Comparison of Dose Estimate Results from Radioecological Risk Assessment Models RESRAD-BIOTA, ERICA Tool and SENES Risk Model Using a Case Study

N. Garisto, R. Kovacs and A. Janes,
SENES Consultants Limited, Richmond Hill, Ontario, Canada

Abstract

There are many software programs designed to estimate the risk to non-human biota from exposure to radioactivity. Three models have been selected for comparison in this study: US DOE RESRAD-BIOTA Model, EC ERICA Tool and SENES Risk Model. It appears that the methodology for these models is similar, whereas the parameters used to model a case study are different, creating different outputs. Issues surrounding combined or 'lumped' parameters were identified with implications on the transparency and uncertainty of results. These issues are explored so that they may be avoided by choosing the appropriate model and implementation for a given scenario.

1. Introduction

The purpose of this project is to compare three popular radioecology risk assessment models to determine their similarities, differences and noteworthy characteristics. The three models selected for comparison are the ERICA Tool (ERICA Tool) [1], RESRAD-BIOTA Code (RESRAD Model) [2] and the SENES Risk Model (SENES Model) [3]. Each model is designed to perform the same overall function: to estimate the impact of radioactive material on non-human ecosystems. A common set of radionuclide concentrations were used in all three models. These concentrations are empirically derived values, obtained from on-site sampling of a case study location. A brief description of each model is provided below:

1.1 ERICA tool

The ERICA Tool is a software program designed to assess the potential exposure, dose and risk to non-human biota from scenarios involving the release of radioactive contaminants into the environment. The Tool is part of a larger framework called the ERICA Integrated Approach: a guide for the decision-making processes and assessment of environmental risk from ionizing radiation, with emphasis on the preservation of ecosystem structure and function [2]. The ERICA Tool can be used as part of the overall Integrated Approach, or as a separate computational model for both existing and simulated scenarios. Both the Approach and the Tool are designed to be simple enough to allow widespread use, yet intricate enough to properly assess a wide range of ecosystems.

The ERICA Tool and Integrated Approach are the final result of the *European Community (EC) 6th Framework Programme (FP) ERICA - March 2004 to February 2007;* an international project with input from several government initiatives from the United States, Canada, the United Kingdom, and over fifty other organizations across the globe.

1.2 RESRAD-BIOTA code (RESRAD model)

RESRAD is a suite of software programs designed to estimate the dose to receptors from residual radioactive source material. RESRAD-BIOTA is a member of the RESRAD software suite focusing on a graded approach to determining the dose to non-human biota from radioactive contaminants released into the environment. The original RESRAD Code was first released in 1989. It has been updated and expanded, including creation of the RESRAD-BIOTA program and others, by the United States Department of Energy (US DOE) with support from the United States Environmental Protection Agency (US EPA) and United States Nuclear Regulatory Commission (NRC).

While RESRAD can be used to simply compute estimated dose, it is not limited to this purpose. RESRAD programs are, by their design, able to estimate dose in various ecosystems and compare these data to DOE regulatory criteria in order to evaluate compliance. As a result, DOE maintains strict control over modifications to the RESRAD suite of programs and requires prior authorization before modifications can be made. RESRAD is capable of modeling doses to not only biota, but humans as well.

1.3 SENES model

The SENES Model is a proprietary software program and associated database developed by SENES Consultants Limited in order to conduct Environmental Risk Assessments of radioactive compounds released into the environment. The SENES model has been designed to maximize transparency, allowing the user to view all variables, results and intermediary calculations at any point. Examples of the specificity and transparency are explained in following sections. The SENES Model was first created in 2002 based on extensive reviews of established radioecological risk assessment methods and modern environmental data. In 2009 the SENES Model was upgraded to include current radioecological principles. It has been applied to nuclear reactor sites, uranium refining and conversion facilities as well as sites with mixed radioactive and chemical contamination. The databases and methodologies that support the SENES Model are updated regularly in order to supply the most modern, current data for use in assessments. The SENES Model is also capable of modeling dose to humans.

2. Parameter comparison

2.1 Kd values

Kd is the sediment-water equilibrium distribution coefficient. It represents a compounds' ability to partition itself from one medium to another. It is often used to estimate sediment concentrations from known water concentrations, or vice-versa.

