transfer of radionuclides from one compartment to the next is defined using rate constants. For biota that inhabit a freshwater environment, activity concentrations in river water and riverbed sediments are used to calculate dose rates. The river model can be selected from a predefined list or set up by the user. The predefined list includes some of the larger European rivers with sections that are typically hundreds of kilometres long, a hundred metres wide and a few metres deep. If the dimensions of these rivers are not an adequate representation of the river characteristics for the region occupied by biota then the user should enter their own data. However, it is worth noting that the selection of an appropriate flow rate for the river section occupied by biota is the most important factor in determining environmental activity concentrations. Within the biota module of PC-CREAM 08 the user must select the dynamic river model for use in the biota dose assessment and the appropriate river section to represent the habitat for each RAP and user defined RO considered.

4.2.3 Calculation of activity concentrations from liquid discharges to the marine environment

Liquid discharges to the sea and subsequent dispersion are modelled in the same way for biota as they are for humans. The source term is expressed as the annual discharge rate (Bq y^{-1}) of each radionuclide considered and dispersion in the marine environment is modelled using the PC-CREAM 08 DORIS model. DORIS is a compartmental model in which compartments represent different sea regions and radionuclide transfer between compartments is modelled using rate constants. For biota that inhabit a marine environment, the activity concentrations in seawater and seabed sediments in the compartments of the DORIS model are used to calculate dose rates. Each nuclear site contained in the PC-CREAM 08 database is associated with a predefined local compartment into which the discharge initially occurs. The highest activity concentrations and doses are generally found in the local compartment. The local compartment volumes and water exchange rates vary considerably depending on the coastal geography. These parameters have been recently reviewed (Smith, 2019) but they can be changed to better represent the conditions of the region occupied by biota if appropriate data are available. The rate of exchange of water between the local compartment and the adjacent regional compartment is generally the most important parameter in determining environmental activity concentrations. Within the biota module of PC-CREAM 08 the user must select the DORIS model for use in the biota dose assessment. The user must also select the appropriate model compartment for each RAP and user defined RO considered.

4.3 Transfer of radionuclides from the environment to biota

Once activity concentrations in the environment have been calculated using the PC-CREAM 08 dispersion models the uptake of activity by biota must be determined in order to calculate internal exposures. This is done in PC-CREAM 08 using concentration ratios (CRs) that relate activity concentrations in environmental media to whole-body activity concentrations in biota. The CRs are based on empirical data and incorporate implicitly all the uptake pathways ie ingestion of food/soil/water, inhalation and adsorption. PC-CREAM 08 includes concentration ratios for the 12 ICRP RAPs and 39 elements taken from ICRP Publication 114 (ICRP, 2009) as default values. Different CRs can be entered into PC-CREAM 08 by the user in situations where the default RAPs are not appropriate from other sources of data available, such as IAEA report TRS 479 (IAEA, 2014a) which provides CRs for an extended list of biota. The surrounding media for which CRs are available are soil for terrestrial RAPs and water for aquatic RAPs. Some RAPs, eg duck, are exposed to both soil and water and therefore CRs are available for both media. For radionuclides where there is significant exchange between terrestrial biota and the atmosphere (ie ^{3}H, ^{14}C, ^{32}P, ^{33}P and

^{35}S) uptake is based on the activity concentration in air rather than soil. Detailed equations on how whole-body activity concentrations in biota are calculated are given in Section 4.7.

The CRs published in ICRP Publication 114 (ICRP, 2009) are for adult forms of the RAPs only. This is because there is a lack of data that can be used to estimate CRs for other life stages. The dose rate calculations performed in PC-CREAM 08 for the RAPs are therefore for adult organisms. It should be noted that even for adult organisms it was necessary for ICRP to devise a set of rules under which surrogate values could be considered in order to complete the dataset for every RAP-element combination (ICRP, 2009).

