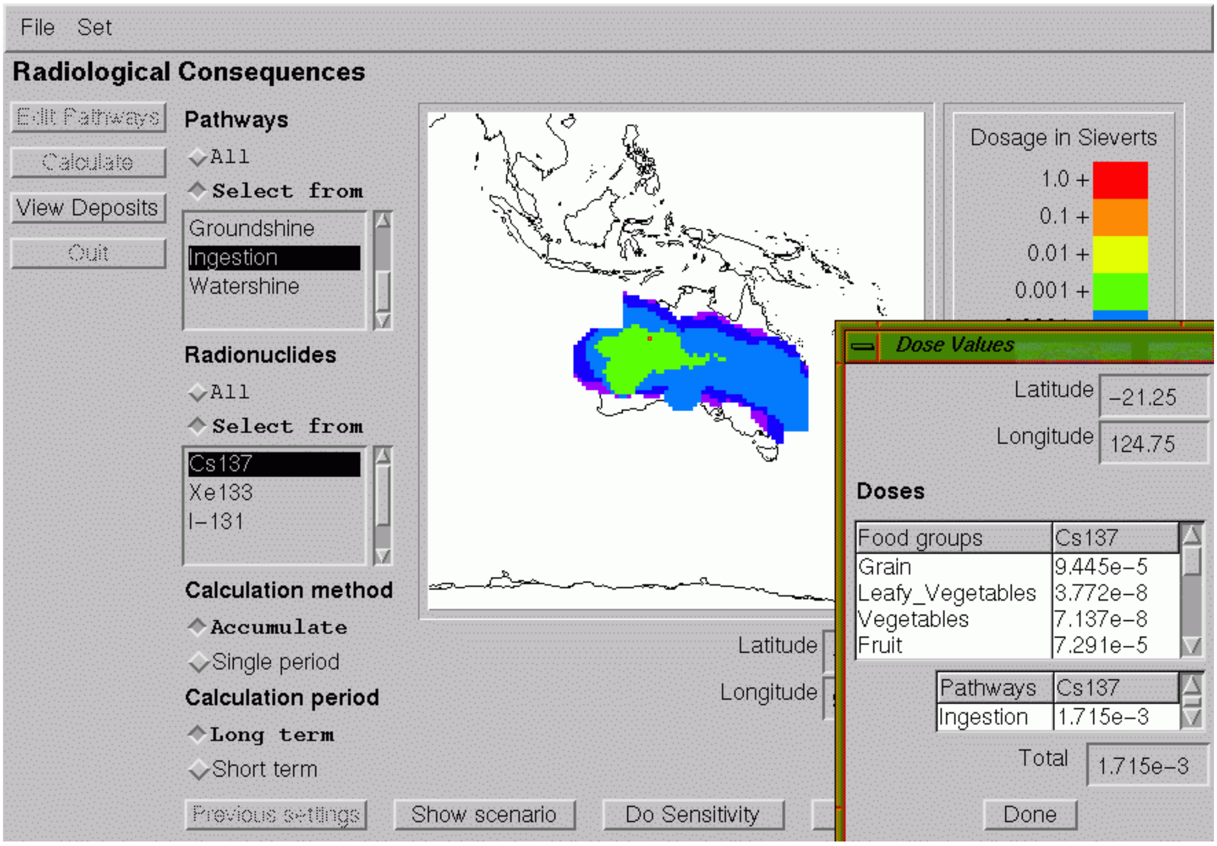
ANSTO/E-744

RadCon: A Radiological Consequences Model



Technical Guide

Version 2.0

J. Crawford
R.U. Domel
F.F. Harris
J.R. Twining

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1. Introduction

The post Chernobyl era has seen the development of a plethora of radiological consequence models. The information used in these models pertains mostly to temperate and cold climate environments.

At the Australian Nuclear Science and Technology Organisation (ANSTO), a model – RadCon - is being developed, to assist in assessing the radiological consequences, after an incident, in any climate, using appropriate meteorological and radiological transfer parameters. The major areas of interest to the developers are tropical and subtropical climates. This is particularly so given that it is anticipated that nuclear energy will become a mainstay for economies in these regions within the foreseeable future. Therefore, data acquisition and use of parameter values have been concentrated primarily on these climate types.

Atmospheric dispersion and deposition for Australia can be modelled and supplied by the Regional Specialised Meteorological Centre (RSMC, one of five in the world) which is part of the Bureau of Meteorology Research Centre (BMRC), Puri *et al*. (1992). RadCon combines these data (*i.e.* the time dependent air and ground concentration generated by the dispersion model or measured quantities in the case of an actual incident) with specific regional parameter values to determine the dose to people via the major pathways of external and internal irradiation. Figure 1 shows the pathways implemented in RadCon. The air concentration and the deposition on the soil is calculated outside of RadCon.

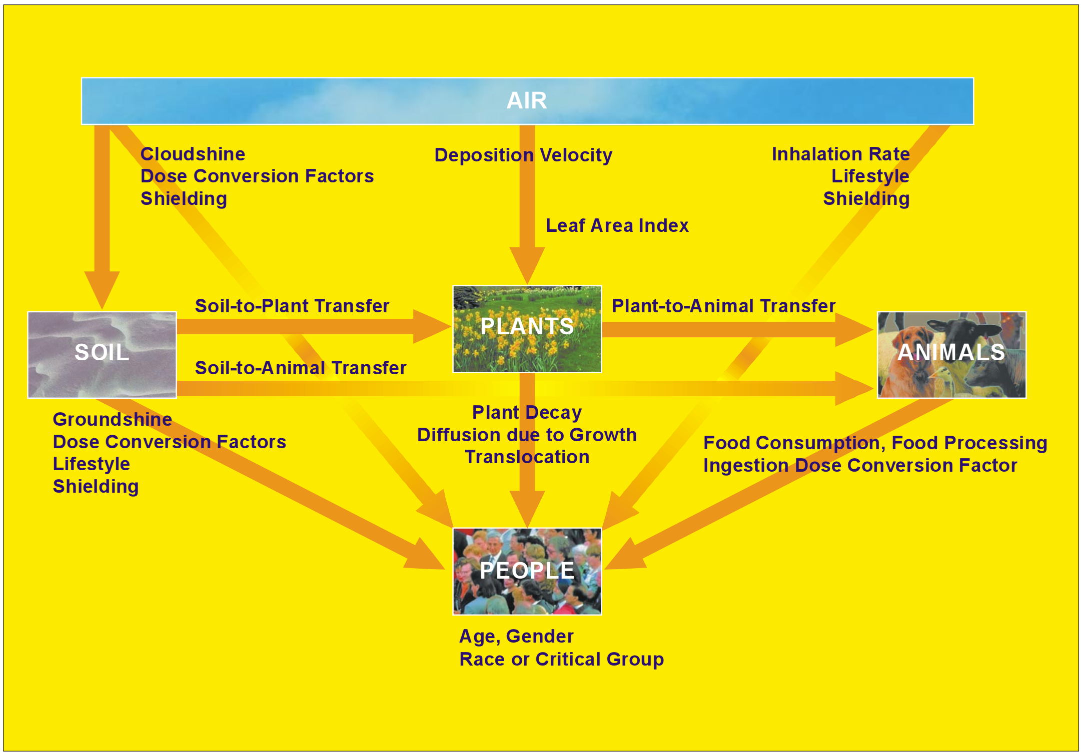

Figure 1: RadCon: Exposure pathways.