For the case study, Kd values used were as follows:

Element	Kd SENES (L/kgDW)	Kd ERICA (L/kgDW)	Kd RESRAD[10] (L/kgDW)
Pb	2.70E+02[4]	1.00E+05[7]	4.00E+04
Po	1.50E+02[4]	2.00E+07[7]	6.00E+01
Ra	5.00E+02[5]	1.52E+04[8]	1.40E+02
Th	1.00E+05[6]	1.84E+07[8]	1.20E+05
U	3.30E+02[5]	5.00E+01[9]	1.00E+02

DW – Dry Weight

Table 1 Kd values selected for consideration in this paper.

Between the SENES and the RESRAD Models, the Kds used are similar within two orders of magnitude for all radionuclides presented in this study. The ERICA Tool has consistently higher Kd values, often three to five orders of magnitude higher than the other two models, with the exception of uranium. For uranium, Kds from all three models are similar within one order of magnitude.

With Kd values, the SENES model is generally in the middle of the three models with RESRAD values slightly lower and ERICA values much higher. However, for uranium, the SENES model is the highest of the three. Figures 1 to 4 have been included for a visual comparison of the data presented in Table 1.

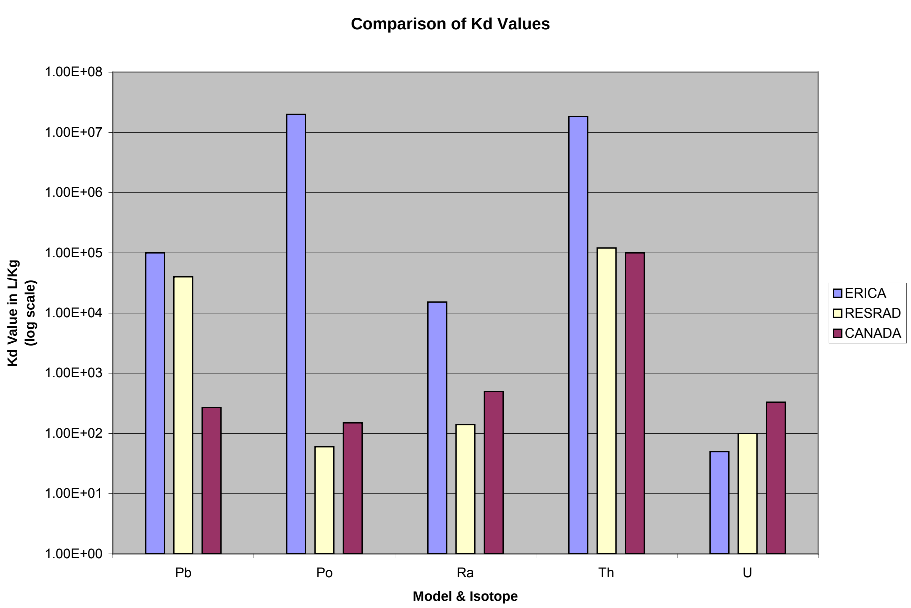

Figure 1: Log scale graph of Kd values for select radionuclides across three models

2.2 Dose Coefficients (DCFs)

In this study, the internal dose was the predominant factor. As such, the comparison focused on internal DCFs. All DCFs are shown with RBE correction factors already applied. The RBE correction factors used are as follows:

Type	SENES RBE [11]	ERICA RBE [2]	RESRAD RBE [1]
alpha	40	10	20
beta	1	3	1
gamma	1	1	1

Table 2 RBE factors from each model.

It is important to note that for lower trophic species, **Benthic Fish** was used as a representative biota in both the SENES model and ERICA. For RESRAD, **Aquatic Animal** was selected. For higher trophic species, in the SENES model a **Scaup** was selected. In the ERICA Tool, the general **Aquatic Bird** species was selected. In RESRAD, **Aquatic Animal** was again selected. The weighted DCFi (internal DCF) values used in each model are as follows:

Element	SENES DCFi [12] Benthic Fish (Gy/y per Bq/kgFW)	ERICA DCFi [2] Benthic Fish (Gy/y per Bq/kgFW)	RESRAD DCFi [13] Aquatic Animal (Gy/y per Bq/kgFW)
Pb-210	2.19E-06	2.28E-06	5.74E-04
Po-210	1.09E-03	2.72E-04	1.08E-02
Ra-226	9.84E-04	1.25E-03	6.04E-02
Th-228	1.77E-04	1.60E-03	3.30E-03
Th-230	9.64E-04	2.37E-04	9.60E-03
Th-232	8.24E-04	2.01E-04	8.04E-02
U-234	9.84E-04	2.45E-04	9.78E-03
U-235	2.46E-05	2.26E-04	4.53E-04
U-238	5.08E-05	2.10E-04	4.41E-04

*FREDERICA Database encompasses established data from the FRED and FASSET radiological effects databases, plus additional data from studies conducted during the ERICA project.
FW – Fresh Weight

Table 3 DCFi (internal DCF) values for benthic fish/aquatic animal from each model.

For benthic fish, internal DCFs (DCFi's) are comparable within one to two orders of magnitude for all radionuclides across all three models. While all three models are similar, the RESRAD model is generally the most conservative for DCFi values for all radionuclides.

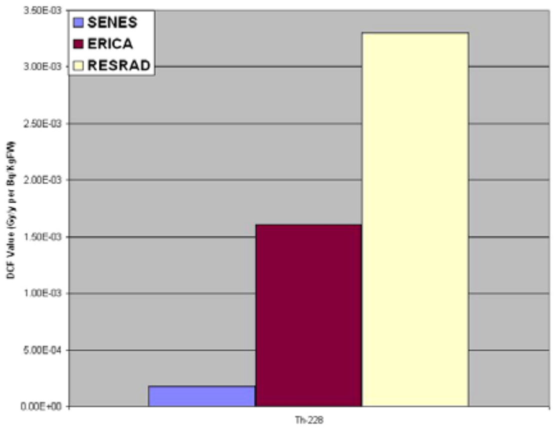

Figure 2 Graph of DCFi values for Th-228 to Benthic Fish across three models.

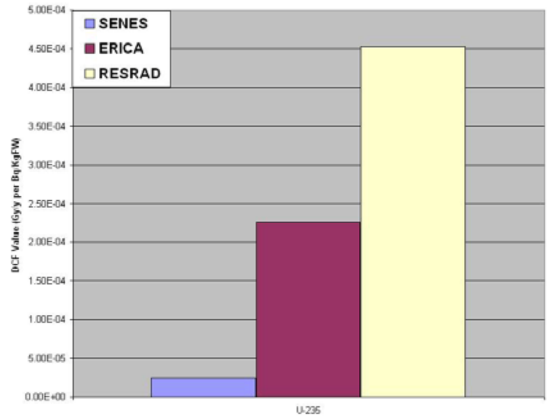

Figure 3 Graph of DCFi values for U-235 to Benthic Fish across three models.

Element	SENES DCFi [12] Scaup (Gy/y per Bq/kgFW)	ERICA DCFi [2] Aquatic Bird (Gy/y per Bq/kgFW)	RESRAD DCFi [13] Aquatic Animal (Gy/y per Bq/kgFW)
Pb-210	2.19E-06	2.28E-06	5.74E-04
Po-210	1.09E-03	2.72E-04	1.08E-02
Ra-226	9.84E-04	1.25E-03	6.04E-02
Th-228	1.77E-04	1.60E-03	3.30E-03
Th-230	9.64E-04	2.37E-04	9.60E-03
Th-232	8.24E-04	2.01E-04	8.04E-02
U-234	9.84E-04	2.45E-04	9.78E-03
U-235	2.46E-05	2.26E-04	4.53E-04
U-238	5.08E-05	2.10E-04	4.41E-04

*FREDERICA Database encompasses established data from the FRED and FASSET radiological effects databases, plus additional data from studies conducted during the ERICA project.
FW – Fresh Weight

Table 4 DCFi values for Scaup/Aquatic Bird/Aquatic Animal from each model.

For the aquatic bird species, internal DCFs are also comparable within one to two orders of magnitude for all radionuclides across all three models. While all three models are similar, the RESRAD model is generally the most conservative for all DCFi values for all radionuclides.

