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Evaluation of the bioaccumulation processes for a wide set of radionuclides under accidental releases by biota

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Abstract

It was shown that it is impossible to use two approaches for the bioaccumulation process at the same time: (i) bioaccumulation based on the concentration rate approach and (ii) kinetic modelling of the bioaccumulation process. Simultaneous use of these two approaches provides a wrong description of the bioaccumulation process and concentration of radionuclides in biota, especially during the first period of exposure. In this connection, the evaluation of the kinetic parameters for bioaccumulation process for a wide set of radionuclides and biota has been provided. Preliminary evaluation of the kinetic parameters has been provided based on literature review and the extraction from existing databases. The selected kinetic parameters have been further improved based on mathematical experiments, including the successive simulations of bioaccumulation processes during increasing trophic levels. The sub-model with the modified kinetic parameters for bioaccumulation process has been used based on simulations from the compartmental model, which uses the non-instantaneous dispersion of radioactivity in the marine environment. The selected release scenario corresponds to a potential accident with nuclear submarine reactor in the Gulf of Finland. Concentrations of radionuclides in biota, doses to humans and dose rates to the marine organisms have been evaluated. The results of the present study can be used to improve the ability to evaluate the consequences to humans and biota after a radioactive release into marine environment. It was shown that the methodology, which was used in the present study allows to find a suitable set of kinetic parameters.

Key words

Radionuclides, bioaccumulation, kinetic modelling, consequences to humans and biota

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Evaluation of the bioaccumulation processes for a wide set of radionuclides under accidental releases by biota (BIORAD)

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Contents

1. Introduction

Bioaccumulation of radionuclides by biota is a crucial topic within the analysis of consequences for humans and animals following radionuclide releases to the environment.

Kinetic modelling of the bioaccumulation processes has been shown to provide more realistic results when compared to an appoach based on equlibrium concentration ratio (CR). Calculations for both approaches are shown in Figure 1, adopted from Iosjpe et al. (2016).

Blue and red lines in Figure 1 correspond with concentrations in water and fish (with equlibrium concentration ratio, CR, approach), correspondently. Therefore, these plots have the same shape. Biokinetic modelling describes the “delay” with the changing of concentration of radionuclides in water. It is a clear demonstration that the dynamic modelling of the bioaccumulation processes provides a more correct description of the concentration of radionuclides in biota (up to an order of magnitude).

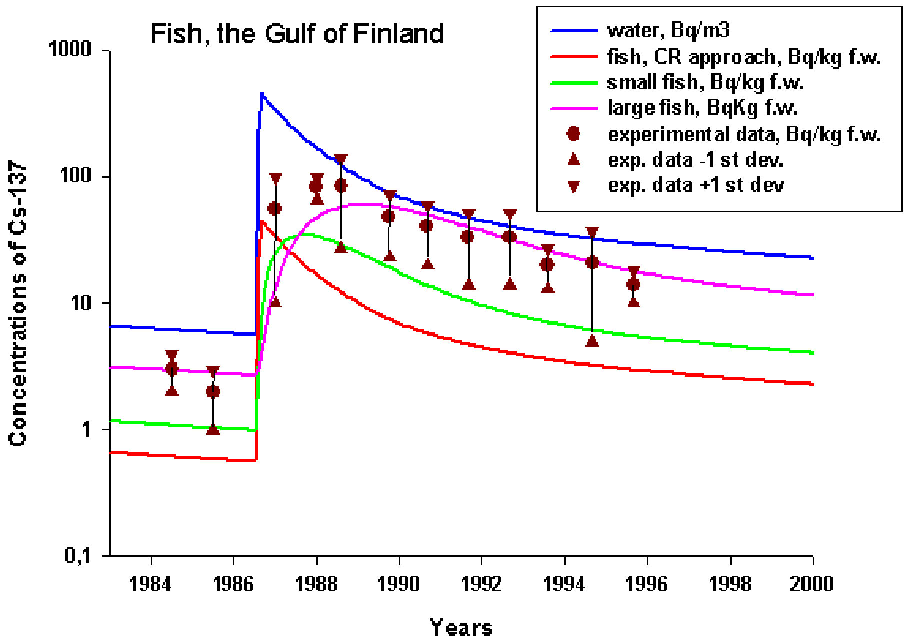


Figure 1. Comparison of the prediction of the concentration of Cs-137 in fish with experimental data for the Gulf of Finland for both the constant concentration factor approach and the biokinetic modelling for the Chernobyl accident for different food chain assumptions.

The present study will use the radionuclide inventories and assumptions about radionuclide releases for nuclear submarine presented by Hosseini et al. (2015) with refinements from Iosjpe et alc. (2020).

Because some radionuclides, with their provenance in a criticality event, have a very short physical half-life or very low inventory, they can be safely discounted. The following radionuclides have therefore been selected for potential consideration in the present study: Am-241, Co-60, Cs-137, Eu-152, Eu-154, Eu-155, Ni-59, Ni-63, Pu-238, Pu-239, Pu-240, Pu-241, Sr-90.

Unfortunately, information about parameters for kinetic modelling for many radionuclides and biota is lacking. Analysis of bioaccumulation processes for potential release scenarios for nuclear submarines demonstrate that it is incorrect to use both kinetic modelling and equlibrium concentration ratio approaches simultaneously as shown in Figure 2 (Iosjpe et al., 2020). Figure 2 shows concentrations in fish for some radionuclides where Cs-137 has been derived using the kinetic approach, and other radionuclides using the equlibrium concentration ratio (i.e. CR) approach. Given its relatively elevated levels in seawater, Cs-137 should strongly dominate the concentration, but during the initial period of the bioaccumulation process, the impact of Cs-137 is negligible in comparison with other radionuclides. This discrepancy corresponds to the fact that during the period when releases of radionuclides start, the concentration in biota is zero (as for Cs-137 in Figure 2), but according to the present release scenarios the equlibrium concentration ratio approach provides maximal concentrations in biota.

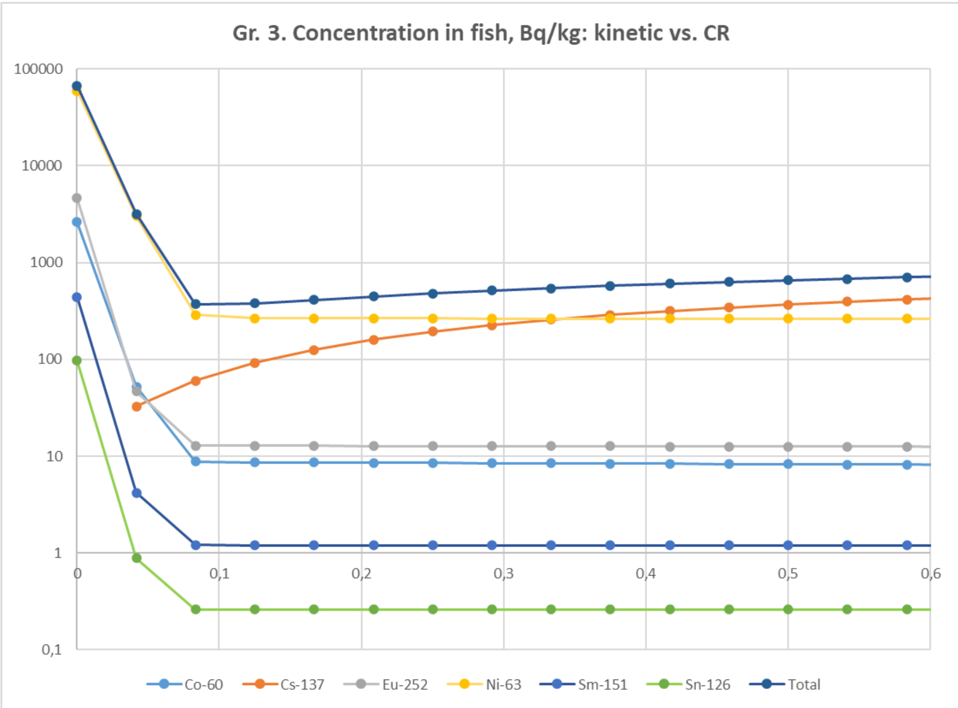


Figure 2. Kinetic modelling (Cs-137) vs. equlibrium concentration ratio approach (Co-60, Eu-252, Ni-63, Sm-151, Sn-126). Simulations are presented within time interval [0, 0.6] years.

The objective of the present NKS BIORAD project is to evaluate the bioaccumulation processes for a wide set of radionuclides and biota with subsequent analysis of the consequences after radionuclides releases into marine environment.

2. Bioaccumulation of radionuclides in marine organisms: food chain

Figure 3 shows the schematic of the food chain for the biokinetic models, which was selected as a basis for the present study (Hosseini et al., 2016, 2017; IAEA 1998; Iosjpe et al., 2016; de With et al., 2021).

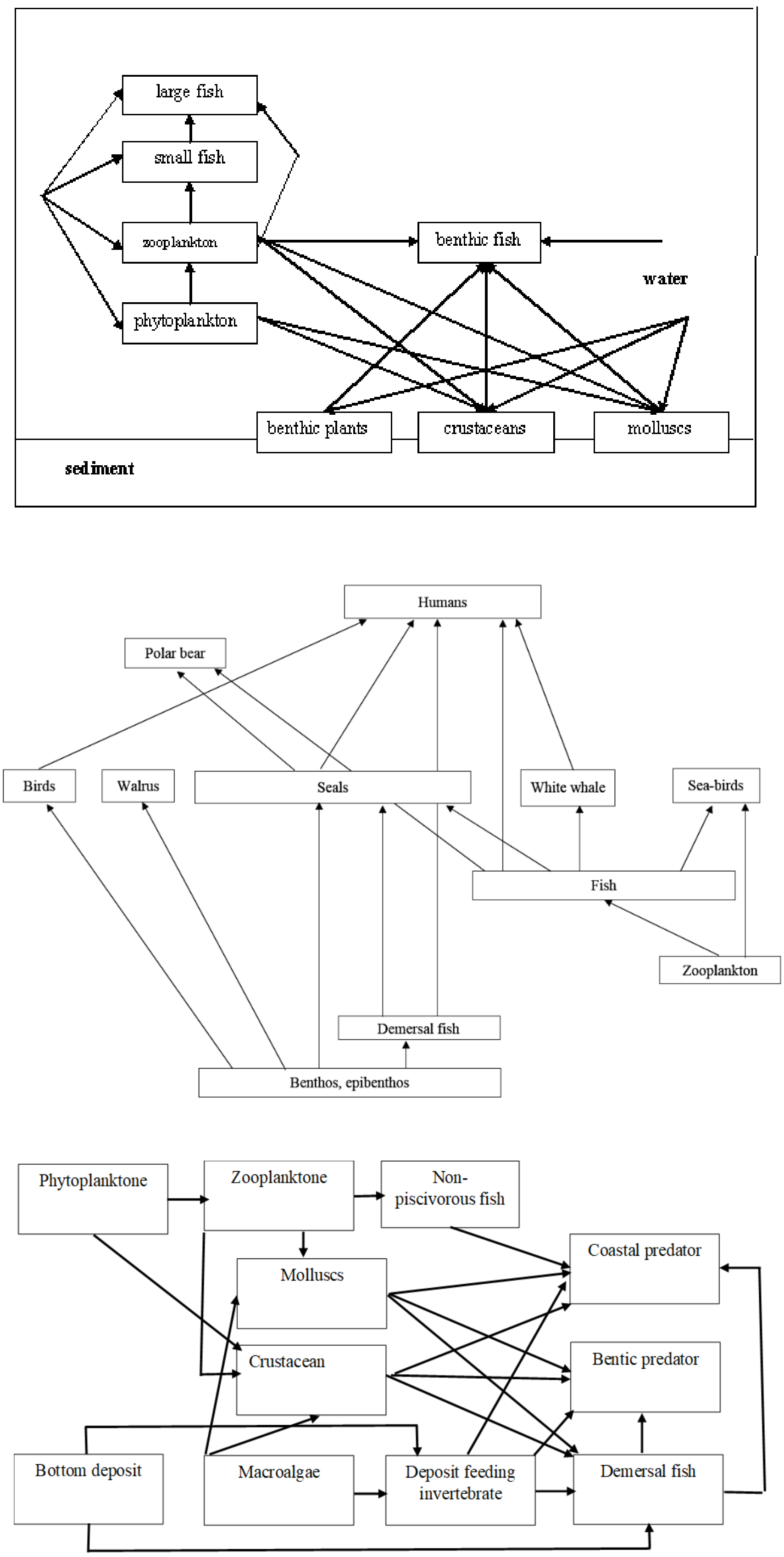


Figure 3. Schematic of the biokinetic models. Arrows correspond to the radionuclide transfer between marine organisms.

3. The system of equations for the bioaccumulation process

The system of equations for the biokinetic model can be described by the following expression, which was chosen after analyzing the existing models (Thomann, 1981; Heling et al., 2002; Brown et al., 2004; Vives i Batlle et al., 2008; Maderich et al., 2013; de With et al., 2021):

$$\frac{dC_i^{(tl)}}{dt} = AE_i \cdot IR_i \cdot C_{i-1}^{(tl)} + k_{u,i} \cdot C_w - C_i^{(tl)} \cdot k_{e,i} \qquad (1)$$

Here $C^{(tl)}_i$ and $C^{(tl)}_{i-1}$ – concentrations of radionuclide in trophic levels ”*i*” and ”*i-1*”; C_W – concentration of radionuclide in water column; AE_i – the assimilation efficiency for trophic level “*i*”, IR_i – ingestion per unit mass for trophic level “*i*”; $k_{u,i}$ – rate of the direct uptake of activity from water column for trophic level “i”; $k_{e,i}$ – the excretion rate for trophic level “i”. Where the consumption for species in trophic levels ”*i*” includes “*m”* different species in trophic levels ”*i-1*”, parameter $C^{(tl)}_{i-1}$ can be described as

$$C_{i-1}^{(tl)} = \sum_{j=1}^{m} w_j \cdot C_{i-1,j}^{(tl)} \qquad (2)$$

Here the consumption for species in trophic level ”*i*” includes *m* species in trophic levels

”*i-1*” with concentration of radionuclide in species *j* (*j=1,…,m*) of $C^{(tl)}_{i-1,j}$; w_j is a fraction of species *j* of all m species, where

$$\sum_{j=1}^{m} w_j = 1$$

It is important to note that knowledge about biokinetic coefficients based on habitat, ingestion of food, diet and excretion of activity for studied species are crucial information for biokinetic modelling.

4. Preliminary choosing of the kinetic parameters based on the literature review and existing databases.

The values of the biokinetic coefficients form equations (1) – (2) are tabulated in Tables 1-5. Tables 1-5 show that the values of the kinetic coefficients differ widely. Such uncertainties can be explained by the definition of the reference organisms, where different species are described by the same reference biota. Further, great variability is associated with the dimensions, masses and habitats for different organisms of the same species. It should also be noted that there are differences in kinetic models for describing the bioaccumulation process in marine organisms that provide a different description of kinetic parameters - the clear examples of such differences are presented by Vives i Batlle et al. (2016).

Ingestion per unit mass of biota (ingestion rate IR) is presnted in Table 1. Consumption for species with food preferences, described as a fraction of w from expression (2), is shown in Table 2. The assimilation efficiency for food consumptions (AE) for marine organisms is presnted in Table 3. The rate of the direct uptake of activity from water column (k_u) for marine organisms is presnted in Table 4. The excretion rate (k_e) for selected radionuclides and marine organisms and Biological half-life of radionuclides in organisms ($T_{1/2}$) are presented in Table 5. A symbol "*" in Tables 1-5 is described in section 6.5 and corresponds to the parameters in this study.

Table 1. Ingestion rates, (kg/d)/kg f.w.

Organism	**IR**	**References**
Zooplankton	0.105*	Thomann, 1981; the present report
	1	de With et al., 2021
Non-piscivorous fish / Pelagic small fish	0.017*	Thomann, 1981; the present report
	0.03	Keum et al., 2015
	0.03	de With et al., 2021; PREPARE, 2015
Piscivorouss fish / Pelagic large fish	0.009*	Thomann, 1981; Hosseini et al., 2017; the present report
	0.0055	PREPARE, 2015
	0.007	de With et al., 2021
	0.03	Keum et al., 2015
Deposit-feeding invertebrate	0.02	de With et al., 2021; the present report
Mollusk	0.06*	de With et al., 2021; PREPARE, 2015; the present report
	0.064	Keum et al., 2015
	0,2	Hosseini et al., 2017
Crustacean	0.015*	de With et al., 2021; PREPARE, 2015; the present report
	0,027	Keum et al., 2015; Hosseini et al., 2017
Demersal fish	0.007*	de With et al., 2021; the present report
	0.03	Keum et al., 2015
Bottom predator	0.03	Keum et al., 2015
	0.007*	de With et al., 2021; the present report
Coastal predator	0.007	de With et al., 2021; the present report
	0.03	Keum et al., 2015
Seal	0.072*	Hosseini et al., 2017; the present report
Sea Bird	0.28*	Hosseini et al., 2017; the present report

Table 2. Consumption for species with food preferences.

Species	w	Consumption	References
Zooplankton	1*	Phytoplanctoon	Thomann, 1981; de With et al., 2021; the present report
Non-piscivorous fish / Pelagic small fish	1*	Zooplanctoon	Thomann, 1981; de With et al., 2021; the present report
Piscivorouss fish / Pelagic large fish	1*	Non-piscivorous fish / Pelagic small fish	Thomann, 1981; de With et al., 2021; the present report
Deposit-feeding invertebrate	0.5	Bottom deposit (organic matter)	de With et al., 2021
	0.5	Macroalgae	
Mollusk	0.8*	Phytoplankton	PREPARE, 2015; the present report
	0.2*	Zooplankton	
	0.6	Phytoplankton	de With et al., 2021
	0.2	Zooplankton	
	0.2	Macroalgae	
Crustacean	0.2*	Phytoplankton	PREPARE, 2015; the present report
	0.8*	Zooplankton	
	0.1	Phytoplankton	de With et al., 2021
	0.8	Zooplankton	
	0.1	Macroalgae	
Demersal fish	0.1*	Bottom deposit (organic matter)	de With et al., 2021; the present report
	0.7*	Deposit-feeding invertebrate	
	0.1*	Mollusk	
	0.1*	Crustacean	
Bottom predator	0.3*	Deposit-feeding invertebrate	de With et al., 2021; the present report
	0.2*	Mollusk	
	0.2*	Crustacean	
	0.3*	Demersal fish	
Coastal predator	0.2*	Non-piscivorous fish	de With et al., 2021; the present report
	0.25*	Deposit-feeding invertebrate	
	0.1*	Mollusk	
	0.2*	Crustacean	
	0.25*	Demersal fish	
Seal	1*	Piscivorouss fish / Pelagic large fish	Hosseini et al., 2016; the present report
Sea Bird	1*	Piscivorouss fish / Pelagic large fish	Hosseini et al., 2016; the present report

Table 3. Assimilation efficiency rates.

Organism	Radionuclide	AE	References
Zooplankton	**Cs-137; Co-60**	0.5*	Thomann, 1981; the present report
		0.2	PREPARE, 2015
	Ni-59; Ni-63	0.2*	The present report
	Eu-152; Eu-154; Eu-155	0.05*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241	0.01	Thomann, 1981
		0.02*	The present report
	Am-241	0.02*	The present report
	General approach that has been applied to **Sr-90**, I-131, Cs-134, and Cs-137	0.2*	PREPARE, 2015; de With et al., 2021; the present approach
Non-piscivorous fish/Pelagic small fish	Cs-137; Co-60; Ni-59; Ni-63	0.5*	Thomann, 1981; Brown et al., 2004; PREPARE, 2015; Hosseini et al., 2017; the present report;
		0.64	Keum et al., 2015
	Eu-152; Eu-154; Eu-155	0.5*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report
	Sr-90	0.64	Keum et al., 2015
		0.3*	Vives i Batlle et al., 2016; Brown et al., 2004; the present report
Non-piscivorous fish/Pelagic small fish	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.5	PREPARE, 2015; de With et al., 2021
Piscivorouss fish/ Pelagic large fish	Cs-137	0.5*	Thomann, 1981; Brown et al., 2004; Hosseini et al., 2017; the present report
		0.64	Keum et al., 2015
	Eu-152; Eu-154; Eu-155; Co-60; Ni-59; Ni-63	0.7*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.1*	The present report
	Sr-90	0.64	Keum et al., 2015
		0.3*	Vives i Batlle et al., 2016; Brown et al., 2004; the present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.7	PREPARE, 2015; de With et al., 2021

Table 3. (continued).

Deposit-feeding invertebrate	General approach that has been applied to **Sr-90**, I-131, Cs-134, **Cs-137, Co-60; Ni-59; Ni-63**	0.3*	de With et al., 2021; the present report
	Eu-152; Eu-154; Eu-155	0.1*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*	The present report
Mollusk	Cs-137; Ni-59; Ni-63	0.5*	Vives i Batlle et al., 2016; Hosseini et al., 2017; the present report
	Eu-152; Eu-154; Eu-155	0.1*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*	The present report
	Sr-90	0.28	Vives i Batlle et al., 2016; Keum et al., 2015
	General approach that has been applied to **Sr-90**, I-131, Cs-134, and Cs-137; **Co-60**	0.5*	de With et al., 2021; PREPARE, 2015; the present report
Crustacean	Cs-137; Co-60; Ni-59; Ni-63	0.5*	Vives i Batlle et al., 2016; Hosseini et al., 2017; the present report
	Eu-152; Eu-154; Eu-155	0.1*	The present report
Crustacean	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*	The present report
	Sr-90	0.28	Vives i Batlle et al., 2016; Keum et al., 2015
	General approach that has been applied to **Sr-90**, I-131, Cs-134, and Cs-137	0.5*	de With et al., 2021; PREPARE, 2015; the present report
Demersal fish	Cs-137; Eu-152, Eu-154, Eu-155; Co-60; Ni-59; Ni-63	0.5*	Brown et al., 2004; de With et al., 2021; Hosseini et al., 2017 the present report;
		0.64	Keum et al., 2015
	Pu-238; Pu-239; Pu-240	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.5	de With et al., 2021; PREPARE, 2015
	Sr-90	0.64	Vives i Batlle et al., 2016; Keum et al., 2015
		0.3*	The present report
Bottom predator	Cs-137	0.7	de With et al., 2021; Hosseini et al., 2017
		0.5*	The present report
		0.64	Keum et al., 2015

Table 3 (continued).

	Eu-152; Eu-154; Eu-155; Co-60; Ni-59; Ni-63	0.7*	The present report
	Pu-238; Pu-239; Pu-240	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.1*	The present report
	Sr-90	0.64	Vives i Batlle et al., 2016; Keum et al., 2015
		0.3*	The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.7	de With et al., 2021; PREPARE, 2015
Coastal predator	Cs-137	0.5*	Brown et al., 2004; Hosseini et al., 2017; the present report
		0.64	Keum et al., 2015
	Eu-152; Eu-154; Eu-155; Co-60; Ni-59; Ni-63	0.7*	The present report
	Pu-238; Pu-239; Pu-240	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.1*	The present report
	Sr-90	0.64	Vives i Batlle et al., 2016; Keum et al., 2015
		0.3*	The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.7	de With et al., 2021
Seal	Cs-137	1*	Gwynn et al., 2006; Hosseini et al., 2017; the present report
	Co-60; Ni-59; Ni-63	0.5*	The present report
	Eu-152; Eu-154; Eu-155	0.2*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report
	Sr-90	0.3*	The present report
Sea Bird	Cs-137	1	Hosseini et al., 2017
		0.5*	The present report
	Ni-59; Ni-63	0.5*	The present report
	Co-60	0.1*	The present report
	Eu-152; Eu-154; Eu-155	0.1*	The present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*	The present report
Sea Bird	Sr-90	0.3*	The present report

Table 4. The rate of the direct uptake of activity from the water column (k_u), $l \cdot kg^{-1} \cdot d^{-1}$ (Some investigators use the k_u dimensionality as d^{-1} under the assumption that the weght of 1 liter is equal to 1 kg).

Organism	**Radionuclide**	**k_u**	**References**
Zooplankton	Cs-137	0.49*	Thomann, 1981; Brown et al., 2004; Hosseini et al., 2017; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	18.7*	Thomann, 1981; the present report
	General approach that has been applied to **Sr-90**, I-131, Cs-134, Cs-137, **Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63**	1.5*	PREPARE, 2015; de With et al., 2021; the present report
Non-piscivorous fish/Pelagic small fish	Cs-137	0.07*	Thomann, 1981; the present report
		0.01	Brown et al., 2004; Hosseini et al., 2017
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.3*	Thomann, 1981; the present report
	General approach that has been applied to **Sr-90**, I-131, Cs-134, Cs-137, **Eu-152, Eu-154, Eu-155, Co-60t, Ni-59, Ni-63**	0.1*	PREPARE, 2015; de With et al., 2021; the present report
Piscivorouss fish/ Pelagic large fish	Cs-137	0.01*	Thomann, 1981; 0.01 Brown et al., 2004; Hosseini et al., 2017; the present report
	Pu-238; Pu-239; Pu-240; Pu-241	0.01	Thomann, 1981
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report
	General approach that has been applied to **Sr-90**, I-131, Cs-134, Cs-137, **Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63**	0.075*	PREPARE, 2015 PREPARE, 2015; de With et al., 2021; the present report
Deposit-feeding invertebrate	General approach that has been applied to **Sr-90**, I-131, Cs-134, **Cs-137, Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63**	0.1*	de With et al., 2021; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.1*	The present report

Table 4. (continued)

Mollusk	Cs-137; Sr-90; Eu-152; Eu-154; Eu-155, Co-60, Ni-59, Ni-63	o0.15*	de With et al., 2021; PREPARE, 2015; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	2.04*	The present report
		4.75	Hosseini et al., 2017
Crustacean	Cs-137	0.49	Hosseini et al., 2017
	General approach that has been applied to **Sr-90**, I-131, Cs-134, **Cs-137, Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63**	0.1*	de With et al., 2021; PREPARE, 2015; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.06*	The present report
Demersal fish	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.05	de With et al., 2021
	Cs-137	0.01	Brown et al., 2004; Hosseini et al., 2017
	Cs-137	0.07*	Thomann, 1981; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*	The present report
	Sr-90, Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63	0.1*	The present report
Bottom predator	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	0.05	de With et al., 2021
	Cs-137	0.01*	Thomann, 1981; Brown et al., 2004; Hosseini et al., 2017; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report
	Sr-90, Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-63	0.075*	The present report
Coastal predator	Cs-137	0.01*	Thomann, 1981; Brown et al., 2004; Hosseini et al., 2017; the present report
	General approach that has been applied to **Sr-90**, I-131, Cs-134, Cs-137, **Eu-152, Eu-154, Eu-155, Co-60 Ni-59, Ni-63**	0.075*	de With et al., 2021; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*	The present report

Table 4. (continued)

Seal	All radionuclides	0*	Brown et al., 2004; Hosseini et al., 2017; the present report
Sea Bird	All radionuclides	0*	Hosseini et al., 2017; the present report

Table 5. The excretion rate (k_e, d^{-1}) for selected radionuclides and marine organisms and Biological half-life of radionuclides in organisms ($T_{1/2}$, d). The parameter range (minimum and maximum values) is shown where possible in parantheses.