For the external irradiation calculations, data are needed on lifestyle information such as the time spent indoors/outdoors, the high/low physical activity rates for different groups of people (especially critical groups) and shielding factors for housing types. For the internal irradiation calculations, data are needed on food consumption, effect of food processing, transfer parameters (soil to plant, plant to animal) and interception values appropriate for the region under study. Where the relevant data are not available default temperate data are currently used. The results of a wide ranging literature search has highlighted where specific research will be initiated to determine the information required for tropical and sub-tropical regions.

The user is able to initiate sensitivity analyses within RadCon. This allows the parameters to be ranked in priority of impact within the scenario being investigated.

The model provides a tool for directing future research and has application as a planning tool for emergency response operations.

2. Implementation

Given the wide variability in the region it was required that the model be implemented such that:

- It would be able to use inputs from different atmospheric transport models.
- All the required parameter data would be separate from the program, thus allowing easy adaptation to new sites.
- It provide a graphical user interface and portability across computer platforms.

RadCon is implemented in the Java programming language and presents a graphical interface to the user. For example, the screen used for carrying out calculations is presented on the title page of this report.

3. RadCon Model Description

3.1 *General Assumptions*

A large number of simplifying assumptions need to be made for any modelling system. Some assumptions for the implementation of this model are listed below. Others, which are pathway specific, are listed under the specific pathway. In the absence of site specific data, the majority of the assumptions are conservative.

- Effects on food chains in large volumes of water or moving streams are not modelled.
- A local production and consumption approach is considered, *i.e.* food produced in a grid location is consumed in that grid location with no transfer between grids. A factor is included to allow the user to specify what fraction of the food consumed by humans is produced locally.
- Food consumed by animals and humans is assumed to be harvested at the time of consumption, *i.e.* no seasonal variation or storage of food or fodder is included.
- Food consumption is considered to be uniform on a daily basis.

4. Pathways

The major pathways used in this model are:

- External irradiation from material in the cloud. (Cloudshine)
- External irradiation from material deposited on the ground. (Groundshine)
- Internal exposure following inhalation.
- Internal exposure from ingestion of contaminated food.

4.1 *External Exposure from the Ground (Groundshine)*

The dose for time period t_0 to t_1 from radioactive material deposited on the ground is modelled by the following mathematical formula, adapted from Müller and Pröhl (1993):

$$D(r,t_0,t_1) = G(r)S(r)d(r)c\int_{t_0}^{t_1}\left[\alpha(r,s)e^{-(\lambda(r)+\lambda_1(r,s))t} + (1-\alpha(r,s))e^{-(\lambda(r)+\lambda_2(r,s))t}\right]dt \qquad (1)$$

Table 1 presents a description of the parameters in this equation, their units and dependencies.

Table 1: Groundshine Parameters

Parameters	*Description*	*Unit*	*Depends on*
$D(r,t_0,t_1)$	dose from radionuclide *r* in the time interval t_0 to t_1	*Sv*	radionuclide
$G(r)$	total ground concentration	$Bq\ m^{-2}$	radionuclide
$S(r)$*	location factor	*dimensionless*	lifestyle**, radionuclide
$d(r)$	dose conversion factor	$\frac{Sv}{Bqs/m^2}$	radionuclide
$\alpha(r,s)$	mobile component factor	*dimensionless*	radionuclide, soil
$\lambda(r)$	radionuclide decay rate	d^{-1}	radionuclide
$\lambda_1(r,s)$	migration rate, mobile component	d^{-1}	radionuclide, soil
$\lambda_2(r,s)$	migration rate, fixed component	d^{-1}	radionuclide, soil
$[t_0,t_1]$	time interval, measured after deposition has stopped	d^{-1}	
c	3600 * 24 (to convert days to seconds)	sd^{-1}	

* *S(r)* = Fraction of Time Out Door x Out Door Shielding Factor +
Fraction of Time In Door x In Door Shielding Factor

** Lifestyle combines rural/residential/urban housing types and indoor/outdoor occupancy factors.

For dose calculation in the short term, (*i.e.* while deposition is occurring) the averaging time, Δt, used by the atmospheric transport model, is used as the interval $[t_0,t_1]$ and *G(r)* is the ground concentration for the associated time step, resulting in a dose being calculated for each time step.

4.1.1 Assumptions for Groundshine

- Gamma radiation only is considered.
- Allowance is made for building attenuation of gamma radiation. In the model, three building types are considered – urban, rural and residential.
- Indoor and outdoor occupancy factors are implemented.
- The gamma dose rate is calculated for 1 metre above ground.

4.2 *External Exposure from the Cloud (Cloudshine)*

External irradiation from radioactive material in the cloud is modelled by the following mathematical formula (which is valid for a semi-infinite cloud, and can be applied without problems at locations far away from the source of emission where the concentration of activity is homogeneous) with the description of parameters given in Table 2.

$$D(r,t_0,t_1) = A(r,t_0,t_1)S(r)d(r)(t_1 - t_0)c \qquad (2)$$

Table 2: Cloudshine Parameters.

Parameters	*Description*	*Unit*	*Depends on*
$D(r,t_0,t_1)$	dose from radionuclide *r*	*Sv*	radionuclide
$A(r,t_0,t_1)$	averaged airborne concentration in time interval $[t_0,t_1]$	$Bq\ m^{-3}$	radionuclide
$S(r)$*	location factor	*dimensionless*	lifestyle, radionuclide
$d(r)$	dose conversion factor	$\frac{Sv}{Bqs/m^3}$	radionuclide
c	3600 * 24	sd^{-1}	
$[t_0,t_1]$	interval of exposure	d	

*S(r) calculates as for Groundshine, but using appropriate values for shielding from the cloud

When an atmospheric transport model has been used to estimate the airborne concentration, the averaging time, Δt, used by the atmospheric transport model is used as the interval $[t_0,t_1]$.

4.2.1 Assumptions for Cloudshine

The model for the Cloudshine pathway has been adapted from Krajewski (1994). It is assumed that:

- The person is immersed in the cloud, therefore ground level air concentration is used.
- Gamma radiation only is considered.
- Allowance is made for the attenuation of gamma radiation by buildings. In the model, three building types are considered, those for the rural, residential or urban areas. Indoor and outdoor occupancy factors are implemented.

