Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Radioactivity 99 (2008) 1371–1383
JOURNAL OF ENVIRONMENTAL RADIOACTIVITY
www.elsevier.com/locate/jenvrad

The ERICA Tool

J.E. Brown [a,*], B. Alfonso [b], R. Avila [b], N.A. Beresford [c], D. Copplestone [d], G. Pröhl [e], A. Ulanovsky [e]

[a] *Norwegian Radiation Protection Authority, Department of Emergency Preparedness and Environmental Radioactivity, Grini næringspark 13, Postbox 55, NO-1332 Østerås, Norway*
[b] *Facilia AB, Gustavslundsvägen 151C, 167 51 Bromma, Sweden*
[c] *Centre for Ecology and Hydrology, CEH-Lancaster, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK*
[d] *Environment Agency, Richard Fairclough House, Knutsford Road, Warrington, Cheshire WA4 1HG, UK*
[e] *GSF-Forschungszentrum für Umwelt und Gesundheit, GmbH, Ingolstädter Landstraße 1, D-85764 Neuherberg, Germany*

Received 17 August 2007; received in revised form 28 November 2007; accepted 14 January 2008
Available online 10 March 2008

Abstract

The ERICA Tool is a computerised, flexible software system that has a structure based upon the ERICA Integrated Approach to assessing the radiological risk to biota. The Tool guides the user through the assessment process, recording information and decisions and allowing the necessary calculations to be performed to estimate risks to selected animals and plants. Tier 1 assessments are media concentration based and use pre-calculated environmental media concentration limits to estimate risk quotients. Tier 2 calculates dose rates but allows the user to examine and edit most of the parameters used in the calculation including concentration ratios, distribution coefficients, percentage dry weight soil or sediment, dose conversion coefficients, radiation weighting factors and occupancy factors. Tier 3 offers the same flexibility as Tier 2 but allows the option to run the assessment probabilistically if the underling parameter probability distribution functions are defined. Results from the Tool can be put into context using incorporated data on dose–effects relationships and background dose rates.

Keywords: Environmental risk assessment; Radioactivity; Software tool; Non-human biota

1. Introduction

A key objective of the EC EURATOM funded ERICA project was to provide the necessary methods to allow scientific, managerial and societal issues concerning environmental exposures to radiation to be dealt with in a robust and comprehensive manner. In order to achieve this, The ERICA Integrated Approach combines elements of environmental management, risk characterisation and impact assessment building on the foundations developed during the preceding projects FASSET (Larsson, 2004) and EPIC (Brown et al., 2003). Central to the ERICA integrated approach is the quantification of environmental risk whereby data on environmental transfer and dosimetry are combined to provide a measure of exposure which is compared to exposure levels at which detrimental effects are known to occur. In view of the large data sets underpinning the assessment approach and the potential to introduce errors when performing numerous calculations by hand, a supporting computer-based tool (the *ERICA Tool*) has been developed.

The assessment element of the ERICA Integrated Approach is organised in to three separate tiers, where satisfying certain criteria in Tiers 1 and 2 allows the user to exit the assessment while being confident that the effects on biota are low or negligible. Tier 3 provides the ability to consider situations of concern in more detail. The tiered approach is described briefly below and in detail in Beresford et al. (2007a) and Larsson (2008). The ERICA Tool is a user friendly software programme that implements the tiered approach and guides the user through the assessment process, recording

* Corresponding author. Tel.: +47 67 16 2663; fax: +47 67 14 7407.
E-mail address: justin.brown@nrpa.no (J.E. Brown).

0265-931X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvrad.2008.01.008

information and decisions and allows the necessary calculations to be performed to estimate risks to selected biota. A detailed manual (Tool Help) is provided within the software which, together with the description of the ERICA Integrated Approach (Beresford et al., 2007a), assists the user in making appropriate choices and inputs as well as in the interpretation of the outputs.

The software has been developed in Java, a widely used, platform-independent programming language (Børretzen et al., 2005). The ERICA Tool is designed to run on Java Runtime Environment Version 6 or higher. Within this article, the basic components of the Tool are presented, any assumptions associated with the derivation of key parameters are described and the underlying calculations defined.

2. The basis for the assessments: underpinning equations and databases

The ERICA assessment draws on the use of reference organisms as defined by Larsson (2004). As the starting point for the selection of appropriate reference organisms those selected for the FASSET Framework (Strand et al., 2001) were considered. The selection process was primarily based on the identification of those biota that might be particularly exposed to radiation through a consideration of the biogeochemical behaviour (primarily transfer and biological uptake) of 20 radionuclides within four terrestrial (i.e. forest, semi-natural, agricultural and wetlands) and three aquatic (i.e. marine, freshwater and brackish) ecosystems (Strand et al., 2001). Some additional consideration was implicitly also paid to the animal or plants' ecological niche, intrinsic sensitivity to chronic low-level irradiation and ecological significance in this selection process. These types of considerations can be made through review and evaluation of published data as described by Beresford et al. (2001). The component ecosystems were selected to be typical for Europe. Within the ERICA project the original list of reference organisms has been rationalised by amalgamating the terrestrial ecosystems into a single representative semi-natural ecosystem and by removing the brackish ecosystem which arguably constitutes a sub-set of the marine system. The rationalisation was justified, in part, because of the lack of radioecological data for some of the ecosystems (e.g. wetlands and brackish waters) and the cross use of data in others (e.g. semi-natural sourced data from all terrestrial ecosystems) (Beresford and Howard, 2005). Furthermore, the original FASSET reference organism list has been amended to encompass the ICRPs proposed list of Reference Animals and Plants – RAPs (see ICRP, 2005). The definitive set of reference organisms has also been constructed to facilitate assessments for species currently protected by European legislation as these may be a focus within some assessments (e.g. Copplestone et al., 2003). The requirement to cover European protected species led to the addition of some reference organism to the final list (e.g. marine reptiles, corals). An overview of the reference organisms and associated ecosystems considered by the ERICA Integrated Approach is provided in Table 1.

Table 1
Reference organisms for each ecosystem in the ERICA Tool; the corresponding ICRP RAPs, for which the ERICA Tool uses the proposed ICRP geometries as default, are indicated in italics within brackets

Freshwater	Marine	Terrestrial
Amphibian (*frog*)	(Wading) bird (*duck*)	Amphibian (*frog*)
Benthic fish	Benthic fish (*flat fish*)	Bird (*duck*)
Bird (*duck*)	Bivalve mollusc	Bird egg (*duck egg*)
Bivalve mollusc	Crustacean (*crab*)	Detritivorous invertebrate
Crustacean	Macroalgae (*brown seaweed*)	Flying insects (*bee*)
Gastropod	Mammal	Gastropod
Insect larvae	Pelagic fish	Grasses and herbs (*wild grass*)
Mammal	Phytoplankton	Lichen and bryophytes
Pelagic fish (*salmonid/trout*)	Polychaete worm	Mammal (*rat*, *deer*)
Phytoplankton	Reptile	Reptile
Vascular plant	Sea anemones/ true corals	Shrub
Zooplankton	Vascular plant	Soil invertebrate (worm) (*earthworm*)
	Zooplankton	Tree (*pine tree*)

The Tool includes default information for a suite of radionuclides selected to cover a wide variety of conceivable exposure situations including those arising from routine authorised discharge regimes, potential releases from repositories for radioactive waste, including High Level Waste, operations involving NORM and accident scenarios. An overview of the radionuclides supported by the tool as default is presented in Table 2; additionally most radionuclides considered within ICRP (1983) can be assessed using the Tool (see Section 2.2).

The assessments carried out in different tiers include two basic calculation steps: (i) estimation of the activity concentrations in biota and environmental media and (ii) estimation of the dose rates to biota. The basic equations and parameters used in these calculations are described below.

2.1. Estimation of activity concentrations

If adequate measured data are unavailable, the activity concentrations of radionuclides in biota within the ERICA tool are calculated by multiplying the corresponding media activity concentrations (soil or air for terrestrial ecosystems and water for aquatic ecosystems) by equilibrium concentration ratios (CRs) as defined by Eqs. (1) or (2) for terrestrial ecosystems and Eq. (3) for aquatic ecosystems.

