

Comparison and applicability analysis of models for estimating radiological dose rates of freshwater biota

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Abstract. A number of inter-comparisons of non-human biota radiation assessment models have been fulfilled by international researchers and organizations. This paper describes the radiological impact to reference biota in Chinese inland nuclear power plant scenario, by using RESRAD-Biota, ERICA and R&D 128. The estimation results are ranging from $6.1 \times 10^{-3} \mu\text{Gy/h}$ to $6.17 \times 10^{-2} \mu\text{Gy/h}$, mainly contributed by ^{134}Cs and ^{137}Cs , obviously below recommended limits and thus prove the biota in reservoir can be adequately protected from effluent discharge. By comparing models characteristics and performances in exercise, we conclude the ERICA tool reveals more applicability in Chinese nuclear sites and propose several suggestions to establish native framework for non-human biota assessment.

1. Introduction

As the development of environmental legislation and policy decision, the radiological impact on non-human biota has been integrated into radiation protection system since this century [1]. Inter-comparison and validations of biota dose assessment models have been carried out in international projects, with large quantity of results and discussions published [2~5]. In China, researchers also use several approaches, including RESRAD-Biota, ERICA Tool and R&D 128, to evaluate the ionizing radiation impact on non-human biota [6], which is required to fulfill in environmental impact assessment (EIA) for nuclear power plant (NPP). Until now, many researches have focused on marine biota around coastal NPP site. Considering the forthcoming development of inland NPP in China, the performance and applicability of models in freshwater ecosystem need to be further studied.

2. Models used

In several international projects such as EMRAS and EMRAS II launched by International Atomic Energy Agency (IAEA), and well-known scenarios, such as Chernobyl exclusion zone and Fukushima adjacent sea, many frameworks, tools and approaches have been used to make inter-comparison of biota dose assessment [3, 5]. Among them, RESRAD-Biota, ERICA and R&D 128 are widely used because they are free and user-friendly.

RESRAD-BIOTA code was primarily developed as a tool for implementing the US DOE graded approach for evaluating radiation doses to biota [7]. It can evaluate radiation exposures of 44 nuclides for specific organisms, including four defaults and eight user-added geometries. Absorbed fraction for specific energy can be calculated using MCNP method and then derive internal and external exposure dose conversion coefficients (DCCs) embedded in code. Bioaccumulation factor (B_p) and distribution



coefficient (K_d) values from literatures [8] are used to calculate the whole-organism activity concentration, while inputting site-specific values are allowed in high level assessment. Moreover, the code includes a kinetic–allometric approach [8] to estimate the transfer of radionuclides from media to biota bodies and tissues.

ERICA tool is the product of an EC 6th Framework project and provides an integrated approach to assess radiological environmental effects [9, 10]. 71 nuclides are included and adding nuclide is allowed. The tool provides the maximum radionuclide-organism parameter combinations compared to other models, mainly from IAEA [11, 12] as well as other European research [13]. One specific module embedded can help derive DCCs for diverse biota-radiation combinations. Three kinds of radiations and 39 default body geometries, including all the International Commission of Radiological Protection (ICRP)'s reference animal and plants (RAP) geometries [14], are given for use in the tool. R&D 128 approach was developed primarily to assess compliance with the EC Habitats Directive at sites receiving radioactive discharges in England and Wales [13, 15]. The model uses B_p and K_d values similar to ERICA, but with few combinations. Using a series of assumptions, such as value from species of similar ecological characteristics, this guidance aims to undertake conservative assessment for non-ionizing radiation. Three Microsoft Office Excel worksheets (coastal, freshwater & terrestrial) are given in the model. In freshwater ecosystem worksheet, 16 nuclides together with 12 reference organisms are included. Besides radio-ecological parameters, weighing factors, occupancy factors and DCCs are also embedded in the sheet but not allowed to modify by assessor.

3. Results in XNNP scenario

3.1. Data Input

The site of Xianning Nuclear Power Plant (XNNP) is located in Yangtze River basin, central China. Although its construction has been paused since the Fukushima accident, it's still regarded as one of preferential candidate inland sites in China.