4.3 *Inhalation*

Contribution of dose to humans is modelled by the following mathematical formula, with a description of the parameters given in Table 3.

$$D(r,t_0,t_1) = A(r,t_0,t_1)F(r)I(r,a)d(r,a)(t_1 - t_0) \qquad (3)$$

Table 3: Inhalation Parameters.

Parameters	*Description*	*Unit*	*Depends on*
$D(r,t_0,t_1)$	dose from radionuclide *r*	*Sv*	radionuclide
$A(r,t_0,t_1)$	averaged airborne concentration	$Bq\ m^{-3}$	provided
$F(r)$*	filtering factor	*dimensionless*	Shielding, radionuclide
$I(r,a)$**	inhalation rate	$m^3\ h^{-1}$	age, race
$d(r,a)$	dose conversion factor	$Sv\ Bq^{-1}$	radionuclide
$[t_0,t_1]$	interval of exposure	h	

* F(r) = Fraction of Time Out Door x Out Door Shielding Factor +
Fraction of Time In Door x In Door Shielding Factor

**I(r,a) = Fraction of Time Resting x Resting Inhalation Rate + Fraction of Time Working x Working Inhalation Rate + Fraction of Time Alternate Activity x Alternate Activity Inhalation Rate, for the particular age group

When an atmospheric transport model has been used to estimate the airborne concentration the averaging time, Δt, used by the atmospheric transport model is used as the interval $[t_0,t_1]$.

4.3.1 Assumption for Inhalation

The model for the inhalation pathway has been adapted from Krajewski (1994). It is assumed that:

- The person is immersed in the cloud, therefore the ground level air concentration is used.
- Indoor air concentration may be assumed to be less than the outdoor, Brown *et al.* (1990). In the model, three building types are included, those for the rural, residential or urban areas. Thus a filtering factor is required for the shielding of building types.
- Indoor and outdoor occupancy factors are required to estimate the overall filtering factor to account for the attenuation.
- Physical activity modifies the breathing rate.
- Dose varies with the age of the individual.

4.4 *Ingestion*

Exposure to radionuclides can result from direct ingestion of contaminated food, which may include the following:

- drinking water ingestion
- crop ingestion
- animal product ingestion
- aquatic food ingestion

In Version 2.0 of RadCon, only ingestion from crops and animals are considered. These two ingestion pathways account for the major long-term dose following an accidental release to the atmosphere. In estimating the dose to humans from these pathways, the following are considered:

- soil to plant
- direct deposition on foliage
- interception by foliage
- plant to animal and plant to human
- animal to human

The mathematical formulae adapted for this model are described in the following sections. A local production/consumption is assumed. A factor is, however, included which the user can specify, indicating what fraction of the food consumed by humans is produced locally. A reduction factor to account for food processing is also included in this model.

4.4.1 Radionuclide concentration in plant products

Contribution to contamination of plants can be included from the following:

- root uptake,
- direct deposit on foliage,
- interception by foliage, and
- uptake from contaminated water supplies.

Uptake from contaminated water is not implemented in Version 2.0 of RadCon.

4.4.1.1 Contamination due to root uptake

The concentration of radionuclide r in plant product p, due to transfer from the soil, is modelled by the following equation with the description of the parameters given in Table 4.

$$P_r(r,p,t)=\frac{G(r)T_{sp}(r,p,s)}{P(s)K(s)}\left[\alpha(r,s)e^{-(\lambda(r)+\lambda_f(r,s)+\lambda_1(r,s))t}+(1-\alpha(r,s))e^{-(\lambda(r)+\lambda_f(r,s)+\lambda_2(r,s))t}\right] \tag{4}$$

Table 4: Parameters for Root Uptake.

Parameters	*Description*	Unit	*Depends on*
$P_r(r,p,t)$	concentration of radionuclide r in edible part of plant p, at time t due to root uptake	*Bq kg^{-1}*	radionuclide, plant, time from deposit
G(r)	ground concentration	*Bq m^{-2}*	radionuclide
$T_{sp}(r,p,s)$	transfer factor from *soil* to plant *p*	*Bq kg^{-1} crop per Bq kg^{-1} dry wt soil*	radionuclide and plant, soil type
P(s)	initial soil bulk density	*kg m^{-2}*	soil type
K(s)	soil reduction factor	*dimensionless*	migration of radionuclides *
$\lambda_1(r,s)$	rate of migration below root zone of mobile component of radionuclide	*d^{-1}*	radionuclide, soil
$\lambda_2(r,s)$	rate of migration below root zone of fixed component of radionuclide	*d^{-1}*	radionuclide, soil
$\alpha(r,s)$	mobile component fraction	*dimensionless*	radionuclide, soil
$\lambda(r)$	radioactive decay	*d^{-1}*	radionuclide
$\lambda_f(r,s)$	Rate of fixation	*d^{-1}*	radionuclide, soil
t	time	*d*	

* Depends on agricultural practices, *e.g.* ploughing.

4.4.1.2 Contamination due to direct deposition and interception fraction

Concentration in plant products and grass due to direct deposition and interception is modelled as in Müller and Pröhl (1993). A distinction is made between plants that are used totally (*e.g.* leafy vegetables) and those that are used only partially (*e.g.* cereals, potatoes and fruit). For plants with a specific edible part, the translocation of the activity from the foliage to the edible part is modelled, for those used totally a weathering factor is included. Grass forms a third group, where harvesting is continuous. In the implementation, a flag is used with each crop presented to the model to indicate which process (*i.e* translocation, weathering as in leafy vegetables or grass like behaviour as in section 4.4.1.2.1) should be included in calculating the concentration in the plant product at harvest.

The total deposition onto plants is modelled according to Müller and Pröhl (1993). Total deposition to plants is given by the following equation with a description of the parameters given in Table 5.

$$
\begin{aligned}
A(r,p) &= A_d(r,p) + f_w(r,p)A_w(r,p) \\
A_d(r,p) &= v(r,p)C_a(r) \\
v(r,p) &= v_{\max}(r,p)\frac{LAI(p)}{LAI_{\max}(p)} \\
f_w(r,p) &= \frac{LAI(p)S(p)}{R}\left[1-\exp\left(\frac{-\ln(2)}{3S(p)}R\right)\right]
\end{aligned}
\tag{5}
$$

Table 5: Parameters for total deposition onto plants.