Terrestrial biota

$$\mathrm{CR} = \frac{\text{Activity concentration in biota whole body } \left(\mathrm{Bq\,kg^{-1}} \text{ fresh weight}\right)}{\text{Activity concentration in soil } \left(\mathrm{Bq\,kg^{-1}} \text{ dry weight}\right)} \quad (1)$$

Table 2
Radionuclides supported by default databases within the Tool

Element		Isotopes	Element		Isotopes
Ag	Silver	Ag-110	P	Phosphorus	P-32, P-33
Am	Americium	Am-241	Pb	Lead	Pb-210
C	Carbon	C-14	Po	Polonium	Po-210
Cd	Cadmium	Cd-109	Pu	Plutonium	Pu-238, Pu-239, Pu-240, Pu-241
Ce	Cerium	Ce-141, Ce-144	Ra	Radium	Ra-226, Ra-228
Cl	Chlorine	Cl-36	Ru	Ruthenium	Ru-103, Ru-106
Cm	Curium	Cm-242, Cm-243, Cm-244	S	Sulphur	S-35
Co	Cobalt	Co-57, Co-58, Co-60	Sb	Antimony	Sb-124, Sb-1255
Cs	Caesium	Cs-134, Cs-135, Cs-136, Cs-137	Se	Selenium	Se-75, Se-79
Eu	Europium	Eu-152, Eu-154	Sr	Strontium	Sr-89, Sr-90
H	Tritium	H-3	Tc	Technetium	Tc-99
I	Iodine	I-125, I-129, I-131, I-132, I-133	Te	Tellurium	Te-129m, Te-132
Mn	Manganese	Mn-54	Th	Thorium	Th-227, Th-228, Th-230, Th-231, Th-232, Th-234
Nb	Niobium	Nb-94, Nb-95	U	Uranium	U-234, U-235, U-238
Ni	Nickel	Ni-59, Ni-63	Zr	Zirconium	Zr-95
Np	Neptunium	Np-237			

Exceptions are for chronic atmospheric releases of ^{3}H, ^{14}C, ^{32}P and ^{35}S where:

$$CR = \frac{\text{Activity concentration in biota whole body } \left(\text{Bq kg}^{-1}\text{fresh weight}\right)}{\text{Activity concentration in air } \left(\text{Bq m}^{-3}\right)} \quad (2)$$

Aquatic biota

$$CR = \frac{\text{Activity concentration in biota whole body } \left(\text{Bq kg}^{-1}\text{ fresh weight}\right)}{\text{Activity concentration of filtered water } \left(\text{Bq l}^{-1}\right)} \quad (3)$$

Default values of the concentration ratios are stored in the Tool transfer databases (''Radioecology'' database), providing a value for each element and reference organism, originally in the format of Microsoft Excel. These, and all other, databases can be accessed via the tool using the ''*Show database*'' option under the ''*Assessment*'' tab at the top of the screen or by accessing the Excel spreadsheets stored under the folder ''My ERICA database''.

The CR values included in the database were derived from reviews of original publications by preference. However, in numerous cases, no empirical data were available resulting in the derivation of values using various methods such as taxonomic and biogeochemical analogues. These approaches are described in more detail by Beresford et al. (2008) and Hosseini et al. (2008). Of specific note, with regards to the characterisation of these data within the default transfer database, is the fact that the derivation method is cited allowing the assessor to identify how each default value was selected.

It should be noted that the Tool, at Tiers 2 and 3, also allows for estimation of activity concentrations in the environmental media from activity concentrations in the biota, by dividing the latter by the corresponding CR. For the aquatic environment, distribution coefficients are used to derive activity concentrations in sediment from water concentrations and *vice versa*. The distribution coefficients are defined as the quotient of the activity concentration per unit mass of sediment to the activity concentration per unit mass (or volume) of (normally filtered) water. The default values of distribution coefficients included in the database have been primarily drawn from IAEA reviews on this subject (IAEA, 2001, 2004). There is a set of rules that have been devised in order to fill the data matrix, required for the calculations at Tiers 2 and 3 and defining activity concentrations in selected reference organisms and media, from the available information entered by the user. This is considered in more detail (Section 3.2) below.

The derivation of each default transfer parameter included within the ERICA Tool is described by Beresford et al. (2008) and Hosseini et al. (2008) for terrestrial and aquatic ecosystems, respectively. These data include not only information on expected values or weighted means but also on statistical parameters including the number of samples on which the values are based, the standard deviation and the underlying probability distribution function (PDF).

Media activity concentrations can also be estimated from discharge data using generic ''transport'' models based upon IAEA SRS-19 (IAEA, 2001). These are for use only in Tiers 1 and 2 (see below) as they are primarily screening models designed to estimate levels of radionuclides in atmospheric and in aquatic systems whilst minimising the possibility that the calculated results would underestimate real doses (to a human critical group) by more than a factor of 10. The dispersion models are appropriate to estimate average concentrations in water or air from a single source continuous release assuming that an equilibrium or quasi-equilibrium has been established with respect to the released radionuclides and the relevant components of the environment. As with any model, the results have an associated uncertainty which is described in more detail within IAEA SRS-19 (IAEA, 2001) and the Help of the ERICA Tool. The following transport models are available within the Tool: Small lake ($<400\,km^2$); Large

lake (≥400 km^2); Estuarine; River; Coastal and Air. The implementation of these generic models within the tool has been tested rigorously via comparison with the example calculations provided within the original IAEA publication and comparison with other codes implementing the SRS-19 models.

2.2. Dose-rate calculations

Once activity concentrations in media and biota have been derived, the basic underlying equations (Eqs. (4) and (5)) utilise these data in order to derive internal (D_{int}) and external (D_{ext}) absorbed dose rates (in units of μGy h^{-1}), the total absorbed dose-rate being the sum of these components, through the application of dose conversion coefficients (DCCs).

$$\dot{D}^b_{\text{int}} = \sum_i C^b_i \text{DCC}^b_{\text{int},i} \tag{4}$$

where C^b_i is the average concentration of radionuclide i in the reference organism b (Bq kg^{-1} fresh weight), $\text{DCC}^b_{\text{int},i}$ is the radionuclide-specific dose conversion coefficient (DCC) for internal exposure defined as the ratio between the average activity concentration of radionuclide i in the organism j and the dose rate to the organism b (μGy h^{-1} per Bq kg^{-1} fresh weight).

$$\dot{D}^b_{\text{ext}} = \sum_z v_z \sum_i C^{\text{ref}}_{zi} \text{DCC}^b_{\text{ext},zi} \tag{5}$$

where v_z is the occupancy factor, i.e. fraction of the time that the organism b spends at a specified position z in its habitat. C^{ref}_{zi} is the average concentration of radionuclide i in the reference media of a given location z (Bq kg^{-1} fresh weight (soil or sediment) or Bq l^{-1} (water)), $\text{DCC}^j_{\text{ext},zi}$ is the dose conversion coefficient for external exposure defined as the ratio between the average activity concentration of radionuclide i in the reference media corresponding to the location z and the dose rate to organism b (μGy h^{-1} per Bq kg^{-1} fresh weight or Bq l^{-1}).

Weighted total dose rates (in μGy h^{-1}) are estimated by the Tool through the application of weighting factors (dimensionless) for alpha, low beta and high beta-gamma radiation (Eqs. (6) and (7)).

$$\text{DCC}_{\text{int}} = \text{wf}_{\text{low }\beta}\text{DCC}_{\text{int,low }\beta} + \text{wf}_{\beta+\gamma}\text{DCC}_{\text{int},\beta+\gamma} + \text{wf}_{\alpha}\text{DCC}_{\text{int},\alpha} \tag{6}$$

$$\text{DCC}_{\text{ext}} = \text{wf}_{\text{low }\beta}\text{DCC}_{\text{ext,low }\beta} + \text{wf}_{\beta+\gamma}\text{DCC}_{\text{ext},\beta+\gamma} \tag{7}$$

where wf, weighting factors for various components of radiation (low β, β + γ and α); DCC, dose conversion coefficients in μGy h^{-1} per Bq l^{-1} or Bq kg^{-1}.