4.4 Dose coefficients

PC-CREAM 08 uses Dose Coefficients (DCs) from ICRP Publication 136 (ICRP, 2017) to calculate absorbed dose rates from internal and external exposures. Dose rates for internal exposures are calculated by multiplying the activity concentrations in the organism by the internal dose coefficients, while for external exposure, dose rates are calculated by multiplying the activity concentrations in the surrounding environmental medium by the external dose coefficients.

Unlike for humans, internal dose coefficients for the RAPs do not account for the method of intake, transfer within the body or the radiosensitivity of different tissues. Publication 136 (ICRP, 2017) lists DCs for the 12 RAPs and for a set of 75 radionuclides that is consistent with those included in Publication 114 (ICRP, 2009) for the CRs. Publication 136 (ICRP, 2017) does not provide DCs for different life stages of the RAPs (e.g. duck egg, frog spawn) as was done in Publication 108 (ICRP, 2008a). The main reason given is that the ICRP software tool BiotaDC (http://biotadc.icrp.org) can be used to calculate both internal and external DCs for organisms not well represented by the adult RAPs. This tool can be used to calculate DCs for user created ROs and entered manually into PC CREAM 08. However, to calculate dose rates the user must also manually enter concentration ratios and occupancy factors for these ROs.

There are six categories of DC, one for internal exposure and five for external exposure in different habitats. For internal exposure, dose coefficients are given in terms of $\mu Gy\ h^{-1}$ per $Bq\ kg^{-1}$ fresh weight of the biota, while dose coefficients for external exposure are given in terms of $\mu Gy\ h^{-1}$ per $Bq\ kg^{-1}$ in the environmental media. The five habitats for external exposure are: ‘aquatic’ for application to biota that are submerged in an infinite volume of water; ‘in soil’ for biota located in a 50 cm deep soil layer of infinite lateral extent; ‘on ground’ for biota exposed on top of a 10 cm deep soil layer of infinite lateral extent; ‘above ground’ for biota flying above the ground but receiving an external exposure from a 10 cm deep soil layer of infinite lateral extent and ‘immersion in air’ for biota immersed in an infinite volume of air. For terrestrial RAPs, DCs for external exposure only include irradiation by photons because alpha and beta particles are readily absorbed by inert layers such as fur and feathers. Therefore, these DCs are set to zero for some radionuclides eg H, C, P and S.

It should be noted that soil layer depths in the GRANIS model are restricted to 1, 5, 15, 30 and 100 cm. The average activity concentration in soil layers down to a depth of 30 cm rather than 50 cm) is used to calculate external dose rates for the ‘in soil’ habitat. This is likely to give a cautious estimate of dose rate as most of the activity remains in the top 30 cm of soil for the first few decades after discharges begin. For the ‘on ground’ and ‘above ground’ habitats the average activity concentration in soil layers down to a depth of 15 cm (rather than 10 cm) is used to calculate external dose rates. This is unlikely to make a significant difference to the dose rate calculated.

4.4.1 Progeny included in dose coefficients

The dose coefficients published in ICRP 136 (ICRP, 2017) include contributions from radioactive progeny that can be considered to be in secular equilibrium with the parent. Table 2 below provides a list of parent and progeny radionuclides, taken from Publication 136 (ICRP, 2017), for those cases where the contribution of the decay chain is considered.

Although PC-CREAM 08 calculates the in-growth of key radioactive progeny during dispersion in the environment, the predicted environmental activity concentrations of these progeny are not used in the calculation of dose rates to biota. Instead the approach taken is to calculate biota dose rates using the activity concentration of the parent radionuclide and the corresponding DCs which include contributions from the progeny. This avoids double counting of dose contribution from the progeny. However, the ratio of the activity concentration of progeny to parent in the environment will vary with time depending on the duration of the release and the time since the release began. This will impact on the value of the DCs. ICRP 136 (ICRP, 2017) recognizes this and recommends that in some situations the tabulated DCs in the report may not be appropriate and should be recalculated using the BiotaDC tool (http://biotadc.icrp.org). To use DCs calculated using BiotaDC in PC-CREAM 08 a user defined RO must be set up and the DCs assigned to it. It is not possible to change the DCs for the 12 RAPs already included in PC-CREAM 08, however, the DCs for the 12 RAPs can be assigned to a new RO.