Parameters	Description	Unit	Depends on
A(r,p)	total deposition onto plant p	Bq m^{-2}	radionuclide, plant
A_d(r,p)	total dry deposition onto plant p	Bq m^{-2}	radionuclide, plant
f_w(r,p)	interception fraction for plant p	dimensionless	radionuclide, plant
A_w(r,p)	total wet deposition onto plant p	Bq m^{-2}	radionuclide, plant
v(r,p)	deposition velocity for plant p	m s^{-1}	radionuclide, plant
V_{max}(r,p)	maximum deposition velocity for plant p, i.e. for a fully developed plant	m s^{-1}	radionuclide, plant
LAI(p)*	leaf area index of plant p at the time of deposition	m^2 m^{-2}	plant
LAI_{max}(p)	maximum leaf area index of plant p at the time of fully developed foliage	m^2 m^{-2}	plant
S(p)	retention coefficient of plant p	mm	plant
C_a(r)	time-integrated activity concentration in air	Bq s m^{-3}	radionuclide
R	amount of rainfall	mm	

* LAI is defined as the area of leaves present on a unit area of ground.

4.4.1.2.1 **Modelling of grass**

Until further information is obtained for local conditions the ability to express the LAI of grass by use of yield has been implemented, as in Müller and Pröhl (1993), using the following equation, with a description of the parameters given in Table 6.

$$
LAI(g) = LAI_{\max}(g)\left[1-e^{-kY_1(g)}\right]
\tag{6}
$$

The total deposition on grass, *A(r,g)*, is estimated using equation 5, using the information for grass as the plant type.

Table 6: Parameters for grass.

Parameters	Description	Unit	Depends on
A(r,g)	total deposition onto grass (g)	Bq m^{-2}	radionuclide, grass
LAI(g)	leaf area index of grass at the time of deposition	m^2 m^{-2}	grass
LAI_{max}(g)	maximum leaf area index of grass	m^2 m^{-2}	grass
Y_1(g)	yield of grass at the time of deposition	kg m^{-2}	grass
k	normalisation factor	m^2 kg^{-1}	

4.4.1.2.2 **Foliar uptake of radionuclides**

Three groups of plants are considered:

- Plants that are used totally, *e.g.* leafy vegetables, where the concentration of the plant at time of harvest ($P_{d,1}$ in equation 7) is determined by the amount deposited, followed by activity loss due to weathering, radioactive decay and dilution due to growth.
- For plants that are only partly consumed, *e.g.* cereals, potatoes, translocation from the deposited material to the edible part is modelled (concentration is given by $P_{d,3}$ in equation 7).
- Grass, due to its continuous harvest. Here concentration ($P_{d,2}$ in equation 7) is decreased due to growth, weathering, radioactive decay and translocation to the root zone.

The following three equations are used (taken from Müller and Pröhl (1993)), with the parameters described in Table 7.

$$
\begin{aligned}
P_{d,1}(r,p,t) &= \frac{A(r,p)}{Y(p)} e^{-\left(\lambda_w(r,p)+\lambda(r)\right)t} \\
P_{d,2}(r,g,t) &= \frac{A(r,g)}{Y_1(g)} \left\{ (1-\alpha(r,g)) e^{-\left(\lambda_b(r,g)+\lambda_w(r,g)+\lambda(r)\right)t} + \alpha(r,g) e^{-\left(\lambda_t(r,g)+\lambda(r)\right)t} \right\} \\
P_{d,3}(r,p,t) &= \frac{A(r,p)}{Y(p)} T(r,p,t) e^{-(\lambda(r))t}
\end{aligned}
\tag{7}
$$

Table 7: Parameters for foliar uptake by plants.

Parameters	Description	Unit	Depends on
$P_{d,i}(r,p,t)$	concentration of radionuclide r in plant p at time of harvest due to deposition and interception	Bq kg	radionuclide, plant
A(r,p) , A(r,g)	total deposition onto plant p, or grass (g)		
Y(p)	yield of plant p at time of harvest	kg m^{-2}	plant
$Y_1(g)$	yield of grass at the time of deposition	kg m^{-2}	
$\lambda_w(r,p)$	loss rate due to weathering for plant p or grass (g)	d^{-1}	radionuclide, plant
$\lambda_b(r,g)$	dilution rate by increase of biomass in grass	d^{-1}	radionuclide, grass
$\lambda_t(r,g)$	rate of activity decrease due to translocation to the root zone in grass	d^{-1}	radionuclide, grass
$\lambda(r)$	radioactive decay	d^{-1}	radionuclide
$\alpha(r,g)$	fraction of activity translocated to the root zone in grass	dimensionless	
T(r,p,t)	time dependent translocation factor for plant p – fraction of the activity deposited on the foliage that is transferred to the edible part of the plants at harvest	dimensionless	radionuclide, plant, t is the time from deposition

4.4.2 Dose to humans due to ingestion of plant products

Dose to humans from radionuclide *r* due to consumption of plant product *p* over a time period $[t_0,t_1]$ is modelled by the following mathematical formula, with a description of parameters given in Table 8. In this version of RadCon it is assumed that food is consumed at harvest, *i.e.* all foodstuff is available for harvesting at the time of consumption.

$$D_p(r,p,t_0,t_1) = \int_{t_0}^{t_1} (P_r(r,p,t) + P_d(r,p,t))d(r,a)Q_p(p)F(p)P(p)dt \qquad (8)$$

Table 8: Parameters for Crop Ingestion by Humans.

Parameters	*Description*	*Unit*	*Depends on*
$D_p(r,p,t_0,t_1)$	committed effective dose from radionuclide *r* due to consumption of plant *p* from time t_0 to t_1	*Sv*	radionuclide, plant, time from deposit
$P_r(r,p,t)$	concentration of radionuclide *r* in plant *p* due to root uptake	*Bq* kg^{-1}	radionuclide, plant
$P_d(r,p,t)$	concentration of radionuclide *r* in plant *p* due to deposition and interception, and translocation where appropriate	*Bq* kg^{-1}	radionuclide, plant
d(r,a)	dose conversion factor	*Sv* Bq^{-1}	radionuclide, race, age
$Q_p(p)$	intake of food *p*	*kg* day^{-1}	diet
F(p)	fraction of total food consumed which is local	*dimensionless*	
P(p)	remainder of activity after food processing	*dimensionless*	

4.4.2.1 ***Assumptions for dose to humans due to radionuclide uptake from plants***

- only the specified local fraction, F, of the food is contaminated
- a local production/consumption model is assumed
- dose is calculated assuming the plant are harvested at the time of consumption

4.4.3 Radionuclide contamination in animal products

Contamination to animals due to consumption of contaminated soil and crops is considered. Inhalation by animals and water intake is not taken into account. Research from the temperate climate studies had demonstrated minimal dose from these two pathways, Safety Series 57 (IAEA, 1982). The concentration of radionuclide *r* in animal product *m* at time *t* is modelled by the following equation:

$$M_c(r,m,t) = M_{cs}(r,m,t) + \sum_{i=1}^{P} A_c(r,m,t,i) \qquad (9)$$

Where:

- $M_c(r,m,t)$ is the concentration at time *t* of radionuclide *r* in animal product *m* (Bq kg^{-1})
- $M_{cs}(r,m,t)$ is the concentration at time *t* of radionuclide *r* in animal product *m* due to soil ingestion
- $A_c(r,m,t,i)$ is the concentration at time *t* of radionuclide *r* in animal product *m* due to ingestion of plant product *i*
- *P* is the number of plant products in the animal diet.