Default radiation weighting factors of 10 for alpha radiation, 3 for low energy beta and 1 for (high energy) beta and gamma radiation are applied in the Tool in line with the provisional, illustrative values, used in the FASSET framework (Pröhl et al., 2003). This is also consistent with the upper bound on the range of variation reported by Chambers et al. (2006) for α-radiation weighting factors in relation to population relevant deterministic endpoints (mainly mortality). At Tiers 2 and 3, the radiation weighting factors can be altered if the user wishes to use alternative values. If unweighted absorbed dose rates are required the assessor can simply set the weighting factors to unity.

The dosimetric calculation underpinning the derivation of DCCs is dealt with in detail elsewhere (Ulanovsky and Pröhl, 2006, 2008). Although methods (for aquatic and terrestrial systems) have been applied to derive DCCs for the suite of reference organisms and radionuclides specified in Tables 1 and 2, respectively, the calculation can be performed for other user-defined organisms within certain limits (the limitations on the method are elucidated in the Tool Help) and most radionuclides included in ICRP Publication 38 (ICRP, 1983). This forms the basis for the "*Add organism*" and "*Add isotope*" functions that are available at Tiers 2 and 3 within the Tool.

Radioactive daughter nuclides are included in the calculation of the DCCs if their half-lives are shorter than 10 days. Furthermore, DCCs for internal exposure were derived assuming a homogeneous distribution of the radionuclide in the organism. The implications of this latter assumption in relation to the level of uncertainty introduced are explored by Zinger (2007) and are also addressed in the Tool Help.

As for the case of the transfer data, the underlying DCC data, categorised in terms of radionuclide and reference organism and split into components of internal and external irradiation and the radiation types alpha, (<10 keV) low beta and high beta-gamma radiations, can be accessed in the underlying databases for the Tool within the "Dosimetry" database.

3. Overview of the tiered approach for the assessments

Key differences between the tiers in terms of underlying calculations, data requirements and the provision of concomitant contextual information are highlighted below; an overview of the three ERICA tiers is provided in Table 3 and a flow diagram illustrating how the tiers are structured within the tool are presented in Fig. 1.

3.1. Tier 1

At Tier 1, the Tool uses Environmental Media Concentration Limits (EMCLs), defined as the activity concentration in the selected media (soil or air (H, C, S and P only) in terrestrial environments, water or sediment in aquatic environments) that would result in a dose-rate to the most exposed reference organism equal to that of the selected screening dose-rate (see below). The first stage in the EMCL derivation involves the calculation of intermediate-EMCL values calculated for all reference organisms for a selected radionuclide and media (Eq. (8)). The minimum intermediate-EMCL value across all organisms is then selected to define the unique EMCL value for a particular radionuclide. In other words, there is only one EMCL value per radionuclide and the limiting organism may be different for different radionuclides.

Table 3
The Tiers in a nutshell

The Tiers of the ERICA Tool
Tier 1
• Highly conservative. • Requires minimal data input. • Simple and can be used by non-specialist users. • Maximum measured media concentrations suggested as input. • Compares input media concentrations to Environmental Media Concentration Limits calculated for the most limiting reference organism for each radionuclide. • If the Tool recommends that the assessment can be exited the situation can be considered to be of negligible radiological concern.
Tier 2

• Less conservative screening tier.
• User can edit transfer parameters.
• Media and biota activity concentrations can be input (best estimate values are recommended).
• Estimated wholebody absorbed dose rates compared directly to the screening dose rate.
• 'Traffic light' system indicates if situation is:
  • of negligible concern (with a high degree of confidence) – user is recommended in exit the assessment process;
• of potential concern – user recommended to review and amend assessment;
  • of concern – user recommended to continue the assessment.
• Results can be assessed against summarised tables of effects and exposure due to naturally occurring radionuelides.

Tier 3
• Not a screening tier – so no screening dose rate. • Not prescriptive and has no 'yes/no' answer. • Provides user with guidance, template and tool to help conduct more detailed assessment. • Probabilistic and sensitivity analyses. • Access to up to date on-line database of radiological effects.

Examples can be given for the terrestrial environment for which the limiting organisms for ^{137}Cs, ^{239}Pu and ^{210}Po are mammal (deer), gastropod and lichen–bryophyte, respectively. As a consequence the user cannot select reference organisms at Tier 1.

$$\mathrm{EMCL} = \frac{\mathrm{SDR}}{F} \tag{8}$$

where F, the maximum dose rate that an organism will receive for a unit activity concentration of a given radionuclide in an environmental medium (μGy h^{-1} per Bq l^{-1} or per Bq kg^{-1} (dry weight) or per Bq m^{-3} (air) of medium). SDR, the screening dose rate (μGy h^{-1}) selected by the assessor at the assessment context stage.

In deriving F, the selection of the default location within the habitat is based on the configuration that will result in maximum exposure of the reference organism. For example, for the terrestrial soil invertebrate, the assumption is made that the organism spends 100% of its time underground (when in reality it may also spend some of its time at the soil surface). As an example of the equations used to estimate F, the case for a soil invertebrate is provided in Eq. (9).

$$F = [\mathrm{DCC}_{\mathrm{int,si}}\mathrm{CR}_{\mathrm{si}} + \mathrm{DCC}_{\mathrm{ext,si}}] \tag{9}$$

where $\mathrm{DCC}_{\mathrm{int,si}}$, internal dose conversion coefficient for soil invertebrate; $\mathrm{CR}_{\mathrm{si}}$, concentration ratio for soil invertebrate; $\mathrm{DCC}_{\mathrm{ext,si}}$, external DCC for in-soil configuration, i.e. volumetric source for soil invertebrate.

The full set of equations, covering all ecosystems and reference organisms, is provided in the Help function for the Tool.

The F values are calculated using all available information, which includes probability density functions of parameters for which these are available (namely CR values and distribution coefficients). Calculations are thus performed probabilistically using a Monte Carlo approach, outside of the tool, resulting in a PDF for the F value from which any percentile of the F value can be selected. As the default, the 95th percentile F value has been selected for use in the calculations (i.e. this value is entered into Eq. (8)) to yield a 5th percentile EMCL. An illustrative example of this type of probabilistic derivation is presented in Fig. 2.

The Tool uses a default screening dose rate (at Tiers 1 and 2), applicable to incremental (i.e. above background) exposures, of 10 μGy h^{-1}. The derivation of this value is described elsewhere Garnier-Laplace and Gilbin (2006) and Garnier-Laplace et al. (2008). The Tool also allows other screening dose rates to be used:

- 40 μGy h^{-1} for terrestrial animals or 400 μGy h^{-1} for terrestrial plants and all aquatic species. These numbers are derived from the IAEA (1992) and UNSCEAR (1996) reports and are really benchmarks below which populations are unlikely to be significantly harmed based on previous reviews of the scientific literature. These also correspond to the USDoE dose limit of 10 mGy d^{-1} ($\approx$400 μGy h^{-1}) for native aquatic animals and benchmarks of 400 and 40 μGy h^{-1} for terrestrial plants and terrestrial animals, respectively (based on the intent of appropriate DoE orders as no statutory dose limits were in place as of 2006), and used in the USDoE's graded approach (USDoE, 2002).
- User-defined value (i.e. the user can enter their own number applicable for all organisms into this option). The Tool deals with user-defined values by scaling the results of the risk quotients from the calculations made using the environmental media concentration limits (EMCLs) derived from the default ERICA value of 10 μGy h^{-1}. For example, if a screening dose rate of 20 μGy h^{-1} has been defined by the user, the Tool simply divides the calculated risk quotients (see below) by a factor of 2.