Organism	**Radionuclide**	k_e	$T_{1/2}$	**References**
Zooplankton	Am-241	0.020	34	Beresford et al., 2015
	Cs-137	0.03*		Thomann, 1981; the present report
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.05*		Thomann, 1981; the present report
	Eu-152, Eu-154, Eu-155, Co-60, Ni-59, Ni-62	0.139*		The present report
Zooplankton	General approach that has been applied to **Sr-90**, I-131, Cs-134, Cs-137	0.139* 0.139*	5	The present report PREPARE, 2015; de With et al., 2021: the present report
Non-piscivorous fish/Pelagic small fish	Co-60	4.99E-2	13.9	Beresford et al., 2015
	Cs-137	0.003*		Thomann, 1981; the present report
		0.0107		Hosseini et al., 2017
		0.053	13	Keum et al., 2015; Vives i Batlle et al., 2016
		0.0107	65	Vives i Batlle et al., 2016
		7.3E-3	95 (White fish)	Present study. Suolanen, 2021
	Eu-152	0.03455*		The present report
	Eu-154, Eu-155	0.03466*		The present report
	Ni-59, Ni-63	0.01*		The present report

Table 5. (continued).

Organism	Radionuclide	k_e	$T_{1/2}$	References
Non-piscivorous fish/Pelagic small fish		7.32E-3 (3.09E-3; 1.96E-2)	94.7 (35.4; 224)	Beresford et al., 2015
	Sr-90	0.053	13	Keum et al., 2015; Vives i Batlle et al., 2016
		0.0139*		The present report
		4.95E-03	140	Vives i Batlle et al., 2016
	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.02*		Thomann, 1981; the present report
	General approach that has been applied to Sr-90, I-131, Cs-134, Cs-137	1.39E-03 9.24E-03 3.47E-02 0.231	500 (Bone) 75 (Flesh) 20 (Organs) 3 (Stomach)	PREPARE, 2015; de With et al., 2021
	Co-60	0.0112*		The present report
Piscivorouss fish / Pelagic large fish	Co-60	1,89E-02 (1.40E-2; 2.40E-2)	36.6 (28.9; 9.5)	Beresford et al., 2015 (Whole organism)
		1,85E-02 (1.42E-2; 2.67E-2)	37.5 (26; 48.7)	Beresford et al., 2015 (Intestine)
Piscivorouss fish / Pelagic large fish		1.34E-02 (1.15E-2; 1.80E-2)	51.6 (38.5; 60.3)	Beresford et al., 2015 (Muscle)
		1,60E-02 (1,44E-2;1,81E-2)	43.3 (38.4; 8.1)	Beresford et al., 2015 (Liver)
Piscivorouss fish / Pelagic large fish	Cs-137	1.8E-03*		Thomann, 1981; the present report
		0.0107		Hosseini et al., 2017
		0.053	13	Keum et al., 2015;
		0.0107	65	Vives i Batlle et al., 2016
		2.3E-3	300 (Pike)	Present study. Suolanen, 2021
		3E-3 (2.8E-3; 3.5E-3)	225 (200-250) (Small and large Pearch)	Present study. Suolanen, 2021

Table 5. (continued).

Piscivorouss fish / Pelagic large fish	Pu-238; Pu-239; Pu-240; Pu-241; Am-241	0.01*		Thomann, 1981; the present report
	Sr-90	0.053	13	Keum et al., 2015;
		4.95E-03	140	Vives i Batlle et al., 2016
		4.88E-03*		The present report
	Eu-152	0.0172*		The present report
	Eu-154, Eu-155	0.0173*		The present report
	Co-60	0.005*		The present report
	Ni-59, Ni-63	0.009*		The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	6.93E-04 4.62E-03 1.73E-02 0.139	1000 (Bone) 150 (Flesh) 40 (Organs) 5 (Stomach)	PREPARE, 2015; de With et al., 2021
Deposit-feeding invertebrate	Cs-137	1.02E-1 (3.50E-2; 2.67E-1)	6.77 (2.6; 19.8)	Beresford et al., 2015
	General approach that has been applied to Sr-90, I-131, Cs-134, and **Cs-137**	4.62E-02*	15	de With et al., 2021; the present report
Deposit-feeding invertebrate	Co-60	3.06E-2 (9.50E-3; 8.80E-02)	22.7 (7.9; 73)	Beresford et al., 2015
	Pu-238, Pu-239, Pu-240, Pu,241, Am-241	0.029*		The present report
	Sr-90, Co-60	1.04E-02*		The present report
	Eu-152	0.0381*		The present report
	Eu-154, Eu-155	0.0382*		The present report
	Ni-59, Ni-63	1.04E-02*		The present report
Mollusk	Am-241	2.51E-2 (1.78E-2; 4.31E-2)	27.6 (16.1; 39)	Beresford et al., 2015
	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	2.5E-2*		The present report
	Co-60	5.21E-3 (1.51E-2; 2.21E-3)	133 (31.4; 460)	Beresford et al., 2015

Table 5. (continued).

Mollusk	Pu-238, Pu-239, Pu-240	7.22E-3 (9.79E-4; 1.07E-1)	96.1 (6.5; 708)	Beresford et al., 2015
	Sr-90	1.18E-2 (5.98E-3; 6.73E-2)	58.7 (10.3; 116)	Beresford et al., 2015
		3.01E-02	23	Keum et al., 2015;
	Sr-90, Ni-59, Ni-63	1.39E-02*		The present report
		2.175E-02	32	Vives i Batlle et al., 2016
	Eu-152	0.0694*		The present report
	Eu-154, Eu-155	0.0695*		The present report
	Cs-137	1.70E-2 (4.33E-1; 7.70E-3)	40.8 (1.6; 90)	Beresford et al., 2015
	Cs-137, Co-60	1.39E-02*		The present report
		3.01E-02	23	Keum et al., 2015;
		3.85E-02	18	Vives i Batlle et al., 2016
		0.04		Hosseini et al., 2017
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	1.39E-02	50	PREPARE, 2015; de With et al., 2021
Crustacean	Co-60	4.45E-2; (2.57E-2; 1.00E-1)	15.6 (6.9; 27)	Beresford et al., 2015
	Pu-238, Pu-239, Pu-240	2.59E-2 (4.62E-2; 1.82E-2)	26.8 (15; 38)	Beresford et al., 2015
	Pu-238, Pu-239, Pu-240, Pu-241, Am-241	0.033*		The present report
	Sr-90	2.42E-2 (1.58E-2; 5.17E-2)	28.7 (13.4; 44)	Beresford et al., 2015
		1.50E-02	46	Keum et al., 2015;
		6.93E-03*		The present report
		1.20E-02	58	Vives i Batlle et al., 2016

Table 5. (continued).

Crustacean	Eu-152	6.82E-03*		The present report
	Eu-154, Eu-155, Co-60, Ni-59, Ni-63	6.93E-03*		The present report
	Cs-137	2.31E-02	30	Beresford et al., 2015
		0.01		Hosseini et al., 2017
		1.50E-02	46	Keum et al., 2015;
		0.34	2	Vives i Batlle et al., 2016
	General approach that has been applied to Sr-90, I-131, Cs-134, and **Cs-137**	6.93E-03*	100	PREPARE, 2015; de With et al., 2021; the present report
Demersal fish	Co-60	9.99E-03 (4.18E-3; 2.24E-2)	69.4 (31; 166)	Beresford et al., 2015
	Sr-90	6.30E-3	110	Beresford et al., 2015
		0.053	13	Keum et al., 2015;
		4.95E-03	140	Vives i Batlle et al., 2016
		0.0139*		The present report
	Cs-137	1.64E-2 (1.02E-2; 3.85E-2)	42.2 (18; 68)	Beresford et al., 2015
		0.0107	65	Hosseini et al., 2017; Vives i Batlle et al., 2016
		0.003*		The present report
		5.33E-02	13	Keum et al., 2015;
	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	0.02*		The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	1.39E-03 9.24E-03 3.47E-02 0.231	500 (Bone) 75 (Flesh) 20 (Organs) 3 (Stomach)	With et al., 2021
	Eu-152	0.03455*		The present report
	Eu-154, Eu-155	0.03466*		The present report
	Co-60	0.0112*		The present report
	Ni-59, Ni-63	0.01*		The present report

Table 5. (continued).

Bottom predator	Co-60	1.10E-02	63	Beresford et al., 2015
	Sr-90	1.59E-3 (1.00E-3; 3.89E-3)	436 (178; 693)	Beresford et al., 2015
		0.053	13	Keum et al., 2015;
		4.95E-03	140	Vives i Batlle et al., 2016
		4.88E-03*		The present report
	Cs-137	2.04E-02	34	Beresford et al., 2015
		0.0107		Vives i Batlle et al., 2016; Hosseini et al., 2017
		0.0018*		The present report
	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	0.01*		The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	6.93E-04 4.62E-03 1.73E-02 0.139	1000 (Bone) 150 (Flesh) 40 (Organs) 5 (Stomach)	With et al., 2021
	Eu-152	0.0172*		The present report
	Eu-154, Eu-155	0.0173*		The present report
	Co-60	0.005*		The present report
	Ni-59, Ni-63	0.009*		The present report
Coastal predator	Cs-137	7.32E-3 (3.09E-3; 1.96E-2)	94.7 (35.4; 224)	Beresford et al., 2015
	Cs-137	5.33E-02	13	Keum et al., 2015;
Coastal predator	Cs-137	0.0107	65	Hosseini et al., 2017; Vives i Batlle et al., 2016
		0.0018*		The present report
	Sr-90	0.053	13	Keum et al., 2015;
	Sr-90	4.95E-03	140	Vives i Batlle et al., 2016
		4.88E-03*		The present report
	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	0.01*		The present report
	General approach that has been applied to Sr-90, I-131, Cs-134, and Cs-137	6.93E-04 4.62E-03 1.73E-02 0.139	1000 (Bone) 150 (Flesh) 40 (Organs) 5 (Stomach)	PREPARE, 2015; de With et al., 2021
	Eu-152	0.0172*		The present report

Table 5. (continued).

Coastal predator	Eu-154, Eu-155	0.0173*		The present report
	Co-60	0.005*		The present report
	Ni-59, Ni-63	0.009*		The present report
Seal	Cs-137	0.0239*		Gwynn et al., 2006; Hosseini et al., 2017; the present report
Seal	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	2.0E-03*		The present report
	Eu-152	0.0172*		The present report
	Eu-154, Eu-155	0.0173*		The present report
	Sr-90	4.88E-03*		The present report
	Co-60	0.05*		The present report
	Ni-59, Ni-63	0.02*		The present report
Sea Bird	Cs-137	0.036*		Hosseini et al., 2017; the present report
	Am-241, Pu-238, Pu-239, Pu-240, Pu-241	1.4E-02*		The present report
	Sr-90	5.28E-03*		The present report
	Eu-152	0.0345*		The present report
	Eu-154, Eu-155	0.0346*		The present report
	Co-60	0.05*		The present report
	Ni-59, Ni-63	0.04*		The present report

Additionally, Table A1 of the Appendix includes information about equilibrium/quasi-equilibrium concentration ratios (*CR*) for considered biota and radionuclides. The reason for including the concentration ratio data in the present report is a statement that evaluation of the bioaccumulation of radionuclides in biota by kinetic modelling approach and by the equilibrium concentration ratio approach have to provide the similar results under simulation of the equilibrium / quasi equilibrium conditions. This statement is important for controlling the simulation results, as well as for determining the kinetic parameters.

5. The lack and uncertainties of available information

The following radionuclides have been selected for potential consideration in the present study: Am-241, Co-60, Cs-137, Eu-152, Eu-154, Eu-155, Ni-59, Ni-63, Pu-238, Pu-239, Pu-240, Pu-241, Sr-90.

Tables 1-5 show that there is information about some kinetic coefficients for following marine organisms: (1) phytoplankton, (2) zooplankton, (3) macroalgae, (4) different kind of non-piscivorous and piscivorous fish (different kind of fish are caused by different consumption and food preferences for species), (5) deposit-feeding invertebrate, (6) molluscs, (7) crustaceans, (8) seals and (9) sea birds/sea bird eggs.

According to collected information in Tables 1-5 and A1 there are estimations/information about equilibrium/quasi-equilibrium concentration ratios and ingesting rates for all selected organisms and radionuclides (however, it should be emphasized that there are the differences up to orders of magnitude even for the concentration ratios in different sources). The lack of information is shown in Table 6, where red colour corresponds to lack of information of three parameters (the assimilation efficiency, the rate of the direct uptake of activity from the water column and the excretion rate), blue colour corresponds to the lack of information for two of them, yellow colour corresponds to the lack of information about one parameter and green colour means that there is information about all three parameters.

Table 6. The lack of information about kinetic parameters.

	Radionuclides												
Biota	**^{241}Am**	**^{60}Co**	**^{137}Cs**	**^{152}Eu**	**^{154}Eu**	**^{155}Eu**	**^{59}Ni**	**^{63}Ni**	**^{238}Pu**	**^{239}Pu**	**^{240}Pu**	**^{241}Pu**	**^{90}Sr**
1													
2													
3													
4													
5													
6													
7													
8													
9													

It is nessasary to note that evaluation of bioaccumulation of radionuclides by phytoplankton and macroalagae is based on the assumption that equilibrium concentration ratio approach is suitable for this biota (Thomann, 1981).

It is also important to note that additionally to lack of information for kinetic parameters, there is a significant uncertainty for the known values of the parameters (up to orders of magnitude) according to information collected in Tables 1-5 and A1. The main reason for such uncertainties is a great variability of the environmental conditions for biota, habitats and significant mass variation for the same kind of species.

6. Potential reduction and control of the uncertainty for evaluation of the kinetic parameters of the model for bioaccumulation of radionuclides in biota

6.1. Allometric approach

The allometric approach is widely used for evaluation of the kinetic parameters for different species.

As example, we can consider an allometric approach, which is provided by Nagy (2001) in form of expressions for the fresh intake for seals (FMI_S), and birds (FMI_B), (g/day):

$$FMI_S=0.348M_S^{0.859} \quad (3)$$

$$FMI_B=3.221M_B^{0.658}, \quad (4)$$

where M_S and M_B are the weights of the adult seals and birds, (g), correspondently.

According to definition of the ingestion rate (IR) it is easy to write an expression for IR due the fresh intake (FMI) and mass (M) of the species:

$$IR = FMI / M$$

Therefore, expressions for the ingesting rates for adult seals (IR_S) and sea birds (IR_B) can be written as

$$IR_S = 0.348 \cdot M_S^{0.859-1} = 0.348 \cdot M_S^{-0.141} \quad (5)$$

$$IR_B = 3.221 \cdot M_B^{0.658-1} = 3.221 \cdot M_B^{-0.342}, \quad (6)$$

where M_S and M_B are weights of the seals and birds in grams.

Expressions (5) and (6) are illustrated by Figures 4 and 5.

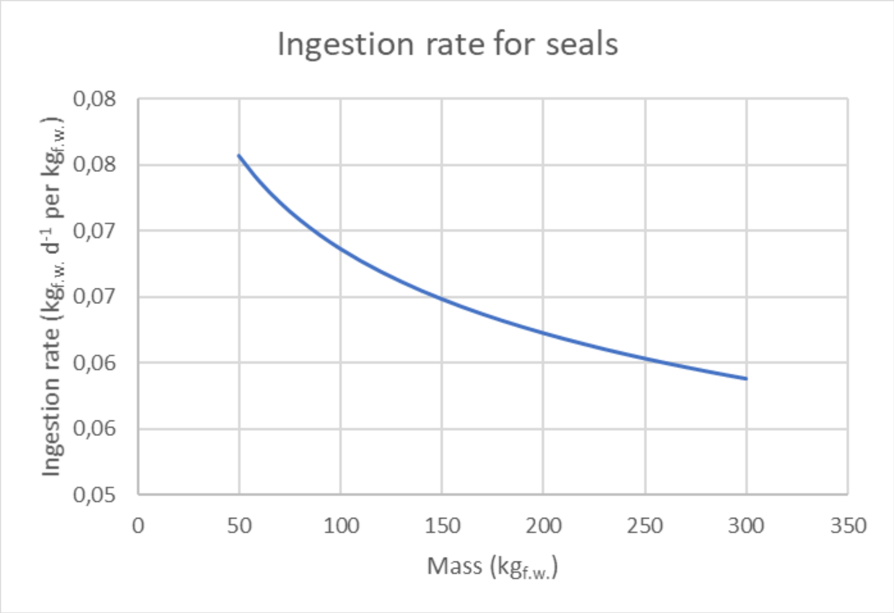


Figure 4. The relationship between mass and ingestion rates for seals.

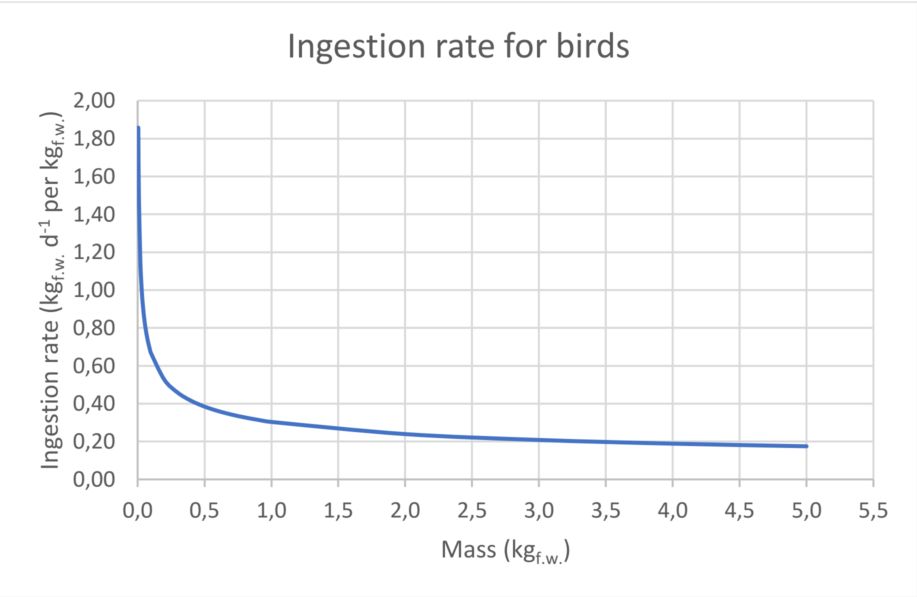


Figure 5. The relationship between mass and ingestion rates for sea birds.

Another example corresponds to allometric expressions for extration rates for seals and birds for Cs-137 and Pu-239:

Cs-137 and Pu-239 excretion rates for seals are provided by U.S. Department of Energy (2002) and Whicker and Shultz (1982):

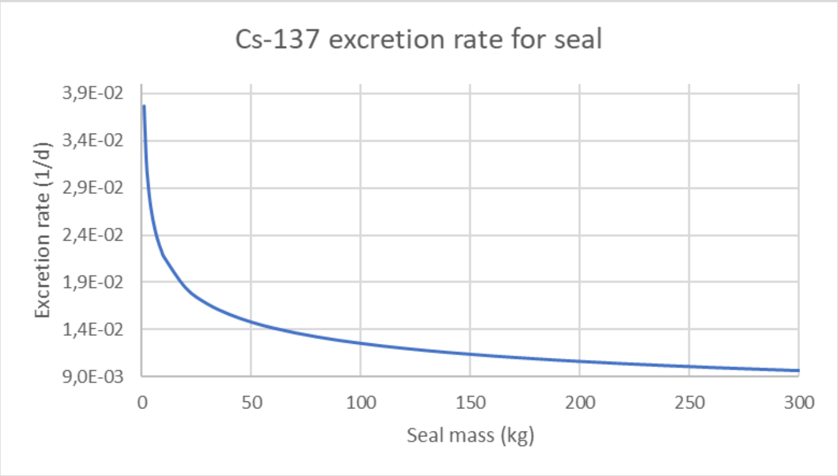
$$k_e^{(S,Cs)} = \frac{ln2}{3.5M_S^{0.24}} \quad (7)$$

$$k_e^{(S,Pu)} = \frac{ln2}{0.8M_S^{0.81}} \quad (8)$$

$$k_e^{(B,Cs)} = \frac{ln2}{18.36M_B^{0.24}} \quad (9)$$

Here $k_e^{(S,Cs)}$, $k_e^{(S,Pu)}$ and $k_e^{(B,Cs)}$ are Cs-137 and Pu-239 excretion rates for seals and the Cs-137 excretion rate for birds (d^{-1}); M_S and M_B are mass for seals and birds in grams (f. w.).

Expressions (7) - (9) are illustrated by Figures 6 - 8.



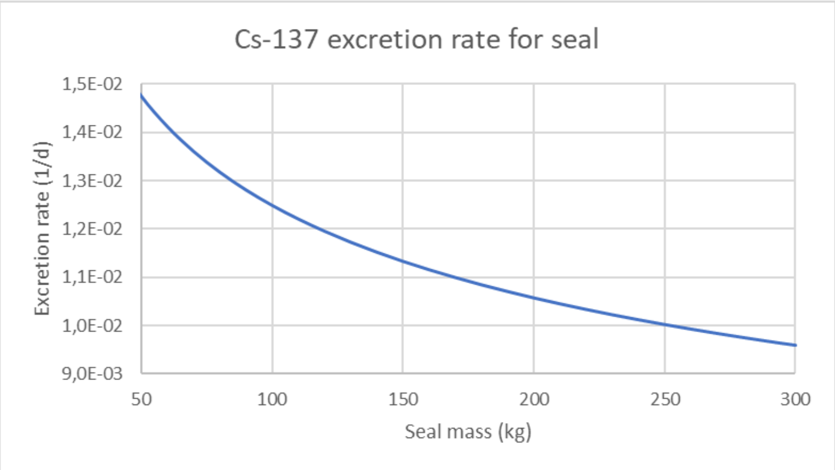
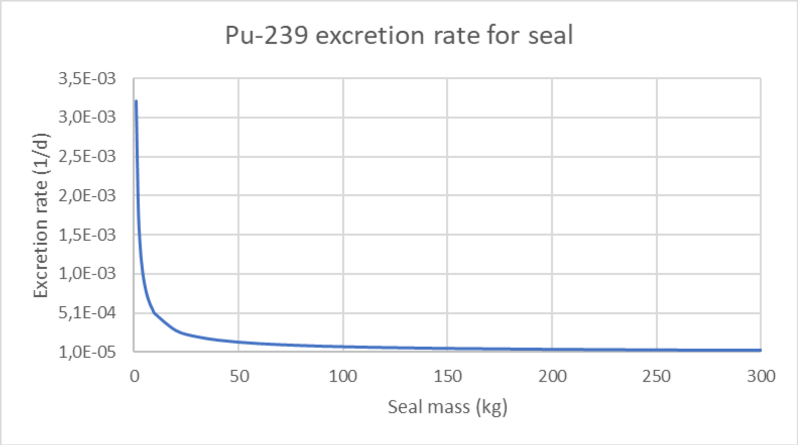


Figure 6. The relationship between mass and excretion rates for Cs-137 for seals.



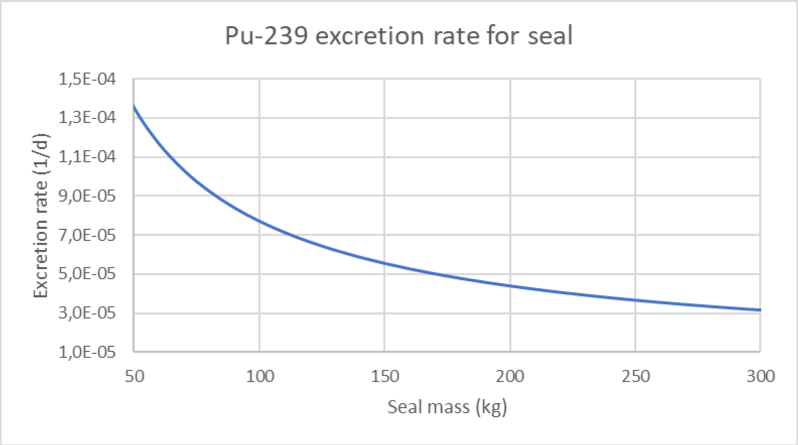


Figure 7. The relationship between mass and excretion rates for Pu-239 for seals.

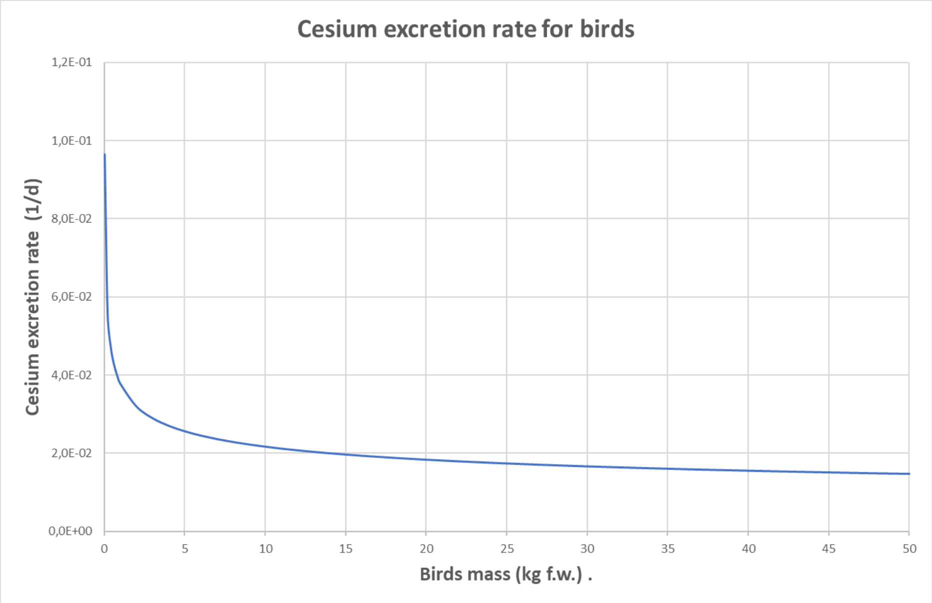


Figure 8. The relationship between mass and excretion rates for Cs-137 for sea birds.

Results described by expressions (5) - (9) and illustrated in Figures (4) - (8) show that allometric approach could be very useful for determining and controlling of the parameters of the same type of organisms with different masses. It has also demonstrated that estimating parameters with unknown mass of organism can lead to significant uncertainties. Therefore, it is necessary to consider this statement under verification of the bioaccumulation models.

6.2. The excretion rates for the isotopes of the radioactive element

We can adopt a reasonable assumption that the assimilation efficiency (AE_i), the ingestion per unit mass (IR_i) and rate of the direct uptake of activity from the water column ($k_{u,i}$) are the same for each isotope of the same radioactive element.

The excretion rate for organism of trophic level "i" ($k_{e,i}$) is calculated by expression (10):

$$k_{e,i} = \frac{ln2}{T_{1/2,i}}, \tag{10}$$

where $T_{1/2,i}$ is the effective half-life of radionuclide in this organism.

$T_{1/2,i}$ can be defined from equation

$$\frac{1}{T_{1/2,i}} = \frac{1}{T_{1/2,i}^{(B)}} + \frac{1}{T_{1/2,i}^{(R)}}, \tag{11}$$

where $T_{1/2,i}^{(B)}$ and $T_{1/2,i}^{(R)}$ are biological and radioactive/physical half-life, respectively.