4.4.3.1 ***Animal contamination due to plant product ingestion***

Concentration in meat product *m* due to the consumption of feed crop *p* is modelled by the following equation, with a short description of parameters given in Table 9**.**

$$A_c(r,m,t,p) = T_{pm}(r,m)Q(p,m)\int_{t-T}^{t}\left([P_r(r,p,x) + P_d(r,p,x)]f(r,m,t,x)\right)dx$$

$$f(m,r,t,x) = \alpha_m(m,r)\lambda_{m1}(m,r)e^{-(\lambda_{m1}(m,r)+\lambda(r))(t-x)} + (1-\alpha_m(m,r))\lambda_{m2}(m,r)e^{-(\lambda_{m2}(r,m)+\lambda(r))(t-x)}$$

(10)

Table 9: Parameters for Plant to Animal Transfer.

Parameters	*Description*	*Unit*	*Depends on*
$A_c(r,m,t,p)$	concentration of radionuclide *r* in meat *m* from ingestion of plant *p*	$Bq\ kg^{-1}$	radionuclide, animal, plant
$P_r(r,p,t)$	concentration of radionuclide *r* in feed crop *p* due to root uptake	$Bq\ kg^{-1}$	radionuclide, plant
$P_d(r,p,t)$	concentration of radionuclide *r* in feed crop *p* due to deposition and interception	$Bq\ kg^{-1}$	radionuclide, plant
T	age of animal	*d*	
$\lambda_{m1}(m,r)$	removal rate constant (fast)of radionuclide concentration in an animal due to physiological processes	d^{-1}	animal, radionuclide
$\lambda_{m2}(m,r)$	removal rate constant (slow)of radionuclide concentration in an animal due to physiological processes	d^{-1}	animal, radionuclide
$\alpha_{m1}(m,r)$	fast removal component fraction	*dimensionless*	
$T_{pm}(r,m)$	transfer factor for radionuclide *r* from plants to animal *m*	$d\ kg^{-1}$	radionuclide, animal
$Q(p,m)$	quantity of feed crop *p* consumed by animal *m*	$kg\ day^{-1}$	plant, animal

4.4.3.1.1 **Assumptions for radionuclide uptake by animals from plants**

- Seasonal variation in diet is not considered, *i.e.* animals are fed uniformly throughout the year
- Animal feed is harvested at the time of consumption.

4.4.3.2 Animal contamination due to soil ingestion

The available soil concentration, $C_s(r,t)$, is modelled in following equation, with the description of the parameters as given in Table 4:

$$C_s(r,t)=\frac{G(r)}{P(s)K(s)}\left[\alpha(r,s)e^{-(\lambda(r)+\lambda_f(r,s)+\lambda_1(r,s))t}+(1-\alpha(r,s))e^{-(\lambda(r)+\lambda_f(r,s)+\lambda_2(r,s))t}\right] \tag{11}$$

Concentration in meat product *m* due to consumption of soil is given in the following equation with the parameters as defined in Table 10.

$$M_{cs}(r,m,t)=C_s(r,t)Q(m)T_{pm}(r,m) \tag{12}$$

Table 10: Parameters for Soil to Animal Transfer.

Parameters	*Description*	*Unit*	*Depends on*
$M_{cs}(r,m,t)$	concentration of radionuclide *r* in meat *m*	$Bq\ kg^{-1}$	meat and radionuclide
$C_s(r,t)$	concentration of radionuclide *r* in soil	$Bq\ kg^{-1}$	radionuclide
$T_{pm}(r,m)$	transfer factor for radionuclide *r* to meat *m*	$day\ kg^{-1}$ *of meat or soil*	radionuclide, animal
Q(m)	quantity of soil consumed by animal *m*	$kg\ day^{-1}$	animal

4.4.3.2.1 **Assumptions for radionuclide uptake by animals via soil ingestion**

- the transfer coefficient from soil to animal is the same as the one used for plant ingestion, again presenting the most conservative situation

4.4.4 Dose to humans due to ingestion of animal products

Dose to humans from radionuclide *r* due to consumption of animal product *m* is modelled by the following mathematical formula, with a description of the parameters given in Table 11.

$$D_m(r,m,t) = \int_{t_0}^{t_1} M_c(r,m,t)\,d(r,a)\,Q(m)\,F(m)\,P(m)\,dt \qquad (13)$$

Table 11: Parameters for Animal Product Ingestion by Humans.

Parameters	*Description*	*Unit*	*Depends on*
$D_m(r,m,t)$	committed effective dose from radionuclide *r* due to consumption of meat *m*, at time *t*	*Sv*	radionuclide, meat, time from deposit
$M_c(r,m,t)$	concentration of radionuclide *r* in animal product *m*	$Bq\ kg^{-1}$	radionuclide, meat
$d(r,a)$	dose conversion factor	$Sv\ Bq^{-1}$	radionuclide, age, race
$Q(m)$	quantity of food *m* consumed	$kg\ day^{-1}$	diet
$F(m)$	fraction of food *m* consumed which is local	*dimensionless*	
$P(m)$	fraction of activity remaining after food processing	*dimensionless*	

4.4.4.1 ***Assumptions for dose to humans due to ingestion of animal products***

- only the specified fraction, F, of the meat is contaminated
- a local production/consumption model is assumed
- there is no long term storage of food

4.4.5 Total dose to humans from the ingestion pathway

The contribution from consumption of crop and animal products is considered. The total dose to humans from the ingestion pathway at time *t* is given by:

$$TotalDose(t) = \sum_r \left[\sum_{p=1}^{P} D_p(r,p,t) + \sum_{m=1}^{M} D_m(r,m,t) \right] \qquad (14)$$

Where *P* and *M* are the number of crop and animal products consumed respectively.

5. Sensitivity Analysis in RadCon

One of the aims of the project was to identify the parameters which contribute most to the final dose to humans, such that any future research could be directed towards the most important parameters. To assist with this, two parameter sensitivity analysis techniques have been implemented in RadCon, which are described in subsequent sections.

5.1 *Problem Formulation*

In general, Downing *et al.* (1985), we may let X_1, X_2, ….. X_k denote the *k* input parameters and Y denote the output (dose). There is a deterministic relationship between Y and X_1, X_2, … X_k, such that:

$$Y = h(X_1, X_2, \ldots X_k) \qquad (14)$$

This notation is used in the subsequent sections. In addition, for the current analysis, parameters are assumed to be independent.