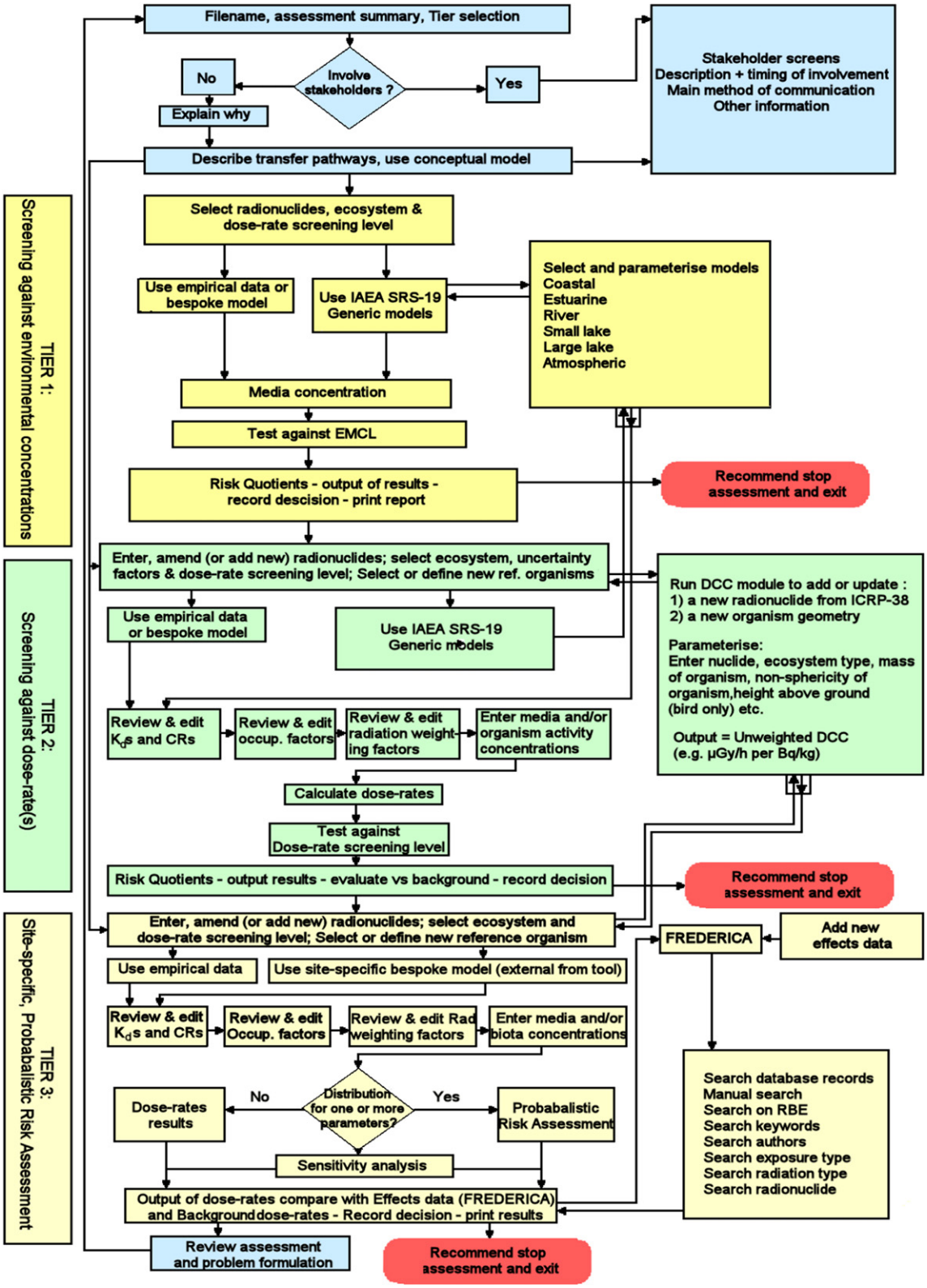

Fig. 1. Flow chart showing how the assessment process is organised within the Tool.

The default EMCL values can be accessed in the underlying databases. They can be found in the directory ''Risk Characterisation''. The database includes the numerical value of the EMCL and the limiting organism upon which the value is based.

At Tier 1, the data entry required is in the form of maximum activity concentrations for each selected radionuclide in environmental media only. The format of the required information will depend on the ecosystem studied:

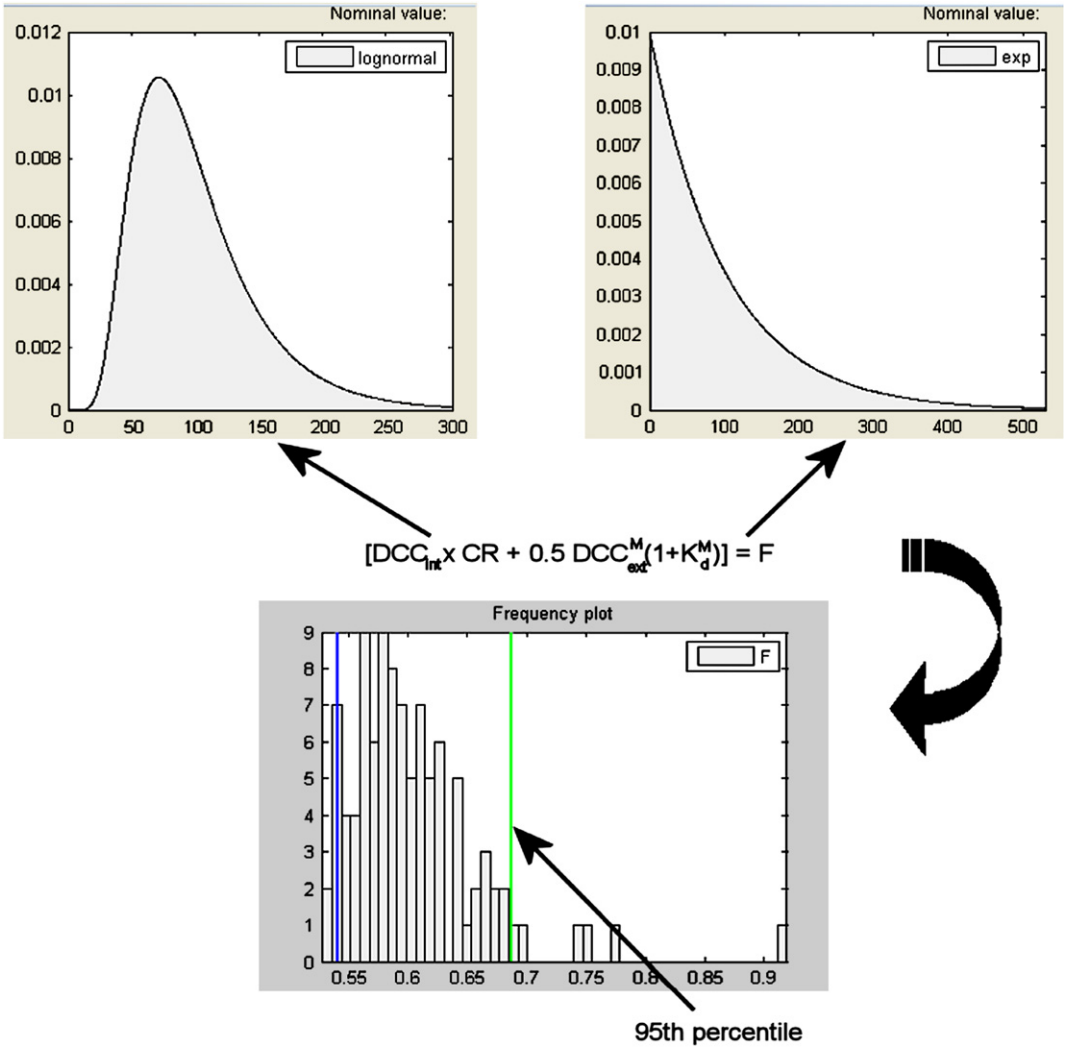

Fig. 2. Example of use of probabilistic calculations in the derivation of F values (the equation here is for a benthic organism present at the sediment–water interface).

- *terrestrial ecosystems*: activity concentration in soil (Bq kg^{-1} dry weight) or for radioisotopes of C, S, P or H in air (Bq m^{-3});
- *aquatic ecosystems*: activity concentrations in water (Bq l^{-1}) or sediment (Bq kg^{-1} dry weight) or both.