Table 2 Progeny included in dose coefficients (DC) (ICRP, 2017)

Parent radionuclide	Progeny included
^{90}Sr	^{90}Y
^{103}Ru	^{130m}Rh
^{106}Ru	^{106}Rh
^{129m}Te	^{129}Te
^{132}Te	^{132}I
^{137}Cs	^{137m}Ba
^{140}Ba	^{140}La
^{144}Ce	^{144}Pr
^{210}Pb	^{210}Bi
^{226}Ra	^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po
^{228}Ra	^{228}Ac
^{228}Th	^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{212}Tl
^{234}Th	^{234m}Pa
^{235}U	^{231}Th
^{241}Pu	^{237}U

4.5 Radiation weighting factors

In Publication 148 (ICRP, 2021), ICRP reviewed data on the relative biological effectiveness (RBE) of beta radiation from tritium, and alpha particles on biota. The RBE depends on many factors including the dose and dose rate, the reference radiation and the endpoints considered. The publication notes that the data are limited and that further studies of RBE for a broader range of organisms is required. Nevertheless, the ICRP review suggests that similarities in RBE exist across organisms and the same RBE weighting factors can be applied to all RAPs and ROs.

The values of RBE recommended in Publication 148 (ICRP, 2021) are 1 for all low-LET radiations, and 10 for alpha particles. These factors should be applied to the internal dose coefficients published in ICRP 136 (ICRP, 2017) to calculate dose rates for comparison with the DCRLs. When using PC-CREAM 08 to carry out an assessment of dose rate to biota, radiation weighting factors can be included in the biota module.

Publication 148 (ICRP, 2021) states that its recommendations are consistent with those of UNSCEAR for non-human biota, but notes that "If internal exposures to tritium beta particles or other low-energy, low-LET radiations are within or close to the DCRL, additional review and possible modification of weighting of the absorbed doses might be warranted".

4.6 Occupancy factors

To account for the time spent by animals in different habitats with different levels of exposure, occupancy factors are used to scale the dose rates accordingly. Table 3 below gives details of the default occupancy factors used for RAPs in PC-CREAM 08. The default values can be replaced by the user if necessary, but it should be noted that the total occupancy cannot exceed one. It should also be noted that the occupancy factors presented in Table 3 are for different external exposure pathways but do not include 'Immersion in air'. The occupancy factor for time spent immersed in air, $O_{air\ immersion}$, is derived from the occupancy factor for time spent above ground, $O_{above\ ground}$, and the occupancy factor for time spent on the ground, $O_{on\ ground}$, as follows:

$$O_{air\ immersion}(j) = O_{above\ ground}(j) + 0.5\ O_{on\ ground}(j)$$

O_{on_ground} is multiplied by a factor of 0.5 because during this time exposure is to half the volume of air only.

The occupancy factors for internal exposures are derived from the occupancy factors for external exposure pathways. For internal exposure in the terrestrial environment the 'on ground' and 'above ground' external occupancies are summed to obtain a total occupancy factor that can be used to calculate dose rates for the surface habitat. For internal exposure in the aquatic environments the occupancy factors for each aquatic external pathway are summed to obtain total occupancy factors for the freshwater and marine environment.

