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Approaches to providing missing transfer parameter values in the ERICA Tool – how well do they work?

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1. Introduction

The ERICA Integrated Approach was designed to provide guidance on assessment of impacts of radioactivity on the environment. Emphasis was placed on protecting the structure and function of ecosystems from the harmful effects of ionising radiation (Larsson, 2008), and supporting software (the ERICA Tool) was developed to facilitate the assessment process (Brown et al., 2008). The exposure assessment part of the Integrated Approach (Figure 1) encapsulates the quantification of risk to organisms in the environment through the application of transfer and dosimetric models and, for screening purposes, the comparison of predicted exposure dose rates with appropriately derived benchmarks.

Radionuclide transfer is complex, being influenced by factors such as the physicochemical form of the radionuclide, the physical and chemical nature of the receiving medium and biological factors such as homeostatic control, requirements for and availability of the element (or close analogues) and distribution within the organism. Clearly, such complexity requires simplification in the procedure of developing practicable models to assess the exposure of wildlife. This task is facilitated in many models (Beresford et al. 2008a) by limiting the requirements of transfer modeling to the derivation of activity concentrations in plants and animals from a starting point of known, or model-derived, activity concentrations in environmental media including water, sediments and soil (with units of Bq kg^{-1} or Bq l^{-1}). The method used in the ERICA Tool is the whole-body concentration ratio (CR_{wo}), which, for terrestrial biota, is defined as (Equation1) :

$$CR_{wo} = \frac{A_{b,r}^{biota}}{A_{r}^{soil}} \qquad (1)$$

Where

$A^{biota}_{b,r}$ = Activity concentration of radionuclide ‘r’ in the whole organism of biota ‘b’ (Bq kg^{-1} fresh weight (fw));

A^{soil}_{r} = Activity concentration of radionuclide ‘r’ in soil (Bq kg^{-1} dry weight (dw))

For aquatic organisms activity concentrations in soil are replaced by those in water.

Although this approach has limitations, including with regards to the assumption of equilibrium as described elsewhere (Coughtrey and Thorne, 1983; Brown et al., 2004, Wood et al., this issue), it is generally considered to be a simple, transparent and user-friendly approach to determining internal activity concentrations in wild plants and animals (Howard et al., in press). It is also consistent with other available wildlife assessment approaches (Copplestone et al. 2001; USDOE 2002) and some elements of human food-chain assessment models (e.g. IAEA 2010).

1.1 Transfer in ERICA

The collation of data for the ERICA Tool was simplified by acknowledging the impracticability of providing transfer data for every organism type within the earth’s many and varied ecosystems and thus opting to structure data around a set of 38 generic organism groups and three generic ecosystems (freshwater, marine and terrestrial). Even with these simplifications, as the ERICA Tool incorporates radionuclides for 31 elements, a matrix consisting of 1178 radionuclide-organism CR value combinations was required for its parameterisation. It was necessary to fill all data gaps because these values were required for the initial screening tier in the Tool. Available data for selected radionuclides and organisms were collated through the review of published literature, details of which are given in

Beresford et al. (2008b) and Hosseini et al. (2008) for terrestrial and aquatic environments respectively. The collated data were largely direct measurements of organisms and environmental media sampled under field conditions. At the time of publication of the ERICA approach, in 2008, data were available to derive CR values for less than 40% of the required radionuclide-organism combinations. The remaining 60% were derived using a variety of extrapolation approaches:

- Use an available CR value for an organism of similar taxonomy, referred to in subsequent article tables using the code 'ST', within that ecosystem for the radionuclide under assessment (preferred option).
- Use an available CR value for a similar reference organism , 'SRO', (preferred option).
- Use CR values recommended in previous reviews, 'PR', or derive them from previously published reviews (preferred option).
- Use specific activity models for ^{3}H and ^{14}C, 'SA' (preferred option).
- Use an available CR value for the given reference organism for an element of similar biogeochemistry, 'ROSB'.
- Use an available CR value for biogeochemically similar elements for organisms of similar taxonomy, 'STSB'.
- Use an available CR value for biogeochemically similar elements available for a similar reference organism, 'SROSB'.
- Use allometric relationships, or other modelling approaches, 'MA', to derive appropriate CRs
- Assume the highest available CR, 'HA' (least preferred option).
- Reference organism in a different ecosystem, 'RODE' (aquatic only - least preferred option)

- Combination of approaches, ‘CA’.

The list above includes ‘preferred’, ‘neutral’ and ‘least preferred’ options. Within these 3 specific categories, there is no order of preference. The approach selected depended upon the availability of data/knowledge; if more than one approach could be used based upon a similar degree of knowledge then the value selected was the most conservative (i.e. highest). The ‘combination of approaches’ was treated as a least preferred option by Hosseini et al. (2008) but as a ‘neutral’ option by Beresford et al. (2008b).

Although more data became available through the transfer database presented by Copplestone et al. (this issue) the International Commission on Radiological Protection (ICRP) was still forced to rely on extrapolation guidance in generating their best-estimate concentration ratios for numerous radionuclides characterizing transfer to Reference Animals and Plants (ICRP, 2009). In fact, only 25 % of the 546 radionuclide organism combinations reported by the ICRP contained CR values based on empirical data specifically for Reference Animals and Plants. The extrapolation method used by the ICRP was an adaptation of the ERICA methodology.

1.2 Requirement for conservatism

The ERICA approach is based around a tiered system where the assessor initially applies a screening tier(s) requiring little information and can exit the assessment with a stated high degree of confidence that impacts are negligible if screening criteria are not exceeded. If this is not the case the assessment needs to move to higher tiers assessment where more detailed information is required and more elaborate modelling approaches, such a probabilistic calculations to account for uncertainty, can be used. Therefore, the parameters applied at screening tiers need to provide some assurance that predictions of dose-rate and thereafter the risk quotients based upon these exposure estimates are conservative, i.e. tend to overpredict the actual dose-rate.

At Tier 1, the screening criteria are based on activity concentrations referred to as 'Environmental Media Concentration Limits' (EMCLs). EMCLs are back calculated from a screening dose-rate (ERICA uses a default value of 10 µGy h^{-1}) divided by 'F' - the dose rate per unit activity concentration for a given radionuclide and organism (see Brown et al. 2008). To incorporate conservatism, the calculations for 'F' are run probabilistically using distributions from concentration ratios and, for aquatic ecosystems, sediment-water distribution coefficients (K_ds). The 95th percentile, from the resultant distribution of 'F', is then used. What this means in practice is that for the terrestrial ecosystem, the conservatism inherent in 'F' is entirely attributable to the 95th percentile of the CR value, all other parameters, i.e. dose conversion factors, being best estimates. For aquatic systems the conservatism in 'F' should be ascribable to the 95th percentile of the CR value where exposure from sediment is not considered or is negligible, i.e. for pelagic organisms and in other cases where internal exposure is the overwhelmingly dominant exposure pathway. The EMCL value used in the Tool is that derived for the organism with the highest 95th percentile dose rate per unit activity concentration of a given radionuclide. The derived EMCL value is then compared to the input activity concentration. The user is recommended to input maximum observed or modelled media activity concentrations within Tier 1 to further ensure the conservative nature of this simple assessment.

1.3 Aim

As indicated above, some of the extrapolation approaches adopted by ERICA were preferable to others; the application of each approach to derive default values within the ERICA Tool is described by Beresford et al. (2008b) and Hosseini et al. (2008). Whilst similar approaches are used in other models (e.g. Copplestone et al. 2003; USDOE 2002), there has been little attempt to see how well they perform. Evaluation of their performance has been limited to international model inter-comparison exercises (Beresford et al. 2008c; 2010; Yankovich et al. 2010) although these have not concentrated on the initial screening tier application for which the values derived using the above approaches are intended. The aim of this paper is to redress this oversight by testing the efficacy of the approaches used to derive extrapolated values in the default ERICA Tool parameter databases (Beresford et al. 2008b; Hosseini et al. 2008).

The fulfillment of this aim has been facilitated to a large extent by the development and population of the 'Wildlife transfer database' (Copplestone et al., this issue; Wildlife transfer database, 2012). This has involved the incorporation of the databases used in ERICA, following additional quality control, with the collation of new (or formerly unused) data, a portion of which covers radionuclide-organism CR combinations for which no data were previously available. This paper is especially timely as the 'Wildlife transfer database' will be used to help update the ERICA Tool CR values as mentioned by Howard et al. (in press).

