A Comparison of Environmental Modelling Approaches on the Case-study of the Chalk River Laboratories Site

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Abstract

Robust and speedy assessment of radiological impact on non-human biota is crucial for the nuclear industry and the public. The most frequently used techniques for dose estimation in aquatic biota are compared on the practical case-study of the Chalk River Laboratories (CRL) site. The tools used are the RESRAD-BIOTA code and ERICA software. Additionally, an analytic calculation method using the point-source-distribution model with rescaled DCCs is performed. A detailed MCNP dosimetric model of the studied biota is used to assess error. Deviations between the calculation and the software tools are observable mainly for radionuclide concentrations in the sediment. Comparison with the MCNPX model reveals weaknesses of the analytical tools when calculating dose from low-energy beta particles and in small geometries.

Dose to Aquatic Biota

A) Nuclide Concentrations

Concentrations of nuclides in water are from the Annual Safety Report of the CRL (Tab. 1) [1] and concentrations in biota and the sediment can be calculated using bioaccumulation factors (BAF) and distribution coeficients (K_d) respectively [2]

$$BAF = \frac{\text{Concentration in biota}}{\text{Concentration in surrounding water}}$$

$$C_{\text{Sediment (fw)}} = \frac{\theta C_W + (1-\theta) C_W K_d \rho_S}{\theta \rho_S + (1-\theta)\rho_S}$$

B) Dose Calculation [3]

$$D_{internal} = 5.76 \cdot 10^{-4} E_\nu Y_\nu \Phi C_{int}$$
$$D_{sediment} = 2.88 \cdot 10^{-4} E_\nu Y_\nu (1-\Phi) C_s R$$
$$D_{water} = 5.76 \cdot 10^{-4} E_\nu Y_\nu (1-\Phi) C_w$$

C) Rescaling Factors [4]

$$\Phi = RF(\eta) \cdot \Phi_0$$
$$RF(\eta) = \left(1 - \|1-\eta\|^{1/s}\right)$$

Software Tools: RESRAD-BIOTA and ERICA

RESRAD-BIOTA

The RESRAD-BIOTA code is designed as a tool for evaluating radiation doses to aquatic and terrestrial biota by Argonne National Laboratory (ANL). The level of analysis is set to 3 and a wizard tool provides the possibility of adding new organisms in equivalent geometry groups.

ERICA ASSESSMENT TOOL

ERICA is a tiered software system developed to assess the radiological risk to terrestrial, freshwater and marine biota. A Tier 2 analysis is performed. The investigated organisms are created with a wizard tool using the original dimensions. A more specific input of the occupancy in the water column or at the sediment-water interface is also possible.

Nuclide Concentrations in Investigated Environments

Tab. 1: Two environments on the Chalk River Laboratories site with nuclide concentrations in water and the investigated biota with dimensions and bioaccumulation factors. [1,2]

Site	Biota	Size [cm]	^{3}H [Bq/L]	BAF ^{3}H [L/kg]	^{90}Sr [Bq/L]	BAF ^{90}Sr [L/kg]
Perch Lake	Pumpkinseed	11 x 3 x 5	2.7 x 10^3	1	55	945
Perch Lake	Pumpkinseed Eggs	0.1 diameter		1		945
Duke Stream	Pike	11 x 3 x 5	13 x 10^3	1	0.15	430

Simplified equation used to calculate activity in the sediment by ERICA and RESRAD BIOTA:

$$C_{\text{Sediment}} = K_d \cdot C_{\text{Water}}$$

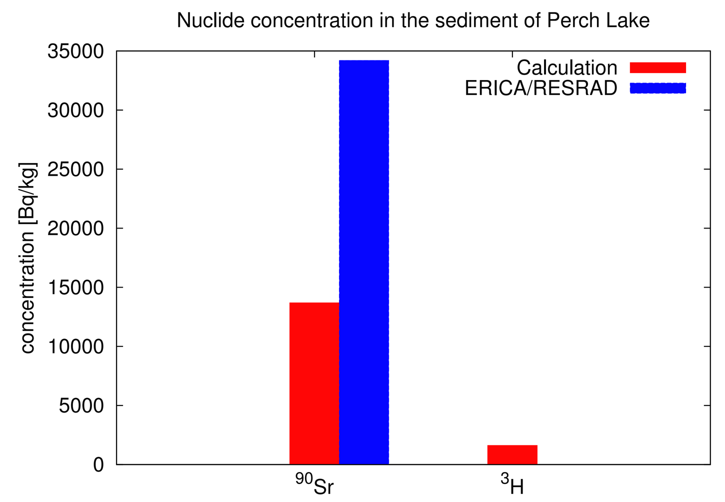

Fig. 1: Concentration of ^{3}H and ^{90}Sr in the sediment of Perch Lake.

MCNP Model

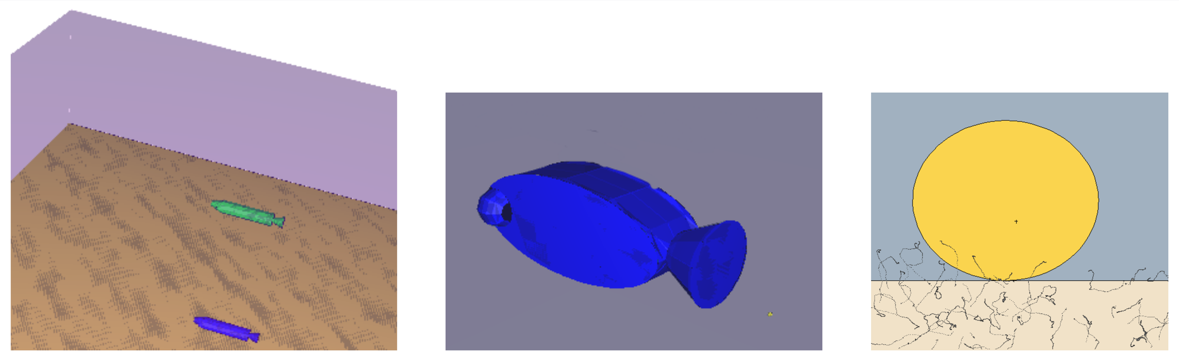

Fig. 2: Schematic representation of the simulation set-up and details of the pumpkinseed and egg geometry.

A dosimetric model is developed in MCNPX for evaluating the absorbed dose to each of the studied species. The geometry for the fish phantoms is a combination of ellipsoids and cones. The tissue composition is 1.02E-1 H, 1.23E-1 C, 3.50E-2 N, 7.29E-1 O, 8.00E-4 Na, 2.00E-4 Mg, 2.00E-3 P, 5.00E-3 S, 3.00E-3 K and 7.00E-5 Ca. The irradiation geometry is shown in Fig. 2. The relative positioning of the biota to the soil is representative of the occupancy on the sediment-water interface.