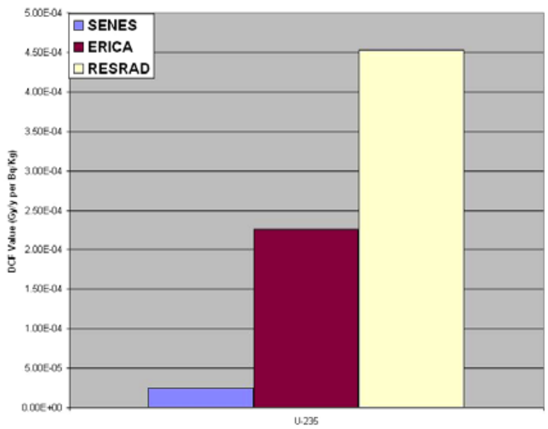

Figure 4: Graph of DCF values for U-235 to Aquatic Birds (Scaup) across three models.

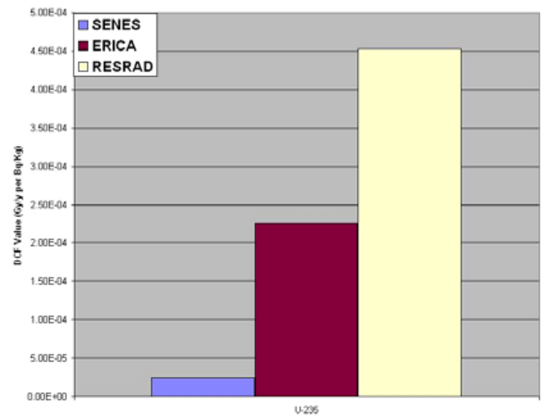

Figure 5: Graph of DCF values for Th-228 to Aquatic Birds (Scaup) across three models.

2.3 Bioaccumulation Factors

For all models, with lower trophic species such as fish and plants, a single bioaccumulation factor is used to convert media concentration into a biota tissue concentration. For higher trophic species, both the ERICA and RESRAD models still use a single bioaccumulation factor to calculate activity in bird and animal tissue. The SENES model is more detailed, using a distinct factor for each intake pathway and summing the results. For the sake of comparison, a single integrated bioaccumulation factor was calculated for the SENES model by using the ecological transfer factors (TF's) for the scaup as an example.

As with DCFs, lower and higher trophic species are represented in this paper. For lower trophic species, **Pelagic Fish** was chosen for ERICA and the SENES model. **Aquatic Animal** was chosen for RESRAD which does not distinguish among aquatic animals. For higher trophic species, **Aquatic Bird** was chosen for ERICA, **Scaup** for the SENES model and **Aquatic Animal** was again chosen from RESRAD. Bioaccumulation factors for each model are as follows.

Element	SENES Pelagic Fish Bioaccumulation Factor (L/kgFW)	ERICA Pelagic Fish Bioaccumulation Factor (L/kgFW)	RESRAD Aquatic Animal Bioaccumulation Factor[13] (L/kgFW)
Pb-210	3.00E+02[14]	3.00E+02[9]	3.00E+02
Po-210	1.00E+02[14]	2.40E+02*	5.00E+02
Ra-226	5.00E+01[5]	8.00E+01*	3.20E+03
Th-228	1.00E+02[5]	1.10E+02*	8.00E+01
Th-230	1.00E+02[5]	1.10E+02*	8.00E+01
Th-232	1.00E+02[5]	1.10E+02*	8.00E+01
U-234	2.00E+01[5]	3.00E+01*	1.00E+03
U-235	2.00E+01[5]	3.00E+01*	1.00E+03
U-238	2.00E+01[5]	3.00E+01*	1.00E+03

*Bioaccumulation Factors (Concentration Ratios (CR) within the ERICA Tool) have been empirically derived under the ERICA Project by reviewing numerous literature sources, consolidating their results and performing a number of manipulations and normalizing operations. Data in its present form can be referenced to the ERICA Project, though the underlying research and results lies with over 1000 individual studies.
FW – Fresh Weight

Table 5 Bioaccumulation Factors for Pelagic Fish from each model.

For pelagic fish, all three models are generally within one order of magnitude for lead, polonium and thorium and within two orders of magnitude for radium and uranium. For radium and uranium, where the range is larger, RESRAD is the most conservative with ERICA and the SENES model showing very similar values.