It is easy to derive following statements from expressions (10) and (11):

If $T_{1/2,i}^{(B)} << T_{1/2,i}^{(R)}$ then $T_{1/2,i} \approx T_{1/2,i}^{(B)}$ (12)

If $T_{1/2,i}^{(B)} >> T_{1/2,i}^{(R)}$ then $T_{1/2,i} \approx T_{1/2,i}^{(R)}$ (13)

If $T_{1/2,i}^{(R*)} > T_{1/2,i}^{(R**)}$ then $T_{1/2,i}^{(*)} > T_{1/2,i}^{(**)}$ (14)

Here, $T_{1/2,i}^{(R*)}$ and $T_{1/2,i}^{(R**)}$ are radioactive / physical half-life for isotopes (*) and (**) of the same radioactive element, respectively; $T_{1/2,i}^{(*)}$ and $T_{1/2,i}^{(**)}$ are the effective half-life of isotopes (*) and (**) in this organism, respectively.

Expressions (10) – (14) allow control of the determination of excretion rates for isotopes with different physical half-life and may be useful during verification of the bioaccumulation model.

6.3. Simplification of the modeling approach

The simplification of the bioaccumulation model can be used where we have a lack of information on kinetic parameters.

Most models of marine bioaccumulation assume that the equilibrium/quasi-equilibrium concentration ratio approach can be applied to the accumulation of radionuclides in phytoplankton based on the concentration of the radionuclide in water. One of the simplifications is an extension of this approach to all kinds of prey / low trophic levels, if these organisms are not a final biota of the study (Hosseini et al., 2017).

Another possibility to simplify bioaccumulation models is to reduce the number of kinetic coefficients. Several models that practically combine the process of food ingestion and direct absorption of activity from water have been described in (Vives i Batlle et al., 2016).

In many cases, the simplified modeling approach can provide at least quite good conservative dose estimates of the main exposure pathways.

6.4. The similarity of the distribution of radionuclides in biota

Information about distribution of accumulated radionuclide in marine organisms can be useful for evaluation and control of the kinetic parameters. For example, according to (Yankovich et al. (2010), Cs-137 and Sr-90 are accumulated mainly in fish muscles and fish bones, respectively. PREPARE (2015) collected similar information about the main target in fish body for wide set of radionuclides.

It is possible to assume that similar distributions of activity of radionuclides in the different parts of marine organisms are based on the similar metabolism, and it is possible to consider such radionuclides as analogs. Therefore, in the absence of information about kinetic parameters, for the considered radionuclide, it is possible to use information from well-known analog as preliminary evaluation. In spite of such estimations are very rough, it can be useful to consider these estimations as initial points for following mathematical experiments.

6.5. The successive simulations of bioaccumulation processes during increasing trophic levels.

In consequences of (i) significant lack of information regarding kinetic parameters for wide set of radionuclides and (ii) very large uncertainties for parameters presented in databases, evaluation of the kinetic parameters through the successive simulations of bioaccumulation processes under increasing trophic levels makes considerable promise. Such methodology provides an opportunity to compare results of simulations under equilibrium conditions with the concentration-ratio approach, which has the most developed database.

Mathematical experiments in this section were performed with assistance of the approaches described in sections 6.1 – 6.4 of the present report.

Figures 9-15 show results for kinetic modelling of Cs-137 bioaccumulation in different marine organisms according to the food chain presented in the present report. Modelling has been performed for constant concentration of 1 Bq/l in marine water. The figures clearly show that concentration of Cs-137 in marine organisms tends to equilibrium or quasi-equilibrium state, which can be described by the concentration ratio approach.

Results presented in Figures 9-15 can be considered as verification of the present modelling approach. A part of parameters had been validated by result for the Finland Bay after Chernobyl accident (EFMARE, 2015). Nevertheless, Figures 9-15 demonstrate that even for Cs-137 there are different possibilities of describing the kinetic parameters to fit different values of the concentration ratios corresponding to different sources.

Figures 16-50 show similar results for Eu-155, Ni-63, Pu-239 and Sr-90.

For some radionuclides and biota there is information about arithmetical and geometrical mean values (AM and GM, correspondently) and the range for potential values (Min and Max, correspondently) of concentration ratios. This information is also presented in figures.

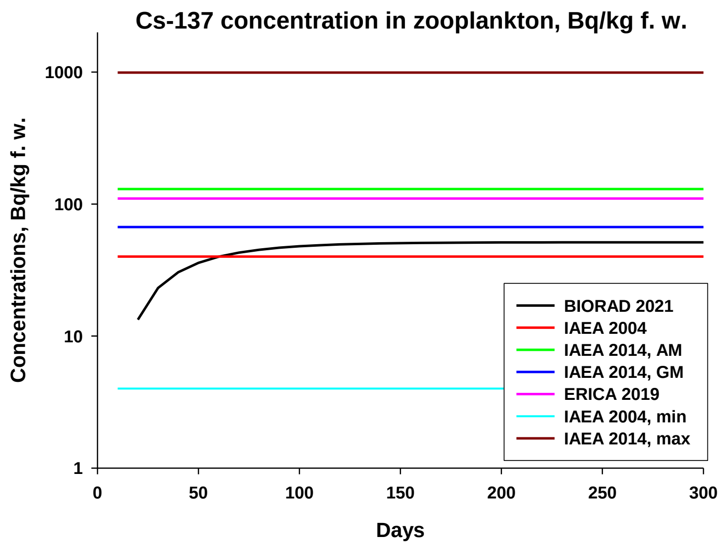


Figure 9. Kinetic model for Cs-137 bioaccumulation in zooplankton.

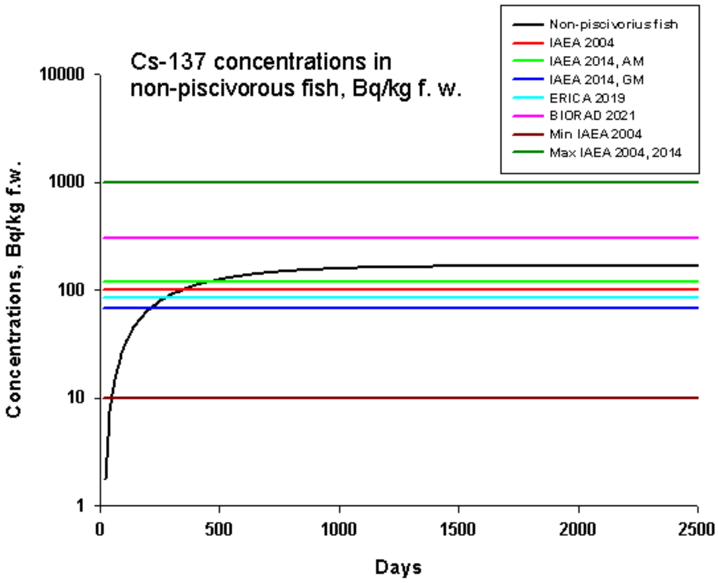


Figure 10. Kinetic model for Cs-137 bioaccumulation in non-piscivorous fish.

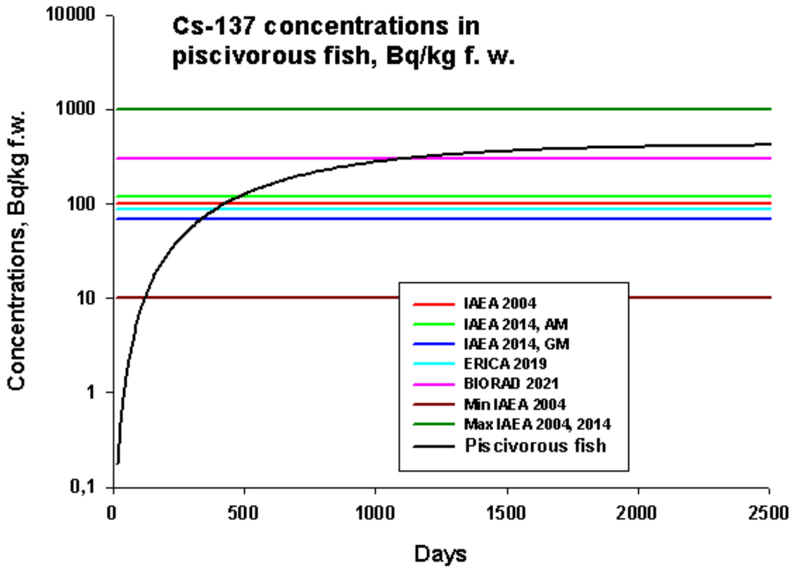


Figure 11. Kinetic model for Cs-137 bioaccumulation in piscivorous fish.

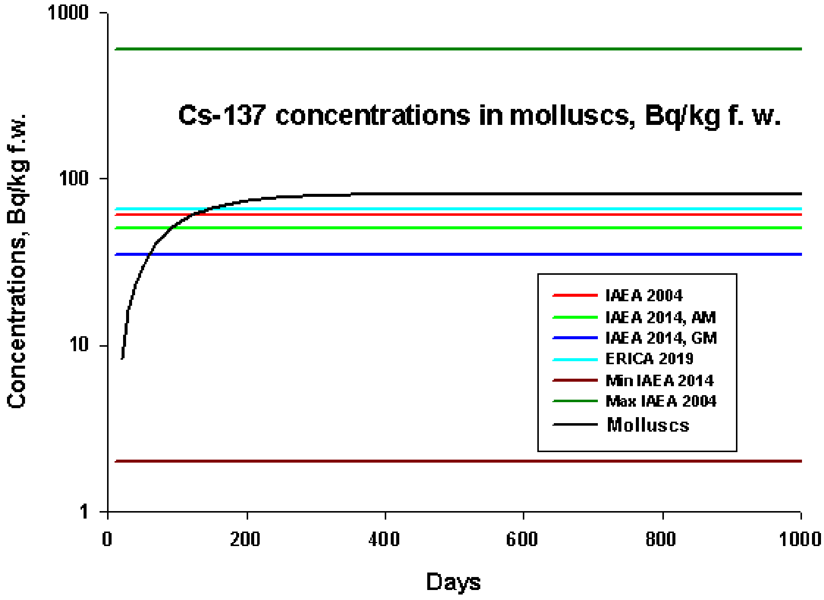


Figure 12. Kinetic model for Cs-137 bioaccumulation in molluscs.

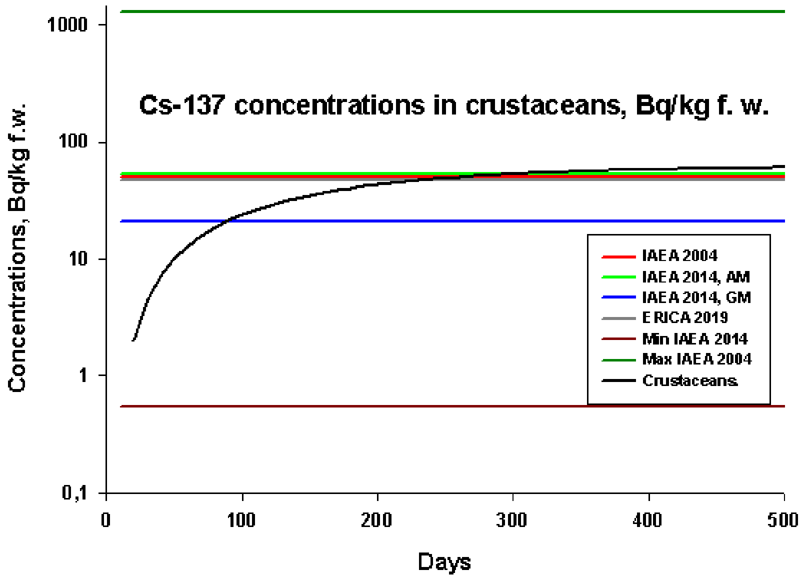


Figure 13. Kinetic model for Cs-137 bioaccumulation in crustaceans.

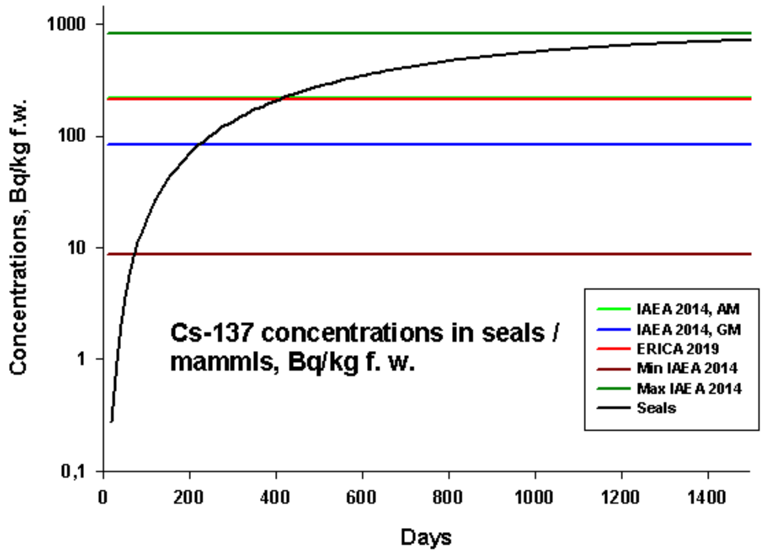


Figure 14. Kinetic model for Cs-137 bioaccumulation in seals.

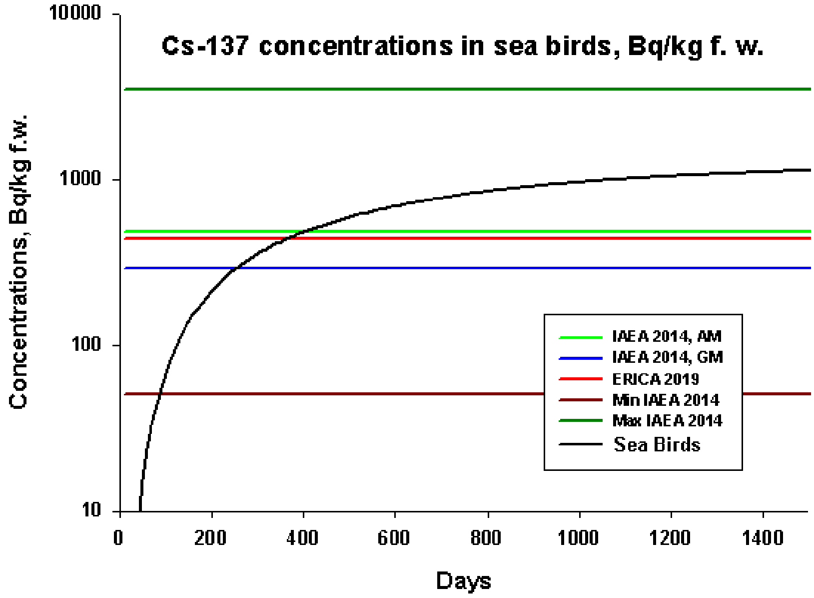


Figure 15. Kinetic model for Cs-137 bioaccumulation in sea birds.

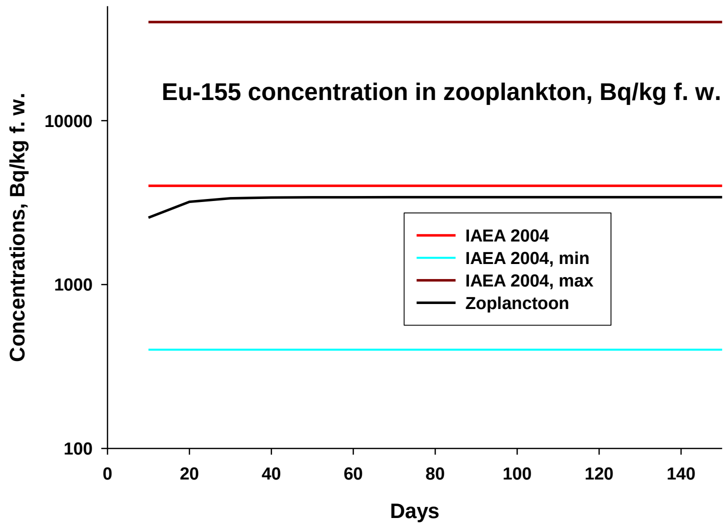


Figure 16. Kinetic model for Eu-155 bioaccumulation in zooplankton.

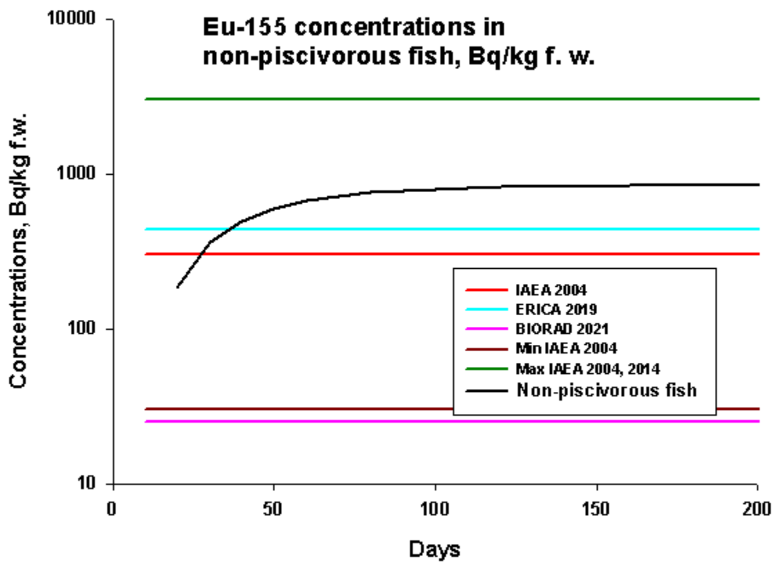


Figure 17. Kinetic model for Eu-155 bioaccumulation in non-piscivorous fish

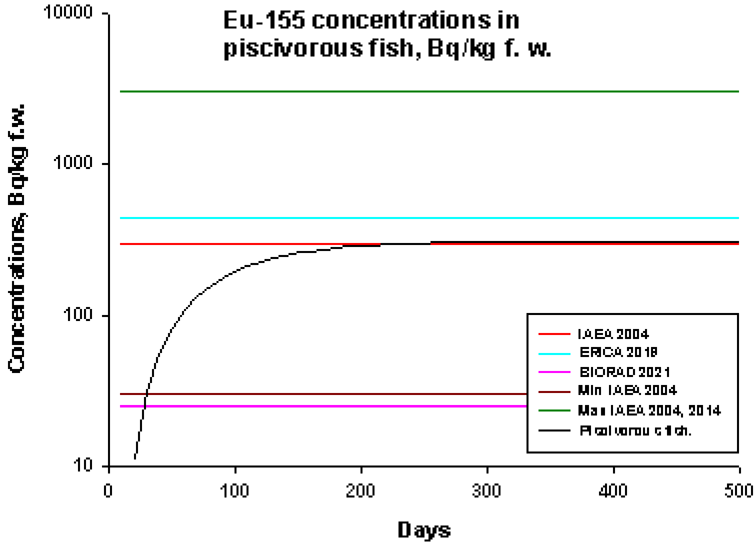


Figure 18. Kinetic model for Eu-155 bioaccumulation in piscivorous fish.

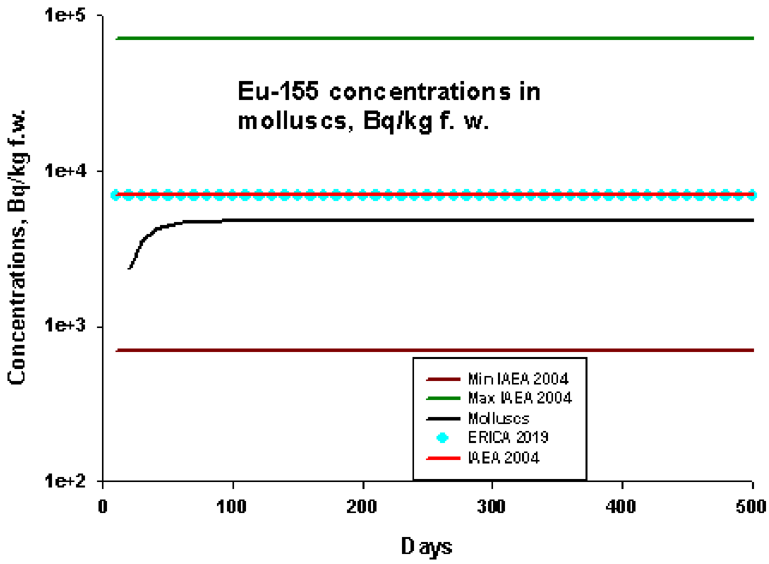


Figure 19. Kinetic model for Eu-155 bioaccumulation in molluscs

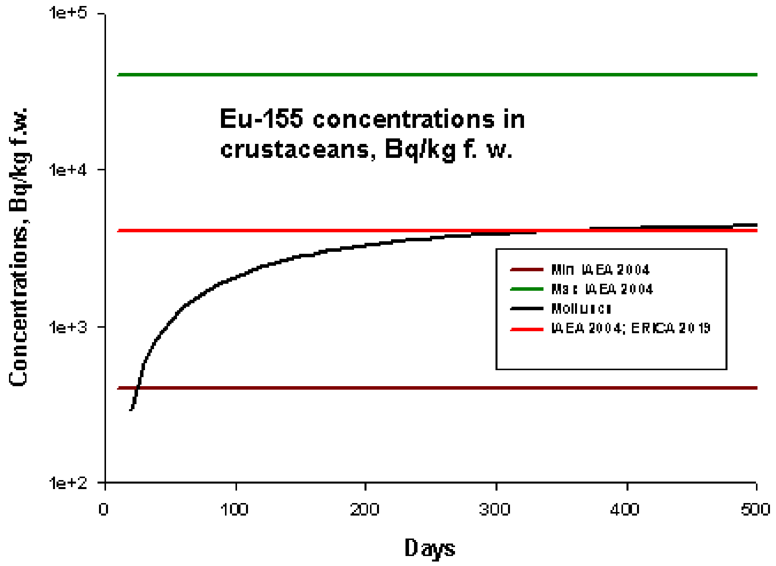


Figure 20. Kinetic model for Eu-155 bioaccumulation in crustaceans.

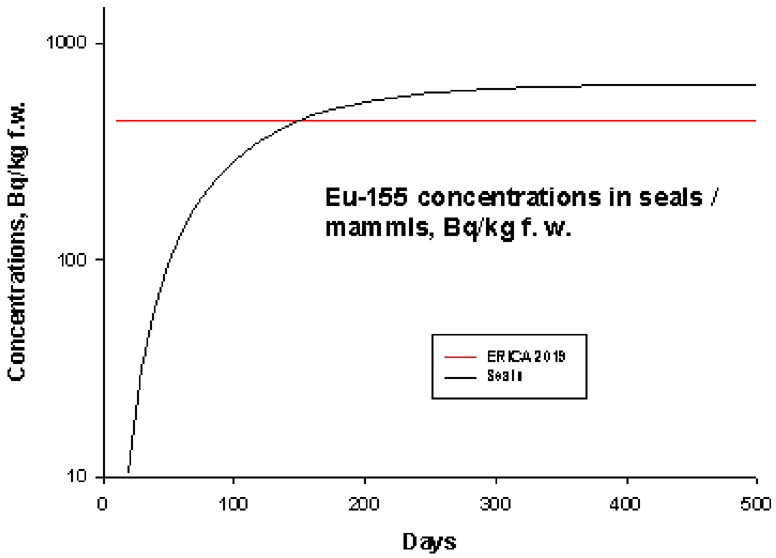


Figure 21. Kinetic model for Eu-155 bioaccumulation in seals.

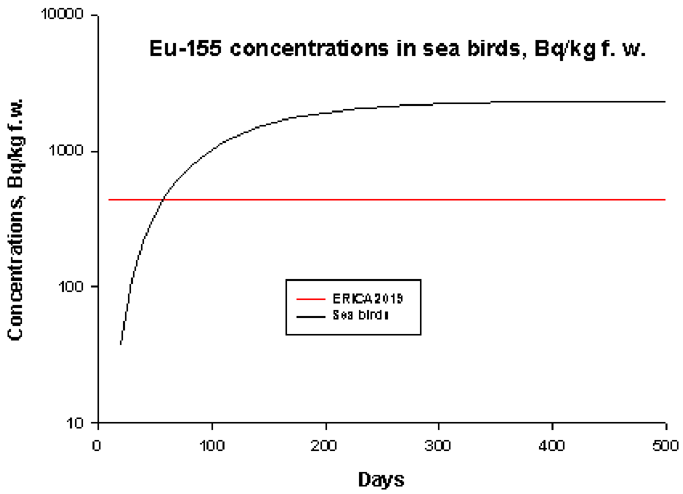


Figure 22. Kinetic model for Eu-155 bioaccumulation in sea birds

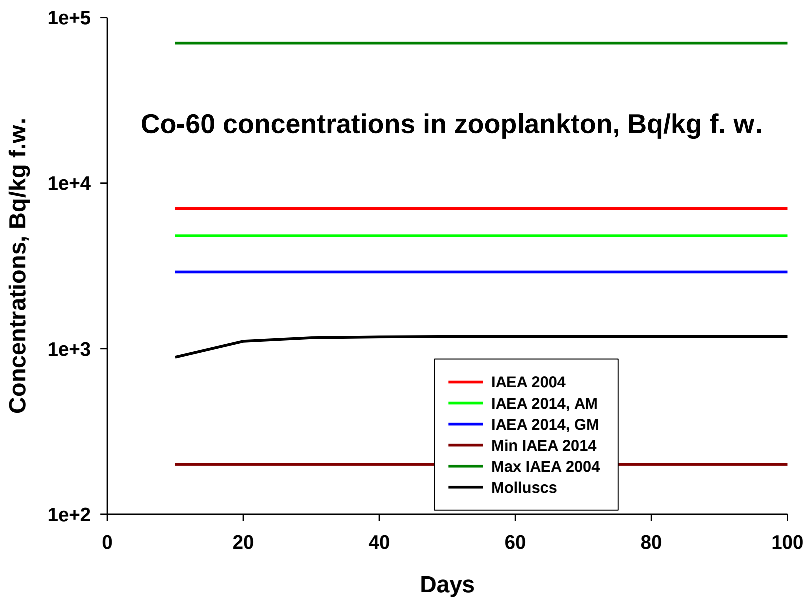


Figure 23. Kinetic model for Co-60 bioaccumulation in zooplankton.

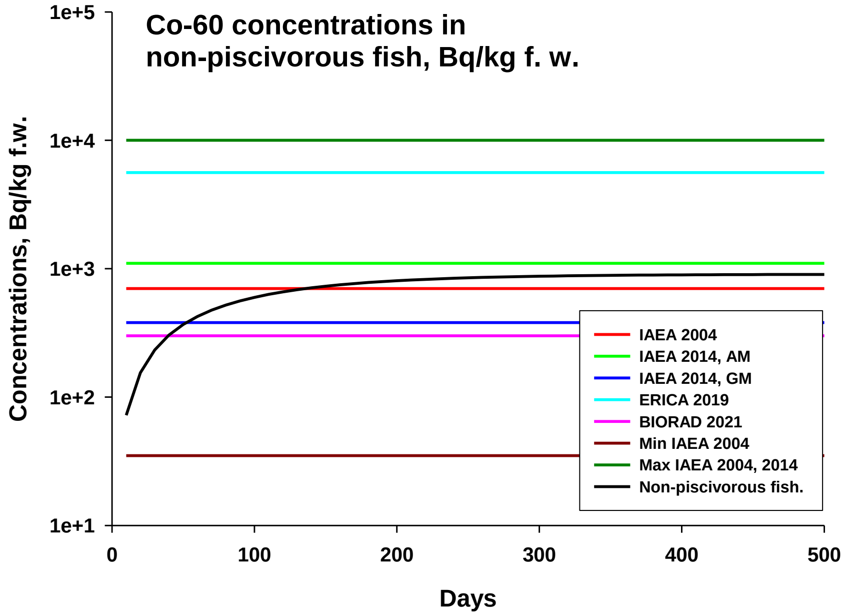


Figure 24. Kinetic model for Co-60 bioaccumulation in non-piscivorous fish.