Results and Intercomparison of the Standard Models

A) Absorbed Dose

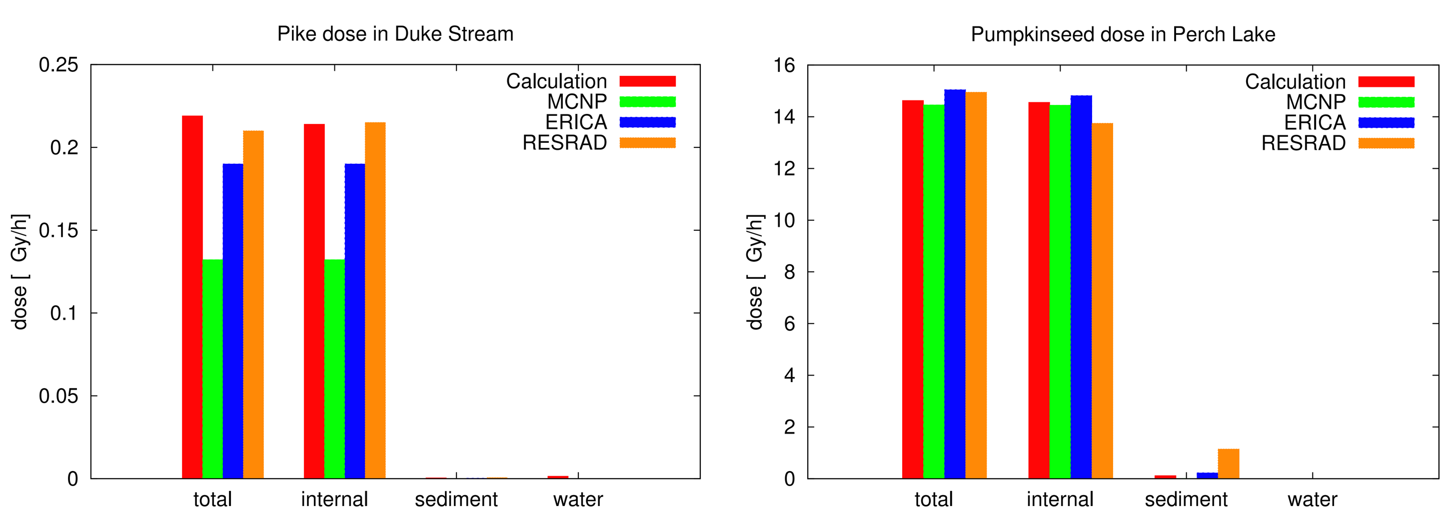

Fig. 3: Total dose to pike in Duke Stream and to pumpkinseed in Perch Lake. Contribution from internal contamination, water and sediment.

B) Internal Dose Breakdown

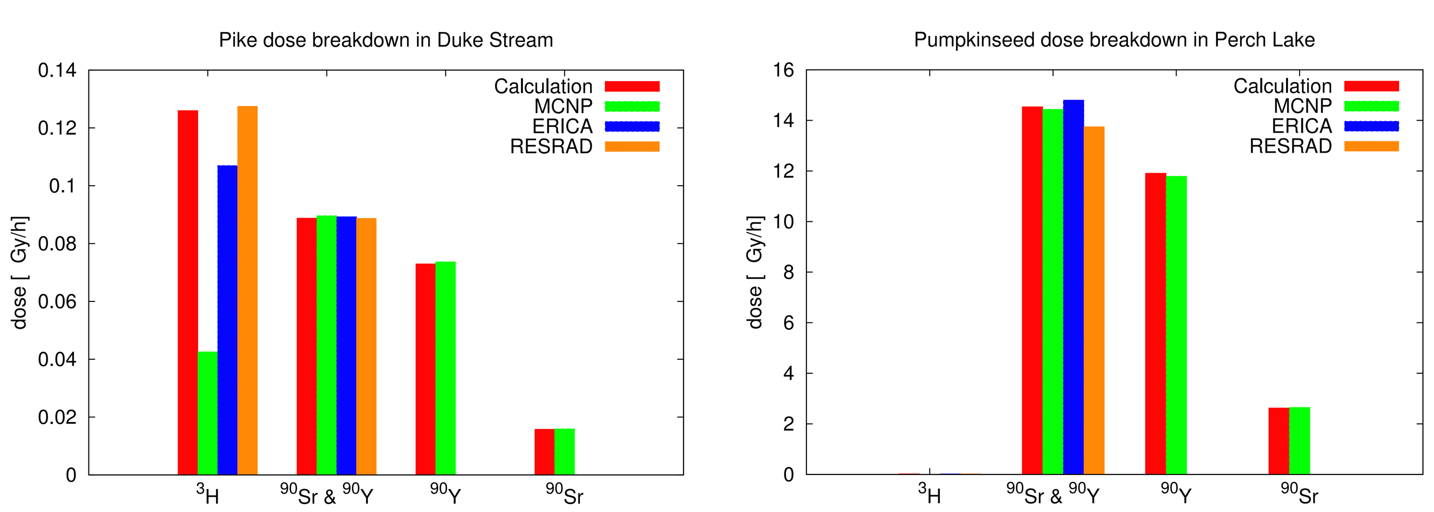

Fig. 4: Nuclide contribution to pike and pumkinseed internal dose. A breakdown of the strontium contribution into the daughter nuclide was only possible with MCNP and the analytic calculation.