Table 3 Occupancy factors used in PC-CREAM 08 for external exposure of RAPs

	Terrestrial			Freshwater				Marine			
RAP	On ground	Above ground	In soil	On river	Under river	On river bank	Bottom of river	On sea	Under sea	On beach	Bottom of sea
Deer	1										
Rat	0.5		0.5								
Duck	0.33	0.33		0.11	0.11	0.11					
Frog	0.5			0.125	0.125	0.125	0.125				
Bee	0.5	0.5									
Earthworm			1								
Pine tree	1										
Grass	1										
Trout					1						
Flatfish								0	0		1
Crab								0	0	0	1
Brown seaweed								0	0	0	1

4.7 Calculation of dose rates to biota

This section illustrates the equations used in the biota module of PC-CREAM 08 to calculate dose rates to biota from atmospheric, riverine and marine discharges. It demonstrates how the parameters described in preceding sections, namely activity concentrations, concentration ratios, dose coefficients and occupancy factors are used. Based on the dose rates and time spent in each location, ie terrestrial target area, river section and/or marine compartment (Section 4.2), a total dose rate can be calculated in PC-CREAM 08.

4.7.1 Calculation of dose rates from atmospheric discharges

Dose rates from internal exposure are calculated using the equation:

$$DR_{int,terr}(i,j) = A_{int,terr}(i,j)\, DC_{int}(i,j)$$

Where $A_{int,terr}(i,j)$ is the whole-body activity concentration of radionuclide *i* in biota *j* (Bq kg^{-1}) and is calculated as follows:

For radioisotopes of H, C, P and S:

$$A_{int,terr}(i,j) = A_{air}(i)\left(O_{on\ ground}(j) + O_{above\ ground}(j) + O_{in\ soil}(j)\right) CR_{terr}(i,j)$$

For all other radionuclides:

$$A_{int,terr}(i,j) = \Big(A_{on\ ground}(i)\left(O_{on\ ground}(j) + O_{above\ ground}(j)\right) \\ + A_{in\ soil}(i) O_{in\ soil}(j)\Big)\, CR_{terr}(i,j)$$

Dose rates from external exposure are calculated using the following equations:

Exposure on ground:

$$DR_{ext,on\ ground}(i,j) = A_{on\ ground}(i)\ O_{on\ ground}(j)\ DC_{ext,on\ ground}(i,j)$$

Exposure in soil:

$$DR_{ext,in\ soil}(i,j) = A_{in\ soil}(i)\ O_{in\ soil}(j)\ DC_{ext,in\ soil}(i,j)$$

Exposure above ground:

$$DR_{ext,above\ ground}(i,j) = A_{on\ ground}(i)\ O_{above\ ground}(j)\ DC_{ext,above\ ground}(i,j)$$

Exposure for immersion in air:

$$DR_{ext,immersion}(i,j) = A_{air}(i)\left(O_{above\ ground}(j) + 0.5\ O_{on\ ground}(j)\right) DC_{ext,immersion}(i,j)$$

Table 5 provides a summary of the quantities described in the equations used in the calculation of doses from atmospheric discharges.

Table 5 Quantities used in PC-CREAM 08 to calculate dose rates to biota from atmospheric discharges