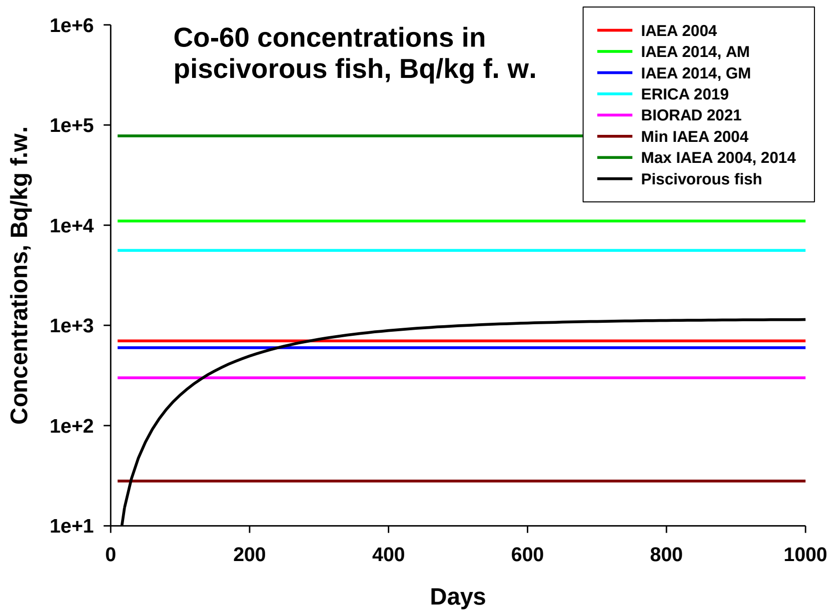


Figure 25. Kinetic model for Co-60 bioaccumulation in piscivorous fish.

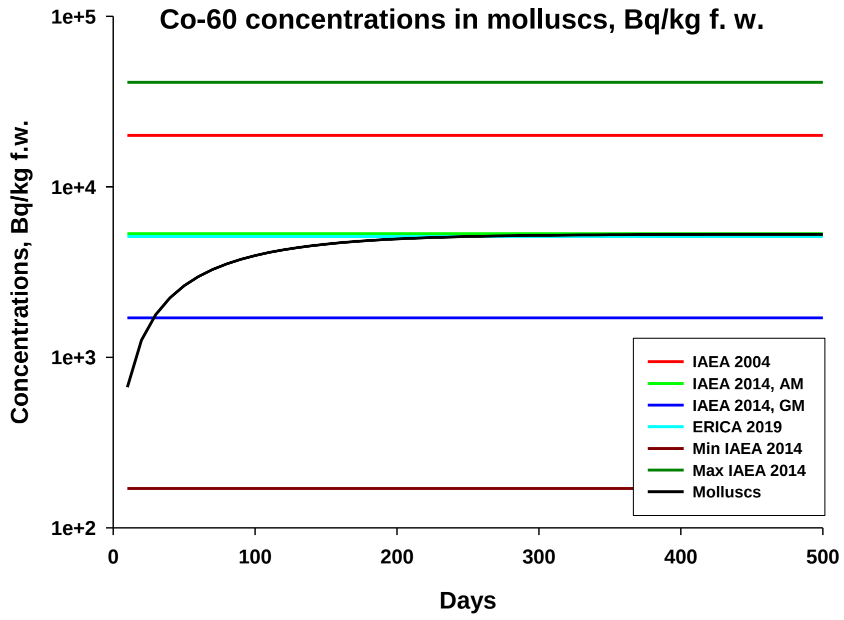


Figure 26. Kinetic model for Co-60 bioaccumulation in molluscs.

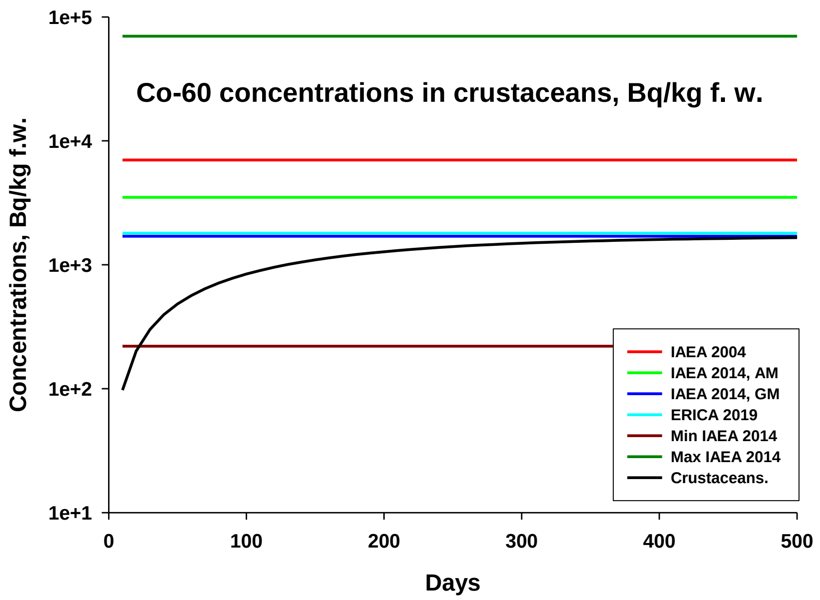


Figure 27. Kinetic model for Co-60 bioaccumulation in crustaceans.

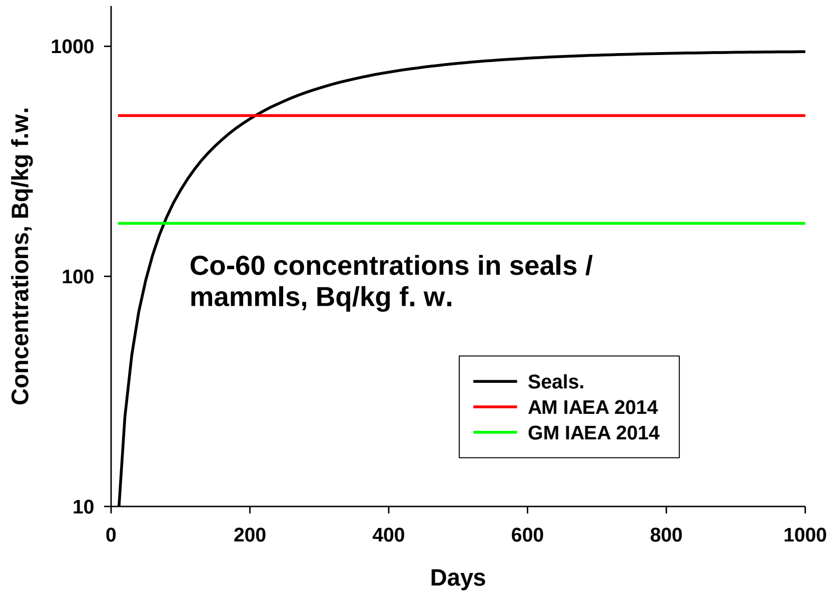


Figure 28. Kinetic model for Co-60 bioaccumulation in seals.

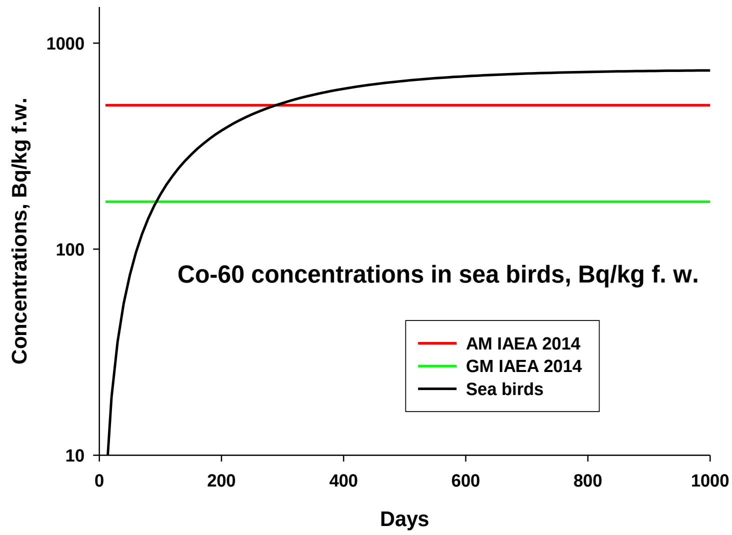


Figure 29. Kinetic model for Co-60 bioaccumulation in sea birds.

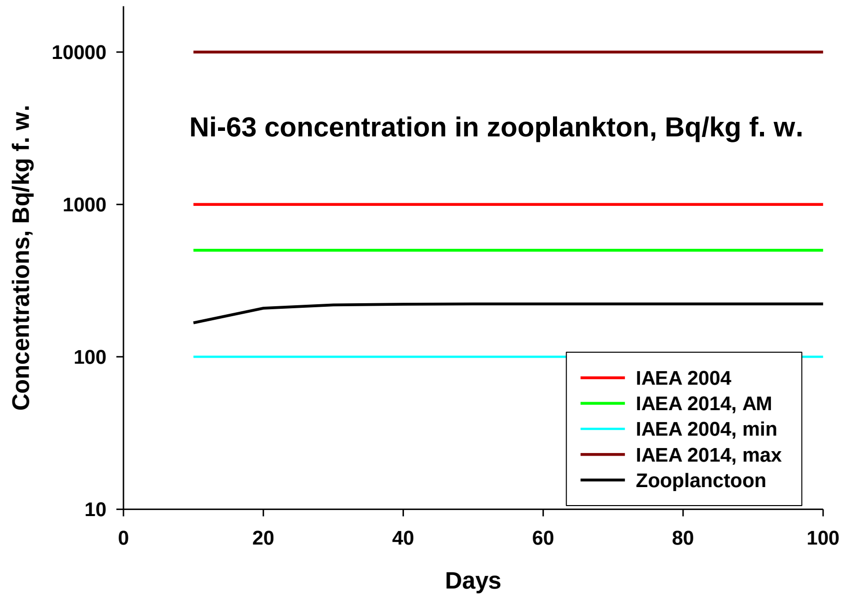


Figure 30. Kinetic model for Ni-63 bioaccumulation in zooplankton.

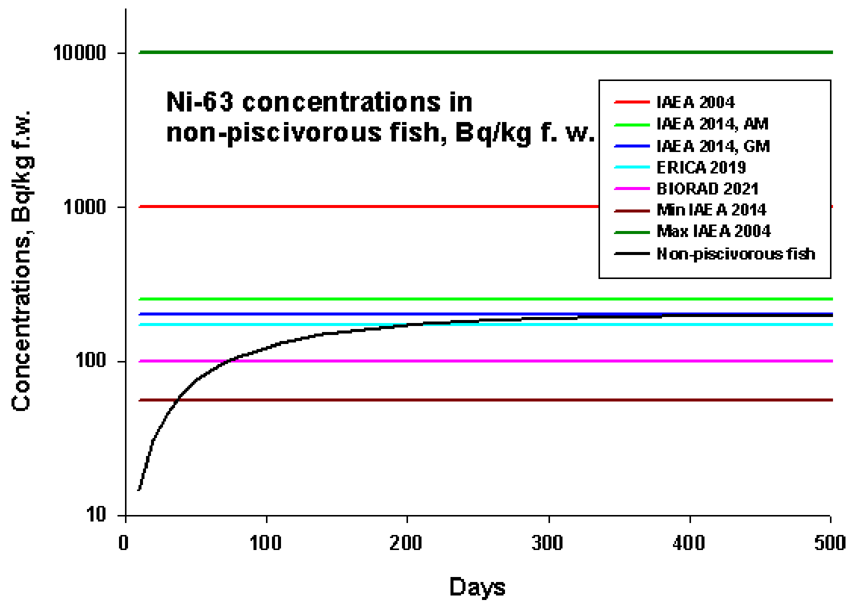


Figure 31. Kinetic model for Ni-63 bioaccumulation in non-piscivorous fish.

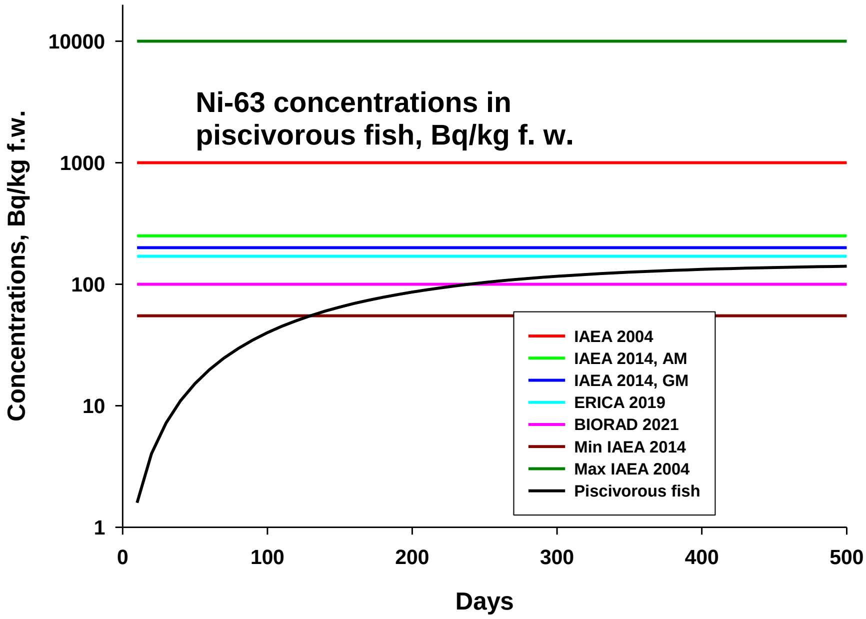


Figure 32. Kinetic model for Ni-63 bioaccumulation in piscivorous fish.

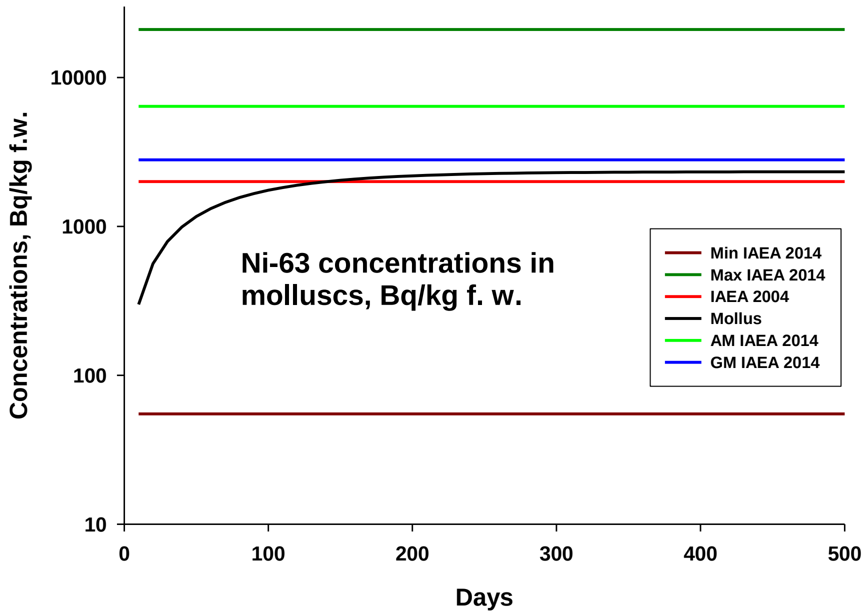


Figure 33. Kinetic model for Ni-63 bioaccumulation in molluscs.

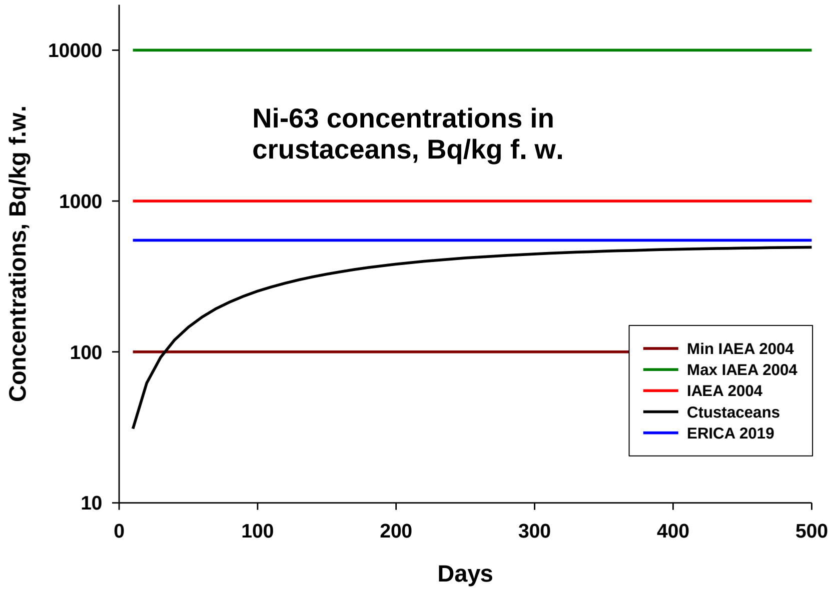


Figure 34. Kinetic model for Ni-63 bioaccumulation in crustaceans.

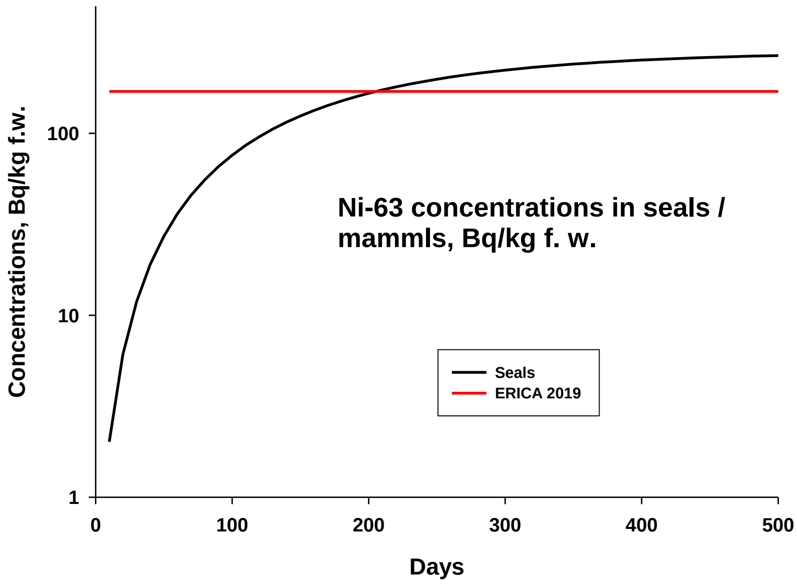


Figure 35. Kinetic model for Ni-63 bioaccumulation in seals.

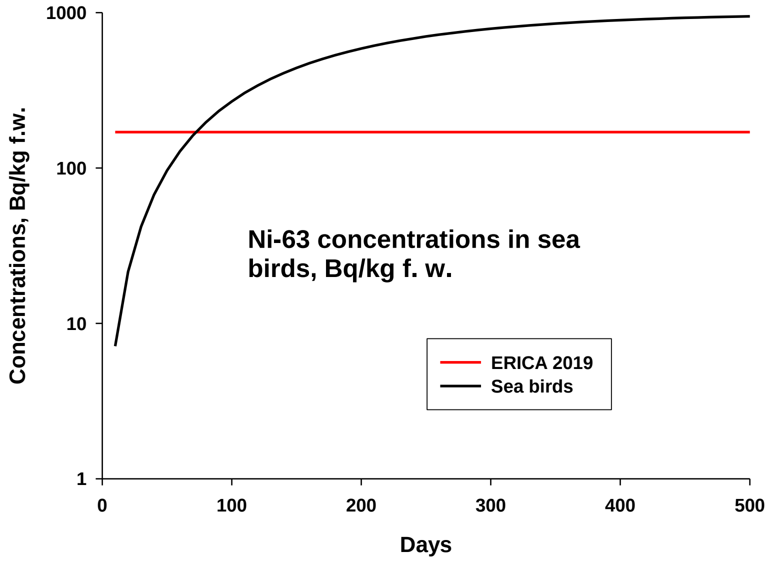


Figure 36. Kinetic model for Ni-63 bioaccumulation in sea birds.

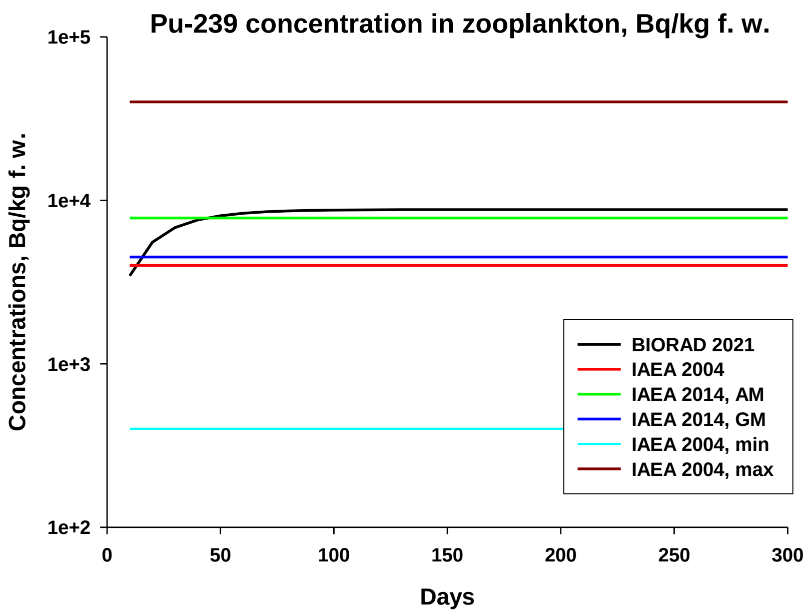


Figure 37. Kinetic model for Pu-239 bioaccumulation in zooplankton.

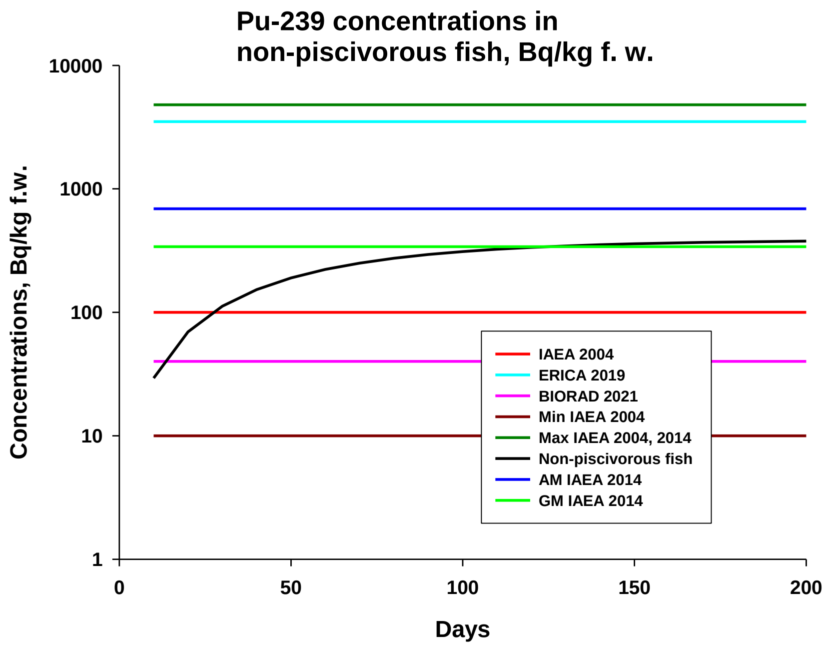


Figure 38. Kinetic model for Pu-239 bioaccumulation in non-piscivorous fish.

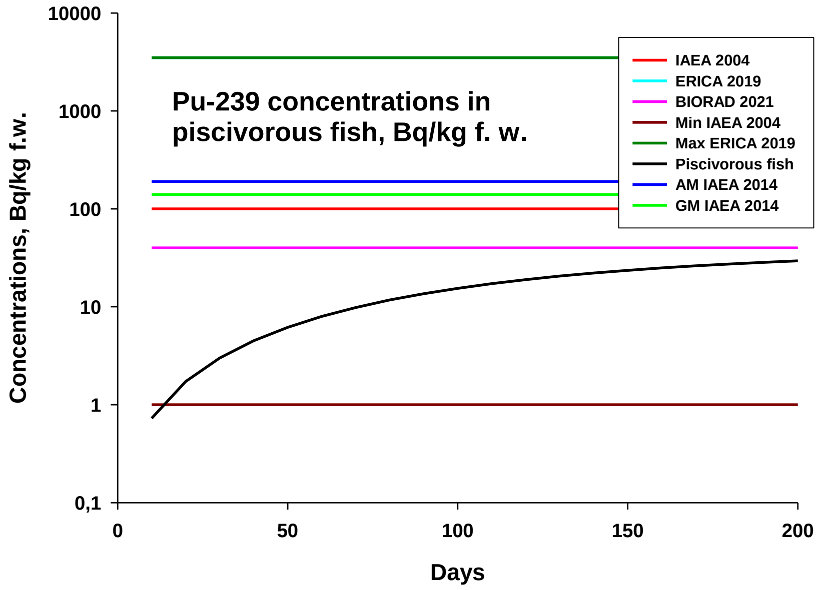


Figure 39. Kinetic model for Pu-239 bioaccumulation in piscivorous fish.

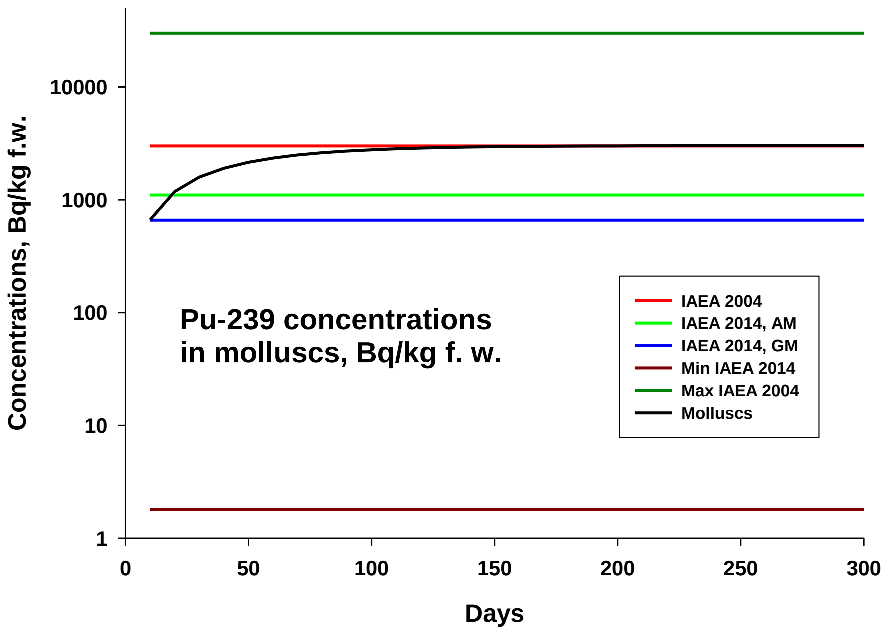


Figure 40. Kinetic model for Pu-239 bioaccumulation in molluscs.