2. Methodology

2.1 Comparing default CRs in the ERICA Tool derived using extrapolation approaches with new empirical data

The first step in the process was to identify and extract data for those radionuclide-reference organism combinations where new empirical CR data have been collated and where previously values had been derived using extrapolation methods. Newly acquired CR data were selected from the wildlife transfer database (Copplestone et al., this issue), which has been used by the ICRP (2009) and will be used in a new IAEA Technical Report Series (TRS) handbook (Howard et al., in press). Corresponding guidance-based extrapolated data (for the same radionuclide-reference organism combination) were then taken from the ERICA Tool databases. The derivation of these latter values has been reported in Beresford et al. (2008b) and Hosseini et al. (2008). In a few instances, there were differences between the CRs incorporated in the Tool databases and the CRs reported in these two papers. In such cases, reference has been made to the Beresford et al. and Hosseini et al. articles as the definitive source of information.

Since the 95th percentile dose rate per unit activity concentration was used to derive the ERICA Tool's EMCL values, as described above, we have selected a 95th percentile from the extrapolated CR values based on the ERICA Tool database. This is compared with the estimated 95th percentile values from the recently collated empirical datasets.

The probabilistic functionality of Tier 3 of the ERICA Tool was used to derive the 95th percentiles. The ERICA Tool default values which had been derived using extrapolation approaches were assumed to represent the arithmetic mean and the model run assuming that the underlying distribution was exponential; this is compatible with how these values were treated in the derivation of the ERICA Tool EMCL values (see Brown et al. 2008, Oughton et al., 2008). For the newly acquired empirical data, the arithmetic mean and standard deviation were entered and the underlying distribution was assumed to be log-normal, once more in line with the approach used by Brown et al. (2008) to derive EMCL values from empirical data. In this way, it was possible to compare 40 values for the terrestrial ecosystem and 44 values for aquatic systems (36 of which were freshwater and 8 marine). If an empirical value was based on a single observation, then an exponential distribution was assumed; this was only required in 9 cases.

2.2 Testing the efficacy of different extrapolation approaches used in ERICA

The element-reference organism combinations for which recent CR data have been collated tend to be those cases that originally employed a preferred option such as utilisation of taxonomic analogues, similar reference organisms or previously published review/recommended values. Over 82 % of the tested approaches fell into these preferred options in the initial analyses. Therefore, many of the extrapolation methods have not been considered in the comparison described above. For this reason, in the second part of the present work, attempts were made to give consideration to all the methods that have been previously used when generating values for the ERICA Tool databases. This has been undertaken for the marine ecosystem only, the other two ecosystems having been considered more thoroughly in the initial analysis described above (reflecting the fact the marine CR values have changed the least from those of the ERICA compilation (Howard et al., in press)).

Radionuclide-reference organism combinations have been selected where the original ERICA Tool default CR was based on empirical data (generally with 3 or more observations). It was then assumed that no data were available and the extrapolation guidance followed to generate a surrogate value. The surrogate value and empirical data were then compared to indicate whether the guidance provided sensible proxy information. Ninety-fifth percentile values were derived using the ERICA Tool as described above.

3. Results and Discussion

3.1 ERICA extrapolated default values versus newly acquired CR data from the wildlife transfer database

3.1.1 Terrestrial

For the terrestrial datasets (Figure 2 and Table 1), approximately 63 % of the CR 95th percentile predictions based on extrapolation approaches, fell within one order of magnitude of the 95th percentile empirical values (i.e. 25 of 40 extrapolated 95th percentile values fell in the range 0.1 to 10 times the corresponding empirical values). The extrapolation approaches underpredicted the 95th percentile (21 of 40 values) approximately as often as they overpredicted (19 of 40 values). Therefore, the extrapolation guidance if applied generally across all types of plants and animals does not necessarily ensure conservatism in the estimated value. In view of the requirement to account adequately for uncertainty in impact assessments and the conservative nature of the assessment tiers wherein default CR values are applied, this is not satisfactory.

More understanding can be gained from disaggregating the data to consider whether trends exist for particular elements or organism groups. Predictions for Ce (based upon general review, stable element and taxonomic analogue information) appeared to produce conservative estimates. The same appeared to be true for Co and Eu in plants with close to empirical predictions being made for Co in lichen and bryophyte. Extrapolation guidance, when applied to Pu, seemed to produce conservative estimates for birds and reptiles (based on mammal CRs) but yielded slight underpredictions for lichen and bryophyte (based on biogeochemical analogues) and shrubs (based on generic review). For radionuclides other than those considered above and apart from the numerous cases where the number of organism groups covered for a particular radionuclide was too low, i.e.<3 groups encompassed, to make useful comment about trends, there was more of a tendency for the guidance to produce underpredictions than overpredictions. Especially in the case of Sb in grass and shrub (based on generic review values), the degree of underprediction was substantial although the empirical data for grass consists of only one value. Furthermore, the IAEA TRS values for CR in shrub include some exceptionally high values (from Ghuman et al., 1993) raising questions over the suitability of this particular dataset, which originates from observations around an operating nuclear facility, for inclusion in generating equilibrium CRs. The predicted values for reptiles (based predominately on a Similar Reference Organism) were, with the exception of Pu, below the corresponding empirical values and for Po and U predicted values were approximately a factor of 4000 below measured data. However, the high values result from the inclusion of CR values derived for reptiles at a site in Australia contaminated by windborne spray from wet acidic mine tailings. The use of these data in a generic database has previously been questioned (Wood et al., 2010).

3.1.2 Aquatic

For the aquatic (freshwater and marine) ecosystems, the extrapolation approaches used for the ERICA Tool generated 95^{th} percentile CR predictions that fell within one order of magnitude of the 95^{th} percentiles for empirical data in approximately 64 % of cases (Figure 3 and Table 2). This corresponded to 28 of 44 cases of extrapolated 95^{th} percentile values falling in the range 0.1 to 10 times the corresponding empirical values. Therefore, the application of extrapolation approaches to aquatic ecosystems produced a similar level of efficacy to that observed for the terrestrial ecosystem. However, the guidance, when applied to the aquatic system, had a greater tendency to produce conservative values, with a resultant 27 overpredictions compared to 17 underpredictions. Nonetheless, this is still unsatisfactory for application in an environmental impact assessment in that the guidance is not consistently providing values that are conservative. Conversely, some of the predictions being produced are arguably overly conservative falling at levels 3-4 orders of magnitude above the empirical 95^{th} percentiles. This may lead to unnecessarily restrictive screening assessment results and suggests that the guidance or its application may require refinement.

In considering trends for particular radionuclides, the number of reference organism groups covered per radionuclide was often too small (<3 organism groups covered) to allow any additional comment to be made. Where the number of organism groups encompassed was larger, in the cases of Ni, P, Pb and Se, the application of the extrapolation approach produced over and underpredictions, approximately, in equal measure. A consideration by reference organism group was more informative. The guidance provided conservative estimates for vascular plants in freshwater ecosystems. This derivation was based on biogeochemical analogues, for Eu and Np, and the use of a marine value for Pb as described by Hosseini et al. (2008). Conservative estimates were also derived for vascular plants in marine ecosystems (a similar reference organism, macroalgae, was used by Hosseini et al. (2008) in all cases for the elements Co, Sr and I). Although this conservatism might be deemed acceptable in the context of screening assessments, the degree of overprediction is quite substantial (predictions are greater than one order of magnitude above empirical data although only I in marine exceeded by two orders of magnitude). Evaluation of the Wildlife transfer database (2012) suggests that marine macroalgae tend to have much higher concentration ratios than marine vascular plants for the few element where values are reported for the latter. However, there were two notable exceptions, U and Mn, where the macroalgae values are lower. There is little evidence to suggest that using marine data as a proxy for freshwater data is appropriate although admittedly there is no overwhelming evidence to the contrary. A consideration, for example, of the comparison provided by Howard et al. (in press) for molluscs in aquatic ecosystems suggests that for this particular case CR values between ecosystems generally fall, with the exception of I, within 1 order of magnitude of one another. Nonetheless, using marine mollusc CRs for Cs, Sr and Pu as proxies for the corresponding freshwater CRs would lead to some underprediction and substantial overprediction for I.

3.2 ERICA extrapolation guidance versus ERICA empirical CR data for marine organisms

Comparing CR values derived using extrapolation guidance with data from the ERICA empirical database for marine organisms (Hosseini et al., 2008), the predicted 95th percentile values fell within one order of magnitude of the corresponding empirical data in 63 % of cases (Figure 4) which is consistent with the similarity between predicted and observed in the analyses discussed above (ERICA predicted versus TRS 'observed' values). All but one predicted value fell within two orders of magnitude of the measured values. Results from this analysis are compared for individual extrapolation approaches below.