Quantity	Description	Unit	Source
$A_{air}(i)$	Activity concentration in air of radionuclide *i*	Bq m^{-3}	PLUME model
$A_{on\ ground}(i)$	Activity concentration averaged over a soil depth of 15 cm of radionuclide *i*	Bq kg^{-1}	PLUME and GRANIS models
$A_{in\ soil}(i)$	Activity concentration averaged over a soil depth of 30 cm of radionuclide *i*	Bq kg^{-1}	PLUME and GRANIS models
$CR_{terr}(i,j)$	Concentration ratio for the terrestrial environment of radionuclide *i* for biota *j*	Bq kg^{-1} fresh weight per Bq kg^{-1}	ICRP 114 (ICRP, 2009)
		Bq kg^{-1} fresh weight per Bq m^{-3} for H, C, P and S	
$O_{on\ ground}(j)$	Fraction of time spent on the soil surface by biota *j*	Adimensional	See Table 3 for values for RAPs
$O_{in\ soil}(j)$	Fraction of time spent within the soil by biota *j*	Adimensional	See Table 3 for values for RAPs
$O_{above\ ground}(j)$	Fraction of time spent above the soil surface by biota *j*	Adimensional	See Table 3 for values for RAPs
$DC_{int}(i,j)$	Internal dose coefficient of radionuclide *i* in biota *j*	µGy h^{-1} per Bq kg^{-1} in biota	ICRP 136 (ICRP, 2017)
$DC_{ext,\ on\ ground}(i,j)$	External dose coefficient of radionuclide *i* in biota *j* for exposure on the soil surface	µGy h^{-1} per Bq kg^{-1} in soil to 10 cm depth	ICRP 136 (ICRP, 2017)
$DC_{ext,\ in\ soil}(i,j)$	External dose coefficient of radionuclide *i* in biota *j* for exposure within the soil	µGy h^{-1} per Bq kg^{-1} in soil to 50 cm depth	ICRP 136 (ICRP, 2017)
$DC_{ext,\ above\ ground}(i,j)$	External dose coefficient of radionuclide *i* in biota *j* for exposure above the soil	µGy h^{-1} per Bq kg^{-1} in soil to 10 cm depth	ICRP 136 (ICRP, 2017)
$DC_{ext,\ immersion}(i,j)$	External dose coefficient of radionuclide *i* in biota *j* for exposure from immersion in air	µGy h^{-1} per Bq m^{-3}	ICRP 136 (ICRP, 2017)

4.7.2 Calculation of dose rates from riverine discharges

Dose rates from internal exposure are calculated using the equation:

$$DR_{int,fresh}(i,j) = A_{int,fresh}(i,j)DC_{int}(i,j)$$

Where $A_{int,\ fresh}(i,j)$ is the activity concentration of radionuclide *i* in biota *j* (Bq kg^{-1}) and is calculated as follows:

$$A_{int,fresh}(i,j) = A_{filt\ fresh}(i)\left(O_{fresh}(j) + O_{air/fresh}(j) + O_{air/sed}(j) + O_{fresh/sed}(j)\right) CR_{fresh}(i,j)$$

Dose rates from external exposure are calculated using the following equations:

Exposure in river water:

$$DR_{ext,fresh}(i,j) = A_{unfilt\ fresh}(i)\ O_{fresh}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on river water:

$$DR_{ext,air/fresh}(i,j) = 0.5\ A_{unfilt\ fresh}(i)\ O_{air/fresh}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on river sediment:

$$DR_{ext,air/sed}(i,j) = 0.5\ A_{sed}(i)\ O_{air/sed}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on the river water/sediment interface:

$$DR_{ext,fresh/sed}(i,j) = 0.5\left(A_{sed}(i) + A_{unfil\ fresh}(i)\right) O_{fresh/sed}(j)DC_{ext,aqua}(i,j)$$

Table 6 provides a summary of the quantities described in the equations used in the calculation of doses from riverine discharges.

Table 6 Quantities used in PC-CREAM 08 to calculate dose rates to biota from riverine discharges

Quantity	Description	Unit	Source
$A_{filt\ fresh}(i)$	Activity concentration in filtered river water of radionuclide *i*	Bq l^{-1}	Dynamic river model
$A_{unfilt\ fresh}(i)$	Activity concentration in unfiltered river water of radionuclide *i*	Bq l^{-1}	Dynamic river model
$A_{sed}(i)$	Activity concentration in river sediment of radionuclide *i*	Bq kg^{-1}	Dynamic river model
$CR_{fresh}(i,j)$	Concentration ratio for the riverine environment of radionuclide *i* in biota *j*	Bq kg^{-1} fresh weight per Bq l^{-1}	ICRP 114 (ICRP, 2009)
$O_{fresh}(j)$	Fraction of time spent by biota *j* immersed in river water	Adimensional	See Table 3 for values for RAPs
$O_{air/fresh}(j)$	Fraction of time spent by biota *j* at the atmosphere/river water interface	Adimensional	See Table 3 for values for RAPs
$O_{air/sed}(j)$	Fraction of time spent by biota *j* at the atmosphere/river sediment interface	Adimensional	See Table 3 for values for RAPs
$O_{fresh/sed}(j)$	Fraction of time spent by biota *j* at the river water/river sediment interface	Adimensional	See Table 3 for values for RAPs
$DC_{int}(i,j)$	Internal dose coefficient of radionuclide *i* for biota *j*	µGy h^{-1} per Bq kg^{-1}	ICRP 136 (ICRP, 2017)