5.2 *Sensitivity Analysis Methods*

Sensitivity analysis can be loosely grouped into those methods that:

- operate on one variable at a time (local)
- rely on the generation of an input matrix and an associated output vector,

Two local sensitivity analysis techniques have been implemented for RadCon, which are detailed in the following sections. Interested readers are referred to Hamby (1994) for a survey of these and additional sensitivity analysis techniques.

5.2.3 Differential Sensitivity Analysis

In this method, Hamby (1994), the sensitivity coefficient, ϕ_i, for a particular independent variable can be calculated from the partial derivative of the dependent variable with respect to the independent variable, *i.e.*

$$\phi_i = \frac{\partial Y}{\partial X_i}\left(\frac{X_i}{Y}\right) \qquad (16)$$

Where the quotient, X_i/Y , is introduced to normalise the coefficient by removing the effect of units. An alternative normalisation technique is used in Iman and Helton (1985), *i.e.* the standard deviations of the dependent and independent variables are used to remove the effect of units. The resultant coefficients indicate the fractional effect on the dependent variable of fractional changes in the individual input variables.

Although differential analysis could be performed for RadCon, this was considered impractical due to the number of parameters. In addition any modifications to the underlying models would require reworking of the derivatives.

5.2.2 One-at-a-time Sensitivity Measures

In this approach a base case scenario is needed. A sensitivity ranking can be obtained quickly by perturbing each parameter by a given percentage (*e.g.* 1%) while leaving all other parameters constant *i.e.*

$$\phi_i = \frac{(Y(X_i + \Delta X_i) - Y(X_i))}{\Delta X_i}\left(\frac{X_i}{Y}\right) \tag{17}$$

Where the quotient, X_i/Y , is introduced to normalise the coefficient by removing the effect of units.

5.2.3 Extended one-at-a-time

This technique, Downing *et al.* (1985), examines the change in output as each parameter is individually increased by a factor of its standard deviation. This sensitivity measure takes into account the parameter's variability and the associated influence on model output.

Let s_j be the standard deviation of the output resulting from changing X_j from μ_j to $(\mu_j - c\sigma_j)$ and $(\mu_j + c\sigma_j)$, where μ_j and σ_j are the mean and standard deviation of the jth input variable and *c* is some constant. Then s_j is a useful measure of the effect X_j has on the output. Large values of s_j indicate a marked effect whereas small values indicate little or no monotonic effect. This can be extended to:

$$s_j^2 = \frac{1}{n}\sum_k \left[Y(\mu_j \pm k\sigma) - Y(\mu_j)\right]^2 \tag{18}$$

for k = 0, 1, 2, 3,4 and *n* is the total number of values in the range:

$$Y_{\min} \le Y(\mu_j \pm k\sigma) - Y(\mu_j) \le Y_{\max}$$

The reported values are generated as s_j normalised by the dose when all parameters are set to their default value, ie $Y(\mu_j)$.

5.3 *Sensitivity analysis for an Australian Scenario*

A parameter sensitivity analysis was undertaken for an Australian scenario, which had been specified in a previous report, Hess *et al.* (1998). The 'worst case' simulation was used and a number of variations were computed, including the use of diet determined by the cultural origin within Australia, different soil types, different times over which dose was calculated, gender and the use of the maximum leaf area index for all plants at the time of deposition.

For ^{137}Cs, the comparison of the results demonstrated that the parameters having the greatest impact on dose in the first year were different to the highest ranked parameters for year five, year ten and thirty years after deposition. At one year after deposition the parameters for air concentration, and deposition on fruit trees were ranked higher, whereas parameters affecting the effective availability of radionuclides for root uptake, ie soil characteristics, migration of radionuclides in the soil and soil fixation were ranked higher for the fifth year. Fruit consumption, removal of activity by food processing and deposition on fruit trees were the parameters which ranked the highest for contribution to dose in the first year, whereas ground fruit and tuber parameters ranked the highest for contribution to dose in year five, ten and thirty years after the initial deposit. Parameters associated with rice consumption ranked the highest both at one and five year time periods for the Asian diet within Australia.

6. Model Implementation

6.1 *Program Structure*

Figure 2 shows the separate components that the RadCon implementation brings together. The *mathematical models* define the transport processes that use the input data to determine a spatially and time varying dose. The BoM simulation generates the ground and airborne concentrations over the region of interest over a specified time period. A pre-processor is used to generate the results in a format suitable for input to the RadCon code. For any region to which the RadCon model is to be applied, it is anticipated that an atmospheric transport model suitable for the region under study will be chosen and the output will be either produced or re-formatted in a format suitable for input to RadCon.

The regional map is included for visualisation purposes, and is prepared outside of RadCon. The dose is calculated for the affected region, which is then displayed superimposed on the map, so that the user can easily identify affected regions. The dimension of the BoM simulation determines the dimensions to be used by RadCon. The mathematical models are applied over the two dimensional region, performing calculations for each grid point. In addition time varying calculations of the dose to humans are carried out according to user selected options.

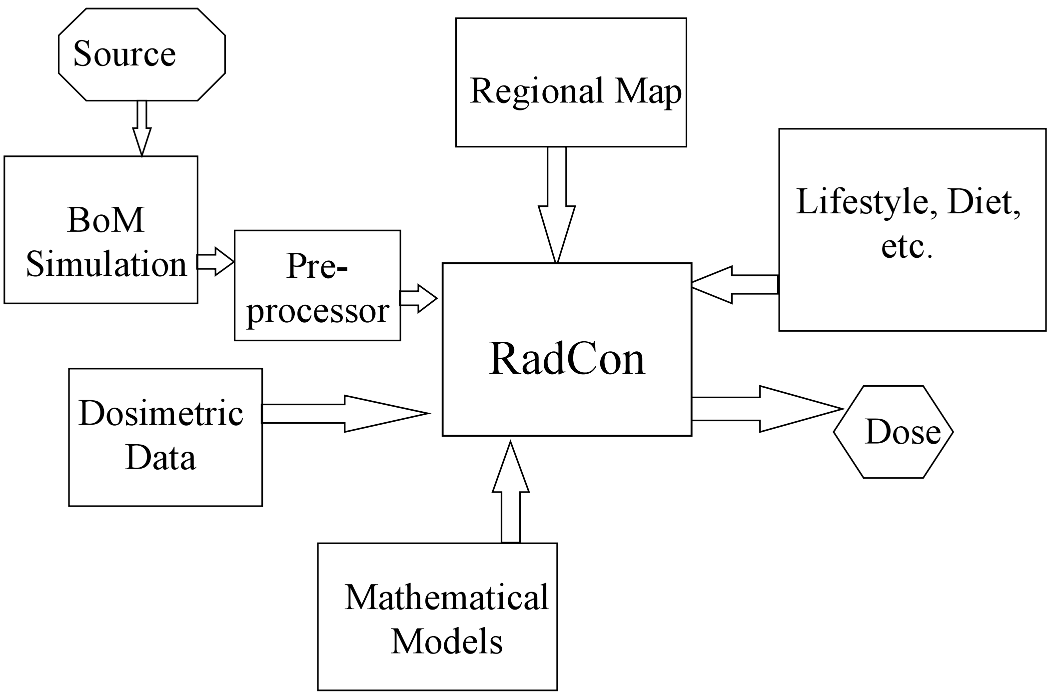

Figure 2: Function of Computer Code.