3.2.1 Similar taxonomy and reference organism (preferred options)

The rationale behind using CR values from organisms with a similar taxonomy or more general characteristics (i.e. similar reference organism) was based upon a number of working hypotheses concerning the transfer of radionuclides from the ongoing work of several research groups. For example, work with chondrichthyan and teleost fishes has indicated that accumulation from seawater for a broad suite of radionuclides may be influenced by phylogeny (Jeffree et al., 2010). Soil-to-plant transfer has also been shown to be influenced by phylogeny at least in the case of monocots and eudicots (Willey, 2010). Similarly, Yankovich et al. (this issue) have demonstrated a phyologentic effect on the transfer of Cs to fish using the data analyses approach described by Willey (2010). Although, strictly speaking, phylogeny systemizes living organisms in relation to evolutionary history whereas taxonomy characterises according to shared traits, the two are closely related as phylogenies are often inferred by identifying biotic features. The guidance to use similar taxonomic or similar reference organisms for the derivation of CRs might therefore be expected to provide appropriate surrogate values.

The taxonomic analogue approach was, for marine systems in the ERICA database, largely used in the derivation of values for (a) invertebrates (e.g. using molluscs as a proxy for worms (polychaetes)) and for (b) marine plants (e.g. using macroalgae as a proxy for vascular plant). Therefore focus has been placed on these organism categories in this assessment. The similar reference organism approach was widely used in deriving bird CRs via the application of mammals CRs and in a few cases in deriving mammal CRs via the application of fish CRs (i.e. using data for one vertebrate reference organism for a different vertebrate reference organism). In retrospect, on revisiting the way in which the extrapolation guidance was applied, it seems clear that the distinction between the taxonomic analogues and similar reference organisms was sometimes ambiguous. For example, treating macroalgae and vascular plants as taxonomic analogues is questionable bearing in mind that they belong to two separate phyla.

Comparison of derived values using the taxonomic analogue or similar reference organism approach and empirical data are presented in Table 3.

The taxonomic analogue approach gave 95th percentile predictions for Cs, Pu and Mn in polychaetes (worm) that fell within one order of magnitude of the empirical 95th percentile. Although Cs CRs for vascular plant do not appear to be particularly well represented by Cs CRs for macroalgae, the guidance 95th percentile values are again within one order of magnitude of the empirical 95th percentiles and at least provide a conservative prediction. In 4 of the 5 cases using the taxonomic analogue approach it is not really possible to draw any robust conclusions because the number of observations are so low. However, derived values (95th percentile) are generally within one order of magnitude of empirical (95th percentile) CRs although they are not consistently conservative.

The predictions of CRs derived from the guidance to use a 'Similar reference organism' provide a similar level of efficacy to that observed for the taxonomic analogue approach. With the exception of Pu in 'Bird', all derived 95th percentile values fall within one order of magnitude of the empirical 95th percentiles. Again the approach does not appear to provide necessarily conservative estimates.

3.2.2 From published reviews

In the absence of empirical information on CRs for the marine environment, recourse was most often made to IAEA (2004) which was developed with human impact assessment in mind. Consequently the values presented in IAEA (2004) are for marine organisms as consumed by humans and when they were originally used (i.e. at the time of completion of the first version of the ERICA Tool) no amendments of the values to whole organism were made. In light of new information on tissue to whole-body conversion factors (Yankovich et al., 2010) such amendments should now be performed if IAEA (2004) values were used to provide CR values for environmental assessment. A comparison of selected values from the ERICA CR databases with those from IAEA (2004) is made in Table 4.

The Cs CR values correspond closely;   Cs is known to be distributed more or less homogeneously within organisms and therefore, by example, CRs derived for the nominally edible parts of fish ('nominally' as IAEA (2004) weights CR data to account for the slight contamination of industrially prepared fillets by bone and body organs and the consumption of a small proportion of some fish, such as anchovies, in their entirety) might be expected to correspond to whole body concentrations as characterised by the ERICA review. The Pu CR data for fish are somewhat more noteworthy. In this case, the IAEA (2004) values are slightly higher for (the nominally edible parts of) fish compared to the empirically derived ERICA value for which a correction factor has been applied to weight for the known accumulation of Pu in other (normally not ingested) body organs. There is an expectation that the IAEA (2004) values would underestimate whole body concentrations. Nonetheless, the 95th percentile based on the IAEA value is a factor of 2 higher than the empirically based 95th percentile.

The Pu CRs for Polar bear muscle "recommended" by the IAEA is substantially lower that the empirical ERICA value which is partly explained by the use of a muscle to whole-body conversion factor of 9 used within the ERICA database. Pinniped muscle Cd CR 95th percentile values from IAEA (2004) correspond reasonably with ERICA CR data for mammals as do 95th percentile CR values for Mn in crustacean although the latter provides an underestimate by more than a factor of 5.

The use of published review data for CRs would not be expected to generate conservative estimates in the absence of empirically derived data as the published values will tend to be 'best estimates'. It should be noted that the ERICA database has drawn upon some common literature sources with IAEA (2004) but the latter provides a set of "recommended" values with no underlying statistical information. This overlap of source data arguably limits the usefulness of this particular comparison.

3.2.3 Similar (a) biogeochemistry, (b) biogeochemistry and taxonomy and (c) biogeochemistry and reference organism

Using elements from the same group or, as in the case of lanthanides and actinides, series would also appear to have some potential in providing suitable analogue parameters for transfer (Varga et al., 2009). At a simple level of understanding, elements from the same group exhibit the same oxidation state, bind in the same way to ligands within natural systems and therefore might be expected to express similar mobility and bioavailability under the same environmental conditions. Of course, this initial simplistic consideration is complicated by the fact that many elements express two or more valence states and are often more strongly and differentially influenced by the chemistry of the surrounding media than by general laws related to their oxidation state or binding characteristics. Moreover, despite their chemical similarity, elements from the same group or series may have different biological function (Varga et al., 2009). Sheppard and Evenden (1990) in their analysis of one species of plant concluded that CR values for various elements generally reflected the periodic classification of the elements and that interpolation using periodic classification might therefore be considered justifiable. However, when considered over numerous plant species, CR values as a function of chemical group showed only a limited correlation (Higley, 2010). Noting this limitation, the same author suggested that ionic potential may have more utility as an indicator of the potential for cations to form water-soluble forms, thereby enhancing bioavailability, and thus providing a means to estimate transfer in the absence of direct empirical information.

In populating the ERICA marine transfer database, approaches based around similar biogeochemistry (sometimes in combination with taxonomic analogues or similar reference organisms) were primarily applied for actinides, lanthanides and the group II element Ra, where Sr was used as the analogue. The comparison between derived guidance values and empirical data from ERICA is shown in Table 5.

The predictions made using the extrapolation approaches based around similar biogeochemistry are not particularly robust and 95th percentile predictions are at least one order of magnitude higher or lower than the 95th percentile in approximately half of the cases considered. Using Am as an analogue for Cm provided surprisingly poor predictions in view of the fact that both form (III) valence complexes and are considered to have broadly similar environmental behaviours (and have been consider as such in IAEA (2004) by using them as biogeochemical analogues in the derivation of transfer parameters). Ce appears to provide a reasonable analogue for Eu, although the datasets are arguably too small to establish any definitive conclusions. The use of Sr as an analogue for Ra appears to work reasonably well for mollusc but less so for fish, leading to 95th percentile estimates that fall more than one order of magnitude below the 95th percentile based on empirical data.

The derived values do not generally provide conservative estimates, in 8 of the 11 examples, the empirical 95th percentile value is greater than the derived 95th percentile value.

3.2.4 Allometric or other modelling approaches

Dynamic or biokinetic models predict the transfer from the environment to plants and animals using mathematical expressions that take into account variations in environmental activity concentrations over time. Typically, such models are characterised by discrete compartments representing particular abiotic and biotic components within the environment, and with transfer from or between compartments being described by rate constants, e.g. rates characterising biological half-lives of uptake and elimination (ICRP, 2009). Allometry, or 'biological scaling', involves the consideration of the effect of mass on biological variables such as transfer factors. The approach has been applied in a number of radioecological models in recent years (Higley and Bytwerk, 2007, Vives i Battle et al., 2007) and is often used in combination with kinetic or biokinetic models in the process of parameterisation (Brown et al., 2004).

In the ERICA marine database, biokinetic-allometric models have been applied in the derivation of a limited suite of values for Mammals and Birds extending to the (radio)elements Ra, U, Tc, Th, and Np. The models applied, which include multi-compartmental models for organisms in some cases, have been reported in Brown et al. (2003). As the models were developed explicitly for mammals and (sea)birds, these reference organisms have been considered for a suite of selected radionuclides (Table 6).

For the Pu predictions in mammal and bird, the CR values reported, like those for all other radionuclides, are for equilibrium conditions. However, in the case of mammals the predicted time to equilibrium was in excess of 250 years and in the case of bird in excess of 10 years. This suggests that equilibrium between abiotic and biotic environmental compartments, will not have occurred over timescales commensurate with the organisms life span or contact time with a particular contaminated environment. However, although predictions made for mammals at equilibrium might be expected to be conservative they actually produce CRs lower than empirical values. Assumptions concerning the organisms' diet and CR values for prey species substantially influence the kinetic allometric modelling results and undoubtedly partly explain the differences observed between modelled and empirical data.