The radionuclide activity concentrations in the soil, water or sediment entered either as site-specific values or through the use of one of the in-built SRS-19 model are compared with the corresponding EMCLs. This produces a risk quotient (RQ) for each specific radionuclide included in the assessment. A total (or sum of) risk quotient (RQ) is also estimated, defined by (Eq. (10)):

$$\mathrm{RQ} = \sum_{1}^{n} \frac{M_n}{\mathrm{EMCL}_n} \tag{10}$$

where RQ, (Total) Risk quotient; M_n, measured or predicted maximal activity concentration for radionuclide "n" in the medium in Bq l^{-1} for water, Bq kg^{-1} (dry weight) for soil or sediment or Bq m^{-3} for air; EMCL_n, Environmental Media Concentration Limit for radionuclide "n" (same units as media) and defined in Eq. (8).

For aquatic ecosystems limiting RQs for different radionuclides may be for different media (i.e. water or sediment). In this case, RQs based on different media types are added together to produce the total RQ. Moreover, when summing RQs across the radionuclides present in a given situation, the limiting reference organism may not be the same for each radionuclide. Although this approach might appear highly conservative, it has been selected because it is reasonably consistent with other assessment approaches currently available (e.g. USDoE, 2002) and, through the provision of only a single EMCL value for each radionuclide, maintains the intended simple nature of Tier 1.

If the sum of the risk quotients is <1, then the user can be assured that there is a very low probability that the assessment dose rate to any organism exceeds the incremental screening dose rate and therefore the risk to non-human biota can be considered negligible. If the RQ is equal to or exceeds

1, a more in depth study (progressing to Tier 2 or 3) would normally be required and the Tool indicates this to the assessor.

3.2. Tier 2

At Tier 2 the estimated total (internal and external summed) weighted absorbed dose rates for each reference organism included in the assessment are compared directly with the dose rate screening value that was selected by the assessor for use in the assessment. This produces a risk quotient for each organism included in the assessment (Eq. (11)):

$$RQ_{org} = \frac{DR_{org}}{SDR} \tag{11}$$

where RQ_n, risk quotient for reference organism "org"; DR_n, estimated total dose rate ($\mu Gy\,h^{-1}$) for reference organism "org"; SDR, the screening dose rate ($\mu Gy\,h^{-1}$) selected by the assessor at the assessment context stage.

In this tier greater flexibility is introduced as many of the parameters involved in the calculations (as defined by Eqs. (1)–(5)) can be reviewed and edited. These parameters include:

- distribution coefficients – K_ds (marine and freshwater);
- CRs, in this case, the methods used to derive the ERICA default values in the absence of empirical data are identified on the appropriate screen;
- percentage dry weight soil or sediment;
- occupancy factors; and
- radiation weighting factors.

User-specified geometries, can be added by using the *Add organism* functionality and if a radioisotope of interest is not represented in the ERICA default database, new radionuclides can be added by accessing the *Add isotope* wizard. The assessor is required to enter additional parameters (CRs, K_ds, etc.) for new geometries and radionuclides.

Tier 2 allows the user to enter one or more media or biota activity concentrations that have been collated for use in the assessment:

- For aquatic ecosystems: water activity concentrations ($Bq\,L^{-1}$), sediment activity concentrations ($Bq\,kg^{-1}$, dry weight) and biota activity concentrations ($Bq\,kg^{-1}$, fresh weight) can be entered.
- For terrestrial ecosystems: soil activity concentrations ($Bq\,kg^{-1}$, dry weight); air activity concentrations ($Bq\,m^{-3}$) for the isotopes of C, S, P and H and biota activity concentrations ($Bq\,kg^{-1}$, fresh weight) can be entered.

At this tier it is recommended to enter expected (or "best estimate") value activity concentrations – concentrations that are representative of an area in time and space. This differs from Tier 1 where maximum activity concentrations are normally the most appropriate input values. Depending upon the amount of data that you are able to enter the Tool follows a set of rules to calculate input values for all media and reference organisms with respect to a particular radionuclide. There must be at least one activity concentration (i.e. for a media or any of the selected reference organisms) input for each radionuclide for the assessment to continue. The rules make use of the concentration ratios (CRs), and for aquatic ecosystems the K_d values, entered earlier in the assessment process. Essentially, the rules provide details on which data are used in extrapolating from one data type to another. For example, in the aquatic environment when activity concentration data are available for water these data are used directly in preference to available sediment and biota concentrations in deriving unknown biota activity concentrations via appropriate CRs. This process is performed automatically by the tool during the dose-rate calculations at Tiers 2 and 3 and the full set of rules are provided in the Tool Help.

In addition to "expected values" of the RQs (based on expected values for the inputs and parameters), conservative estimates of RQs are also reported. These are obtained by multiplying the expected RQs by Uncertainty Factors (UFs). The UF is an approximation applied to account for uncertainty in the dose-rate estimation and is defined as: the ratio between the 95th, 99th or any other percentile (above the expected value) and the expected value of the probability distribution of the dose rate (and RQ). To estimate the UF it was assumed that the dose rate and the RQ follow exponential distributions with means equal to the estimated expected values. In this case, the UFs corresponding to the 95th and 99th percentiles are equal to 3 and 5, respectively. The assessor can also enter their own UF value. The user-defined UF may be substantially lower than the default settings, for example, when many site-specific data are available there may be some justification for refining the UF. However, such calculations require knowledge of the distribution of the RQ and the propagation of uncertainties in the dose calculations.

The UFs also maintain conservatism between Tiers 1 and 2. In the case where the same input values are entered and default settings are selected (i.e. for any single radionuclide and corresponding limiting reference organism), the results for Tiers 1 and 2 (conservative estimates) should correspond approximately to one another because essentially the assessor has not provided more detail and has not amended the problem formulation accordingly. The results will not be identical for the same input values in both Tiers, however, because in Tier 1 the EMCL is derived by extracting a 95th percentile derived from uncertainty propagation based on "real" PDFs (e.g. many CR values are characterised by lognormal distributions) whereas at Tier 2, the 95th percentile (of the RQ) is derived from applying a UF to the expected value. In other words, the underlying assumption at Tier 2 is that the PDF of the RQ can be approximated using an exponential distribution whereas the PDF derived at Tier 1 (for the EMCL and therefore the RQ) will reflect a combination of various distributions that may or may not be of exponential form.

Using the exponential distribution in deriving the UF can be justified as it is the least biased distribution that can be assumed

if only the expected value of the distribution is available, as is the case at Tier 2. This is supported by the principle of maximum entropy (see Harr, 1987). Although experience shows that in reality most parameters are log-normally distributed, the use of a lognormal distribution requires the standard deviation to be known as well. So for simplicity, the assessor is not expected to enter such information at Tier 2 but may do so in Tier 3 if there is a requirement to perform a more thorough evaluation of the data. It should also be noted that when the standard deviation is numerically smaller than the mean, the 95th and other percentiles estimated using a lognormal distribution tend to be lower than the corresponding values estimated from an equivalent exponential distribution using the same mean. It can be concluded that the assumption of an exponential distribution provides cautious (or conservative) estimates of the percentiles as long as the coefficient of variation of the estimates is less than 100%.

The calculated RQs used in combination with the other information provided within the Tier 2 assessment screens (as discussed below) enable the assessor to make a decision on whether the assessment can be concluded or should continue. The assessor is helped by the Tool which uses various criteria and appropriate conditional recommendations are illustrated in Fig. 3.

In those cases where is it recommended that 'the assessment is continued' or 'the assessment and results are reviewed' an automatic progression to a Tier 3 assessment is not always necessary. For instance, it may be possible to refine the input data or Tool parameters (e.g. derive CR values applicable to the site or make measurements of radionuclide activity concentrations in biota from the site) if justifiable and to then rerun the assessment at Tier 2. However, in this context the assessor should be aware that a recent comparison of site-specific data to generic data (specifically, soil–plant concentration ratios), concluded that generic data may often constitute the best choice, owing to the very large inherent variability in transfer parameters, which a few site-specific measurements may not encapsulate (Sheppard, 2005). Assessors should, therefore, consider carefully whether the quality of any available site-specific data justifies its application. Site-specific data will always provide a useful comparison with predictions generated using the Tool's generic parameters.

In instances where the conservative RQ is above 1 whilst the best estimate RQ is below 1, interpretation of the results may lead to a decision that the assessment can be justifiable exited. In this respect, the Tool provides ancillary information to aid in the decision-making process. To help the assessor put their results into context the results screen tabs labelled ''Background'' and ''Effects'' contain summarised information.