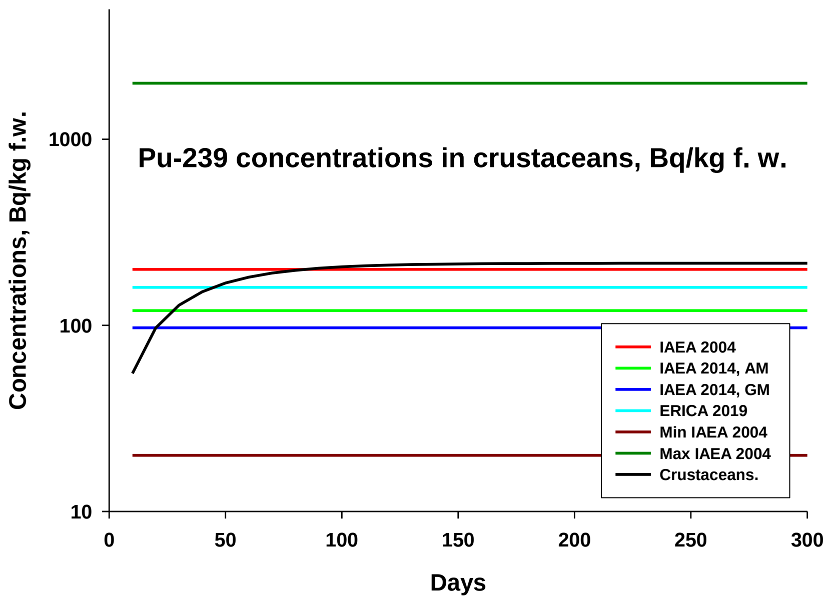


Figure 41. Kinetic model for Pu-239 bioaccumulation in crustaceans.

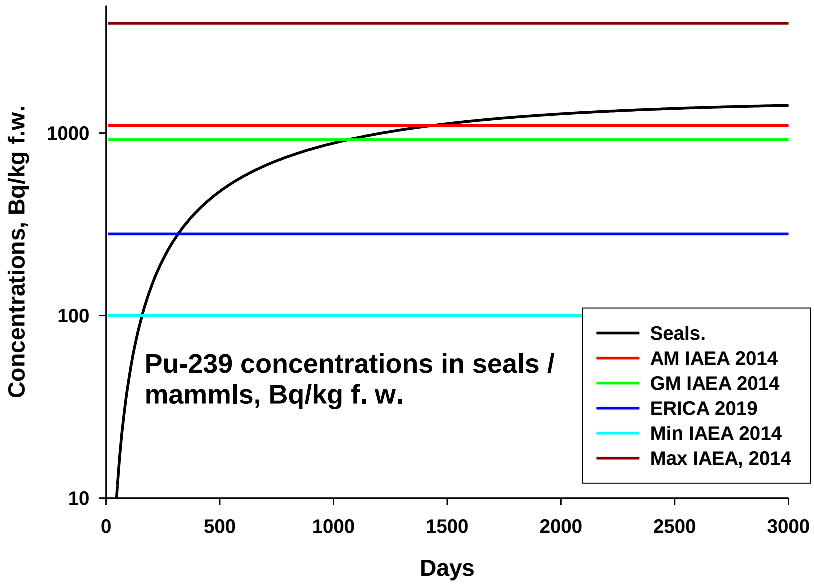


Figure.42. Kinetic model for Pu-239 bioaccumulation in seals.

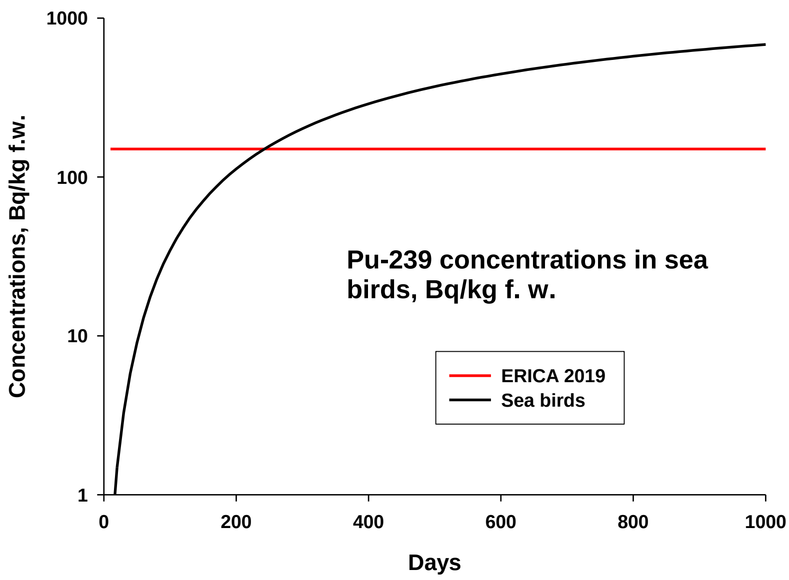


Figure 43. Kinetic model for Pu-239 bioaccumulation in sea birds.

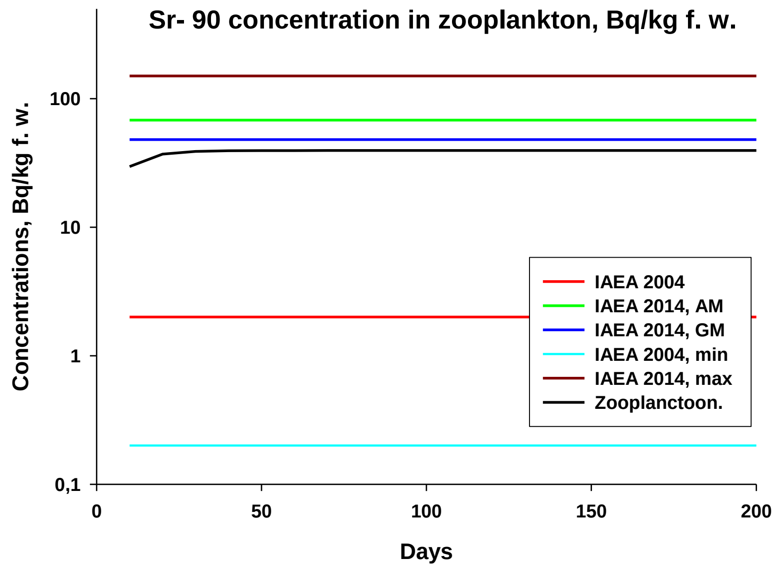


Figure 44. Kinetic model for Sr-90 bioaccumulation in zooplankton.

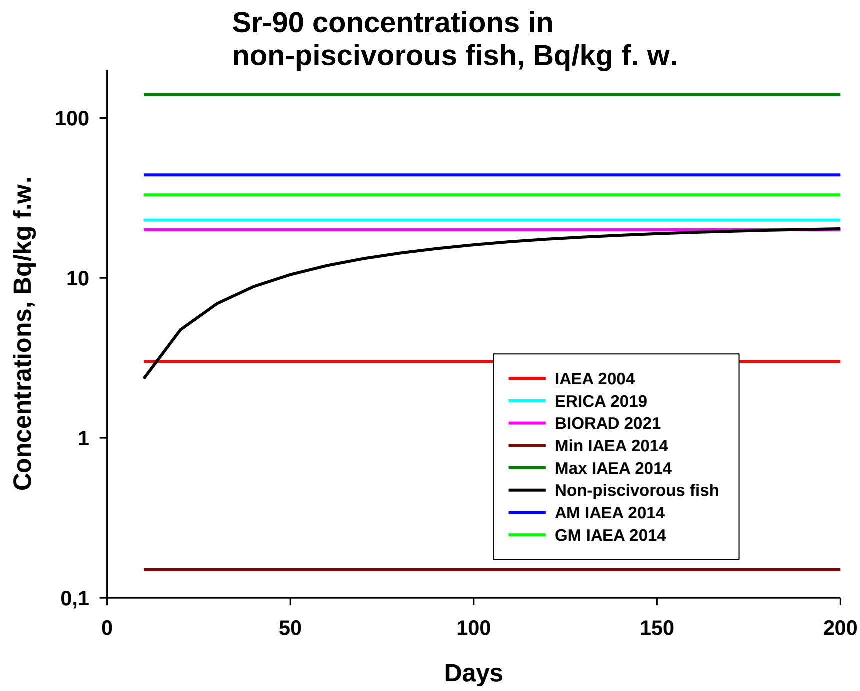


Figure 45. Kinetic model for Sr-90 bioaccumulation in non-piscivorous fish.

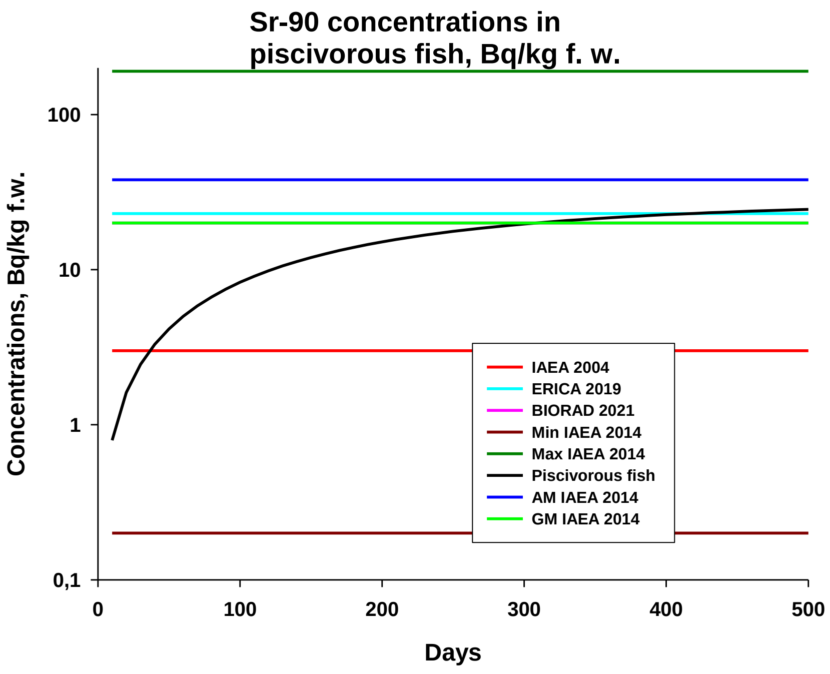


Figure 46. Kinetic model for Sr-90 bioaccumulation in piscivorous fish.

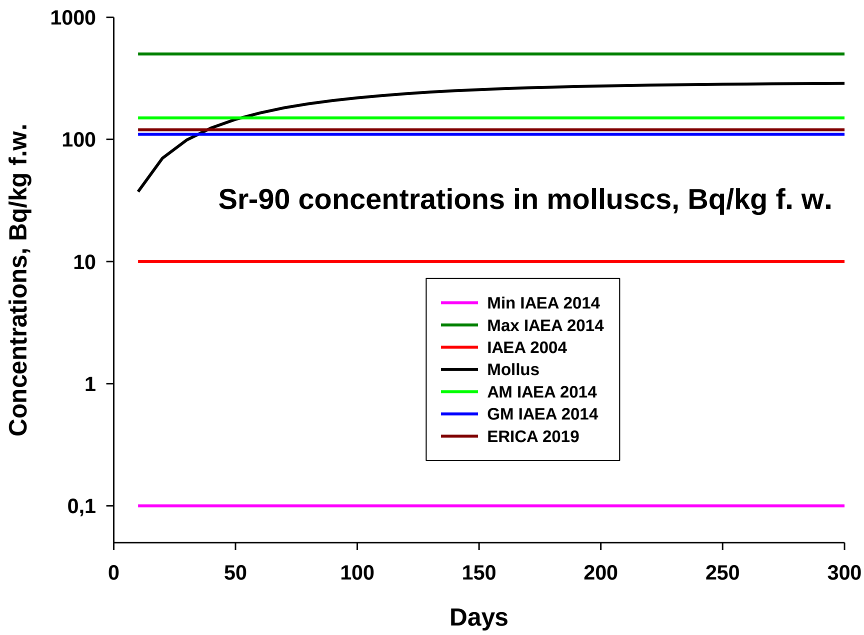


Figure 47. Kinetic model for Sr-90 bioaccumulation in molluscs.

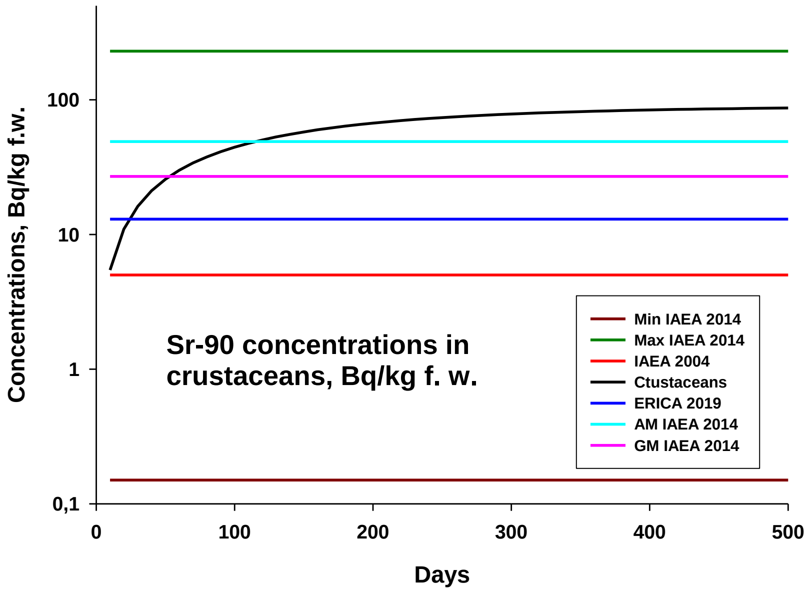


Figure 48. Kinetic model for Sr-90 bioaccumulation in crustaceans.

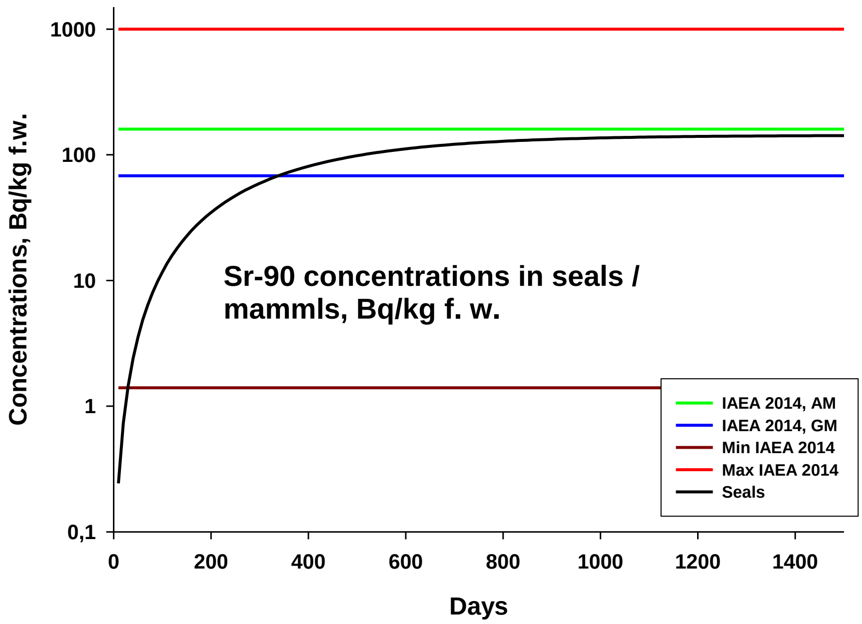


Figure 49. Kinetic model for Sr-90 bioaccumulation in seals.

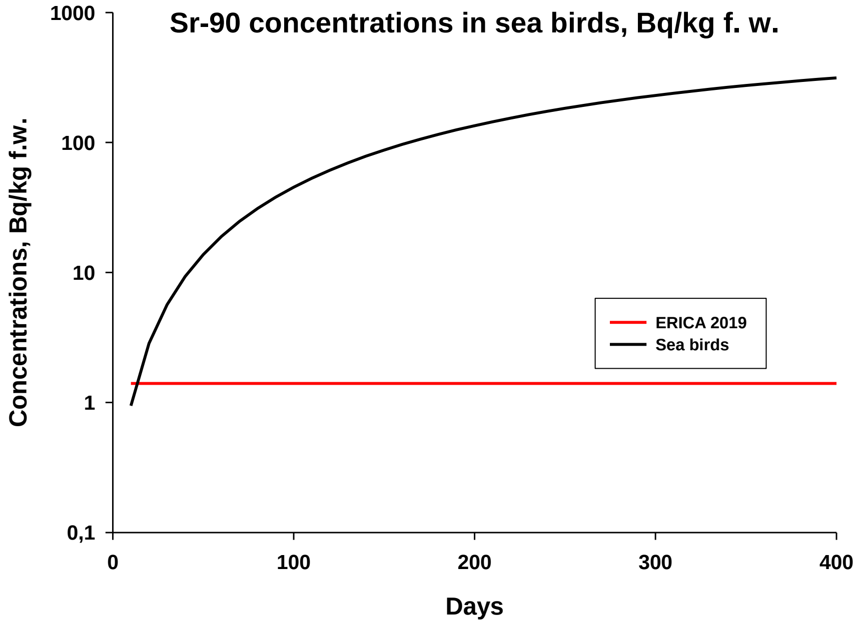


Figure 50. Kinetic model for Sr-90 bioaccumulation in sea birds.

Figures 16-50 show that the values of the kinetic coefficients selected due performed mathematical experiments can provide suitable comparison with concentration ratio approach related to equilibrium (the selected kinetic coefficients in Tables 1-5 are noted by sign “*”, reference “the present report” and bold letters, if necessary). Mathematical experiments were based on the successive simulations of bioaccumulation processes during increasing trophic levels. It is necessary to stress that such methodology allow to find suitable set of kinetic parameters, but it is impossible to proof that this set of parameters is best (Iosjpe, 2014). Therefore, it is important to justify the correctness of the parameters by site-specific information from considered marine regions.

7. Consequences after potential nuclear accident: implementation of the kinetic modelling for bioaccumulation of radionuclides in biota.

7.1. The ARCTICMAR model.

The present model uses a modified approach for compartmental modelling (Iosjpe et al., 2002, 2009; Iosjpe, 2006), which allows the study of dispersion of radionuclides over time (non-instantaneous mixing in the oceanic space). The box structures for surface, mid-depth and deep-water layers have been developed based on the description of polar, Atlantic and deep waters in the Arctic Ocean and the Northern Seas and site-specific information for the boxes generated from the 3D hydrodynamic model NAOSIM (Karcher and Harms, 2000). The model contains 345 water and sediment compartments. The surface structure of the model is presented in Figure 51.

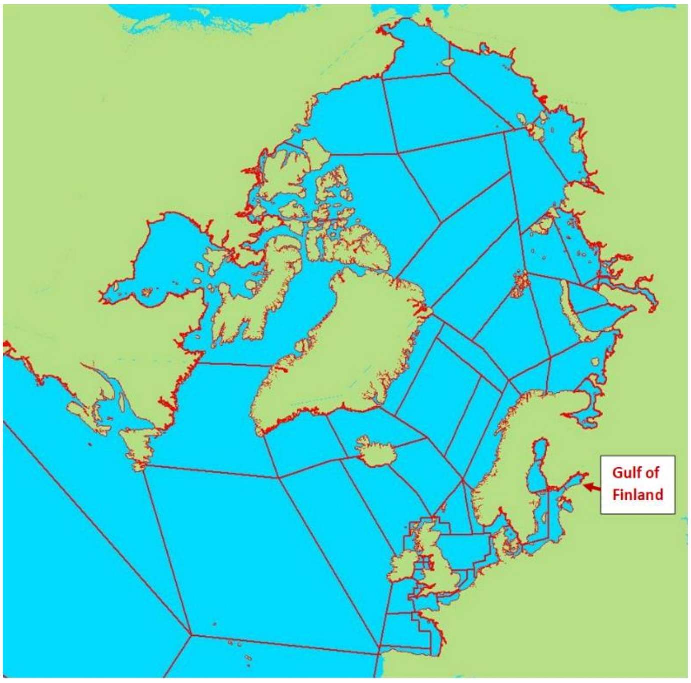


Figure 51. The structure of the surface water boxes for the ARCTICMAR box model.

The box model includes the processes of advection of radioactivity between compartments, sedimentation, diffusion of radioactivity through pore water in sediments, particle mixing, pore water mixing and a burial process of radioactivity in deep sediment layers. Radioactive decay is calculated for all compartments. Accumulation of contamination by biota is further calculated from radionuclide concentrations in filtered seawater in different water regions. Doses to humans are calculated on the basis of given seafood consumptions, based on available data for seafood catches and assumptions about human diet in the respective areas. Dose rates to biota are derived on the basis of calculated radionuclide concentrations in marine organisms, water and sediment, using dose conversion factors.

7.1.1. Main equations for the dispersion of radionuclides in the oceanic space

The equations of the transfer of radionuclides between the boxes are of the form:

$$\frac{dA_i}{dt} = \sum_{j=1}^{n} k_{ji} A_j \gamma[t \geq (T_j + w_{ji})] - \sum_{j=1}^{n} k_{ij} A_i \gamma[t \geq (T_i + w_{ij})] - k_i A_i \gamma(t \geq T_i) + Q_i,\ t \geq T_i \qquad (15)$$

$$A_i = 0, t < T_i$$

where $k_{ii}=0$ for all i, A_i and A_j are activities (Bq) at time t in boxes i and j; k_{ij} and k_{ji} are rates of transfer (y^{-1}) between boxes i and j; k_i is an effective rate of transfer of activity (y^{-1}) from box i taking into account loss of material from the compartment without transfer to another, for example radioactive decay; Q_i is a source of input into box i ($Bq\ y^{-1}$); n is the number of boxes in the system, T_i is the time of availability for box i (the first times when box i is open for dispersion of radionuclides) and γ is an unit function:

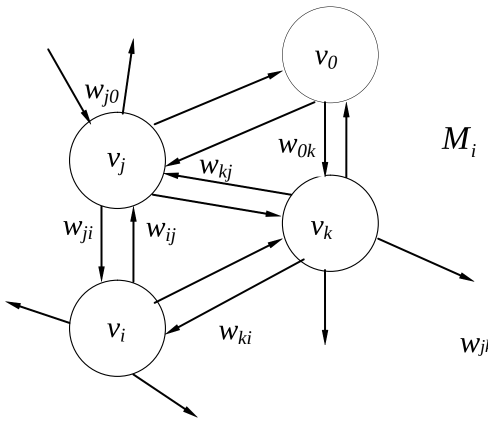
$$\gamma(t \geq T_i) = \begin{cases} 1, & t \geq T_i \\ 0, & t < T_i \end{cases} .$$

The times of availability T_i

$$T_i = \min_{\mu_m(v_0, v_i) \in M_i} \sum_{j,k} w_{jk} \tag{16}$$

are calculated as a minimized sum of the weights for all paths $\mu_m(v_0,\ldots,v_i)$ from the initial box (v_0) with discharge of radionuclides to the box i on the oriented graph $G=(V, E)$ with a set V of nodes v_j correspondent to boxes and a set E of arcs e_{jk} correspondent to the transfer possibility between the boxes j and k (graph elements as well as available paths are illustrated by Figure 52). Every arc e_{jk} has a weight w_{jk} which is defined as the time required before the transfer of radionuclides from box j to box k can begin (without any way through other boxes). Weight, w_{jk}, is considered as a discrete function F of the water fluxes f_{jk}, f_{kj} between boxes j and k, geographical information g_{jk} and expert evaluation X_{jk}. M_i is a set of feasible paths from the initial box (v_0) to the box i (v_i).

The traditional box modelling is a particular case of the present approach when all times of availability in (1) are zero: $\{T_i\} = 0, i = 1, \ldots, n.$



$$M_i = \begin{cases} \mu_1(v_0, v_j, v_i) \\ \mu_2(v_0, v_k, v_i) \\ \mu_3(v_0, v_j, v_k, v_i) \\ \mu_4(v_0, v_k, v_j, v_i) \end{cases}$$

$$w_{jk} = F(f_{jk}, f_{kj}, g_{jk}, X_{jk})$$

Figure 52. Graph elements.

Expressions for the transfer rates of radioactivity between the bottom water and sediment compartments (Iosjpe, 2011) will be useful in the present analysis (the transfer rates are shown in Figure 53):

$$k_{WS} = \frac{SR \cdot k_d}{d \cdot (1 + k_d \cdot SSL)} + \frac{D}{d \cdot h_S (1 + k_d \cdot SSL)} + \frac{R_T \cdot \omega \cdot h_S}{d \cdot (1 + k_d \cdot SSL)} + $$

$$+ \frac{R_W \cdot \rho \cdot k_d \cdot (1 - \omega)}{d \cdot (1 + k_d \cdot SSL)}$$

$$k_{SW} = \frac{D}{h_S^2 \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]} + \frac{R_T \cdot \omega}{\omega + k_d \cdot \rho \cdot (1 - \omega)} + \frac{R_W \cdot \rho \cdot k_d \cdot (1 - \omega)}{h_S \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]}$$

$$k_{SM} = \frac{D \cdot \omega}{h_S^2 \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]} + \frac{k_d \cdot SR}{h_S \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]} \tag{17}$$

$$k_{MS} = \frac{D \cdot \omega}{h_S \cdot h_{SM} \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]}$$

$$k_{MD} = \frac{k_d \cdot SR}{h_{SM} \cdot [\omega + k_d \cdot \rho \cdot (1 - \omega)]} .$$

Here k_{WS} is composed of expressions describing the transfer of activity by sedimentation, molecular diffusion, pore water mixing and particle mixing, respectively. Similarly, k_{SW} is composed of expressions describing the transfer of radioactivity by molecular diffusion, pore water mixing and particle mixing. k_{SM} is composed of expressions describing the transfer of radioactivity by sedimentation and molecular diffusion. k_{MS} corresponds to the transfer by molecular diffusion. Finally, k_{MD} corresponds to the transfer of radioactivity by sedimentation. R_W (m y^{-1}) is the sediment reworking rate; R_T (y^{-1}) is the pore-water turnover rate; k_d (m^3 t^{-1}) is the sediment distribution coefficient; SSL (t m^{-3}) is the suspended sediment load in the water column; SR (t m^{-2} y^{-1}) is the sedimentation rate; D (m^2 y^{-1}) is the molecular diffusion coefficient, h_S (m) and h_{SM} (m) are the surface and middle sediment thickness respectively; ω is the porosity of the bottom sediment; ρ (t m^{-3}) is the density of the sediment material and d is the depth of the water column.