The values derived in applying biokinetic models for radiocaesium are reasonably close to the mean values from the empirical datasets. However, application of the models for other radionuclides is less than robust, with derived 95% percentile CR values often exceeding one order of magnitude above or below the corresponding empirical data.

This modelling approach does not produce consistently conservative estimations for CRs. For Po in mammal the approach appears to substantially underpredict whereas for Sr in mammal the derived value is elevated compared to the empirical data. This latter result parallels the analysis undertaken by Beresford et al. (2010), where models based on biokenetic-allometric approaches had a tendency to overpredict the transfer of ^{90}Sr to some bird and small mammal species in terrestrial environments. Nonetheless, in the same study biokinetic-allometric models were considered to perform no worse than CR approaches in the derivation of whole body activity concentrations for selected radionuclides in selected biota.

3.2.5 Highest available value (least preferred option) and Combination of approaches

In practice the 'highest available' value approach was never actually applied for the marine ecosystem in deriving ERICA marine CR values. Nonetheless, a simple test was performed by selecting one organism type, in this case mammal, discarding the associated CR data and keeping all available CR data across the remaining suite of reference organisms considered before selecting the highest value as surrogate data (Table 7).

A combined approach was applied in 4 cases during the process of deriving values for the marine CR database and concerned the reference organisms reptile and bird and the (radio)elements U, Th, and Np. For this test, a decision was made to make predictions for mammal (for sake of consistency with the 'highest available' prediction), based on the similar reference organism (Sea)bird. The allometric biokinetic models presented for (Sea)bird in Brown et al. (2003) have been used to predict values for mammals in conjunction with the selection of a biogeochemical analogue in order to test the predictive efficacy of the 'combined approach' as it was used in the derivation of ERICA marine values (Table 7).

The predictions made for CRs using the 'highest available' derived values are quite pessimistic (predicted 95th percentiles are more than 10 times higher than observed 95th percentiles) for Pu and Co but match closely with empirically-based values for Cs and Po. Although it was not a great surprise that the Mammal CR prediction for Cs was reasonable having been based on a best estimate for the closely (phylogenically speaking) related bird, the proximity of the mammalian (95th percentile) Po CR to the corresponding derived value was perhaps more surprising as the latter had been derived from data for zooplankton.

In all the example cases, the derived value provides a conservative estimate for the CR. However, the production of a conservative value is by no means guaranteed in applying this approach and will clearly depend on data coverage, notably regarding which reference organism CR data are available for. To illustrate this point, if, in deriving Cs CRs for mammal based on the example and datasets given above, only macroalgae data had been available, a best estimate of 42 would have been employed resulting in a substantial (although still below an order of magnitude) underprediction.

The derived value for Pu using the ‘combined approach’ compares well with the value based on empirical data which is probably more a case of ‘luck than judgement’ whereas the derived value for Sr differs considerably from the empirical value. It is not possible to draw definitive conclusions based on this analysis but it might be expected that combined approaches will not necessarily produce particularly inferior predictions to approaches involving biogeochemical based methods or allometric or other modelling approaches.

3.2.6 Reference organism in a different ecosystem (least preferred options)

This approach was not applied for the marine system although it was applied to generate default freshwater CR values as discussed above (Section 3.1.2)

4. Conclusions and other considerations

An important overall conclusion is that the extrapolation methodologies are not guaranteed to overpredict 95th percentiles although we should acknowledge that some (e.g. using review data) could not be expected to provide conservative values. For the terrestrial ecosystem the extrapolation methods provide underpredictions of 95th percentiles as often as they produce overpredictions. In a few cases, when considering all ecosystems, the underestimation of CR values is substantial – by orders of magnitude – which is clearly unacceptable for a screening assessment.

In terms of implications for ERICA Tier 1 EMCLs (as defined in the introduction) , it is important to note that no special focus was placed on the application of approaches for limiting organisms, i.e. those organisms for which the dose per unit media concentration for a given radionuclide is highest and thus those organisms that determine the various EMCLs. Although the analyses were not for limiting organisms in most cases, the general outcome from this work, leading to the avoidance of some extrapolation approaches whilst placing more emphasis on others, may result in substantial changes in the values used for CRs in some cases. In conjunction with the use of newly acquired data from the wildlife database allowing application of more preferred options like the use of similar reference organisms, it is quite easy to envisage that limiting organisms and EMCL values could be radically changed as new data and revised guidance are applied.

The stochastic nature of the analyses conducted in this work means that results for the 95^{th} percentile are not precisely reproducible. Re-running probabilistic determinations, using techniques like the Monte Carlo simulations employed at Tier 3 of the ERICA Tool, can lead to variations in the 95^{th} percentile in the range 0.5 to 1.5 of the mean value. Nonetheless, this has no implications for the general conclusions drawn from this work. With regards the robustness of the extrapolation values, a further consideration might need to be given to the number of sites from which the empirical data were derived. In cases where the empirical data are based on a few values or data from very few sites (often reflected in a low values of ‘n’ in the tables above), it is impracticable to ascertain through comparison whether the predicted values are robust or not (unless the values are very different, i.e. orders of magnitude). Essentially, because of large natural variability in concentration ratios, data from a single site that are within an order of magnitude of generic data cannot be considered significantly different from the generic data (Sheppard, 2005).

Further refinement of the application of extrapolation approaches to derive surrogate values might be attained through a more elaborate consideration of probability distribution functions (pdfs). An alternative to using a best estimate and exponential pdf as currently employed in the ERICA Tool is to use more expansively the statistics provided by a surrogate dataset, e.g. the arithmetic mean, standard deviation and actual (or assumed) distribution of the biochemical analogue or similar organism dataset being used to provide a surrogate 'best estimate' value to which an exponential distribution is then applied. This has the advantage of avoiding the use of exponential distributions which tend not to reflect the distributions observed for parameters in natural systems. These tend to more often follow normal or log-normal distributions. Nonetheless, this can clearly be employed only where surrogate values are based on a dataset made up of 'sufficient' values. Data from models and recommended values from reviews are unlikely to have pdfs associated with them. Consideration should be given to using this approach in the next version of the ERICA Tool.

4.1 Recommendations

Comparison of 95th percentile CR values derived using extrapolation approaches from ERICA with newly acquired information from the wildlife database (Copplestone et al., this issue) for both terrestrial and aquatic ecosystems show that the surrogate 95th percentile values are conservative or fall within one order of magnitude of the 95th percentile empirical values in most cases. Nonetheless, in excess of 14 % of the 95th percentile predicted values are at least 1 order of magnitude below the empirical 95th percentile values and although over-prediction might not be considered as critical, the >22 % of values that are at least 1 order of magnitude greater than empirical values might raise concerns over the appropriateness of some of the values used in screening assessments. Because this first comparison was biased towards a limited number of approaches, the various guidance methods were applied in a second, more systematic way for the ERICA marine datasets. These analyses and other considerations lead us to recommend amendments of the extrapolation approaches used for the derivation of surrogate values for the initial ERICA Tool datasets as described by Hosseini et al. (2008) and Beresford et al. (2008b). We recommend that:

- There is some simplification of the various options (e.g. simply use similar reference organism (alternatively ‘surrogate organisms’) rather than similar taxonomy and similar reference organism);
- On the basis of the above comparison we currently suggest that selecting a CR value for a ’similar reference organism’ (as redefined above) should be used as an approach of choice to select CR values for screening level assessments.
- Less reliance on a guarantee of predictive robustness can be placed upon approaches using similar biogeochemistry (with and without combinations with taxonomic analogue and similar reference organisms) and such approaches should thus be applied with great care. The ‘ionic potential’ approach, as described by Higley (2010), requires further consideration as a more scientifically based alternative.
- Adopting best estimate CR data from other models or reviews should not be expected to result in conservative estimates. Nonetheless, careful consideration and adaptation of such values, for example by selecting high percentiles from underpinning datasets or applying uncertainty factors should render them suitable for use in screening assessments if more robust alternatives are not available.
- If using allometric, or other similar models, to derive values for birds and mammals careful consideration of the assumed dietary parameters is required (perhaps an indicator of appropriate diet choice would be to model the organism for an element for

which there are data to ensure the diet parameterisation gives acceptable results or select a diet which is likely to result in a comparatively high predicted CR value).