3.1.1. Predictive radioactive level in receiving water. Fushui Reservoir, receiving water of XNNP, is an artificially built reservoir, with long and narrow topography and covering area of 54.8km². During the future commission of XNNP, liquid radionuclides released into the reservoir come from the dilution and diffusion of liquid effluent, as well as the deposition of gaseous effluent. After released into surface water, part of nuclides would be adsorbed on suspended matter in water body and deposited on sediment and their transport can be estimated by small lake and reservoir model and decomposition model recommended by IAEA [11]. Based on the source term discharged [16], Table 1 shows the predictive radioactivity concentration after dilution in reservoir during NPP commission.

Table 1. Radioactivity Concentration in water body of Fushui Reservoir

Nuclid e	Conc (Bq/L)	Nuclid e	Conc (Bq/L)	Nuclid e	Conc (Bq/L)	Nuclid e	Conc (Bq/L)	Nuclid e	Conc (Bq/L)
³ H	1.59E+02	⁸⁴ Br	4.52E-10	^{99m} Tc	1.41E-07	^{131m} Te	1.14E-07	¹³⁷ Cs	2.30E-03
²⁴ Na	1.04E-06	⁸⁸ Rb	3.42E-09	¹⁰³ Ru	1.59E-04	¹³¹ Te	5.34E-10	¹⁴⁰ Ba	6.80E-05
⁵¹ Cr	4.89E-05	⁸⁹ Sr	3.68E-05	¹⁰⁶ Ru	8.37E-03	¹³² Te	7.85E-07	¹⁴⁰ La	1.26E-05
⁵⁴ Mn	1.53E-04	⁹⁰ Sr	5.53E-05	^{103m} Rh	1.96E-07	¹³¹ I	1.32E-03	¹⁴¹ Ce	2.81E-06
⁵⁵ Fe	1.40E-04	⁹¹ Sr	8.09E-09	¹⁰⁶ Rh	2.61E-08	¹³² I	1.61E-07	¹⁴³ Ce	2.65E-07
⁵⁹ Fe	7.91E-06	^{91m} Y	3.54E-10	^{110m} Ag	1.05E-04	¹³³ I	4.58E-04	¹⁴³ Pr	1.66E-06
⁵⁷ Co	2.34E-07	⁹³ Y	3.87E-08	¹¹⁰ Ag	4.08E-11	¹³⁴ I	3.03E-08	¹⁴⁴ Ce	3.30E-04
⁵⁸ Co	4.90E-04	⁹⁵ Zr	2.38E-05	¹²⁵ Sb	2.40E-06	¹³⁵ I	1.40E-06	¹⁴⁴ Pr	3.89E-08
⁶⁰ Co	4.31E-04	⁹⁵ Nb	2.67E-05	^{129m} Te	3.41E-06	¹³⁴ Cs	1.42E-03	¹⁸⁷ W	1.32E-07
⁶⁵ Zn	4.05E-05	⁹⁹ Mo	1.58E-06	¹²⁹ Te	7.43E-09	¹³⁶ Cs	8.10E-06	²³⁹ Np	5.71E-07

3.1.2. Reference organisms. Frog, duck and salmonid are listed as freshwater RAPs by ICRP. According to ecological data [16], shape dimension and mass data of regular fishes in Fushui

Reservoir, together with biota information in models (mainly indicated as pelagic fish), are given in Table 2. Considering the extensive distribution of carps in reservoir, and the similarity of geometry assumption, we select pelagic fish as reference organism for assessment.

Table 2. Reference biota information in Fushui Reservoir and models

Species/Models	Shape Dimension (cm)	Mass (g)	Reference
bighead carp	35.5~46.0	590~2015	[22]
silver carp	38.8~47.0	1055~1900	[22]
common carp	25~30	300~800	[22]
RESRAD-Biota	45×8.7×4.9	1000	[11]
ERICA	50×8×6	1260	[19]
R&D 128	45×8.7×4.9	1000	[21]

3.1.3. Radio-ecological parameters. In the estimation, pathways of internal (from body inside) and external irradiation (from water and sediment) are considered based on the life habit of fish. We adopt general equilibrium model, using radio-ecological parameters such as K_d and B_p to estimate the radioactivity in different media including water body, sediment and organism body. The values of parameters compiled in three models are given in Table 3. Data of only several critical nuclides are given due to nuclide coverage difference.