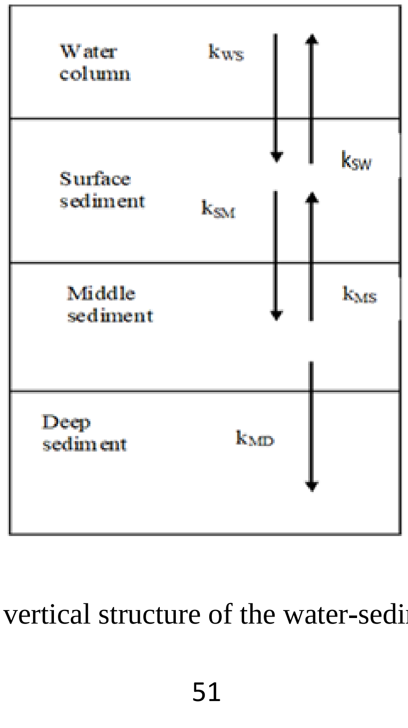


Figure 53. Generic vertical structure of the water-sediment compartments.

The ARCTICMAR model has previously been employed successfully in a number of applications. Results of simulations have been compaered with experimental data, where data have been available (Iosjpe et al., 2009; Iosjpe, 2011; Iosjpe and Liland, 2012; Periánez et al., 2016).

Concentrations of the radionuclides in marine organisms can be calculated from radionuclide concentrations in filtered seawater and the concentrations ratios as well as by the kinetic modelling of the bioaccumulation processes in biota, which is described in the section 3 of the present report.

7.1.2. Dose assessment for humans

The internal dose D can be determined using the following expression:

$$D = \sum_{j=1}^{m} DCF_j \sum_{l=1}^{k} \phi_l \cdot CF_{lj} \sum_{i=1}^{n} A_{il} \int_0^T C_{ij}\,(t)dt \tag{18}$$

where [0, T] is the time interval for dose assessment; DCF_j is the dose conversion factor for radionuclide j (j = 1,2,…, m); CF_{lj} is the concentration factor for radionuclide j in seafood of type l (l = 1,2,…, k); A_{il} is consumption of seafood of type l in the model compartment i; (i = 1,2,…,n) for the critical group for the doses to critical group and catch of seafood for collective doses, if necessary; C_{ij} is the concentration of radionuclide j in filtered seawater in model compartment i; and φ_l is equal 1 for the doses to the critical group and φ_l is the edible fraction for seafood of type i (50% for fish, 35% for crustaceans and 15% for molluscs (CEC, 1990; EC, 2000; IASAP, 2003) for the collective doses, if necessary.

The individual dose rate for the external exposure can be estimated with the following expresson (Iosjpe et al., 2009). Methodology is similar to EC (1994):

$$\mathrm{DR_{ext}} = \mathrm{F_W^{(O)}} \cdot \sum_i \mathrm{DCF_i^{(ext,w)}} \cdot \overline{\mathrm{C}}_\mathrm{i}^{(\mathrm{bulk,w})} + \mathrm{F_S^{(O)}} \cdot \mathrm{f_S} \sum_i \mathrm{DCF_i^{(ext,s)}} \cdot \overline{\mathrm{C}}_\mathrm{i}^{(\mathrm{bulk,s})} \tag{19}$$

where $\overline{C}_i^{(bulk,w)}$ is the average bulk concentration of radionuclide i in the water column with regards to both water and sediment phases; $\overline{C}_i^{(bulk,s)}$ is the average bulk concentration of the sediment phase in the actual sea area; $DCF_i^{(ext,w)}$ and $DCF_i^{(ext,s)}$ are the dose conversion factors for external exposure of radionuclide i, for water immersion and contaminated ground surface, respectively; $F_W^{(O)}$ and $F_S^{(O)}$ are the occupancy factors for "swimming" and the "beach sediment" pathways (in the following calculations it is assumed that both factors are of 0.5); f_S is a part of the sediment concentration, which is considered as beach concentration (following (IASAP, 2003), it is assumed that f_S is 0.1).

In the present study, the doses to man are calculated only for ingestion because the comparison of the contribution to human doses from this pathway against external exposure indicates a clear domination of the former (EC, 1994; IASAP, 2003, Iosjpe et al., 2009).

7.1.3. Dose assessment for biota

The ARCTICMAR model uses the following expressions for internal and external dose rates for biota (Brown and Hosseini, 2019; Hosseini et al., 2016, 2017, Iosjpe et al., 2009).

The basic underlying equations (Equations 8 and 9) utilise activity concentration data in order to derive internal (D_{int}) and external (D_{ext}) absorbed dose-rates (in units of µGy h^{-1}). The total absorbed dose-rate is the sum of these components, through the application of dose conversion coefficients (DCCs).

$$\dot{D}^{b}_{int} = \sum_{i} C^{b}_{i} * DCC^{b}_{int,\,i} \tag{20}$$

where:

C^{b}_{i} is the average concentration of radionuclide *i* in the reference organism *b* (Bq kg^{-1} fresh weight),

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

$$\dot{D}^{b}_{ext} = \sum_{z} v_{z} \sum_{i} C^{ref}_{zi} * DCC^{b}_{ext,zi} \tag{21}$$

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

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

$$DCC_{int} = wf_{low\beta} \cdot DCC_{int,\,low\beta} + wf_{\beta+\gamma} \cdot DCC_{int,\,\beta+\gamma} + wf_{\alpha} \cdot DCC_{int,\,\alpha}$$

(22)

$$DCC_{ext} = wf_{low\beta} \cdot DCC_{ext,low\beta} + wf_{\beta+\gamma} \cdot DCC_{ext,\beta+\gamma}$$

Here "wf" are weighting factors for various components of radiation (low β, β + γ and α), DCC are dose conversion coefficients in µGy h^{-1} per Bq l^{-1} or Bq kg^{-1}. Default radiation weighting factors of 10 for alpha radiation, 1 for low energy beta and 1 for (high energy) beta and gamma radiation are applied in this assessment in line with those applied in UNSCEAR (2008).

7.2. Release scenario.

7.2.1. Inventory and release scenario of the potential accident

The present study is based on the radionuclide inventories presented by Hosseini et al. (2015) and assumptions about the worst-case scenario for releases of radionuclides from the nuclear reactors of the Russian submarine after a potential accident.

For the worst-case scenario, a release pattern, divided into two fractions, was assumed: (i) an instantaneous release of radionuclides and (ii) a slow long-term release similar to models applied in simulating the dissolution of the uranium oxide matrix. This is in line with similar scenarios described, for example, for sunken vessels with spent fuel on board (Reistad, 2008; Iosjpe et al., 2009; Iosjpe and Liland, 2012).

Because some radionuclides, with their provenance in a criticality event, have a very short physical half-life or very low inventory, they can be safely discounted. The following radionuclides have therefore been selected for consideration in the present study: Am-241, Co-60, Cs-137, Eu-152, Eu-155, Ni-59, Ni-63, Pu-238, Pu-239, Pu-240, Pu-241, Sr-90.

It should be noted that the release of fuel corrosion products depends on many factors (fuel matrix construction, seawater temperature, type and extent of damage during the potential accident etc.). Therefore, the annual corrosion rate can differ widely (for example, 0.001% and 1% according to Yefimov (1994) and White Book-2000 (2005), respectively. A corrosion rate of 1% has been chosen here in accordance with assumption about the worst-case scenario.

Instant and continuous releases, which are used in the present report are shown in Figures 54 and 55.

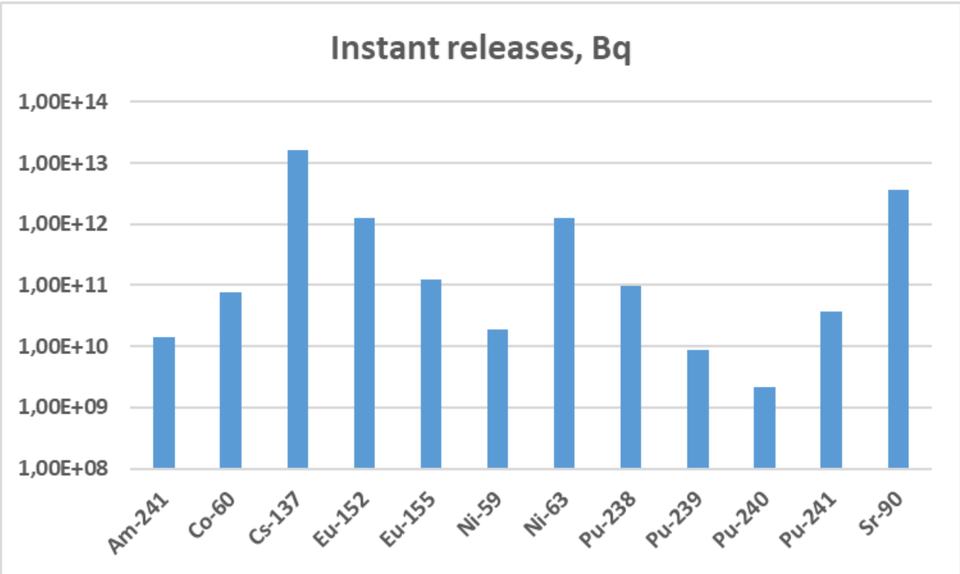


Figure 54. Instantaneous releases of radionuclides.

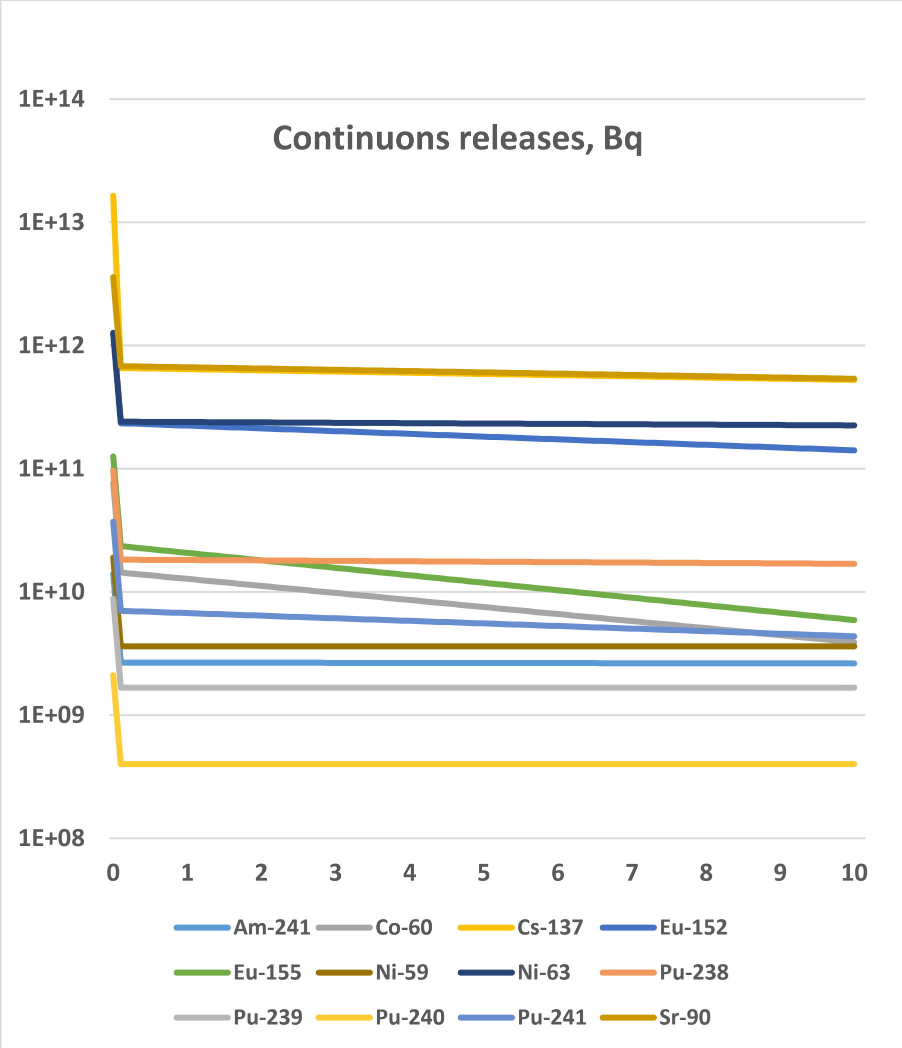


Figure 55. Contionious releases of radionuclides after the potentiaø accident. Simulations are presented within time interval [0, 10] years.

7.2.2. Locations of the potential accident

Previous study (Iosjpe et al., 2016) has demonstrated that the ARCTICMAR model describes the water circulation and water-sediment interactions of radionuclides in the Gulf of Finland in the Baltic Sea with high precision (the Gulf of Finland is shown in Figure 51). Therefore, this region was chosen to study the influence of the kinetic modelling of the bioaccumulation processes to radiological consequences after a potential nuclear accident.

In this study, it was assumed that a potential nuclear accident takes place in the additional local compartment with volume of 10^7 m^3, which has been incorporated into the Gulf of Finland (the volume of the Gulf of Finland is of 10^{12} m^3, approximately).

7.3. Concentrations of radionuclides in marine biota

Following the FAO/WHO (CAC, 2006) recommendations for the suitable levels of radionuclides in food, the model simulations for the radionuclide concentrations in seafood are provided separately for each of four groups of radionuclides presented in Table 7 for the present study.

Table 7. Examples of FAO/WHO international guideline levels for radionuclides in food.

Example radionuclides		Levels (Bq/kg)	
		Infant foods	Other foods
Group 1	^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu	1	10
Group 2	^{90}Sr	100	100
Group 3	^{60}Co, ^{137}Cs, ^{241}Pu	1000	1000
Group 4	^{152}Eu, ^{155}Eu, ^{59}Ni, ^{63}Ni	1000	10 000

It is necessary to note that during the human habit assessment for infants (Smith and Jones, 2003), which was used for the FAO/WHO guideline (CAC, 2006) levels development, the consumption of fish was found to be very low, while consumption of crustaceans and molluscs was not found at all, probably because it is generally recommended to avoid feeding children seafood before the age of 12–36 months, due to allergy concerns (Fiocchi et al., 2006; Kull et al., 2006). Therefore, the results for crustaceans and molluscs have to be used without regards to the infant guideline levels.

Figures 56 – 62 show that concentration in the typical seafood biota vary with time significantly for all groups of radionuclides. It is necessary to note that the calculations, presented in Figures 56 - 62, correspond to the local compartment of the Gulf of Finland described in section 7.2.2.

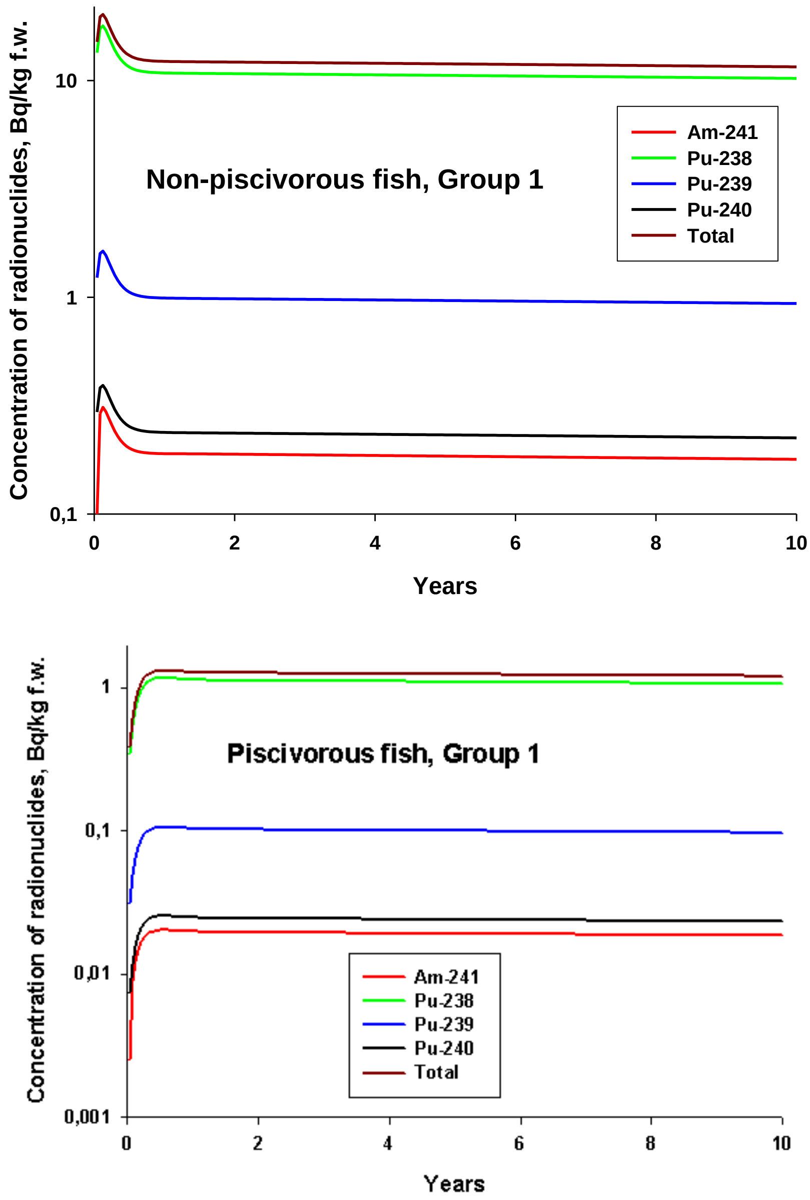


Figure 56. Concentration of radionuclides in fish for Group 1 (CAC, 2006).

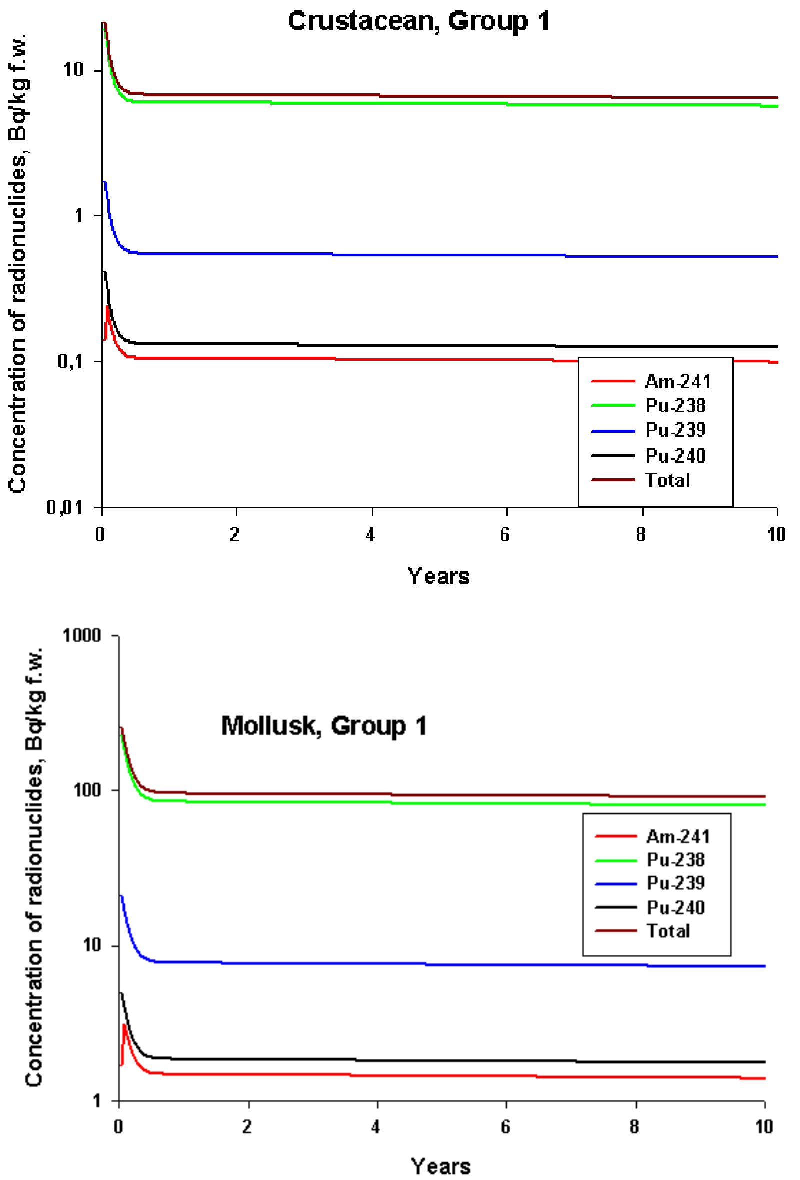


Figure 57. Concentration of radionuclides in crustacean and mollusk for Group 1 (CAC, 2006).

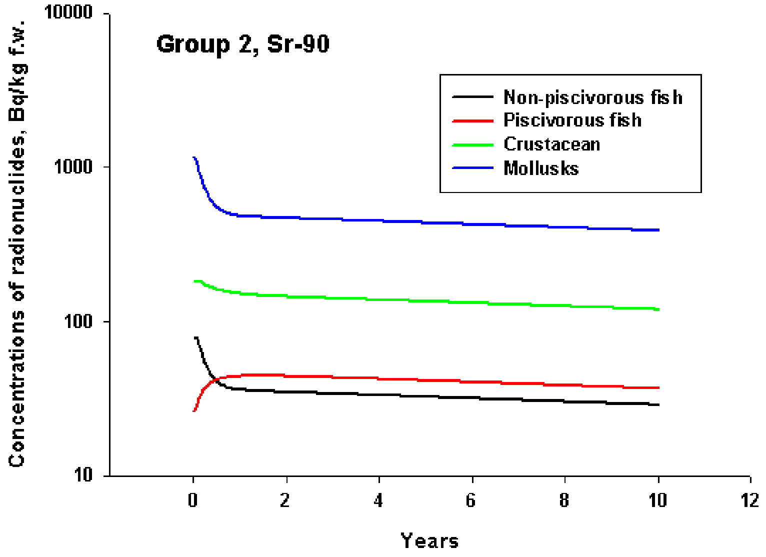


Figure 58. Concentration of radionuclides in biota for Group 2 (CAC, 2006).

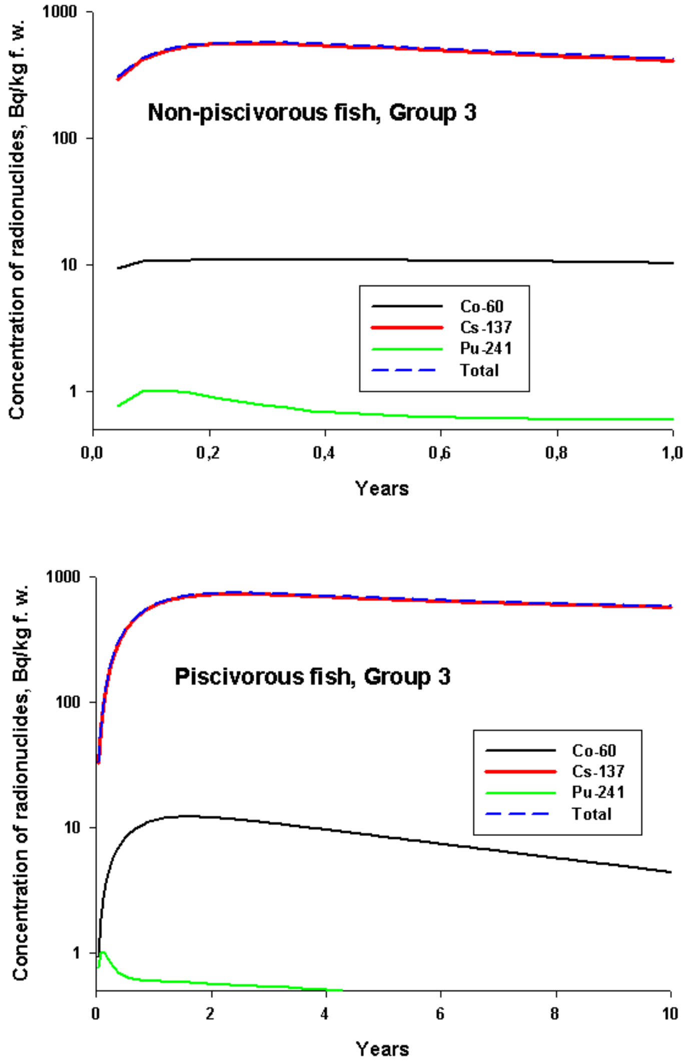


Figure 59. Concentration of radionuclides in fish for Group 3 (CAC, 2006).

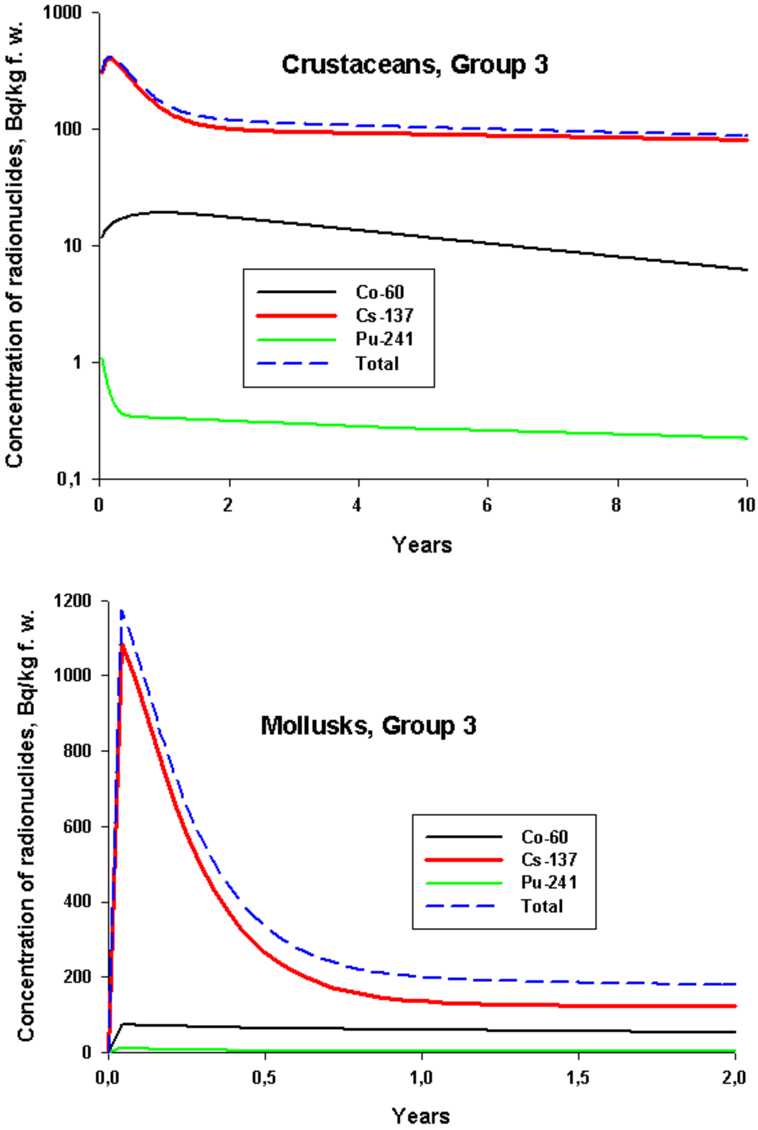


Figure 60. Concentration of radionuclides in crustacean and mollusk for Group 3 (CAC, 2006).