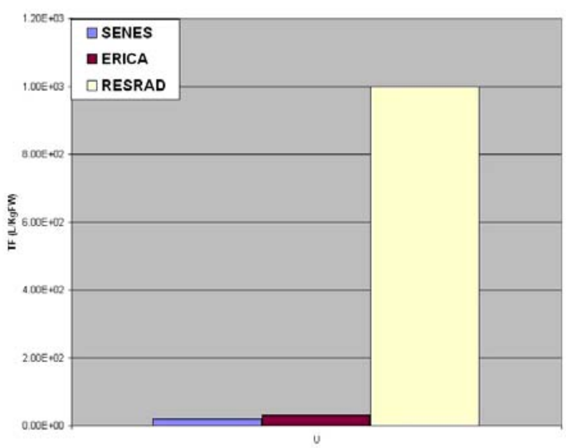

Figure 6 Graph of TF values for Radium to Pelagic Fish across three models.

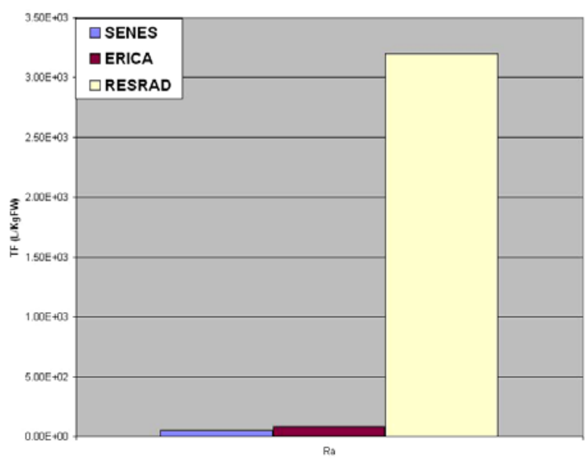

Figure 7 Graph of TF values for Uranium to Pelagic Fish across three models.

Element	SENES Scaup Integrated Bioaccumulation Factor ** (L/kgFW)	ERICA Aquatic Bird Bioaccumulation Factor * (L/kgFW)	RESRAD Aquatic Animal Bioaccumulation Factor[13] (L/kgFW)
Pb-210	1.19E+02	3.00E+02	3.00E+02
Po-210	2.65E+04	2.40E+02	5.00E+02
Ra-226	3.97E+03	8.00E+01	3.20E+03
Th-228	1.46E+01	1.10E+02	8.00E+01
Th-230	1.46E+01	1.10E+02	8.00E+01
Th-232	1.46E+01	1.10E+02	8.00E+01
U-234	1.35E+02	3.00E+01	1.00E+03
U-235	1.35E+02	3.00E+01	1.00E+03
U-238	1.35E+02	3.00E+01	1.00E+03

** calculated for comparison
*Bioaccumulation Factors (Concentration Ratios (CR) within the ERICA Tool) have been empirically derived under the ERICA Project by reviewing numerous literature sources, consolidating their results and performing a number of manipulations and normalizing operations. Data in its present form can be referenced to the ERICA Project, though the underlying research and results lies with over 1000 individual studies.
FW – Fresh Weight

Table 6 Bioaccumulation Factors for Aquatic Bird/Scaup/Aquatic Animal from each model.

For the aquatic bird species, all three models are generally within one to two orders of magnitude for all radionuclides. Across the radionuclides studied, there is a high level of variability regarding which model is most to least conservative. However, both the RESRAD and SENES models are generally more conservative than the ERICA Tool.

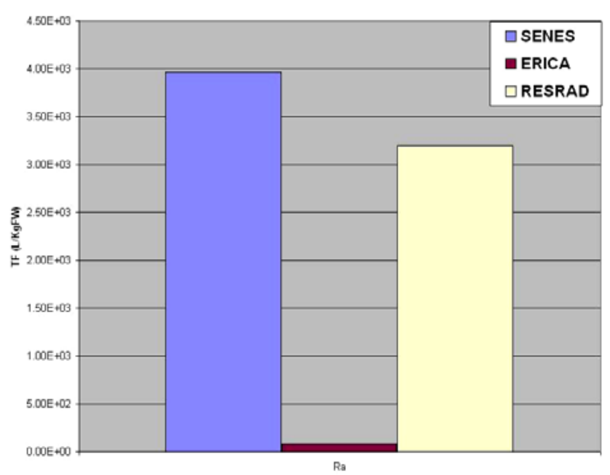

Figure 8: Graph of TF values for Radium to Aquatic Birds/Animal (Scaup) across three models.