Studying the total dose to the fish geometries (Fig. 3) and comparing with the contribution from each nuclide (Fig. 4) several observations can be made:

The biggest contribution to the total dose comes from internal contamination.

^{90}Sr and its daughter nuclide ^{90}Y in secular equilibrium are the main contributers to the internal dose. This is due to the higher energy of those nuclides, and especially ^{90}Y, compared to ^{3}H.

For ^{90}Sr and ^{90}Y the methods used are in good agreement with the MCNPX simulation.

A big discrepancy is noticed between the MCNPX simulation and the analytic methods in calculating the dose from ^{3}H contamination.

Special Case Egg

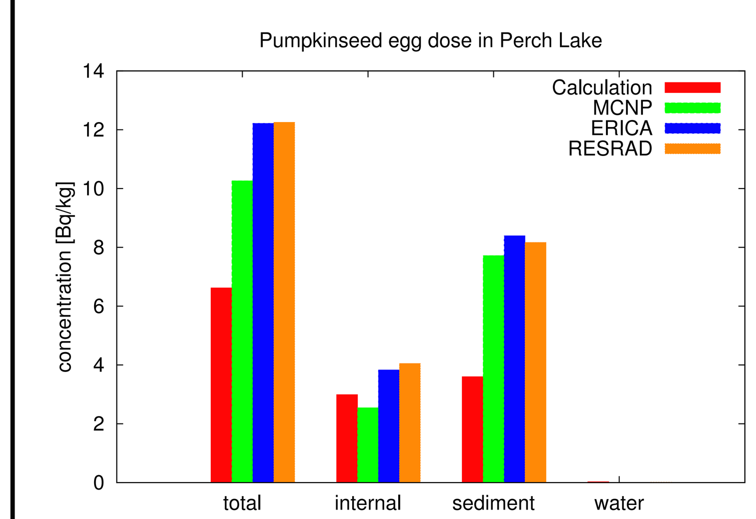

Fig. 5: Concentration of ^{3}H and ^{90}Sr in the sediment of Perch Lake.

The deviation in dose reflects the difference in determining the sediment concentration between the software tools and the calculation. In the MCNPX simulation the analytically calculated concentration value is used but the porosity is not incorporated.

Conclusions

- When calculating nuclide concentration in the sediment without considering soil porosity (ERICA, RESRAD) the concentration for high K_d elements (^{90}Sr) will be overestimated and the concentration for low K_d elements (^{3}H) will be underestimated.
- For large geometries and electron energies the tested estimation methods are in good agreement, especially for internal dose.
- In the case of energies in the range of 0.00568 MeV (^{3}H) the software tools and analytic calculation are in good agreement but deviate from the MCNPX results. Since the contribution from low energy electrons to the dose is very low, the significance of the deviation is limited.
- In the case of small geometries with a plane irradiation source the MCNPX results and the software tools deviate considerably. This can be attributed to the variability of the source-target geometry used in the various methods. Due to the low energy of the source particles and small target geometry even a small variance can considerably change the outcome.

References

[1] T.W.J Pilgrim and M.C.Audet, “Annual Safety Report: Environmentl Monitoring in 2012 at Chalk River Laboratories.”, AECL/EACL, Chalk River, 2012.

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[3] B.G. Blaylock, M.L Frank and B.R. O’Neal, “Methodology for Estimating Radiation Dose Rates to Freshwater Biota Exposed to Radionuclides in the Environment”, Oak Ridge National Laboratory, 1993.

[4] A. Ulanovski, G. Proehl “A practical method for for assessment of dose conversion coefficients for aquatic biota”, Radiation and Environmental Biophysics, vol. 45, no.3, 203-214, 2006.

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