- Rather predictably, the adoption of the highest available value is likely to result in a conservative estimate of the 95th percentile CR value if a poor best estimate value. However, consideration should be given to the available data from which the highest CR can be selected (i.e. applying your knowledge do you anticipate that the organism you are deriving a value for is likely to have the highest CR value?).
- Given the main aim is to derive values for initial screening tier application in the lack of specific data it could be argued that the highest available CR value is always used. However, we feel that this may result in screening assessments which lack plausibility and could be overly restrictive, especially given the other conservative assumptions made, and hence not fit for purpose.
- If more than one possible value is available then the highest of these should be selected for the sake of conservatism (e.g. if a CR for reptile were required and data for bird and mammal were both available the highest CR value for the two groups should be used).
- Although the 'similar reference organism' option is our preferred approach, weight of evidence may on occasions justify the use of an alternative approach. Indeed weight of evidence may on occasion justify the use of a value derived by an extrapolation approach rather than the use of a very limited dataset which does not agree with available knowledge especially if it would result in a non-conservative screening assessment result.
- We advise against the application of data from different ecosystem types unless further investigation of this approach can validate its use (e.g. the database described by

Copplestone et al. (this issue) contains data for estuarine species – these may be appropriate surrogates for other aquatic systems and vice versa).

The topic of defining, evolving and providing the scientific justification for extrapolation techniques is the subject of on-going and recently published work, e.g. phylogeny (Jeffree et al. in press; Yankovich et al. this issue; Willey 2010), application of Bayesian statistics (Hosseini et al. this issue), allometry (Higley 2010), use of surrogate organisms (Tagami & Uchida, 2010; Beresford et al. this issue) and using ionic potential rather than the traditional biogeochemical analogue approach as described above (Higley 2010). As extrapolation approaches evolve it would be prudent to test their predictions using an approach such as that presented in this paper although this would be subject to the availability of appropriate data and too much emphasis should not be placed on comparisons where there are few data (i.e. limited data may not provide a better generic value than a reliable extrapolation approach).

Finally, the present work highlights the possible pitfalls associated with use of extrapolation approaches. It is clear that extrapolation approaches will remain an essential component of screening assessments in the future because data gaps will always be present. However, assessors should be aware of the limitations in applying such approaches and the results they produce. Last, but not least, it is important that the extrapolation methods be reported transparently to provide some indication of the robustness of assumptions and uncertainties associated with the results obtained.

Acknowledgements

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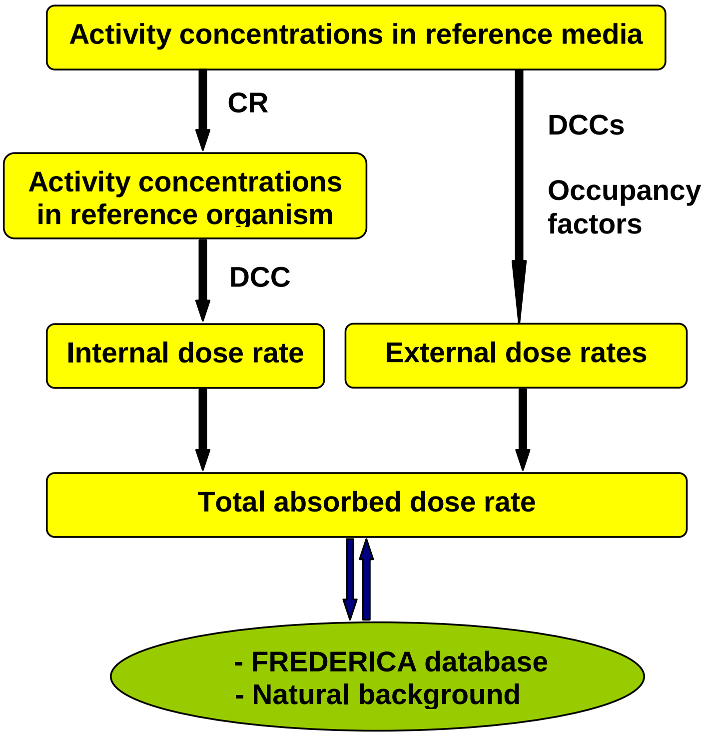
Figure Captions

Figure 1.The ERICA Tool assessment. CR = concentration ratio (see below), DCC = dose conversion coefficient (relating activity concentrations to dose rates); media is soil, water, sediment or air depending upon the ecosystem, available data and radionuclide under assessment. The FREDERICA (radiation effects) database is described in Copplestone et al. (2008).

Figure 2. Histogram showing distribution of the ratio of predicted (ERICA) to empirical (Copplestone et al. this issue and IAEA TRS) data for terrestrial organisms. The 'Bin' 0.1 corresponds to the interval 0.01 to 0.1 (i.e. an underestimate by a factor between 100 and 10) and 'Bin' 1 corresponds to the interval 0.1 to 1 etc.

Figure 3. Histogram showing distribution of predicted (ERICA)/empirical (Copplestone et al. this issue and IAEA TRS) data for aquatic ecosystems (comparisons for marine and freshwater ecosystems have been combined). The 'bin' 0.1 corresponds to the interval 0.01 to 0.1 (i.e. an underestimate by a factor between 100 and 10) and 1 corresponds to the interval 0.1 to 1 etc.

Figure 4. Histogram showing distribution of predicted/empirical data for aquatic (predominantly marine) ecosystems based solely on ERICA data. The 'bin' 0.1 corresponds to the interval 0.01 to 0.1 (i.e. an underestimate by a factor between 100 and 10) and 1 corresponds to the interval 0.1 to 1 etc.



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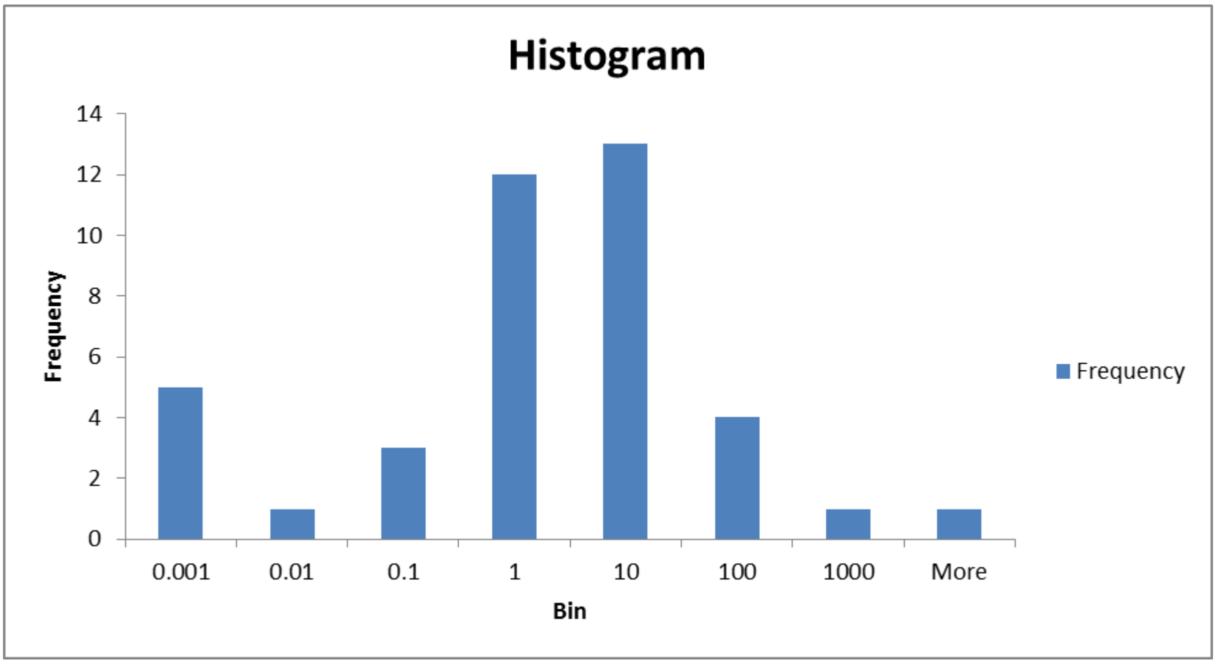