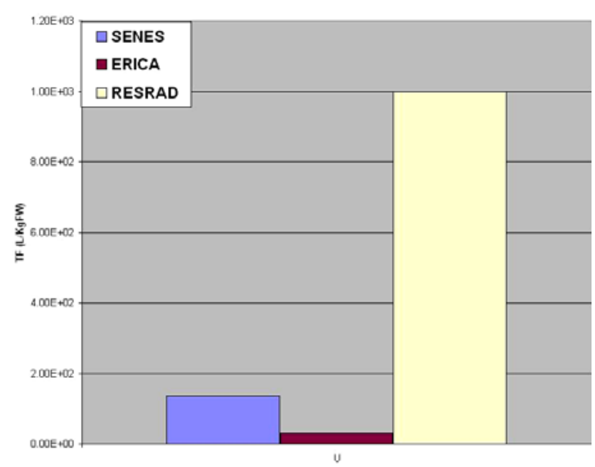

Figure 9: Graph of TF values for Uranium to Aquatic Birds/Animal (Scaup) across three models.

3. Methodology Comparison

All three models are based on a similar methodology, generally as follows:

$$Dose = Conc_{media} \times TF \times DCF_{\text{int}} + Conc_{media} \times DCF_{ext}$$

When the same concentration is entered into each model and default parameters (unique to each model) are used, a proportional result is generated. This shows that the differences between models are likely a result of the selected parameters and not the methodology. If identical parameters are used in all three models, the same result should be obtained from each. This is shown in an example in Figure 11 below. Since the external component of dose is insignificant in all cases studied, for simplicity, it is excluded from the figure.

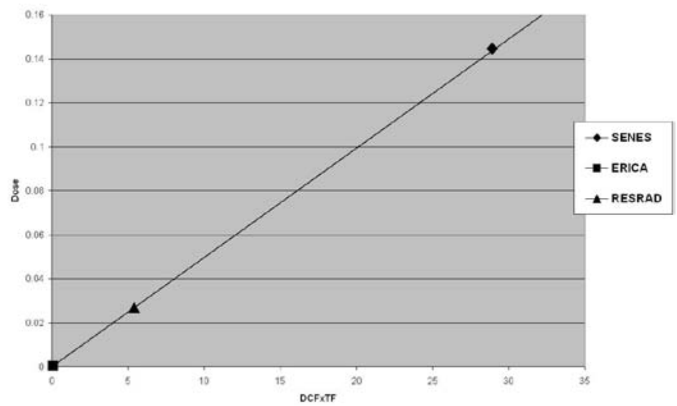

Figure 10: Graph of DCFxTF versus Dose for Po-210 to Aquatic Bird/Scaup/Aquatic Animal

Still, there are important differences in methodology that although they produce the same final result, offer varying degrees of precision at any given step.

For example, the RESRAD and ERICA Tools use a single integrated Bioaccumulation Factors (or concentration ratio) to calculate the whole-body biota activity from the activity in the relevant surrounding media. The SENES model calculates biota activity as the sum of multiple uptake pathways, each governed by their own Transfer Factor (TF). In this way, with the SENES Model it is possible to estimate the portion of biota activity from any particular uptake pathway, say from the ingestion of benthos or the ingestion of aquatic plants. When using the RESRAD or ERICA Tools it is not possible to resolve the biota activity in this manner; their precision is limited to calculating integrated activity in an organism.

The opposite is true for DCF values between the models. ERICA offers the greatest precision by splitting the dose from whole-body activity into 3 fractions (Alpha, Beta-gamma, and low Beta), each governed by its own DCF value. As a result it is possible to determine the fraction of dose coming from any given form of ionizing radiation. The RESRAD and

SENES Models calculate dose by simply applying a single integrated DCF to the whole-body activity of an organism, and are therefore limited to a single lumped value.

RESRAD has perhaps the most significant limitation in terms of being able to realistically represent populations of specific organisms. It calculates activity, dose rates and resulting risk quotients for broad categories of biota - such as a generalized "aquatic animal" or "riparian animal" – not by individual species, as is the method used by the ERICA and SENES Models. As a result, RESRAD is unable to estimate the exposure to any single species –such as a Scaup, or a Trout, or even a generalized Bird - information that is critical in most environmental risk assessments. Similarly, it is less amenable to the calculation of organ dose – which would be possible in a more flexible model.