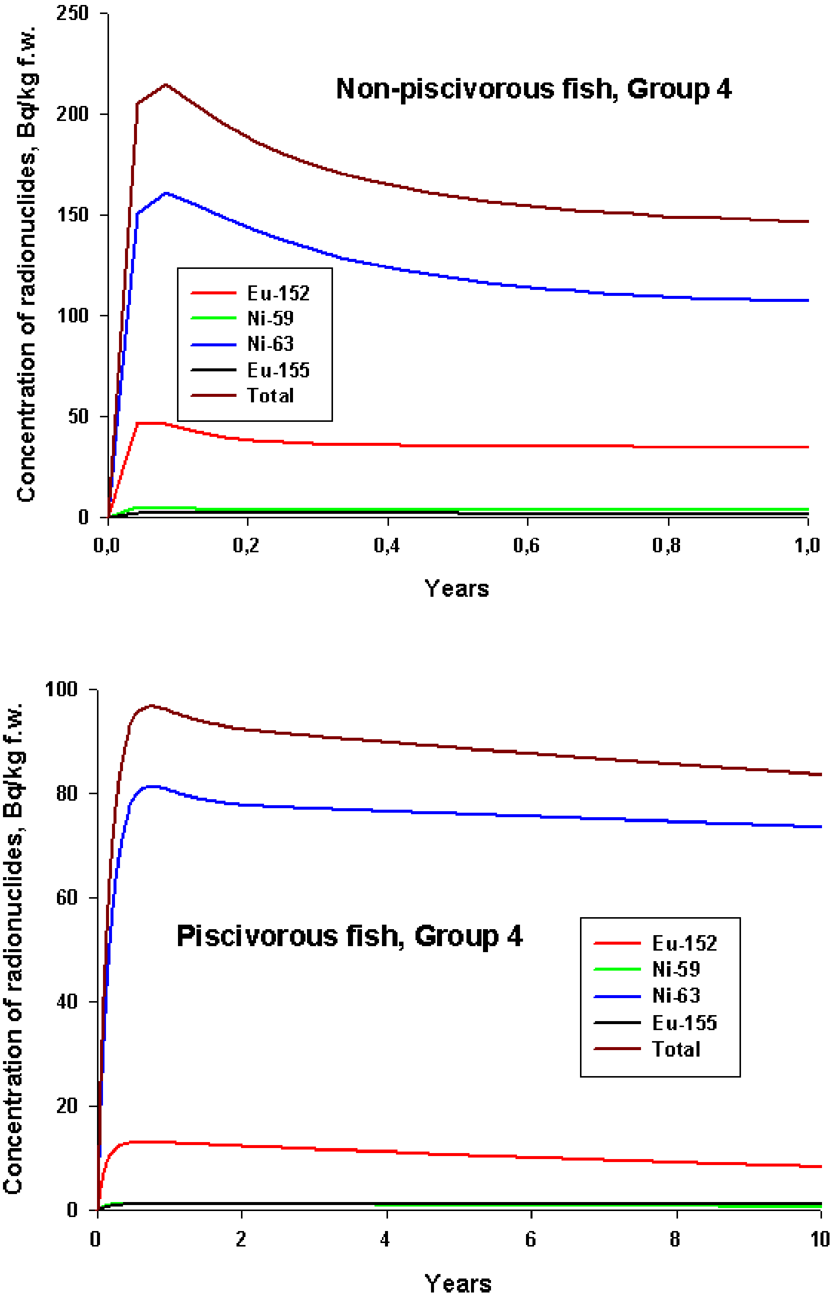


Figure 61. Concentration of radionuclides in fish for Group 4 (CAC, 2006).

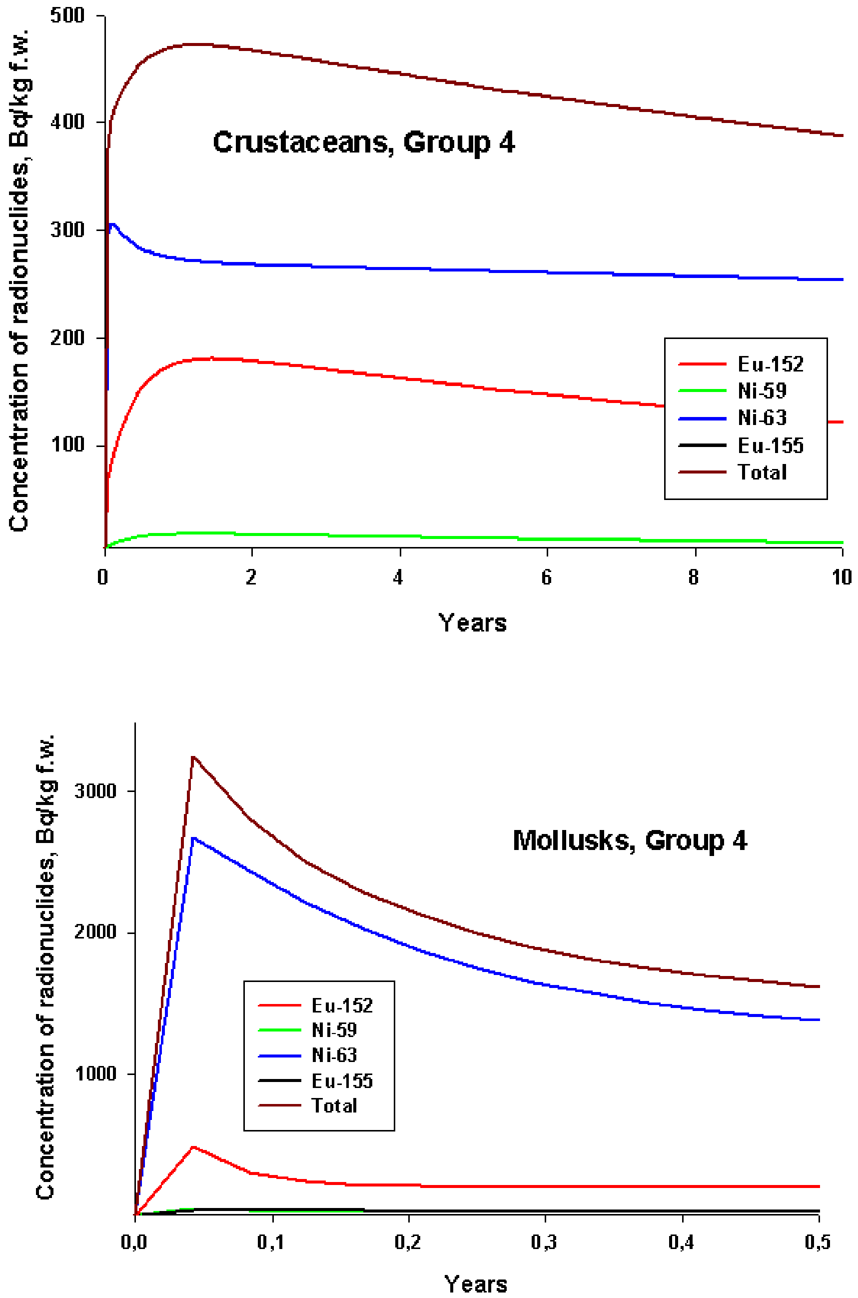


Figure 62. Concentration of radionuclides in crustacean and mollusk for Group 4 (CAC, 2006).

All biota from Groups 3 and 4, have no restrictions as seafood (Figures 59-62). Radionuclide concentrations from Group 1 exceed the Guidance levels values for all marine organisms during the entire period of simulations (ten years) and, therefore, cannot be recommended as seafood without limitations (Figures 56-57). Nevertheless, some biota can be used as sea food with the following limitations: (i) piscivorous fish can be used for adults, (ii) crustacean can be also used as seafood for adults after initial time of releases of radionuclides (two months, approximately). A similar situation is shown in Figure 58 for radionuclides from Group 2, where marine organisms generally cannot be recommended as seafood, except for fish, which can be used without restrictions. Finally, according to the current simulations, only piscivorous fish for adults can be used as seafood from the local compartment of the Gulf of Finland, described in section 7.2.2.

It is important to note that the concentration of radionuclides from Group 1 in biota (mainly Pu-238) is low compared to the concentration of radionuclides from Group 3 (mainly Cs-137). However, despite this, restrictions on the use of seafood is more significant for radionuclides from Group 1 due to dose conversion factors for alpha radiation-emitting radionuclides being much higher than for gamma and beta-emitting radionuclides.

7.4. Doses to a human in the critical group

In the present report, the critical group of humans is defined as persons with high consumption of seafood from the local compartment of the Gulf of Finland (Bergsten, 2003; Iosjpe et al., 2009). It is also assumed here that this group will use crustacean and mollusks in spite of recommended restrictions from the section 7.3 with the following dietary data: (i) sea fish, 200 g/d; (ii) crustacean, 40 g/d; (iii) mollusks, 4 g/d (Bergsten, 2003).

Figures 63 shows the dynamic of the total dose for a human in the critical group. Figure 64 demonstrates that the main impact to the maximal dose for a human in the critical group (1 mSv, approximately, during the third year after start of radioactivity releases) corresponds to Cs-137 (71%), Sr-90 (17%) and Pu-238 (7%).

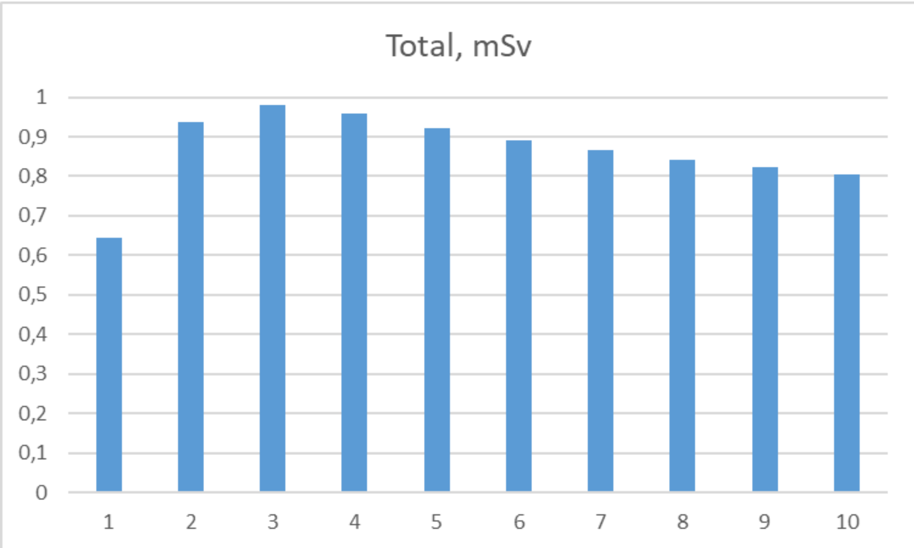


Figure 63. Dynamic of the impact of radionuclides in the effective dose to a human in the critical group. Simulations are presented within time interval [0, 10] years.

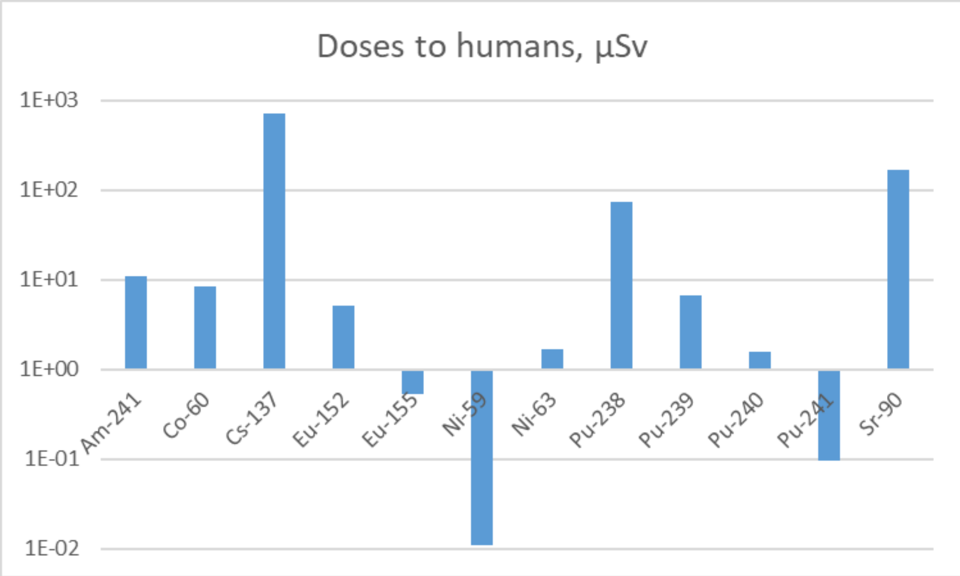
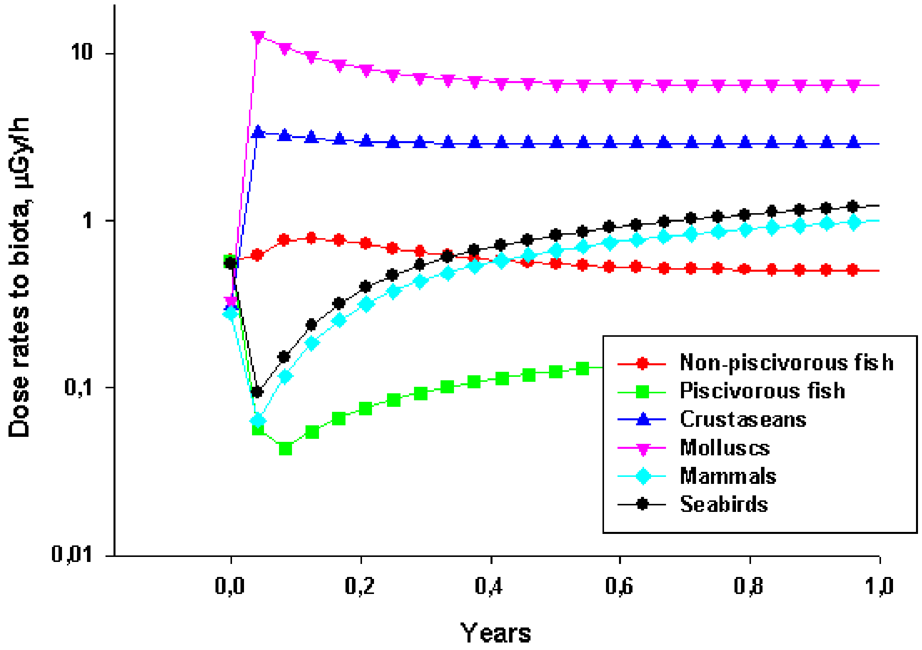


Figure 64. Dynamic of the impact of radionuclides in the effective dose to a human in the critical group.

It is important to note that the dose of 1 mSv per year does not exceeds the public dose limit recommended by the ICRP (ICRP, 1991).

7.5. Dose rates to marine organisms

The dose rates calculated for various marine organisms in the local compartment of the Gulf of Finland (the location for the hypothetical release of radionuclides) are presented in Figures 65-71. A conservative approach is used, which assumes that marine organisms do not leave the compartment during the simulation time. Figure 65 shows the total impact of all selected different radionuclides on dose rate (in units of µGy/h) for biota. The calculations include both internal and external exposure.



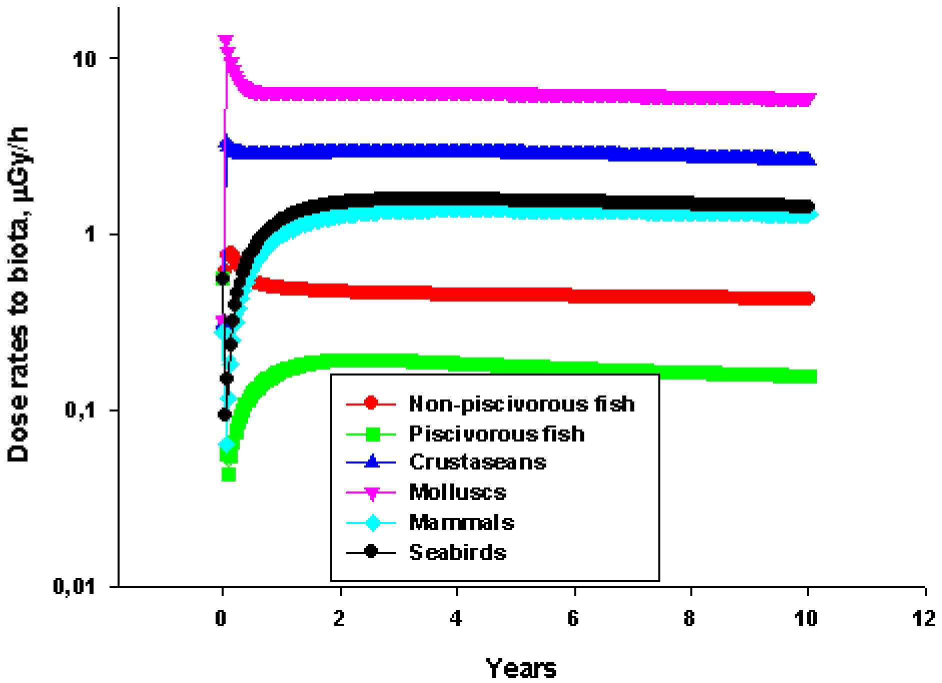
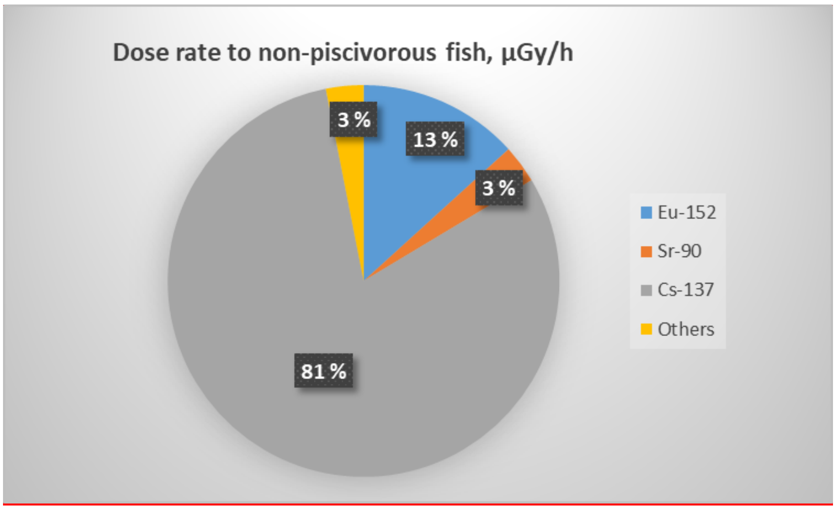


Figure 65. The dose-rates dynamic for selected biota, µGy/h. Simulations are presented within time interval [0, 1] year (top) and [0-10] years (bottom).

Figures 66-71 show the most significant impact of radionuclides to the dose rates of biota. It is important to note that impact of radionuclides to the total dose rates can vary with time in wide limits.

For instance, Figure 66 shows that the main impact to the dose rate to non-piscivorous fish at the onset of discharge corresponds to Cs-137 (81%) while the main impact after 45 days to the dose rate corresponds to Pu-238 (66%).



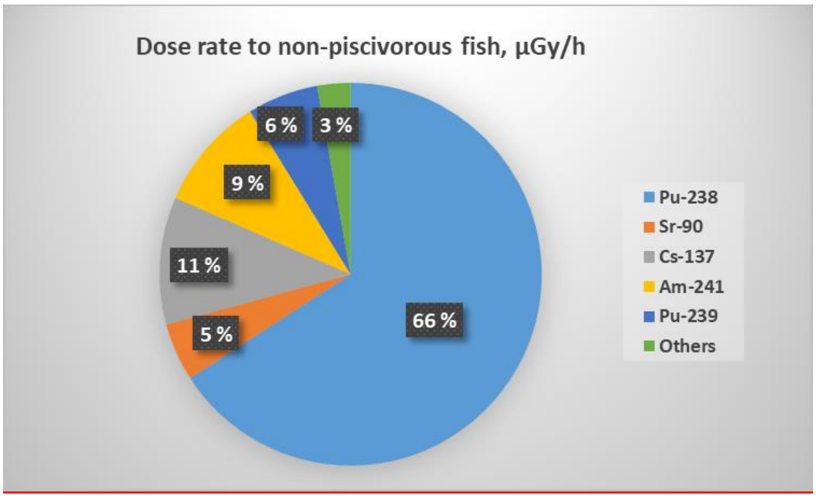
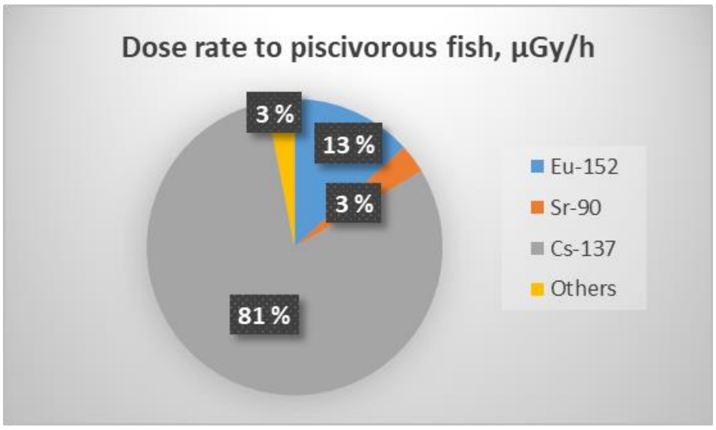


Figure 66. Contribution of various radionuclides to the dose rate for non-piscivorous fish at the onset of discharge (top) and after 45 days from the onset of discharge (bottom) with dose rates of 0.6 and 0.8 µGy/h, respectively.

Significant differences between results presented in Figure 66 can be explained by the fact that immediately after the start of releases, the dose-rate for non-piscivorous fish is dominated by external radiation, mainly from Cs-137. It is necessary to note that Cs-137 dominates instantaneous release according to the present study (see Figure 54). After some time, internal radiation (mainly, Pu-238) dominates the dose-rate for non-piscivorous fish for the present release scenario because of relatively fast and high bioaccumulation and the default radiation weighting factor of 10 for alpha radiation as presented in Section 7.1.3 of the present report.

For piscivorous fish, Cs-137 dose rates dominate almost the entire time (Figure 67). Figure 67 demonstrates that the effect of Pu-238 also increases with time.



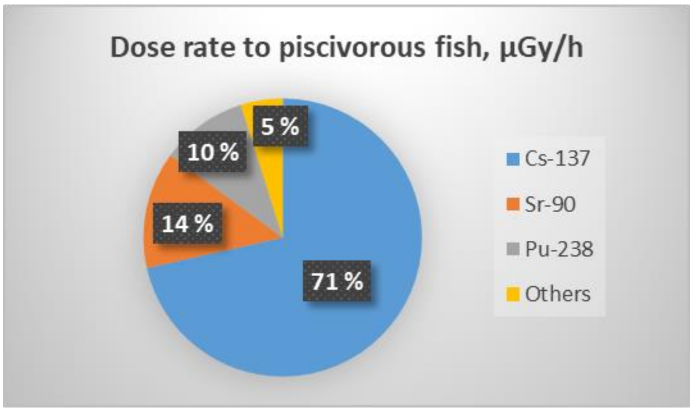
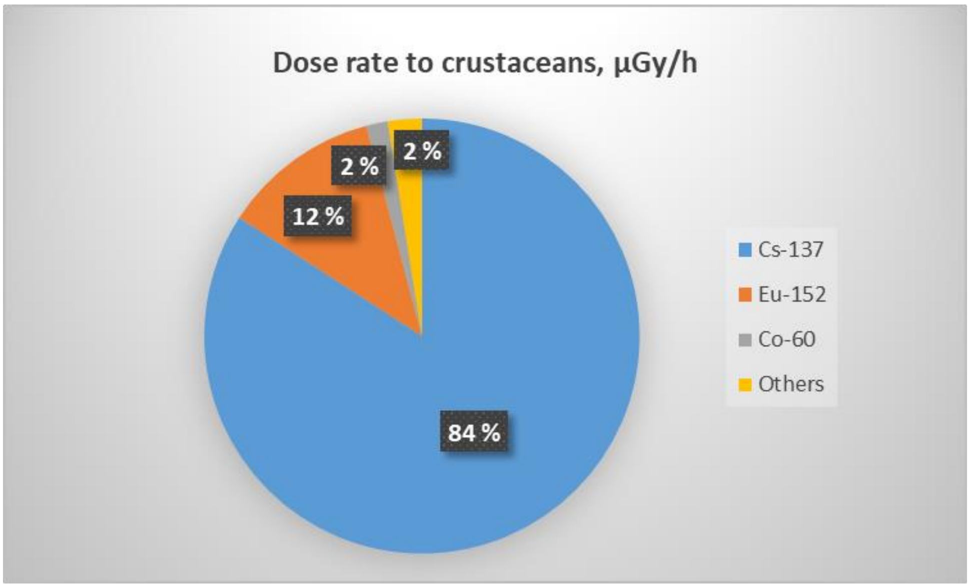


Figure 67. Contribution of various radionuclides to the dose rate for piscivorous fish at the onset of discharge (top) and after 2 years from the onset of discharge (bottom) with dose rates of 0.6 and 0.2 µGy/h, respectively.

The effect of different radionuclides on the crustacean dose rate (i) at initial time (immediately after the start of releases of radionuclides) and (ii) after 15 days from the start of radioactivity release, is shown in Figure 68. At initial time, the dose rate for crustaceans is dominated by Cs-137 because, similar to impact to fish, the dose rate is strongly dominated by external exposure, but after short time after the onset of discharge, Eu-152 and Pu-238 dominate the dose-rate for crustaceans.