The background tab provides ranges in background exposure rates due to naturally occurring radionuclides (weighted using the ERICA default radiation weighting factors of 10 for alpha, 3 for low energy beta and 1 for other beta and gammas). These data are derived from published works (Brown et al., 2004; Beresford et al., 2007c). The ERICA Integrated Approach should be used to assess *incremental doses* from human activities only. If dose rates estimated within Tier 2 result in RQ values in excess of 1 but are insignificant in magnitude relative to natural background exposure rates, the user might conclude that there is negligible cause for concern. This would be in line with the approach described by Pentreath (2002), which is based on derived consideration levels. If activity concentrations of naturally occurring radionuclides are available for the assessment site the assessor could estimate site-specific absorbed doses rates due to these for comparison to dose rates resulting from exposure to radionuclides from anthropogenic sources (but should not add them to the assessment). For sites being assessed for NORM contamination, the

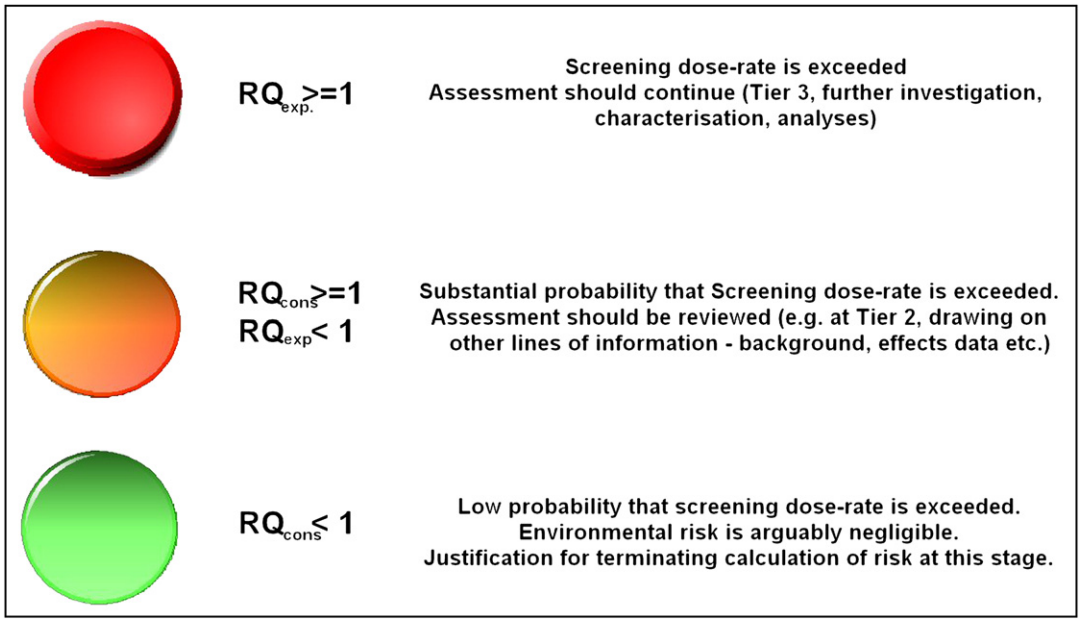

Fig. 3. The criteria for exceedence of benchmark values and recommendations provided for Tier 2 results are shown.

dose rates estimated will include a contribution from background levels of the radionuclides of interest. In this instance the total dose rates should be compared to the summarised background dose rate provided within Tier 2 to determine if the incremental dose is likely to be of concern.

The effects tab contains a series of tables, one for each reference organism group for the ecosystem under assessment. The information is provided to allow a comparison between the predicted dose rates for the selected reference organisms to a summary of information about the known biological effects of ionising radiation on non-human species collated within the FREDERICA database (Copplestone et al., 2008). The effects lookup tables are constructed to provide a short statement on the types of biological effect that may be occurring at particular dose rates. The available information has been summarised to provide the assessor with:

- information on the dose rate at which the biological effect has been observed in an experiment or field controlled study;
- the species on which the experiment was conducted;
- the endpoint (MB = morbidity, MT = mortality, RC = reproductive capacity, MUT = mutation); and
- a brief statement on the type of biological effect observed.

Based on expert judgement the effects were graded either no effect, minor, moderate, major or severe. The biological effects information provided may support decision-making. The assessor can contextualise the predicted dose rates in terms of expected radiation effects in particular organism groups and for specific biological endpoints thus enabling a more informed evaluation of the results of the Tier 2 assessment.

3.3. Tier 3

Tier 3 allows full probabilistic calculations to be performed through the application of Monte Carlo simulations. There is the same degree of flexibility at Tier 3 as that incorporated in Tier 2 in the sense that the assessor may edit and review the various parameters used in the subsequent calculations. In addition, input data, K_d values, CR values and radiation weighting factors have an option allowing the user to assign a probability distribution function (PDF) to them. This may be either as a default PDF (drawn from the underlying ERICA Tool database described above) or as user defined ones. The following distribution types are supported by the Tool:

- exponential (required entry arithmetic mean, with optional lower cut off and upper cut off values);
- normal (required entries arithmetic mean and standard deviation, with optional lower cut off and upper cut off values);
- triangular (required entries minimum, maximum and mode values);
- uniform (required entries minimum and maximum values);
- lognormal (required entries arithmetic mean, and standard deviation, with optional lower cut off and upper cut off values);
- logtriangular (required entries minimum, maximum and mode values); and
- loguniform (required entries minimum and maximum values).

The default PDFs included in the Tool database were defined using the following simple rule:

- where a standard deviation could be determined from the data (normally the number of sample "n" > 1), a lognormal distribution was applied; and
- for all other cases (where the value was derived or "n" = 1) an exponential distribution was applied.

This is based on the observations, as considered above, that the uncertainty for radioecological data, such as CRs and K_ds, are often well fitted by lognormal distributions and that in cases where single, expected values are available the least biased distribution is an exponential one.

To estimate the uncertainty within the endpoints of an exposure assessment, the uncertainties in the inputs and parameters must be propagated though the model. When simple analytical expressions for the probability distributions are available, variance propagation can be applied for propagating the uncertainties (Morgan and Henrion, 1990; Hoffman and Hammonds, 1994). When analytical methods cannot be applied, the uncertainties can be propagated using Monte Carlo analysis. This is the approach used in the tool. The basis of the Monte Carlo method are relatively straightforward (Vose, 1996): point estimates in a model equation are replaced with probability distributions, samples are randomly taken from each distribution, and the results tallied, usually in the form of a probability density function or cumulative distribution. The number of simulations used in the calculation can be selected by the user. This process is illustrated in Fig. 2. This method is particularly powerful in accounting for the variability associated with all inputs and parameters used in the calculations.

The Tier 3 input screen, allows the user to enter the media or biota activity concentrations that have been collated for use in the assessment. The same options as for Tier 2 are available, but now single values or a probability distributions can be entered (a mixture of deterministic and probabilistic data entries is also allowed). Furthermore, the same requirements for data entry as stipulated for Tier 2 are required, i.e. there must be at least one data entry per radionuclide, and the same rules are applied in filling the input data matrix. The parameters to be included in a probabilistic simulation can be selected and the number of simulations defined.

The results reported at Tier 3 provide no information on risk quotients because if the assessment has reached this stage of detailed analyses, screening dose rates are no longer appropriate. The onus would now be on the assessor to derive their own benchmark(s) from which to make comparison with exposure derivations. The results tabs are therefore split into

deterministic data, where information relating to single entry values are reported (in tabulated from only), and probabilistic data, where information relating to probability distribution functions are reported (as figures with summary statistics).

The supporting information available at Tier 3 for interpreting the dose rates predicted within an assessment are biological effects data collated from scientific literature within the FREDERICA database which describe the effects of exposure of ionising radiation on non-human species (Copplestone et al., 2008). The effects tab contains a direct link to the online FREDERICA database which requires an Internet connection. This direct link to FREDERICA ensures that the user will always access the most up to date version of the data available within the FREDERICA database.