4. Conclusions

Following a detailed comparison of the models it is evident that the methodologies in each are very similar, enough that the variability in results is almost entirely due to variation in the parameter values chosen. Variation in results then, is not likely a result of different methodologies. Figure 11 demonstrates that although different, the doses produced by each model are proportional to the transfer factors and dose conversion factors provided within the models.

While there are definite similarities and trends between parameters, there is also a large degree of variance. Differences of one order of magnitude are common, extending to a maximum of five orders of magnitude in the case of polonium's Kd variance between models.

In spite of the differences between the models, the results would be similar if they were applied to similar biota using identical site-specific transfer factors, distribution coefficients and dose conversion factors. Inputting a consistent set of parameters into each model would likely produce results with almost no variance, but this is restricted by RESRAD which is not able to change parameters easily. RESRAD calculations can however be complemented by outside (separate) calculations using the SENES Model to allow for site-specific input, such as more detailed receptor diet characteristics and fraction of time on site. However, it is recognized that it is difficult in general to determine TF values for different species.

An important observation formed during this study is regarding the use of 'lumped' or integrated parameters and their effects on transparency. The use of a lumped parameter approach can severely reduce the transparency and precision of results. An extreme example of this is RESRAD's grouping of animal species into categories like "aquatic animal", where the user is no longer able to determine dose or risk to any specific species. The use of integrated bioaccumulation factors (or transfer factors/concentration ratios) also has negative impacts on transparency. Using a combined transfer factor makes the user unable to determine the uptake from any single pathway. Situations such as these can lead to data gaps, increased uncertainty and decreased confidence in results. The use of lumped parameters and 'black box' calculations should be minimized.

5. References

[1] United States Department of Energy. "RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation." Version 1. ISCORS Technical Report 2004-02. 2004.

[2] Beresford, N.A. et al. « ERICA: An INTEGRATED APPROACH to the Assessment and Management of Environmental Risks from Ionizing Radiation." EC 6th framework project ERICA, Contract No. FI6R-CT-2003-508847. 2003.

[3] See for example these proceedings: Garisto et al. "Ecological Risk Assessment for Radiological and Chemical Contaminants at Site with Historical Contamination." SENES Consultants Limited, Richmond Hill, Ontario, Canada. 2010.

[4] Bechtel Jacobs Company LLC. "Radiological Benchmarks for Screening Contaminants of Potential Concern for Effects on Aquatic Biota at Oak Ridge National Library, Oak Ridge, Tennessee." Prepared for the U.S. Department of Energy Office of Environmental Management BJC/OR-80. 1998.

[5] Canadian Standards Association (CSA). "Guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operation of nuclear facilities." CSA Guideline N288.1-08. 2008.

[6] International Atomic Energy Agency (IAEA). "Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments." Report No. 364. 1994.

[7] International Atomic Energy Agency (IAEA). "Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment." TRS 422. 2004.

[8] International Atomic Energy Agency (IAEA). "Handbook of parameter values for the prediction of radionuclide transfer in temperate environments." Draft updated TRS364. Update of Original TRS 364 (1994). Currently In Press.

[9] International Atomic Energy Agency (IAEA). "Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment." Safety Report Series 19. 2001.

[10] Yu et al. "Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil", Argonne National Laboratory, Argonne, Illinois. 1993.

[11] Environment Canada and Health Canada (EC/C). "Priority Substances List Assessment Report: Releases of Radionuclides from Nuclear Facilities (Impact on Non-Human Biota)." *Canadian Environmental Protection Act*. 2003.

[12] Amiro, B.D. "Radiological Dose Conversion Factors for Generic Non-Human Biota Used for Screening Potential Ecological Impacts." In J. Environ. Radioactivity. 35(1):37-51.1997.

[13] United States Department of Energy (US DOE). "A graded approach for evaluating radiation doses to aquatic and terrestrial biota." Technical Standard DOE-STD-1153-2002. Washington DC, USA. 2002.

[14] National Council on Radiation Protection and Measurements (NCRP). "Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground." NCRP Report No. 123. 1996.