6.2 *User Interface*

RadCon was designed and implemented at ANSTO with focus on its potential use in the Australian and the South East Asian region. Given the large variability in this region, emphasis was given to the ability of the implementation to handle the spatial variability in the region, *e.g.* diets and lifestyle of the population and the various food crops being produced.

Java was chosen as the language of implementation, as portability across computer platforms was required as well as the use of graphical user interfaces. Required parameters are stored in data files (see the RadCon User Guide, Crawford and Domel, (May 2000), for a description of the formats of the data files). The user uses the input screen shown in Figure 4 to set up the options over the region. This is achieved by selecting rectangular sub-regions and setting the alternatives, from a panel as shown in Figure 5. The panel in Figure 5 is used for setting up the options for the ingestion pathway. Alternatives can be chosen for:

- the soil type - sand, loam, clay or coral
- the diet of the target group – race default diet or one of the other pre-set diets, the composition and quantities of which are set up using the RadCon data editor, RadConEd, see Crawford and Domel (May 2000).
- the diet of each of the animals which have been pre-set, once again using RadConEd,
- the race of the target group,
- the age of the target group, and
- the lifestyle, indoor and outdoor occupancy factors are indicated by the lifestyle od the target group.

These are the options currently in RadCon, which could be modified during customisation of RadCon for a particular application. A user guide has been prepared for RadCon and the data files editor, RadConEd, see Crawford and Domel (May 2000).

The cover page shows an output screen of RadCon. This screen is used to carry out calculations based on a scenario that has been established. Some of the options that can be set include:

- Choice of pathways to consider, *i.e.* a subset or all of the pathways within the selected scenarios can be used in the calculation of the total dose.
- Choice of radionuclide, *i.e.* the contribution of all radionuclides or a subset can be calculated.
- Single period calculations can be carried out or cumulative calculations up to that point. This is selected by a choice between the radio buttons, *accumulate/single period.*
- Long term or short term effects can be calculated. Short term effects are those from the *inhalation,* and *external exposure,* as well as the consumption of milk. Short term effects are calculated for the period during the existence of airborne concentration. Long term effects result from the ground concentration and its effect on the food chain (for the Ingestion pathway) as well as dose from groundshine.
- Once all the options have been specified the *Calculate* button is used to signal to the system to carry out the calculations according to the selected options.

- The *Viewing Deposit* screen can be activated in order to cross-reference the dose calculated with the deposition data and to verify that a selected sub region (target group) has indeed received ground deposition.
- The *Show Scenario* screen can be activated in order to view the set-up of the scenario.
- The *Do Sensitivity* button initiates sensitivity analysis for the chosen scenario. Note a dose calculation must have been carried out before a sensitivity analysis can proceed.
- The *Previous Settings* button is used to revert to the previous setting of the options, as used in the last calculation.

The time varying dose over the selected two-dimensional region is calculated and displayed using colour coded contours, as shown on the cover page. The actual values at a particular location can be viewed by selecting the location, in which case the following figure, Figure 3, will appear which gives the total dose at the point, together with a breakdown by pathways, food groups and radionuclide.

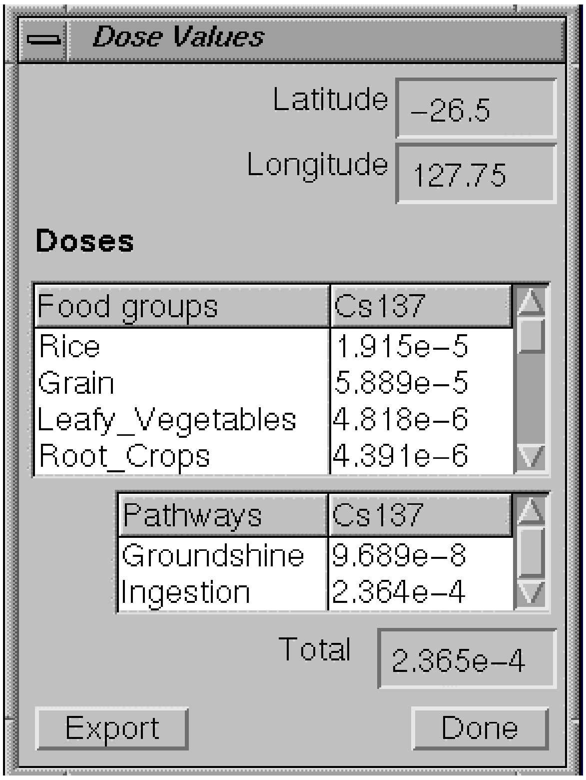

Figure 3: Dose Values at a selected grid location.