Quantity	Description	Unit	Source
$DC_{ext\ aqua}(i,j)$*	External dose coefficient of radionuclide *i* for biota *j* for exposure when immersed in unfiltered river water	µGy h^{-1} per Bq l^{-1}	ICRP 136 (ICRP, 2017)

* This dose coefficient is also used for exposure to seawater and saturated sediments, the assumption being that the density and chemical composition is similar to freshwater (see Annex B of ICRP 136 (ICRP, 2017)).

4.7.3 Calculation of dose rates from marine discharges

Dose rates from internal exposure are calculated using the equation:

$$DR_{int,mar}(i,j) = A_{int,mar}(i,j) DC_{int}(i,j)$$

Where $A_{int,\ mar}(i,j)$ is the activity concentration of radionuclide *i* in biota *j* from marine discharges (Bq kg^{-1}) and is calculated as follows:

$$A_{int,mar}(i,j) = A_{filt\ mar}(i) \left(O_{mar}(j) + O_{air/mar}(j) + O_{air/sed}(j) + O_{mar/sed}(j)\right) CR_{mar}(i,j)$$

Dose rates from external exposure are calculated using the following equations:

Exposure in seawater:

$$DR_{ext,mar}(i,j) = A_{unfilt\ mar}(i)\ O_{mar}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on seawater:

$$DR_{ext\ air,mar}(i,j) = 0.5\ A_{unfilt\ mar}(i)\ O_{air,mar}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on marine sediment:

$$DR_{ext,air/sed}(i,j) = 0.5\ A_{sed}(i)\ O_{air,sed}(j)\ DC_{ext,aqua}(i,j)$$

Exposure on the seawater/sediment interface:

$$DR_{ext\ mar/sed}(i,j) = 0.5 \left(A_{sed}(i) + A_{unfil\ mar}(i)\right) O_{mar\ sed}(j)\ DC_{ext\ aqua}(i,j)$$

Table 7 provides a summary of the quantities described in the equations used in the calculation of doses from marine discharges.

Table 7 Quantities used in PC-CREAM 08 to calculate dose rates to biota from marine discharges

Quantity	Description	Unit	Source
$A_{filt\ mar}(i)$	Activity concentration in filtered seawater of radionuclide *i*	Bq l^{-1}	DORIS model
$A_{unfilt\ mar}(i)$	Activity concentration in unfiltered seawater of radionuclide *i*	Bq l^{-1}	DORIS model
$A_{sed}(i)$	Activity concentration in marine sediment of radionuclide *i*	Bq kg^{-1}	DORIS model
$CR_{far}(i,j)$	Concentration ratio for the marine environment of radionuclide *i* in biota *j*	Bq kg^{-1} fresh weight per Bq l^{-1}	ICRP 114 (ICRP, 2009)

Quantity	Description	Unit	Source
$O_{marine}(j)$	Fraction of time spent by biota *j* immersed in seawater	Adimensional	See Table 3 for values for RAPs
$O_{air/marine}(j)$	Fraction of time spent by biota *j* at the atmosphere/seawater interface	Adimensional	See Table 3 for values for RAPs
$O_{air/sed}(j)$	Fraction of time spent by biota *j* at the atmosphere/marine sediment interface	Adimensional	See Table 3 for values for RAPs
$O_{marine/sed}(j)$	Fraction of time spent by biota *j* at the seawater/marine sediment interface	Adimensional	See Table 3 for values for RAPs
$DC_{int}(i,j)$	Internal dose coefficient of radionuclide *i* for biota *j*	µGy h^{-1} per Bq kg^{-1}	ICRP 136 (ICRP, 2017)
$DC_{ext\ aqua}(i,j)$*	External dose coefficient of radionuclide *i* for biota *j* for exposure when immersed in unfiltered sea water	µGy h^{-1} per Bq l^{-1}	ICRP 136 (ICRP, 2017)