The search conducted is linked to the reference organism and the wildlife group that it belongs to. By selecting the reference organism, the wildlife group will be automatically selected, the search conducted within the FREDERICA database will then identify all the endpoints (e.g. morbidity, mortality, reproductive capacity, mutation) contained within the database. The predicted mean dose rate for a selected reference organism is used as the mid-point of the dose rate range for the search within the FREDERICA database. The subsequent report of the results from the FREDERICA database search contains the following information:

- the literature reference information from which the dose rate data has been taken;
- details of the experiment that was conducted to obtain the dose rate effect data;
- information on the dose rate at which the biological effect has been observed in an experiment or field controlled study;
- the species on which the experiment was conducted;
- the endpoint (MB = morbidity, MT = mortality, RC = reproductive capacity, MUT = mutation); and
- a brief statement on the type of biological effect observed.

Different wildlife groups can be selected in the drop down list at the top of the tab screen and will allow the assessor to access different sets of information. This information may help the assessor to identify areas for research and/or targeted sampling and monitoring to look for known biological effects that may be occurring based on the available data. The dose rate range that is being searched can also be modified using two boxes (called lower and upper value) to the right of the organism drop down list. By default the lower value is always 0 and the upper value is the 95th percentile dose rate predicted by the Tool for the selected organism. This can be modified simply by typing a different value into either the lower or upper value box and clicking the search button to re-submit the query to the database.

Full details of the available information and how to use the FREDERICA database are provided at the FREDERICA website (www.frederica-online.org), this includes a manual on the searches available and describes the ways to export the data from the FREDERICA database.

The Tier 3 results section also provides information in relation to sensitivity analysis. This apportions the relative effect of the uncertain inputs and parameters on the variation and uncertainty of the simulation endpoints (dose rates and activity concentrations). Several sensitivity analysis methods of varying degrees of complexity have been proposed in the literature (Saltelli et al., 2004). The models for calculation of dose rates implemented in the ERICA tool are relatively simple and it is possible to perform sensitivity analyses using simple correlation coefficients between the inputs/parameters and the endpoints. In the present version of the Tool (July 2007), two correlation coefficients are computed every time a probabilistic simulation is carried out: the Pearson Correlation Coefficient (PCC) and the Spearman Rank Correlation Coefficient (SRCC). The PCC assumes linear relationship between variables whereas the SRCC does not.

In the simplest sense, the sensitivity analysis included in the Tool can be used to identify those parameters that are having an overriding influence on the total dose-rate (or components of this dose-rate). If it is found that the parameter/value under investigation is having a large effect on the output, it might be worth investigating/examining this parameter in more detail. If the parameter is a K_d or CR this might simply involve conducting more field or laboratory studies to characterise the value more robustly.

4. Concluding remarks

The ERICA Tool has been successfully developed to automate the assessment component of the ERICA integrated approach. The software leads the user through the assessment process by means of step-wise ‘‘wizards’’ and has been designed to allow a logical format for documenting the assessment procedure and great flexibility in relation to data entry and parameter selection especially as the assessment moves to higher tier, more complex, environmental risk calculations. The development process has been undertaken in close consultation with the group experts constituting ERICA’s end-user group (e.g. Zinger, 2006; Zinger et al., 2008) and constitutes the culmination of 3 years of development activities by the consortium.

The prototype Tool (as of December 2006) was tested through case studies at several terrestrial, freshwater and marine environments, and for a broad suite of anthropogenically derived and technologically enhanced radionuclides (Beresford et al., 2007b). Predictions of activity concentrations in biota and media made by Tool were generally adequately in agreement with observed data. Where this was not the case reasonable arguments could be presented to explain discrepancies. The case studies did not provide any definitive validation of the effects prediction provided by the Tool beyond the observation that, for one particular case where a cursory comparison was practicable, the predictions made were not in contradiction to the observed effects in the field. Many of the limitations relating to the application of the tool, were often associated with a lack of clear explanation in supporting guidance, these were

addressed before the final release of the software. Nonetheless, weaknesses do remain. Although intensive debugging of the software has been undertaken in the period leading up to the release, occasional problems may still arise. Testing of some of the parameters and assumptions used by the Tool, notably the distribution coefficients and the uncertainty factors applied at Tier 2, has not been undertaken in a rigorous fashion to date and could be a focus for more comprehensive evaluation in the future. In addition to the case studies many of the underlying parameters used in the calculations performed by the Tool including numerous (internal and external) DCCs and concentration ratios have been subject to intercomparison with approaches using similar parameters within an international forum (Beresford et al., 2005; Vives i Batlle et al., 2007). This has begun to provide some validation and aids quality assurance.

The tool is currently (as of July 2007) freely available at the EC EURATOM Project PROTECT website – http://www.ceh.ac.uk/protect/. All new users have to register before receiving a download. To use the Tool Java software needs to be installed, this is freely available from http://www.java.com/en/download/index.jsp. The Tool will be developed further in the coming years with a plan to release periodic updates when new data and functionality become available. This will occur under the auspices of core group, consisting of some members from the original ERICA consortium. The development of the Tool will clearly benefit as it becomes used by the wider radiological protection community and the developers receive feedback on limitations and requirements.

Acknowledgements

This work was supported by the EC-EURATOM 6th Framework Programme (2002–2006) and forms part of the ERICA (*Environmental Risk from Ionising Contaminants: Assessment and Management*) project, contract FI6R-CT-2003-508847. The financial support of the EC is gratefully acknowledged. The authors also wish to thank the ERICA consortium (with a special mention for Joanne Hingston who developed the Tool flowchart) and End-User group for their invaluable support and advice in the process of tool development.

References

Beresford, N.A., Wright, S.M., Sazykina, T. (Eds.), 2001. Reference Arctic organisms. Deliverable report 1 for EPIC. EC Inco-Copernicus project ICA2-CT-2000-10032. Norwegian Radiation Protection Authority, Østerås, Norway, p. 40.

Beresford, N.A., Howard, B.J. (Eds.), 2005. DELIVERABLE D9: Application of FASSET framework at case study sites. A Deliverable Report for the Project "ERICA" (Contract No. FI6R-CT-2004-508847) within the EC's VIth Framework Programme. Swedish Radiation Protection Authority, Stockholm, p. 111.

Beresford, N., Brown, J., Copplestone, D., Garnier-Laplace, J., Howard, B., Larsson, C.-M., Oughton, D., Pröhl, G., Zinger, I., 2007a. D ERICA: an INTEGRATED APPROACH to the assessment and management of environmental risks from ionising radiation. Description of purpose, methodology and application. A Deliverable Report for the Project "ERICA" (Contract No. FI6R-CT-2004-508847) within the EC's VIth Framework Programme. Swedish Radiation Protection Authority, Stockholm, p. 82.

Beresford, N.A., Howard, B.J. Barnett, C.L., 2007b. DELIVERABLE D10: application of ERICA integrated approach at case study sites. A Deliverable Report for the Project "ERICA" (Contract No. FI6R-CT-2004-508847) within the EC's VIth Framework Programme. Swedish Radiation Protection Authority, Stockholm, p. 136.

Beresford, N.A., Appleton, J.D., Barnett, C.L., Bescoby, M.W., Breward, N., Jones, D.G., MacKenzie, A.C., Scheib, C., Wood, M.D., Thørring, H., 2007c. Assessment of naturally occurring radionuclides around England and Wales. Project SC030283. Environment Agency, Bristol.

Beresford, N.A., Balonov, M., Beaugelin-Seiller, K., Børretzen, P., Brown, J., Jing-Jey Cheng, J.-J., Copplestone, D., Doi, M., Gaschak, S., Golikov, V., Horyna, J., Hosseini, A., Howard, B.J., Jasserand, F., Kamboj, S., Nedveckaite, T., Olyslaegers, G., Sazykina, T., Vives i Batlle, J., Yankovich, T., Yu, C., 2005. Models and approaches available to estimate the exposure of non-human biota: an international comparison of predictions. In: Strand, P., Børretzen, P., Jølle, T. (Eds.), Proceedings from the 2nd International Conference on Radioactivity in the Environment, 2–6 October 2005, Nice, France. Norwegian Radiation Protection Authority, Østerås, Norway, pp. 146–149. ISBN: 82-90362-21-8.