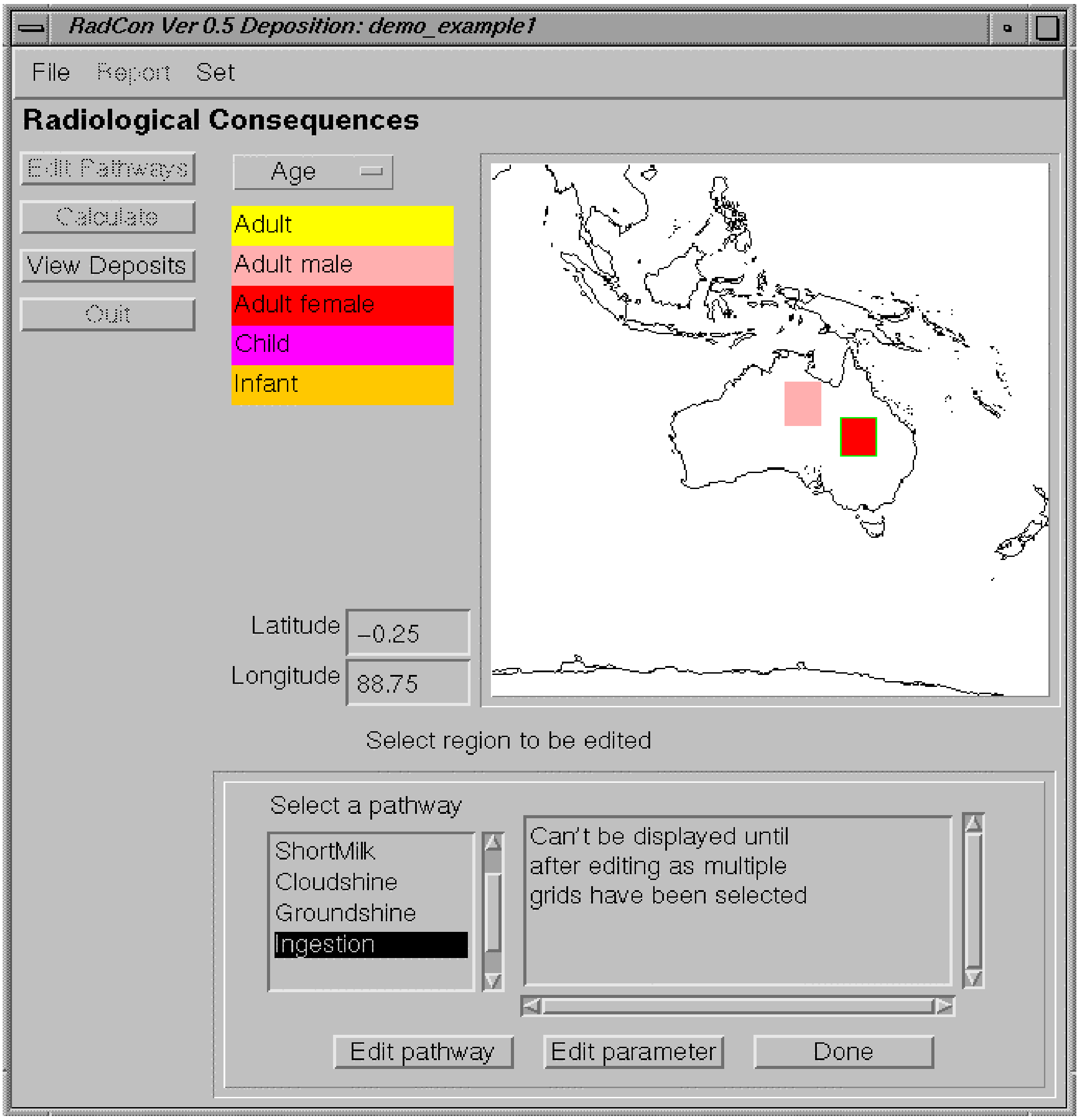

Figure 4: Input Screen.

Figure 5: Options for the Ingestion pathway.

6.3 *Data and Parameter Input into the Model*

In parallel with the development of the RadCon model, a data acquisition and evaluation exercise was undertaken. The aim was to obtain required parameter values for use with RadCon, to enable the estimation of radiological consequences in the Australian and South East Asian Region.

Literature and library searches initiated the data acquisition process, with the available data being analysed and evaluated and then stored in tables in a spreadsheet application. The bulk of the Tropical and Subtropical Data were acquired from the draft IAEA (1997). The data in this document were presented as individual experimental data points for each radionuclide and required further summation and statistical analysis. This study also highlighted that there are still large gaps in the knowledge relating to the transfer of radionuclides in tropical and subtropical environments. To fill the gaps and be able to run the RadCon model, temperate data were used as the default parameters. A summary is presented in Table 12 which outlines the available data for tropical and subtropical environments and where temperate data currently need to be used as the default.

Table 12. Data acquisition and analysis.

What we have	**Origin of data and comments**
General data and parameters:	
Radioisotope decay and dose conversions	IAEA and other available information
Parameters for external dose assessments	IAEA and other available information
Lifestyle parameters:	
Occupancy factors	For temperate and for generalised Australian conditions
Shielding factors	For temperate
Physiological data	IAEA information based on Standard Reference Man and Reference Asian Man
Food chain data and parameters:	
Grain	Temperate; some tropical
Vegetables	Temperate; some tropical
Fruit	Temperate; some tropical (limited)
Natural and semi-natural eg forest products	Temperate
Meat products – time dependent	Temperate; assume no physiology difference for tropical
Food processing	Temperate
Consumption data	Temperate; Australian; limited Asian
Deposition and translocation	Temperate
Soil characteristics	Temperate
Agricultural practices	Temperate; limited Australian
Seasonality	Temperate
Critical Parameter Analysis:	
Distributions	Temperate; limited tropical

What we do not have	
Food chain data and parameters:	
Time dependence	Not implemented
Aquatic products	Not implemented
Countermeasures	Not implemented, but can manipulate other parameters (soil, food processing)
Resuspension	Not implemented

To manage the large volume of literature acquired in this process, input and storage of all titles (with their abstracts, where available) in a database application was effected (Procite), allowing for ease of access, retrieval and minimisation of duplication.

The data acquisition and evaluation has been described in Domel R.U. *et al* (March 2000).

7. RadCon Evaluation

RadCon was developed to predict the potential impact from an accidental release of radionuclides into the atmosphere for the Australian and South East Asian Region. In order to evaluate RadCon's predictions against field data, the team participated in a model inter-comparison exercise sponsored by the International Atomic Energy Agency (IAEA). A number of developers and/or users of radiological consequences models participated in the exercise which involved the estimation of ^{137}Cs in plants, animals and humans and dose to humans in the Bryansk Region in Russia following the Chernobyl accident. The results of the BIOsphere Modelling and ASSessment (BIOMASS) programme were scheduled to be reported in an IAEA-TECDOC in October 2000.

While the results from a model depend on a number of factors, and are strongly influenced by the suitability of the chosen parameter values for the site under consideration, the exercise was used by the RadCon team to evaluate if the most important processes have been included in RadCon and implemented appropriately. The model and implementation evolved over the period of the exercise and the final estimates generated by RadCon were compatible to those reported by other participants and the test data provided. The results are reported in the IAEA-TECDOC , see BIOMASS (October 2000).

A number of countermeasures had been implemented at the test site, and as such these had to be considered in estimating concentrations and the final dose. Application of countermeasures was not an intended function of RadCon. However, we were able to simulate some of the countermeasures, showing RadCon's flexibility which is based on having all the data separate from the program.

Some aspects not yet implemented in RadCon, which may impact on the final dose:

- an aquatic pathway, but the additional ^{137}Cs intake from fish was not a major dietary component and so did not have a major impact on the final dose
- biological half-life of ^{137}Cs in humans – its implementation may reduce the final dose, and would also allow whole body distribution of the radionuclide estimations to be made
- re-suspension

- a separate pathway for the estimation of natural foods such as mushrooms and berries
- ability to add clean fodder to animals before consumption.

Other possible improvements to RadCon include:
- implementation of a more elegant approach to modelling a time-dependent transfer from soil-to-plants – at present a step-function has been implemented
- seasonality of food consumption by animals to present more detail in the form of seasonal fluctuations for radioisotope concentration – at present RadCon presents an average over the whole year which has proven to be a reasonable estimation, but does not predict short term variation in dose.

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