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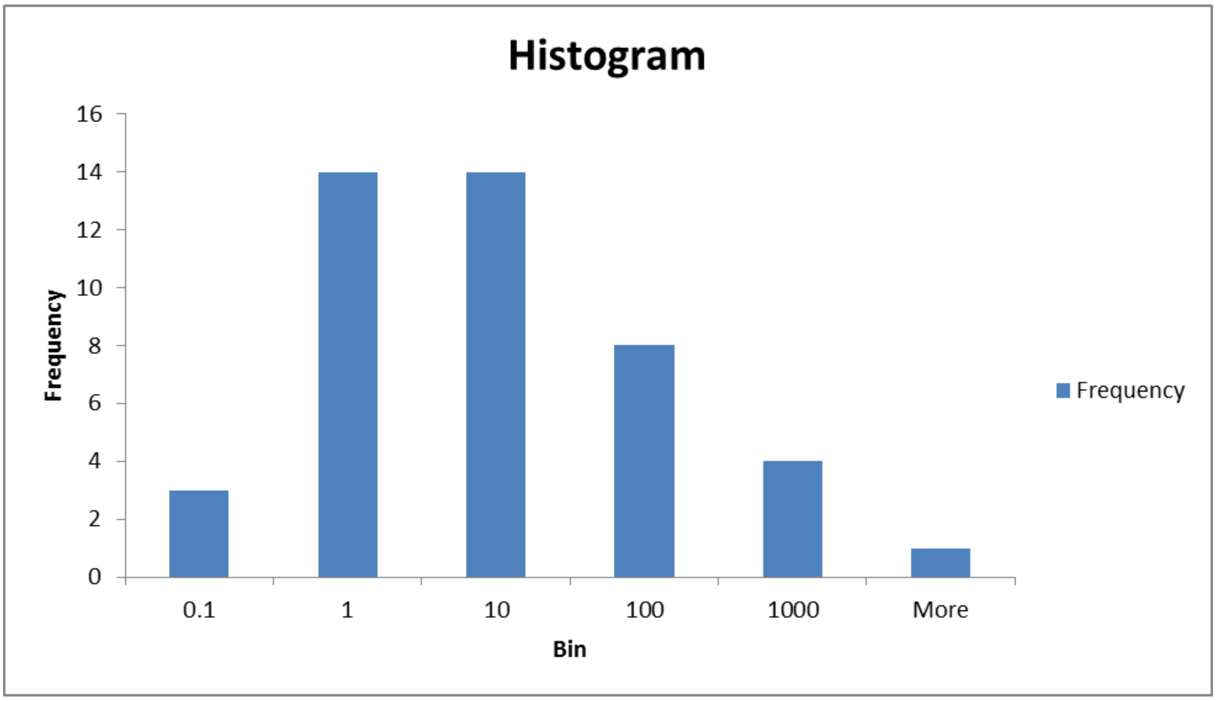

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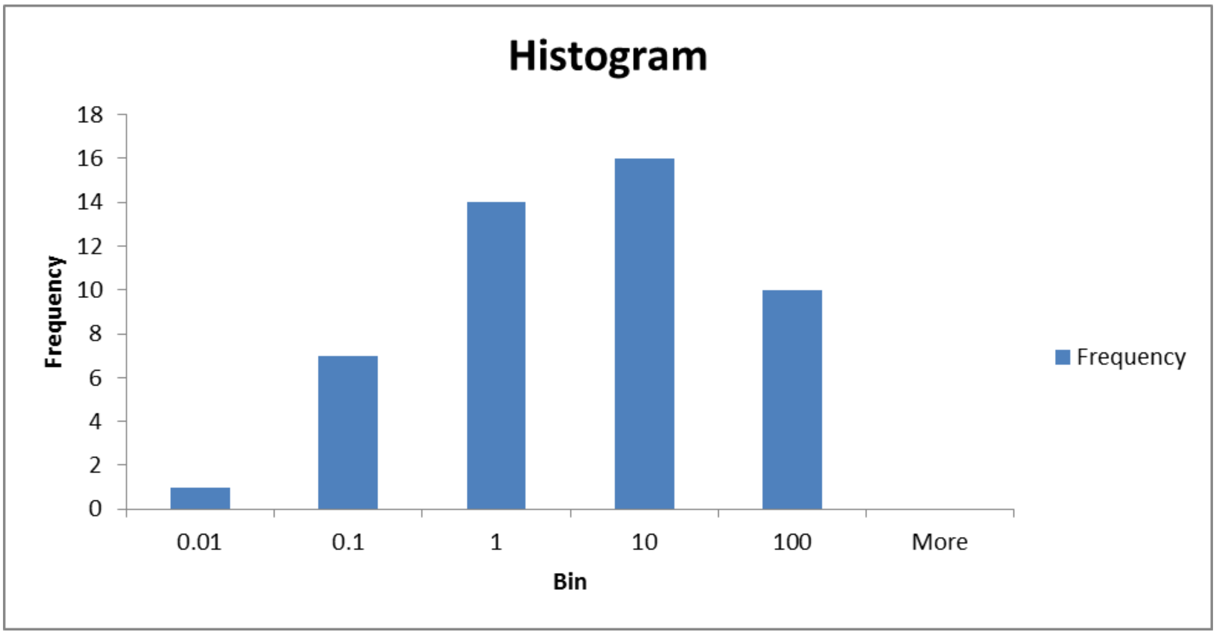

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Table(s)

Table 1. Statistical information for ERICA default values derived using extrapolation approaches and IAEA TRS values - terrestrial ecosystem. The ratio of ERICA(derived) values to the IAEA TRS (Howard et al., in press; Copplestone et al., this issue) are presented in the last column and summarized in Figure 1.

Organism and element	**ERICA - extrapolation**		**IAEA TRS**				**R*****
Amphibian	**Best est***	**95th%ile**	**Mean**	**SD**	**95th%ile**	**n**	
Am	4.1E-02 (*SRO*)	1.2E-01	1.3E-01	3.4E-02	1.9E-01	22	6.3E-01
Bird							
Am	4.1E-02 (*SRO*)	1.2E-01	3.2E-02	1.6E-02	6.1E-02	3	2.0E+00
Po	2.8E-03 (*SRO*)	7.7E-03	1.0E-02	2.9E-03	1.6E-02	5	4.9E-01
Pu	2.3E-02 (*SRO*)	7.3E-02	2.3E-02	4.8E-03	7.3E-03	26	1.0E+01
Grasses&herbs							
Ce	7.5E-03 (*ST*)	2.5E-02	4.7E-03	3.8E-03	1.1E-02	6	2.3E+00
Cm	2.8E-04 (*PR*)	8.1E-04	5.0E-04		1.6E-03	1	5.1E-01
Co	1.4E-02 (*PR*)	3.9E-02	4.2E-03	1.5E-03	6.7E-03	6	5.8E+00
Eu	5.2E-03 (*ST*)	1.6E-02	4.5E-03	3.3E-03	1.0E-02	6	1.6E+00
Sb	2.5E-02 (*PR*)	7.0E-02	4.5E+01		1.1E+02	1	6.2E-04
Lichen&Bryophytes							
Am	1.0E-01 (*ROSB*)	3.0E-01	1.2E+00	1.7E+00	3.4E+00	3	8.8E-02
Cd	1.2E+00 (*PR*)	4.0E+00	4.5E-01	1.2E-01	6.2E-01	30	6.4E+00
Ce	4.0E-02 (*PR*)	1.2E-01	1.3E-02	8.8E-03	2.6E-02	5	4.7E+00
Co	2.2E-01 (*PR*)	6.3E-01	2.4E-01	3.8E-01	9.5E-01	37	6.7E-01
Eu	6.8E-02 (*PR*)	2.1E-01	1.1E-02	7.5E-03	2.6E-02	5	8.0E+00
Mn	3.6E-04 (*PR*)	1.1E-03	1.5E+00	1.0E+00	3.3E+00	32	3.4E-04
Ni	8.6E-02 (*PR*)	2.8E-01	6.7E-01	1.6E+00	2.5E+00	108	1.1E-01
Pu	1.0E-01 (*ROSB*)	2.8E-01	1.3E-01		4.0E-01	2	7.1E-01
Sb	3.2E-01 (*PR*)	9.5E-01	3.9E-01	2.4E-01	9.1E-01	4	1.0E+00
Se	2.0E+01(*PR*)	6.2E+01	3.6E-01	2.0E-01	3.6E+00	18	1.7E+01
Reptile							
Am	4.1E-02 (*SRO*)	1.2E-01	6.4E-02	3.9E-02	1.5E-01	16	8.2E-01
Mn	2.5E-03 (*CA*)	7.5E-03	1.0E-02		2.9E-02	1	2.6E-01
Ni	7.2E-02 (*SRO*)	2.1E-01	3.0E-01		8.6E-01	1	2.4E-01
Pb	6.2E-02 (*SRO*)	1.6E-01	3.7E-01	1.0E+00	1.5E+00	45	1.1E-01
Po	2.8E-03 (*SRO*)	8.7E-03	9.5E+00	2.3E+01	3.7E+01	15	2.4E-04
Pu	2.3E-02 (*SRO*)	7.1E-02	3.3E-03	6.5E-03	1.2E-02	41	5.9E+00
Th	3.9E-04 (*SRO*)	1.2E-03	2.0E-01	4.8E-01	7.6E-01	18	1.5E-03
U	5.0E-04 (*SRO*)	1.6E-03	1.5E+00	3.1E+00	6.1E+00	21	2.7E-04
Shrub							
Ag	6.2E+00 (*PR*)	1.8E+01	2.1E-02	9.1E-03	4.0E-02	5	4.4E+02
Am	5.0E-03 (*ST*)	1.6E-02	2.7E-02	3.3E-02	8.0E-02	12	2.0E-01
Co	7.5E-01 (*PR*)	1.1E+00	7.2E-02	8.5E-02	2.4E-01	128	4.7E+00
Eu	2.4E-01 (*PR*)	7.1E-01	7.7E-03	8.0E-03	2.2E-02	11	3.3E+01
Pu	3.2E-02 (*PR*)	8.5E-02	8.9E-03	1.6E-01	3.3E-01	4	2.6E-01
Ru	4.9E-03(*PR*)	1.6E-02	4.1E-01	3.2E-01	9.5E-01	3	1.7E-02
Sb	2.4E-03 (*PR*)	6.6E-03	7.3E+00	1.5E+01	2.4E+01	8	2.8E-04
Tc	2.0E+01 (*ST*)	6.0E+01	1.2E-01	1.1E-01	3.0E-02	8	2.0E+03
Worm**							
Po	2.8E-03 (*HA*)	8.4E-03	1.0E-01	3.9E-02	1.2E-01	7	7.1E-02
Tree							
Ce	4.9E-02 (*ST*)	1.6E-01	3.3E-03		9.7E-03	2	1.7E+01
Cm	9.4E-03 (*PR*)	2.8E-02	9.4E-03		2.7E-02	2	1.0E+00
Co	1.8E-02 (*PR*)	4.1E-02	8.7E-03	1.3E-02	2.9E-02	7	1.4E+00
Eu	2.4E-01 (*ST*)	7.2E-01	3.1E-03	1.9E-03	6.6E-01	3	1.1E+00