Table 3. Value of radio-ecological parameters of certain nuclides in freshwater ecosystem

Nuclide	K_d Value(L/kg)			B_p Value(L/kg)		
	RESRAD-Biota	ERICA	R&D128	RESRAD-Biota	ERICA	R&D128
H-3	0.001	1	1	0.2	1	1
Sr-90	30	2000	1000	320	17	42.7
Co-60	1000	106000	—	2000	437	—
Tc-99	5	5	5	78	40	45.1
I-131	10	300	10	220	180	40
Cs-137	500	137000	1000	22000	7100	1090

3.1.4. Biological dose conversion coefficient (BDDC). BDDC, with different names, is introduced by all of three models to fulfill the calculation. To acquire the BDDC, biota body geometry and radiation energy plus type are considered by using MCNP method to calculate the adsorption proportion of radiation dose. Besides that, the life habit of reference organisms, related to radiation pathways, and radiation weighting factors (WF) are also be considered. For example, six kinds of radiation are included in R&D 128 model, while ERICA only includes five kinds without α external radiation. RESRAD-Biota offers total, not each kind respectively, internal and external BDDC. As for the relative biological effect (RBE), three models all set WF of β/γ radiation as 1, while ERICA and R&D 128 list low β radiation separately as 3. As for α radiation, RESRAD-Biota and R&D 128 set its WF as 20, while ERICA offers 10. Table 4 gives the BDDCs of certain radionuclides to freshwater fish.

Table 4. BDCC of certain radionuclides to freshwater fish

Nuclide	RESRAD-Biota (Gy/y)/(Bq/kg)		ERICA (μ Gy/h)/(Bq/kg)		R&D128 (μ Gy/h)/(Bq/kg)	
	Internal	External	Internal	External	Internal	External
H-3	2.9E-08	1.4E-08	8.25E-06	3.60E-13	9.90E-06	5.55E-10
Sr-90	5.7E-06	2.8E-06	6.30E-04	2.40E-05	6.20E-04	2.99E-05
Co-60	1.3E-05	6.6E-06	2.10E-04	1.30E-03	2.00E-04	1.31E-03
Tc-99	5.1E-07	2.1E-07	4.93E-05	2.97E-04	5.80E-05	1.63E-07
I-131	2.9E-06	1.4E-06	1.40E-04	1.90E-04	1.30E-04	1.98E-04
Cs-137	4.3E-06	2.0E-06	1.80E-04	2.90E-04	1.71E-04	2.95E-04

3.2. Estimation result analysis

Both RESRAD-Biota and ERICA Tool combine graded methods for assessment and use default parameters in the basic level for screening purpose. The BCG in RESRAD-Biota and EMCL in ERICA Tool are designed to be the maximum radioactivity concentration limit to guarantee the safety of biota. To test the effectiveness and practicability of models, higher level method with elaborated analysis is used to estimate the radiation dose rate to reference biota, by allowing to input more site and species-specific parameters.

3.2.1. Radiation dose and impact to freshwater fish. The estimated total additional dose rates to reference fish are $6.17 \times 10^{-2} \mu\text{Gy/h}$ (RESRAD-Biota), $7.00 \times 10^{-3} \mu\text{Gy/h}$ (ERICA) and $6.1 \times 10^{-3} \mu\text{Gy/h}$ (R&D 128), which are obviously below recommended limits for protecting non-human biota, such as $400 \mu\text{Gy/h}$ (10mGy/d) given by IAEA [9], $10 \mu\text{Gy/h}$ (0.25mGy/d) given by ERICA[9], and $40\text{--}400 \mu\text{Gy/h}$ (1-10mGy/d) set as ICRP's Derived Consideration Reference Level (DCRL) on salmon[14]. Thus, it's estimated that the radiation impact of reference fish in reservoir induced by radionuclides discharged from XNNP is pretty small.

3.2.2. Radionuclides with major dose contribution. The proportion of nuclides making dose contribution depends primarily on their existence in effluent. In this paper, three models present different but a bit similar results. ERICA result shows the major radionuclides are ^{137}Cs (45.14%), ^{134}Cs (32.57%) and ^3H (15.25%), while ^{106}Ru , ^{60}Co and ^{58}Co offer certain contribution. In RESRAD-Biota result, critical nuclides change to ^{134}Cs (50.54%) and ^{137}Cs (40.54%), while ^{144}Ce , ^{60}Co , ^{58}Co and ^3H also offer considerable dose contribution. R&D 128 shows major nuclides are ^{137}Cs (72.13%) and ^3H (26.23%), which is similar to ERICA's.