Beresford, N.A., Barnett, C.L., Howard, B.J., Scott, W.A., Brown, J.E., Copplestone, D., 2008. Derivation of transfer parameters for use within the ERICA Tool and the default concentration ratios for terrestrial biota. Journal of Environmental Radioactivity 99, 1393–1407.

Børretzen, P., Brown, J.E., Strand, P., Johansson, E., Ramstedt, M., Avila, R., Pröhl., G., Ulanovski, A., Copplestone, D., 2005. The ERICA assessment tool. In: Strand, P., Børretzen, P., Jølle, T. (Eds.), Proceedings from the 2nd International Conference on Radioactivity in the Environment, 2–6 October 2005, Nice, France. Norwegian Radiation Protection Authority, Østerås, Norway, pp. 43–46. ISBN 82-90362-21-8.

Brown, J.E., Thørring, H., Hosseini, A., 2003. The "EPIC" impact assessment framework – a deliverable report for EU Funded Project ICA2-CT-2000-10032. Norwegian Radiation Protection Authority, Østerås, p. 175.

Brown, J.E., Jones, S.R., Saxén, R., Thørring, H., Vives i Batlle, J., 2004. Radiation doses to aquatic organisms from natural radionuclides. Journal of Radiological Protection 24, A63–A77.

Chambers, D.B., Osborne, R.V., Garva, A.L., 2006. Choosing an alpha radiation weighting factor for doses to non-human biota. Journal of Environmental Radioactivity 87, 1–14.

Copplestone, D., Wood, M.D., Bielby, S., Jones, S.R., Vives, J., Beresford, N.A., 2003. Habitat regulations for Stage 3 assessments: radioactive substances authorisations. R&D Technical Report P3-101/SP1a. Environment Agency. Bristol.

Copplestone, D., Hingston, J.L., Real, A., 2008. The development and purpose of the FREDERICA radiation effects database. Journal of Environmental Radioactivity 99, 1456–1463.

Garnier-Laplace, J., Gilbin, R. (Eds.), 2006. Derivation of Predicted-No-Effect-Dose-Rate values for ecosystems (and their sub-organisational levels) exposed to radioactive substances. Report D5 to the ERICA project (EC Contract number F16R-CT-2003-508847). Swedish Radiation Protection Authority, p. 88.

Garnier-Laplace, J., Copplestone, D., Gilbin, R., Alonzo, F., Ciffroy, P., Gilek, M., Agüero, A., Björk, M., Oughton, D.H., Jaworska, A., Larsson, C.M., Hingston, J., 2008. Issues and practices in the use of effects data from FREDERICA in the ERICA Integrated Approach. Journal of Environmental Radioactivity 99, 1474–1483.

Harr, M.E., 1987. Reliability-Based Design in Civil Engineering. McGraw-Hill.

Hoffman, F.O., Hammonds, J.S., 1994. Propagation of uncertainty in risk assessments: the need to distinguish between uncertainty due to lack of knowledge and uncertainty due to variability. Risk Analysis 14, 707–712.

Hosseini, A., Thørring, H., Brown, J.E., Saxén, R., Ilus, E., 2008. Transfer of radionuclides in aquatic ecosystems – Default concentrations ratios for aquatic biota in the ERICA Tool assessment. Journal of Environmental Radioactivity 99, 1408–1429.

IAEA, 1992. Effects of ionising radiation on plants and animals at levels implied by current radiation protection standards. Technical Reports Series No. 332. Vienna, International Atomic Energy Agency.

IAEA, 2001. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. IAEA Safety Reports Series 19, 216. STI/PUB/1102.

IAEA, 2004. Sediment distribution coefficients and concentration factors for biota in the marine environment. Technical Reports Series No. 422, International Atomic Energy Agency, Vienna, p. 103.

ICRP, 1983. Radionuclide transformations—energy and intensity of transmissions ICRP Publication 38. Annals of the ICRP 11. Pergamon Press, Oxford.

ICRP, 25-04-2005. The concept and use for reference animals and plants for the purposes of environmental protection. Draft for discussion. Annals of the ICRP. Available from: http://www.icrp.org/docs/Environm_ICRP_found_doc_for_web_cons.pdf.

Larsson, C.-M., 2004. The FASSET Framework for assessment of environmental impact of ionising radiation in European ecosystems – an overview. Journal of Radiological Protection 24, A1–A13.

Larsson, C.M., 2008. An overview of the ERICA Integrated Approach to the assessment and management of environmental risks from ionising contaminants. J. Environ. Radioact. 99, 1364–1370.

Morgan, M.G., Henrion, M., 1990. Uncertainty. Cambridge University Press, p. 332.

Pentreath, R.J., 2002. Radiation protection of people and the environment: developing a common approach. Journal of Radiation Protection 22 (1), 45–56.

Pröhl, G., Brown, J., Gomez-Ros, J.-M., Jones, S., Woodhead, D., Vives, J., Taranenko, V., Thørring, H., 2003. Dosimetric models and data for assessing radiation exposure to biota. Deliverable 3 to the Project "FASSET" Framework for the assessment of Environmental Impact, contract No. FIGE-CT-2000-00102. Swedish Radiation Protection Authority.

Saltelli, A., Tarantola, E., Campolongo, F., Ratto, M., 2004. Sensitivity Analysis in Practice – A Guide to Assessing Scientific Models. John Wiley and Sons Ltd., Chichester.

Sheppard, S.C., 2005. Perspective: transfer parameters: are on-site data really better? Human and Radiological Risk Assessment 11, 939–949.

Strand, P., Beresford, N., Avila, R., Jones, S.R., Larsson, C.-M., 2001. Identification of candidate reference organisms from a radiation exposure pathways perspective. A Deliverable Report for the Project "FASSET" (Contract No. FIGE-CT-2000-00102) within the EC's Vth Framework Programme. Norwegian Radiation Protection Authority, Østerås, Norway, p. 48 (+ 2 Appendices).

Ulanovsky, A., Pröhl, G., 2006. A practical method for assessment of dose conversion coefficients for aquatic biota. Radiation and Environmental Biophysics 45, 203–214.

Ulanovsky, A., Pröhl, G., Gómez-Ros, J.M., 2008. Methods for calculating dose conversion coefficients for terrestrial and aquatic biota. Journal of Environmental Radioactivity 99, 1440–1448.

UNSCEAR, 1996. Effects of radiation on the environment. United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General assembly, Annex 1. United Nations, New York.

USDoE, 2002. A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota. U.S. Department of Energy, Washington D.C., U.S.A. Technical Standard DOE-STD-1153-2002.

Vives i Batlle, J., Balonov, M., Beaugelin-Seiller, K., Beresford, N.A., Brown, J., Cheng, J.-J., Copplestone, C., Doi, M., Filistovic, V., Golikov, V., Horyna, J., Hosseini, A., Howard, B.J., Jones, S.R., Kamboj, S., Kryshev, A.I., Nedveckaite, T., Olyslaegers, G., Pröhl, G., Sazykina, T.G., Ulanovsky, A., Vives-Lynch, S.M., Yankovich, T., Yu, C., 2007. Inter-comparison of absorbed dose rates for non-human biota. Radiation and Environmental Biophysics 46, 349–373.

Vose, D., 1996. Quantitative Risk Analysis – A Guide to Monte Carlo Simulation Modelling. John Wiley and Sons.

Zinger, I. (Ed.), 2006. Summary of the EUG Tool Testing Day Copenhagen, 08 December 2006. Deliverable Report D7h for the Project "ERICA" (Contract No. FI6R-CT-2004-508847) within the EC's VIth Framework Programme. Swedish Radiation Protection Authority, Stockholm, p. 10.

Zinger, I. (Ed.), 2007. Considerations for applying the ERICA Integrated Approach. Deliverable Report D8 for the Project "ERICA" (Contract No. FI6R-CT-2004-508847) within the EC's VIth Framework Programme. Swedish Radiation Protection Authority, Stockholm, p. 127.

Zinger, I., Jones, S., Oughton, D.H., 2008. Stakeholder interaction within the ERICA Integrated Approach. Journal of Environmental Radioactivity 99, 1503–1509.