*From Beresford et al. (2008a); **Annelid in IAEA TRS; ***R is the ratio of Guidance to TRS values (95th percentiles). (ST) CR for organism of similar taxonomy; (SRO) CR for similar reference organism; (PR) CR from published review/recommended values; (ROSB) CR for given reference organism for an element of similar biogeochemistry; (CA) Combined approach; (HA) highest available CR value available.

Table 2. Statistical information for ERICA default values derived using extrapolation approaches and IAEA TRS values (Howard et al., this issue; Copplestone et al., this issue) - aquatic ecosystems. The ratio of ERICA(derived) values to the IAEA TRS are presented in the last column and summarized in Figure 2.

Organism* and element	**ERICA - extrapolation**		**IAEA TRS**				**R*** **
	Best est**	**95th%ile**	**Mean**	**SD**	**95th%ile**	**n**	
Vascular Plant							
Eu	3.0E+03 (*ROSB*)	8.9E+03	7.8E+01	5.0E+01	1.6E+02	6	5.4E+01
Np	3.2E+03 (*ROSB*)	1.3E+04	2.2E+02	8.3E+01	3.6E+02	21	3.6E+01
Pb	1.0E+03 (*RODE*)	2.9E+03	6.2E+01	7.0E+01	1.8E+02	21	1.7E+01
Pelagic Fish							
Zr	3.0E+02 (*PR*)	9.7E+02	1.2E+02	2.0E+02	3.6E+02	20	2.7E+00
P	6.2E+04 (*ST*)	1.9E+05	6.6E+05	2.7E+05	1.2E+06	113	1.7E-01
Ni	1.0E+02 (*PR*)	2.9E+02	7.5E+01	1.2E+02	3.2E+02	116	9.0E-01
Eu	5.0E+01 (*ST*)	1.5E+02	6.8E+01	3.4E+01	1.4E+02	43	1.1E+00
Se	2.0E+02 (*PR*)	6.2E+02	4.2E+03	2.7E+03	1.0E+04	70	6.0E-02
Pb	3.0E+02 (*PR*)	9.2E+02	3.5E+02	7.8E+02	1.2E+03	201	7.8E-01
Benthic Fish							
Po	2.4E+02 (*ST*)	6.7E+02	1.6E+03	4.4E+03	5.2E+03	90	1.3E-01
Ce	1.5E+01 (*ST*)	4.1E+01	5.1E+02	7.3E+02	1.5E+03	44	2.8E-02
Ni	1.0E+02 (*PR*)	3.0E+02	3.6E+02	2.9E+02	9.0E+02	68	3.3E-01
Se	2.0E+02 (*PR*)	4.9E+02	6.2E+03	3.7E+03	1.1E+04	51	4.3E-02
Pb	3.0E+02 (*PR*)	8.3E+02	1.8E+02	6.3E+02	5.7E+02	148	1.4E+00
Crustacean							
Pb	1.0E+04 (*RODE*)	2.9E+04	3.9E+01	4.7E+01	1.1E+02	5	2.6E+02
Bivalve mollusc							
U	1.8E+02 (*PR*)	5.6E+02	5.6E+02	1.3E+02	8.0E+02	3	6.9E-01
Ni	6.4E+03 (*RODE*)	1.9E+04	1.2E+02	3.2E+01	1.8E+02	3	1.1E+02
Pb	1.7E+03 (*RODE*)	4.5E+03	6.0E+03	1.5E+04	1.8E+04	32	2.5E-01
Phytoplankton							
Co	1.0E+03 (*PR*)	3.3E+03	6.5E+02	1.2E+03	1.8E+03	35	1.9E+00
Th	4.0E+03 (*PR*)	1.1E+04	1.2E+04	1.0E+04	2.8E+04	30	3.9E-01
Zr	3.3E+04 (*RODE*)	9.9E+04	1.9E+03	8.0E+02	3.4E+03	10	2.9E+01
Cd	8.1E+02 (*RODE*)	2.5E+03	1.8E+03	1.2E+03	4.1E+03	30	6.0E-01
P	2.0E+03 (*PR*)	5.5E+03	1.3E+03	1.9E+03	3.8E+03	35	1.5E+00
S	8.4E+01 (*ST*)	2.3E+02	2.0E+02	2.9E+02	5.8E+02	25	4.0E-01
Gastropod							
Sr	2.7E+02 (*ST*)	8.2E+02	4.9E+02	7.0E+02	1.6E+03	60	5.0E-01
Pu	8.2E+02 (*SRO*)	2.2E+03	1.4E+03	2.3E+03	3.9E+03	50	5.6E-01
Sb	2.4E+02 (*ST*)	7.4E+02	4.9E+01		1.5E+02	1	4.9E+00
Se	5.0E+03 (*CA*)	1.5E+04	3.2E+03	2.9E+03	8.2E+03	3	1.8E+00
Insect Larvae							
Cs	1.0E+04 (*SRO*)	3.1E+04	2.0E+03	2.1E+03	6.6E+03	6	4.7E+00
Pu	1.1E+03 (*SRO*)	3.4E+03	2.5E+03		7.5E+03	15	4.5E-01
Sb	2.4E+02 (*SRO*)	7.0E+02	8.2E+01	6.9E+01	2.0E+02	14	3.5E+00
Se	7.1E+03 (*CA*)	2.0E+04	2.4E+03	1.9E+03	6.2E+03	9	3.2E+00
Zooplankton							
Se	6.0E+03 (*RODE*)	1.6E+04	6.6E+03	3.9E+03	1.5E+04	3	1.1E+00
Amphibian							
Pb	3.0E+02 (*SRO*)	9.2E+02	5.3E+00		1.6E+01	2	5.7E+01
Mammal							
Ra	8.0E+01 (*SRO*)	2.6E+02	2.1E-01	1.6E-01	5.1E-01	45	5.0E+02
Mn	9.8E+02 (*SRO*)	2.4E+03	3.4E+02	7.2E+02	8.7E+02	6	2.8E+00
Crustacean (marine)							
Np	1.0E+02 (*PR*)	2.6E+02	1.1E+02		2.9E+02	1	9.1E-01
Zo**oplankton (marine)**							
U	3.0E+01 (*PR*)	9.2E+01	3.7E+00	4.8E+00	1.2E+01	3	7.7E+00
Mammal (marine)							
P	1.9E+05 (*ST*)	5.5E+05	3.8E+04	1.1E+05	1.4E+05	11	4.0E+00
Anemone (marine)							
Mn	1.2E+04 (*ST*)	3.6E+04	1.0E+01		3.0E+01	1	1.2E+03
Ag	3.3E+03 (*ST*)	8.8E+03	1.3E+02		3.5E+02	2	2.5E+01
Vascular Plant (marine)							
Co	2.1E+03 (*ST*)	6.0E+03	5.2E+01	5.9E+01	1.5E+02	3	4.2E+01
Sr	4.2E+01 (*ST*)	1.3E+02	3.0E+00		9.3E+00	1	1.4E+01
I	4.1E+03 (*ST*)	1.2E+04	2.4E+01		7.3E+01	1	1.7E+02

* Freshwater unless (marine) stated; **From Hosseini et al. (2008); ***R is the ratio of Guidance to TRS values (95th percentiles). (ST) CR for organism of similar taxonomy; (SRO) CR for similar reference organism; (PR) CR from published review/recommended values; (ROSB) CR for given reference organism for an element of similar biogeochemistry; (RODE) CR from same reference organism in a different ecosystem; (CA) Combined approach.