* This dose coefficient is also used for exposure to freshwater and saturated sediments, the assumption being that the density and chemical composition are similar to seawater (see Annex B of ICRP 136 (ICRP, 2017)).

4.7.4 Example of calculation of dose rates in ducks

A nuclear power plant discharges radioactivity into the atmosphere and a nearby river. A survey of biota living in the vicinity of a nuclear power plant has identified waterfowl as a RO for the site. This RO is well represented by the duck RAP and therefore an assessment of doses can be carried out for this RAP. The default concentration ratios and dose coefficients for this RAP are held in the PC-CREAM 08 database and will automatically be used for the radionuclides of interest. However, site specific information regarding occupancy of different habitats is available and this shows that these birds spend 20% of their time on the soil surface, 50% on the surface of the nearby river, 10% diving under the river water and 20 % flying. The equations below illustrate how the internal, external and total absorbed dose rates are calculated for the Duck RAP.

For each radionuclide *i* considered in the assessment the calculation of dose rates for internal exposure in ducks (µGy h^{-1}) is performed as follows:

Firstly, the activity concentration of radionuclide *i* in ducks from atmospheric discharges is calculated as follows:

For radioisotopes of H, C, P and S:

$$\begin{aligned} A_{int,terr}(i,\mathrm{duck}) = {} & A_{air}(i)\left(O_{on\ ground}(duck) + O_{above\ ground}(duck)\right. \\ & \left. + O_{in\ soil}(duck)\right) CR_{terr}(i,\mathrm{duck}) = A_{air}(i)(0.2+0.2+0)\ CR_{terr}(i,\mathrm{duck}) \\ & = 0.4A_{air}(i)\ CR_{terr}(i,\mathrm{duck}) \end{aligned}$$

For all other radionuclides:

$$\begin{aligned} A_{int,terr}(i,\mathrm{duck}) = {} & \left(A_{on\ ground}(i)\left(O_{on\ ground}(duck) + O_{above\ ground}(duck)\right)\right. \\ & \left. + A_{in\ soil}(i) O_{in\ soil}(duck)\right) CR_{terr}(i,duck) \\ & = \left(A_{on\ ground}(i)(0.2+0.2) + A_{in\ soil}(i)(0)\right) CR_{terr}(i,duck) \\ & = 0.4\ A_{on\ ground}(i) CR_{terr}(i,duck) \end{aligned}$$

Secondly, the activity concentration of radionuclide *i* in ducks from discharges to the river is calculated as follows:

$$\begin{aligned} A_{int,fresh}(i, duck) &= A_{filt\ fresh}(i)\left(O_{fresh}(duck) + O_{air,fresh}(duck) + O_{air,sed}(duck)\right. \\ &\quad \left. + O_{fresh,sed}(duck)\right) CR_{fresh}(i, duck) \\ &= A_{filt\ fresh}(i)(0.1 + 0.5 + 0 + 0)\ CR_{fresh}(i, duck) \\ &= 0.6\ A_{filt\ fresh}(i)\ CR_{fresh}(i, duck) \end{aligned}$$