3.2.3. Result discussion. For further discussion, we select common radionuclides included in three models and compare their estimated dose rate, as shown in Figure 1. It shows that, no matter for total dose rate and dose rates from individual radionuclide, ERICA and R&D 128 present similar results, whereas RESRAD-Biota's result is relatively conservative. ^{134}Cs and ^{137}Cs are regarded as the critical radionuclides to make major dose contribution, except that R&D 128 doesn't cover ^{134}Cs in its worksheet. Meanwhile, the radiological impacts of ^{60}Co and ^{58}Co to fish shouldn't be neglected. Although tritium's results are relatively high in three models, it's worth noting that tritium's transfer model and radiation mechanism should be different from others, using equilibrium model may misestimate its actual impact. IAEA has finished special project EMRAS aiming at tritium transfer modelling [17]. Radiological dose and impact of tritium to non-human biota should be further studied.

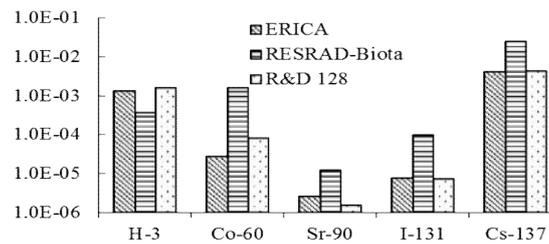


Figure 1. Estimated dose rate by individual radionuclide in three models

4. Models applicability analysis

4.1. Radionuclides covered

Relatively more long half-life radionuclides, such as ^{241}Am , ^{235}U , ^{228}Th , ^{210}Pb , are contained in RESRAD-Biota for assessing the decommission impact of nuclear facilities, thus causing a little difficulty to use when dealing with nuclear power assessment. R&D 128, similar to RESRAD-Biota, can't cover all the major nuclides discharged from NPP, such as $^{110\text{m}}\text{Ag}$, which may cause significant dose rate to mollusk, and ^{58}Co , the key nuclides usually for biota on the beach. ERICA allows users to add new nuclides and provide tools to derive parameter values for calculation, leaving more convenience for use. ERICA's method to calculate DCC has been adopted by ICRP [14], thus demonstrating its acceptance by int'l authorities.

4.2. Radio-ecological parameters.

Generally, equilibrium method and related parameters B_p and K_d are used to model nuclides transfer. Considering the non-uniform accumulation of nuclide distribution in media and organism body, this method should be treated for screening purpose rather than realistic assessment. RESRAD-Biota integrates relatively higher B_p and low K_d values, which are different from IAEA publications. This should be the major reason to present different results here because inter-comparison exercises have concluded the difference of model performance comes mainly from the stimulation of nuclides transfer [17]. RESRAD-Biota can present higher results (up to 4 orders of magnitudes) than using B_p values from allometric approach. Although allometric approach isn't used here, we don't think it's meaningful for assessment because detailed biological parameters used to stimulate nuclides' kinetic distribution in body are difficult to obtain. On the other hand, researchers can use both default and specific radio-ecological parameters in ERICA tool, thus guaranteeing more reasonable assessment.

4.3. Reference biota and exposure assumption

As the assessment to all kinds of biota is impossible, all models choose to use reference species. Among them, ERICA provide the largest number of biota for assessment, 13 kinds respectively for freshwater, marine & terrestrial ecosystem and in correspondence with RAPs recommended by ICRP. RESRAD-Biota only combines 4 kinds, lacking of marine biota making it impractical in assessment for coastal NPP. Moreover, RESRAD-Biota and R&D 128 set fixed values of exposure geometry factors, for example 0.5 from water and sediment exposure for aquatic and riparian animals. ERICA can manually modify values, making assessment to external exposure more flexible and reasonable.

4.4. Comparison Summary and Applicability analysis

RESRAD-Biota, developed firstly for decommission project assessment [7], can present more conservative result. However, its use could be restricted due to the scarcity of reference biota and particularity of radio-ecological data used. ERICA and R&D 128 are both developed by European staff, and use similar setting in reference organisms and DCC. R&D 128 could yield more conservative result, but it doesn't support graded assessment and forbids user to modify input coefficients. ERICA covers all kinds of nuclides and more range of organisms, eg lichen and benthic fish that tend to have high exposure. It supports more biota/site-specific parameters input and

combines the tool to calculate DCC for any user-defined body geometry. Moreover, in higher tiers, it can consider uncertainty factors in dose estimate and make assessment by linking to the biological effects data of FREDERICA database [9]. Therefore, compared to other two models, ERICA reveals more applicability in radiological impact assessment to non-human biota for inland sites.