Table 3. Statistical information on CRs for the applied ‘taxonomic analogue’ or ‘similar reference organism’ approaches (ERICA – extrapolation guidance) and corresponding empirical data (ERICA empirical)

Organism and element	Approach (analogue used)	ERICA – extrapolation guidance		ERICA - empirical				R*
		Best estimate	95th%ile	Mean	SD	95th%ile	n	
Worm								
Cs	ST (Biv)	6.6E+01	1.9E+02	1.8E+02	1.6E+02	4.4E+02	41	4.2E-01
Pu	ST (Biv)	1.1E+03	3.5E+03	1.5E+03	2.2E+03	5.5E+03	3	6.4E-01
Mn	ST (Biv)	1.2E+04	3.6E+04	3.2E+03		9.7E+03	1	3.8E+00
Vas. Plant								
Cs	ST (Malg)	1.2E+02	4.0E+02	2.2E+01	1.5E+01	5.5E+01	9	7.3E+00
U	ST (Malg)	1.2E+02	4.2E+02	2.3E+02	9.7E+01	3.7E+02	2	1.1E+00
Mn	ST (Malg)	8.7E+03	2.6E+04	3.0E+04	3.0E+04	8.4E+04	2	3.1E-01
Bird								
Cs	SRO (Mam)	2.2E+02	6.1E+02	4.6E+02	6.3E+02	1.3E+03	70	4.6E-01
Pu	SRO (Mam)	1.6E+03	5.3E+03	1.5E+02	5.5E+01	2.7E+02	6	2.0E+01
Mammal								
Cs	SRO (Fish)	8.7E+01	2.4E+02	2.2E+02	5.1E+02	5.5E+02	715	4.3E-01
Pu	SRO (Fish)	1.6E+03	4.5E+03	1.6E+03	1.5E+03	4.1E+03	19	1.1E+00
Cd	SRO (Fish)	9.6E+03	2.7E+04	4.7E+03	5.0E+03	1.3E+04	529	2.2E+00

ST = CR for organism of similar taxonomy,; SRO = CR for similar reference organism; Biv = Bivalve mollusc; Malg = Macrolagae; Mam = Mammal; *R is the ratio of Guidance to empirical values (95th percentiles).

Table 4. Statistical information on CRs 'from published reviews' approaches (ERICA – extrapolation guidance) and corresponding empirical data (ERICA empirical); published review values are all taken from IAEA (2004)

Organism and element	Approach	ERICA – extrapolation guidance		ERICA - empirical				R*
		Best est	95th%ile	Mean	SD	95th%ile	n	
Fish								
Cs	PR	1.0E+02	3.0E+02	8.7E+01	1.2E+02	2.9E+02	1764	1.1E+00
Pu	PR	4.0E+03	1.2E+04	1.6E+03	6.4E+03	6.2E+03	111	2.0E+00
Macroalgae								
Cs	PR	5.0E+01	1.4E+02	4.2E+01	3.4E+01	9.5E+01	569	1.4E+00
Mammal								
Pu	PR	7.0E+01	2.0E+02	1.6E+03	1.5E+03	4.1E+03	19	4.9E-02
Cd	PR	2.0E+03	5.7E+03	4.7E+03	5.0E+03	1.3E+04	529	4.5E-01
Crustacean								
Mn	PR	5.0E+03	1.4E+04	2.3E+04	7.5E+04	7.8E+04	14	1.8E-01

PR= CR from published review/recommended values; *R is the ratio of Guidance to empirical values (95th percentiles);

Table 5. Statistical information on CRs Similar (a) biogeochemistry, (b) biogeochemistry and taxonomy and (c) biogeochemistry and reference organism approaches (ERICA – extrapolation guidance) and corresponding empirical data (ERICA empirical).

Organism and element	Approach (analogue used)	ERICA – extrapolation guidance		ERICA – empirical				R*
		Best est	95th%ile	Mean	SD	95th%ile	N	
Mollusc								
Cm	ROSB (Am in Mollusc)	8.1E+03	2.2E+04	3.2E+04	2.7E+04	7.5E+04	10	3.0E-01
Eu	ROSB (Ce in Mollusc)	3.5E+03	1.1E+04	6.9E+03		2.1E+04	1	5.1E-01
Ra	ROSB (Sr in Mollusc)	8.1E+01	2.4E+02	6.5E+01	6.3E+01	1.7E+02	20	1.4E+00
Ra	STSB/SROSB (Sr in Crustacean)	1.2E+01	3.5E+01	6.5E+01	6.3E+01	1.7E+02	20	2.0E-01
Am	STSB/SROSB (Pu in Anenome)	4.9E+02	1.5E+03	8.1E+03	1.1E+04	2.7E+04	28	5.6E-02
Macroalgae								
Cm	ROSB (Am in Macroalgae)	9.2E+02	2.8E+03	1.2E+04	1.2E+04	3.5E+04	23	8.2E-02
Fish								
Eu	ROSB (Ce in Fish)	1.2E+02	3.6E+02	4.4E+02	3.0E+02	9.9E+02	3	3.6E-01
Ra	ROSB (Sr in Fish)	2.3E+01	6.6E+01	2.0E+02	3.8E+02	8.4E+02	47	7.8E-02
Crustacean								
Am	STSB/SROSB (Pu in Mollusc)	1.1E+03	3.3E+03	1.3E+03	1.4E+03	3.8E+03	20	8.8E-01
Vascular plant								
U	STSB/SROSB (Pu in Macroalgae)	4.2E+03	1.2E+04	2.3E+02	9.7E+01	4.0E+02	2	3.0E+01
Zooplankton								
Np	STSB/SROSB (Pu in Crustacean)	1.6E+02	4.7E+02	1.7E+01	5.0E+00	2.6E+01	2	1.8E+01

ROSB = CR value for the given reference organism for an element of similar biogeochemistry ; STSB = CR value for biogeochemically similar element for organisms of similar taxonomy; SROSB = CR value for biogeochemically similar element for a similar reference organism; *R is the ratio of Guidance to empirical values (95th percentiles).

Table 6. Statistical information on CRs 'Allometric or other modelling approaches' (ERICA – extrapolation guidance) and corresponding empirical data (ERICA empirical).

Organism and element	Approach	ERICA – extrapolation guidance		ERICA - empirical				R*
		Best est	95th%ile	Mean	SD	95th%ile	n	
Mammal								
Cs	MA	1.5E+02[b]	4.3E+02	2.2E+02	5.1E+02	8.0E+02	715	5.4E-01
Pu	MA	3.0E+01[a]	8.5E+01	1.6E+03	1.5E+03	4.0E+03	19	2.1E-02
Po	MA	7.6E+02[a]	2.3E+03	3.0E+04	3.6E+04	9.2E+04	3	2.5E-02
Sr	MA	3.2 E+02[b]	9.2E+02	1.6E+01	4.3E+01	5.6E+01	23	1.6E+01
Bird								
Cs	MA	5.4E+02[b]	1.6E+03	4.6E+02	6.3E+02	1.5E+03	70	1.1E+00
Pu	MA	5.4E+02[b]	1.6E+03	1.5E+02	5.5E+01	2.5E+02	6	6.4E+00

MA = allometric relationships, or other modelling approaches;
[a] derived using a multi-compartmental (single for Po) model for elimination normally based on models for man(from Brown et al., 2003); [b] Derived using an allometric relationship to derive a single component elimination rate; *R is the ratio of Guidance to empirical values (95th percentiles).

Table 7. Statistical information on CRs 'Highest available value or Combination of approaches'(ERICA – extrapolation guidance and corresponding empirical data (ERICA empirical).

Organism and element	**Approach**	**ERICA – extrapolation guidance (analogue used)**		**ERICA - empirical**				**R***
		Best est	95th%ile	Mean	SD	95th%ile	n	
Mammal								
Cs	HA	4.60E+02 (from Bird)	1.3E+03	2.2E+02	5.1E+02	7.4E+02	715	1.8E+00
Pu	HA	1.20E+05 (from phytoplankton)	3.9E+05	1.6E+03	1.5E+03	4.7E+03	19	8.2E+01
Co	HA	8.30E+03 (from Worm)	2.4E+04	5.0E+02	1.4E+03	1.8E+03	10	1.3E+01
Po	HA	7.10E+04 (from zooplankton)	2.0E+05	3.0E+04	3.6E+04	8.4E+04	3	2.4E+00
Sr	CA	5.20E+02 (Biokinetic model for Bird for biogeochemical analogue Ra)	1.5E+03	1.6E+01	4.3E+01	5.3E+01	23	2.8E+01
Pu	CA	1.65E+03 (>250 y to equilibrium); (Biokinetic model for Bird for biogeochemical analogue Np)	5.3E+03	1.6E+03	1.5E+03	4.7E+03	19	1.1E+00

HA = highest available CR value available; CA = Combined approach;*R is the ratio of Guidance to empirical values (95th percentiles).