Thirdly, the internal dose rates of radionuclide *i* from atmospheric and riverine discharges are calculated as follows:

$$DR_{int,terr}(i, duck) = A_{int,terr}(i, duck)\ DC_{int}(i, duck)$$

and

$$DR_{int,fresh}(i, duck) = A_{int,fresh}(i, duck) DC_{int}(i, duck)$$

Finally, the total dose rate for internal exposure in ducks of radionuclide *i*, $DR_{int}(i, duck)$, is calculated by summing the internal dose rates from atmospheric and riverine discharges:

$$DR_{int}(i, duck) = DR_{int,terr}(i, duck) + DR_{int,fresh}(i, duck)$$

For each radionuclide *i* considered in the assessment the calculation of dose rates for external exposure in ducks (µGy h^{-1}) is performed as follows:

Firstly, the external dose rate of radionuclide *i* from atmospheric discharges is calculated as follows:

$$\begin{aligned} D_{ext,terr}(i, duck) &= D_{ext,on\ ground}(i, duck) + D_{ext,in\ soil}(i, duck) + D_{ext,above\ ground}(i, duck) \\ &\quad + D_{ext,immersion}(i, duck) \\ &= A_{on\ ground}(i)\ O_{on\ ground}(duck)\ DC_{ext,on\ ground}(i, duck) \\ &\quad + A_{in\ soil}(i)\ O_{in\ soil}(duck)\ DC_{ext,in\ soil}(i, duck) \\ &\quad + A_{on\ ground}(i)\ O_{above\ ground}(duck)\ DC_{ext,above\ ground}(i, duck) \\ &\quad + A_{air}(i)\left(O_{above\ ground}(duck) + 0.5\ O_{on\ ground}(duck)\right) DC_{ext,immersion}(i, duck) \\ &= 0.2\ A_{on\ ground}(i)\ DC_{ext,on\ ground}(i, duck) \\ &\quad + 0.2\ A_{on\ ground}(i)\ DC_{ext,above\ ground}(i, duck) \\ &\quad + (0.2 + 0.1) A_{air}(i) DC_{ext,immersion}(i, duck) \\ &= 0.2\ A_{on\ ground}(i)\ \left(DC_{ext,on\ ground}(i, duck) + DC_{ext,above\ ground}(i, duck)\right) \\ &\quad + 0.3\ A_{air}(i) DC_{ext,immersion}(i, duck) \end{aligned}$$

Secondly, the external dose rate from radionuclide *i* from discharges to the river is calculated as follows:

$$
\begin{aligned}
D_{ext,fresh}(i,duck) \\
&= D_{ext,fresh}(i,duck) + D_{ext,air/fresh}(i,duck) + D_{ext,air/sed}(i,duck) \\
&+ D_{ext,fresh/sed}(i,duck) \\
&= A_{unfilt\ fresh}(i)\ O_{fresh}(duck)\ DC_{ext,aqua}(i,duck) \\
&+ 0.5\ A_{unfilt\ fresh}(i)\ O_{air/fresh}(duck)\ DC_{ext,aqua}(i,duck) \\
&+ 0.5\ A_{sed}(i)\ O_{air/sed}(duck)\ DC_{ext,aqua}(i,duck) \\
&+ 0.5\left(A_{sed}(i) + A_{unfil\ fresh}(i)\right) O_{fresh/sed}(duck) DC_{ext,aqua}(i,duck) \\
&= 0.1\ A_{unfilt\ fresh}(i)\ DC_{ext,aqua}(i,duck) \\
&+ 0.25\ A_{unfilt\ fresh}(i)\ DC_{ext,aqua}(i,duck) \\
&= 0.35\ A_{unfilt\ fresh}(i) DC_{ext,aqua}(i,duck)
\end{aligned}
$$

Thirdly, the total dose rate in ducks for external exposure to radionuclide *i*, $DR_{int}(i,duck)$, is calculated by summing the internal dose rates from atmospheric and riverine discharges:

$$DR_{ext}(i,duck) = DR_{ext,terr}(i,duck) + DR_{ext,fresh}(i,duck)$$

The total dose rate in ducks due to radionuclide *i*, *DR(i,duck),* is calculated by summing the internal and external dose rates:

$$DR(i,duck) = DR_{int}(i,duck) + DR_{ext}(i,duck)$$

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