5. Conclusion and suggestion

Inspired by the inter-comparison exercises of models, this paper is to make comparison on the biota dose rate in Chinese inland NPP scenario, by using three widely used models. The estimation results of freshwater fish are ranging from $6.1 \times 10^{-3} \mu\text{Gy/h}$ to $6.17 \times 10^{-2} \mu\text{Gy/h}$, obviously below the international recommended limits to adequately protect the reference biota in reservoir. Among models, ERICA show more applicability in assessment compared to other two models, because of not only the correspondence to ICRP's recommended framework, but more use convenience.

In China, the development of radiological protection framework with eco-centrism is just starting out. To perfect the method of non-human biota radiological assessment, several researches, such as exploring mechanism of nuclides transfer in biota and media and developing guidance for site-specific reference biota selection, are need to be fulfilled later.

References

- [1] ICRP. A Framework for Assessing the Impact of Ionising Radiation on Non-human Species. ICRP Publication 91. Oxford: Pergamon Press, 2003: 58.
- [2] J.V. Batlle, M. Balonov, K. Beaugelin-Seiller, et al. Inter-comparison of absorbed dose rates for non-human biota. *Radiation Environmental Biophysics*, 2007, 46: 349-373.
- [3] N.A. Beresford, M. Balonov, K. Beaugelin-Seiller, et al. An international comparison of models and approaches for the estimation of the radiological exposure of non-human biota. *Applied Radiation and Isotopes*, 2008, 66: 1745-1749.
- [4] N.A. Beresford, C.L. Barnett, J.E. Brown, et al. Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota. *Radiation Environmental Biophysics*, 2008, 47: 491-514.
- [5] N.A. Beresford, C.L. Barnett, K. Beaugelin-Seiller, et al. Findings and recommendations from an international comparison of models and approaches for the estimation of radiological exposure to non-human biota. *Radioprotection*, 2009, 44 (5): 565-570.
- [6] X.F. Zhang, Z.H. Shanguan, F. Zhao. Assessment of radiological impact on the marine organisms near Yangjiang Nuclear Power Plant. *Journal of Tropical Oceanography*, 2009, 28(6): 35-40. (in Chinese).
- [7] K.A. Higley, S.L. Domotor, E.J. Antonio, et al. Derivation of a screening methodology for evaluation radiation dose to aquatic and terrestrial biota. *Journal of Environmental Radioactivity*, 2003, 66(1): 41-59.
- [8] J.E. Till and H.R. Meyer. *Radiological assessment: a textbook on environmental dose analysis*. NUREG/CR-3332. Washington, D.C.: USNRC, 1983.
- [9] J.E. Brown, B. Alfonso, R. Avila, et al. The ERICA Tool. *Journal of Environmental Radioactivity*, 2008, 99(9): 1371-1383.
- [10] J.E. Brown, B. Alfonso, R. Avila, et al. A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. *Journal of Environmental Radioactivity*, 2016, 153: 141-148.
- [11] IAEA. *Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment*, Safety Reports Series No. 19. Vienna: IAEA, 2001.
- [12] IAEA. *Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment*, Technical Report Series No. 422. Vienna: IAEA, 2004.
- [13] D. Copplestone, N.A. Beresford NA, J.E. Brown, et al. An international database of radionuclide concentration ratios for wildlife: development and uses. *Journal of Environmental Radioactivity*. 2013, 126, 288-298.

- [14] ICRP Environmental Protection: the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Oxford: Pergamon Press, 2008: 14-23.
- [15] UKEA. Impact Assessment of Ionising Radiation on Wildlife. R&D Publication 128. Bristol: Environmental Agency, 2001.
- [16] X.F. Zhang, X.S. Tian, Y.J. Huang, et al. Impact of inland nuclear power plant on reservoir environment: a case on Xianning Nuclear Power Plant. *Journal of Lake Sciences*, 2010, 22 (2): 181-188. (in Chinese).
- [17] IAEA. Environmental Modelling for Radiation Safety — A summary report of the results of the EMRAS programme, IAEA-TECDOC-1678. Vienna: IAEA, 2012.