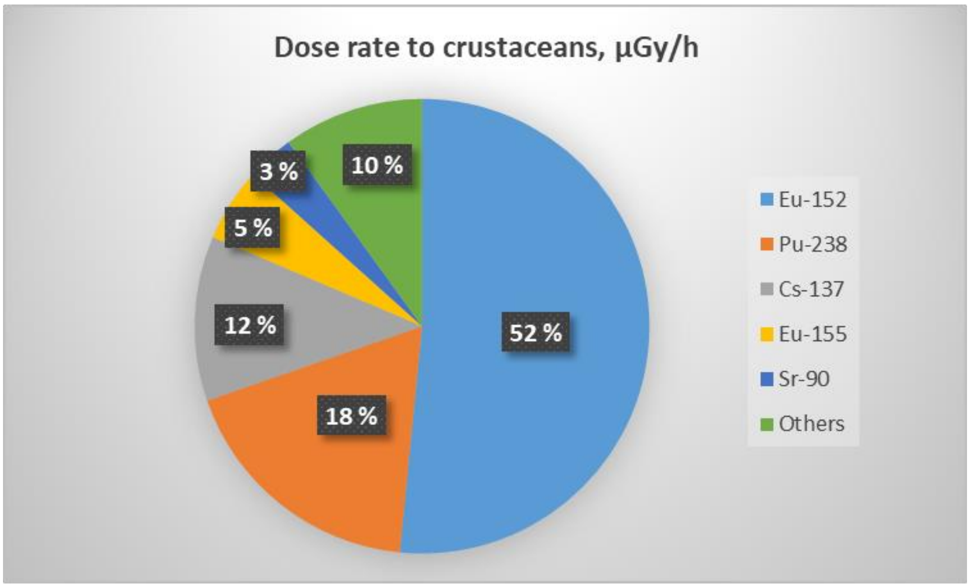
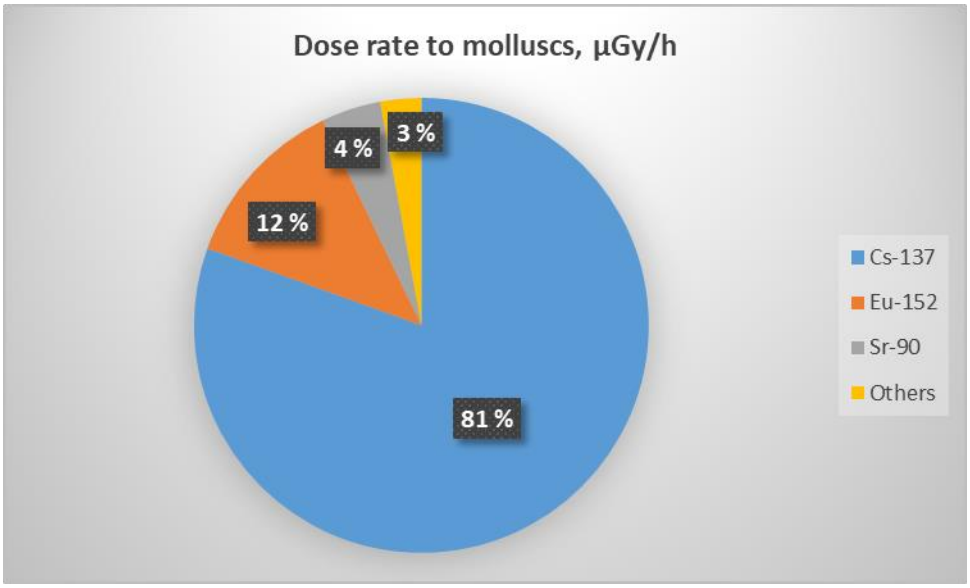


Figure 68. Contribution of various radionuclides to the dose rate for crustaceans at the onset of discharge (top) and after 15 days from the onset of discharge (bottom) with dose rates of 0.3 and 3.4 µGy/h, respectively

The effect of different radionuclides on the molluscs dose rate at initial time and after 15 days from the start of radioactivity release, is shown in Figure 69. Figure 69 shows that Pu-238 dominates the dose-rate for molluscs, but at initial time the dose rate is dominated by Cs-137, similar to the previous results.



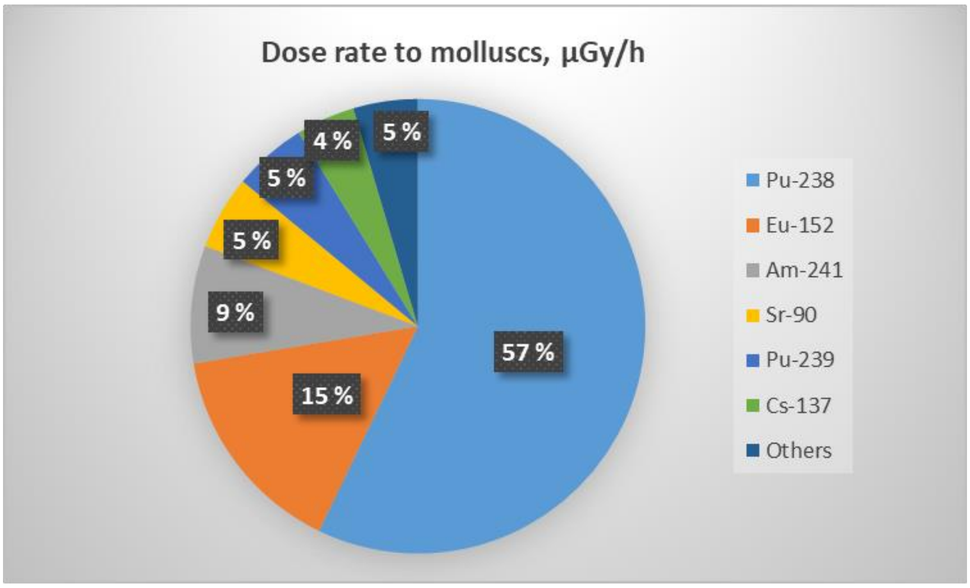


Figure 69. Contribution of various radionuclides to the dose rate for crustaceans at the onset of discharge (top) and after 15 days from the onset of discharge (bottom) with dose rates of 0.3 and 12.8 µGy/h, respectively.

Similar to the previous results, the dose rate for mammals is dominated by Cs-137 at initial time (Figure 70, top). The effect of different radionuclides after 4 years, approximately, is shown in Figure 70 (bottom) where the dose-rate for mammals is dominated by Pu-238 and Cs-137.

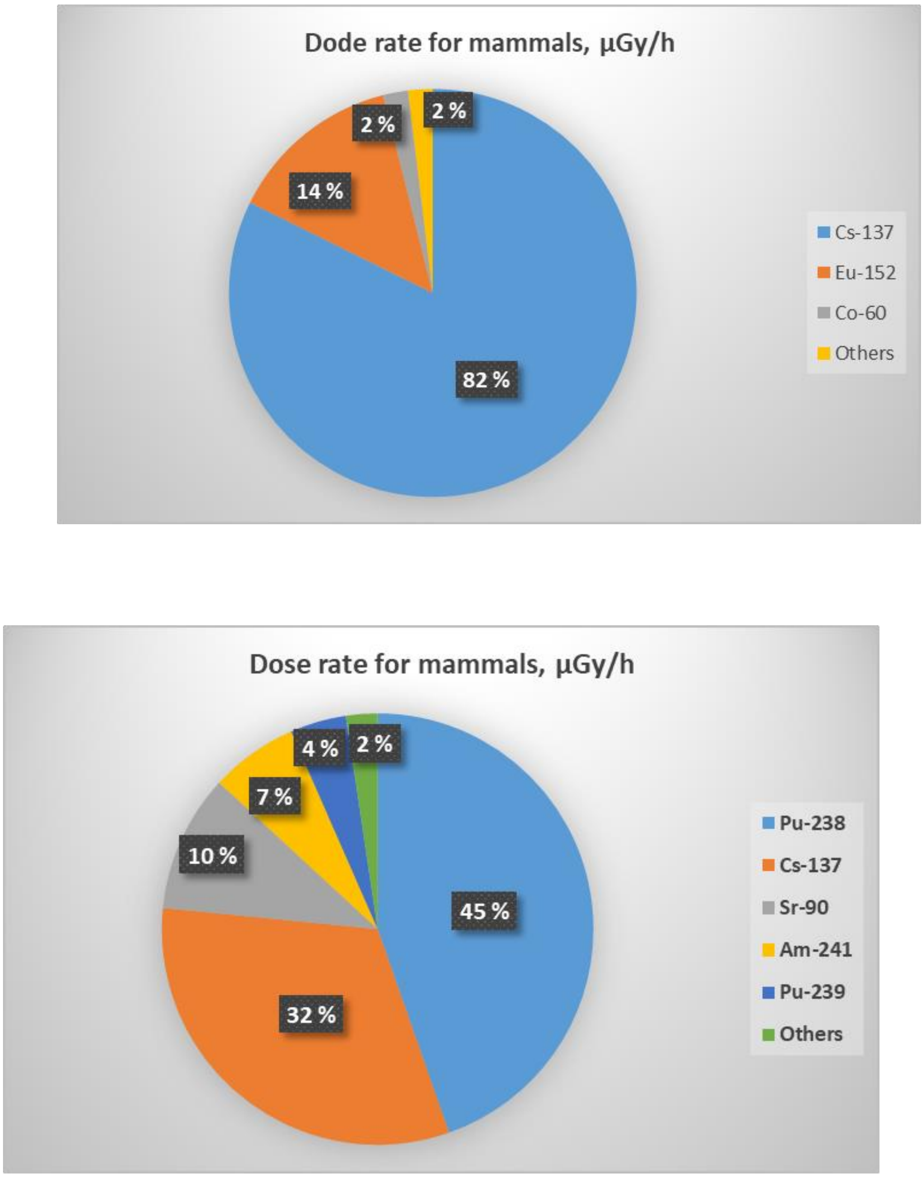
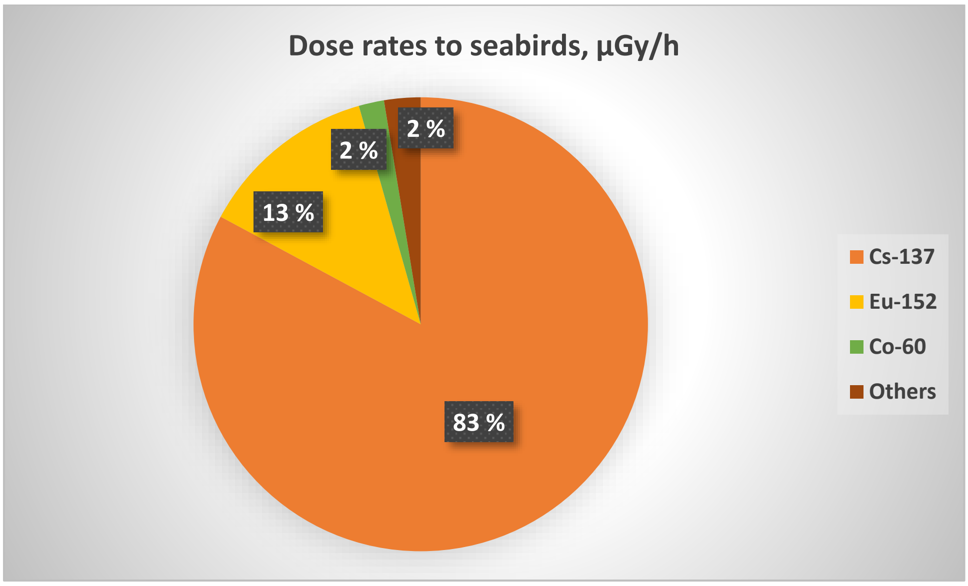


Figure 70. Contribution of various radionuclides to the dose rate for mammals at the onset of discharge (top) and after 50 months from the onset of discharge (bottom) with dose rates of 0.3 and 1.4 µGy/h, respectively.

The results for seabirds are similar to those for marine mammals (see Figure 71). Perhaps it should be noted that around the time when the dose rate for seabirds is maximal (3.5 years, approximately after the first release time), the effects of Cs-137, Pu-238 and Sr-90 are almost equal.



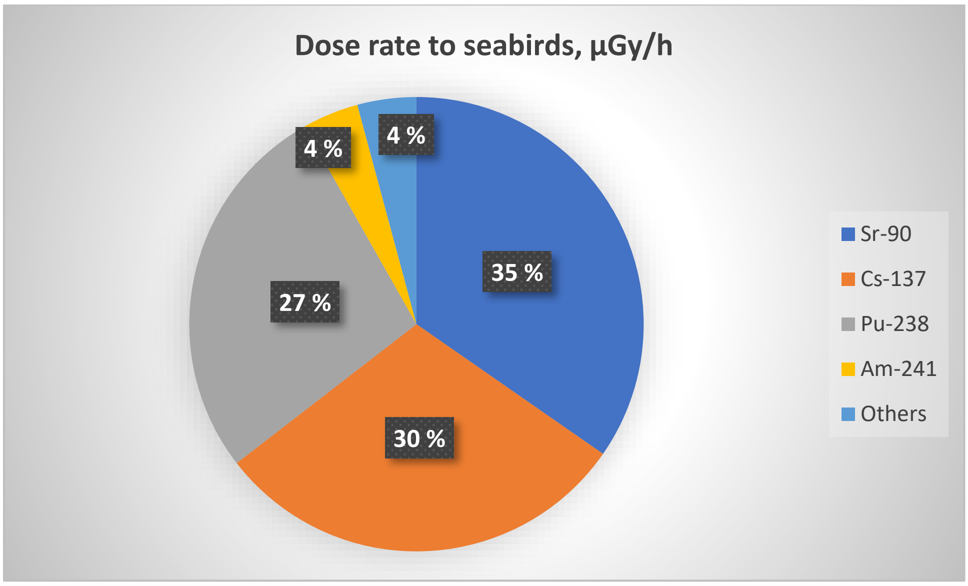


Figure 71. Contribution of various radionuclides to the dose rate for mammals at the onset of discharge (top) and after 50 months from the onset of discharge (bottom) with dose rates of 0.55 and 1.6 µGy/h, respectively.

It is important to note that the calculations presented in Figure 65 show that only for molluscs and only during one at initial time of releases (45 days, approximately) the dose rate exceeds the screening dose (10 µGy/h), which can be considered as a safe level below which the potential for significant impacts on biota would be negligible.

8. Conclusions

It was shown that it is impossible to use two approaches for the bioaccumulation process at the same time: (i) bioaccumulation based on the concentration rate approach and (ii) kinetic modelling of the bioaccumulation process. Simultaneous use of these two approaches provides a wrong description of the bioaccumulation process and concentration of radionuclides in biota, especially during the first period of exposure. In this connection, the evaluation of the kinetic parameters for bioaccumulation process for a wide set of radionuclides and biota has been provided.

Preliminary evaluation of the kinetic parameters has been provided based on literature review and the extraction from existing databases.

The selected kinetic parameters have been further improved based on mathematical experiments, including the successive simulations of bioaccumulation processes during increasing trophic levels.

The sub-model with the modified kinetic parameters for bioaccumulation process has been used based on simulations from the compartmental model, which uses the non-instantaneous dispersion of radioactivity in the marine environment. The selected release scenario corresponds to a potential accident with nuclear submarine reactor in the Gulf of Finland.

Concentrations of radionuclides in biota, doses to humans and dose rates to the marine organisms have been evaluated.

The results of the present study can be used to improve the ability to evaluate the consequences to humans and biota after a radioactive release into marine environment. It was shown that the methodology, which was used here allows to find a suitable set of kinetic parameters, but it is impossible to proof that this set of parameters is the best version. Therefore, it is important to justify the correctness of the parameters by site-specific information from considered marine regions.

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10. Appendix. The equilibrium/quasi-equilibrium concentration rates

The concentration rates are shown in Table A1, where AM is the arithmetic mean, GM is geometric mean, Min and Max are minimum and maximum values of the parameters**.**

Table A1. The concentration rates.

Organism	**Radionuclide**	**AM**	**GM**	**Min**	**Max**	**References**
Phytoplanctoon	Am-241	2.1E5	1.1E5	7.0E3	6.9E5	IAEA, 2014
	Am-241	2.0E5				IAEA, 2004
	Co-60	3.1E3	1.8E3	1.0E2	1.24	IAEA, 2014; Erica, 2019; Brown et al., 2008
	Co-60	2.0E3				IAEA, 2004
	Cs-137	8.5E0	3.6E0	1.0E0	7.3E1	IAEA, 2014
	Cs-137	2.0E1				IAEA, 2004
	Cs-137	1.3E2				Erica, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	9.0E4				IAEA, 2004; ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	5.7E2	3.5E2	1.6E2	1.4E3	IAEA, 2014
	Ni-63, Ni-59	3.0E3				IAEA, 2004
	Ni-63, Ni-59	1.4E3				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.3E5	8.3E4	4.0E2	6.3E5	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	2.0E5				IAEA, 2004; ERICA, 2019; Brown et al., 2008
	Sr-90	1.9E2	9.6E1	4.0E0	1.6E3	IAEA, 2014
	Sr-90	1.0E0				IAEA, 2004
	Sr-90	2.1E2				ERICA, 2019; Brown et al., 2008
Macroalgae	Am-241	4.3E2	2.1E2	3.9E1	3.8E3	IAEA, 2014
	Am-241	8.0E3				IAEA, 2004
	Co-60	1.7E3	7.8E2	9.0E0	1.4E4	IAEA, 2014
	Co-60	6.0E3				IAEA, 2004
	Co-60	2.1E3				ERICA, 2019; Brown et al., 2008
	Cs-137	9.6E1	2.4E1	3.7E0	4.8E3	IAEA, 2014
	Cs-137	5.0E1				IAEA, 2004; ERICA, 2019; Brown et al., 2008

Table A1. The concentration rates (**continued**).

Organism	**Radionuclide**	**AM**	**GM**	**Min**	**Max**	**References**
Macroalgae	Eu-152, Eu-154, Eu-155	1.4E3	1.1E3	3.0E2	2.6E3	IAEA, 2014 ERICA, 2019; Brown et al., 2008;
	Eu-152, Eu-154, Eu-155	3.0E3				IAEA, 2004
	Ni-63, Ni-59	9.5E2	6.9E2	2.5E2	2.8E3	IAEA, 2014
	Ni-63, Ni-59	2.0E3				IAEA, 2004
	Ni-63, Ni-59	7.9E2				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	4.1E3	1.7E3	8.5E1	4.9E4	IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E3				IAEA, 2004
	Sr-90	2.9E1	1.4E1	2.0E-1	3.3E2	IAEA, 2014
	Sr-90	1.0E1				IAEA, 2004
	Sr-90	4.2E1				ERICA, 2019; Brown et al., 2008
Zooplanctoon	Am-241	4.0E3				IAEA, 2004
	Co-60	4.8E3	2.9E3	2.0E2	2.6E4	IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Co-60	7.0E3				IAEA, 2004
	Cs-137	1.3E2	6.7E1	2.9E0	9.9E2	IAEA, 2014
	Cs-137	4.0E1				IAEA, 2004
	Cs-137	1.1E2				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	4.0E3				IAEA, 2004; ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	5.0E2				IAEA, 2014
	Ni-63, Ni-59	1.0E3				IAEA, 2004; ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	7.8E3	4.5E3	2.0E3	2.8E4	IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E3				IAEA, 2004
	Sr-90	6.8E1	4.8E1	1.1E1	1.5E2	IAEA, 2014
	Sr-90	2.0E0				IAEA, 2004
	Sr-90	4.6E0				ERICA, 2019; Brown et al., 2008
	Am-241	1.0E2				IAEA, 2004

Table A1. The concentration rates (continued).

Non-piscivorous fish / Pelagic small fish	Am-241	4.0E1				Present study. Suolanen, 2021
	Co-60	1.1E3	3.8E2	3.5E1	1.0E4	IAEA. 2014
	Co-60	7.0E2				IAEA. 2004
	Co-60	3.0E2				Present study. Suolanen, 2021
	Co-60	5.6E3				ERICA, 2019; Brown et al., 2008
	Cs-137	1.2E2	6.8E1	1.2E1	1.0E3	IAEA, 2014
	Cs-137	8.6E1				ERICA, 2019; Brown et al., 2008
	Cs-137	1.0E2				IAEA. 2004
	Cs-137	3.0E2				Present study. Suolanen, 2021
	Eu-152, Eu-154, Eu-155	7.3E2				IAEA, 2014
	Eu-152, Eu-154, Eu-155	3.0E2				IAEA, 2004
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	2.50E1				Present study. Suolanen, 2021
	Ni-63, Ni-59	2.5E2	2.0E2	5.5E1	6.7E2	IAEA, 2014
	Ni-63, Ni-59	1.0E2				Present study. Suolanen, 2021
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	6.9E2	3.4E2	2.0E2	4.8E3	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	3.5E3				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E1				Present study. Suolanen, 2021
	Sr-90	4.4E1	3.3E1	1.5E-1	1.4E2	IAEA, 2014
	Sr-90	3.0E0				IAEA, 2004
	Sr-90	2.3E1				ERICA, 2019; Brown et al., 2008
	Sr-90	2.0E1				Present study. Suolanen, 2021

Table A1. The concentration rates (**continued**).

Organism	Radionuclide	AM	GM	Min	Max	References
Piscivorouss fish / Pelagic large fish	Am-241	1.0E2				IAEA, 2004
	Am-241	4.0E1				Present study. Suolanen, 2021
	Co-60	1.1E4	5.0E3	28	7.8E4	IAEA, 2014
	Co-60	7.0E2				IAEA. 2004
	Co-60	3.0E2				Present study. Suolanen, 2021
	Co-60	5.6E3				ERICA, 2019; Brown et al., 2008
	Cs-137	7.9E1	5.9E1	7.4E0	3.6E2	IAEA, 2014
	Cs-137	1.0E2				IAEA. 2004
	Cs-137	8.6E1				ERICA, 2019; Brown et al., 2008
	Cs-137	3.0E2				Present study. Suolanen, 2021
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	3.0E2				IAEA, 2004
	Eu-152, Eu-154, Eu-155	2.50E1				Present study. Suolanen, 2021
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	2.5E2	2.0E2	5.5E1	6.7E2	IAEA, 2014
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Ni-63, Ni-59	1.0E2				Present study. Suolanen, 2021
	Pu-238; Pu-239; Pu-240; Pu-241	3.5E3				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.9E2	1.4E2	1.0E0	5.5E2	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	1.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E1				Present study. Suolanen, 2021
	Sr-90	3.8E1	2.0E1	2.0E-1	1.9E2	IAEA, 2014
	Sr-90	3.0E0				IAEA, 2004
	Sr-90	2.3E1				ERICA, 2019; Brown et al., 2008
	Sr-90	2.0E1				Present study. Suolanen, 2021

Table A1. The concentration rates (continued).

Deposit-feeding invertebrate	Am-241	4.5E1	3.3E1	6	120	IAEA, 2014
	Co-60	8.3E3	5.3E3	1.0E3	2.0E4	IAEA, 2014
	Cs-137	1.8E2	1.3E2	1.0E1	5.1E2	IAEA, 2014
	Ni-63, Ni-59	4.2E3				IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	1.5E3	8.4E2	1.0E2	4.1E3	IAEA, 2014
	Sr-90	4.6E-1				IAEA, 2014
Mollusk	Am-241	9.9E3	6.7E3	2E2	2E4	IAEA, 2014
	Am-241	1.0E3				IAEA, 2004
	Co-60	5.3E3	1.7E3	1.7E2	4.1E4	IAEA, 2014
	Co-60	2.0E4				IAEA, 2004
	Co-60	5.1E3				ERICA, 2019; Brown et al., 2008
Mollusk	Cs-137	5.0E1	3.5E1	2.0E0	2.1E2	IAEA, 2014
	Cs-137	6.0E1				IAEA, 2004
	Cs-137	6.6E1				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	6.9E3				IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	7.0E3				IAEA, 2004
	Ni-63, Ni-59	6.4E3	2.8E3	5.5E1	2.1E4	IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	2.0E3				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	1.1E3	6.6E2	1.8E0	9.2E3	IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	3.0E3				IAEA, 2004
	Sr-90	1.5E2	1.1E2	1.0E-1	5.0E2	IAEA, 2014
	Sr-90	1.0E1				IAEA, 2004
	Sr-90	1.2E2				ERICA, 2019; Brown et al., 2008
Crustacean	Am-241	5.0E2				IAEA, 2014
	Am-241	4.0E2				IAEA, 2004
	Co-60	3.5E3	1.7E3	2.2E2	2.2E4	IAEA, 2014
	Co-60	7.0E3				IAEA, 2004
	Co-60	1.8E3				ERICA, 2019; Brown et al., 2008
	Cs-137	5.3E1	2.1E1	5.5E-1	1.3E3	IAEA, 2014

Table A1. The concentration rates (**continued**).

Organism	**Radionuclide**	**AM**	**GM**	**Min**	**Max**	**References**
Crustacean	Cs-137	5.0E1				IAEA, 2004
	Cs-137	4.1E1				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	4.0E3				IAEA, 2004; ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Ni-63, Ni-59	5.5E2				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.2E2	9.7E1	3.8E1	2.7E2	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	2.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	1.6E2				ERICA, 2019; Brown et al., 2008
	Sr-90	4.9E1	2.7E1	1.5E-1	2.3E2	IAEA, 2014
	Sr-90	5.0E0				IAEA, 2004
	Sr-90	1.3E1				ERICA, 2019; Brown et al., 2008
Demersal fish	Am-241	3.2E2	1.9E2	1.7E1	1.5E3	IAEA, 2014
	Am-241	1.0E2				IAEA, 2004
	Am-241	4.0E1				Present study. Suolanen, 2021
	Co-60	4.8E2	2.8E2	5.3E1	3.3E3	IAEA, 2014
	Co-60	7.0E2				IAEA. 2004
	Co-60	3.0E2				Present study. Suolanen, 2021

Table A1. The concentration rates (**continued**).

Organism	Radionuclide	AM	GM	Min	Max	References
Demersal fish	Co-60	5.6E3				ERICA, 2019; Brown et al., 2008
	Cs-137	1.0E2				IAEA. 2004
	Cs-137	7.1E1	3.1E1	5.0E0	1.8E3	IAEA, 2014
	Cs-137	3.0E2				Present study. Suolanen, 2021
	Cs-137	8.6E1				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	3.0E2				IAEA, 2004
	Eu-152, Eu-154, Eu-155	2.50E1				Present study. Suolanen, 2021
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	2.5E2	2.0E2	5.5E1	6.7E2	IAEA, 2014
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Ni-63, Ni-59	1.0E2				Present study. Suolanen, 2021
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	2.5E3	7.3E2	2.0E0	2.7E4	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	1.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E1				Present study. Suolanen, 2021
	Pu-238; Pu-239; Pu-240; Pu-241	3.5E3				ERICA, 2019; Brown et al., 2008

Table A1. The concentration rates (**continued**).

Organism	Radionuclide	AM	GM	Min	Max	References
Demersal fish	Sr-90	1.1E1	7.4E0	3.0E0	6.0E1	IAEA, 2014
	Sr-90	3.0E0				IAEA, 2004
	Sr-90	2.0E1				Present study. Suolanen, 2021
	Sr-90	2.3E1				ERICA, 2019; Brown et al., 2008
Bottom predator	Am-241	3.2E2	1.9E2	1.7E1	1.5E3	IAEA, 2014
	Am-241	1.0E2				IAEA, 2004
	Am-241	4.0E1				Present study. Suolanen, 2021
	Co-60	5.3E3	1.8E3	2.8E1	7.8E4	IAEA, 2014
	Co-60	7.0E2				IAEA. 2004
	Co-60	5.6E3				ERICA, 2019; Brown et al., 2008
	Co-60	3.0E2				Present study. Suolanen, 2021
	Cs-137	8.4E1	4.8E1	5.0E0	1.8E3	IAEA, 2014
	Cs-137	1.0E2				IAEA. 2004
	Cs-137	8.6E1				ERICA, 2019; Brown et al., 2008
	Cs-137	3.0E2				Present study. Suolanen, 2021
	Eu-152, Eu-154, Eu-155	3.0E2				IAEA, 2004

Table A1. The concentration rates (continued).

Organism	Radionuclide	AM	GM	Min	Max	References
Bottom predator	Eu-152, Eu-154, Eu-155	2.50E1				Present study. Suolanen, 2021
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	2.5E2	2.0E2	5.5E1	6.7E2	IAEA, 2014
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	1.0E2				Present study. Suolanen, 2021
	Pu-238; Pu-239; Pu-240; Pu-241	1.5E3	3.6E2	1.0E0	4.5E4	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	3.5E3				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E1				Present study. Suolanen, 2021
	Sr-90	2.5E1	1.4E1	1.5E-1	1.9E2	IAEA, 2014
	Sr-90	3.0E0				IAEA, 2004
	Sr-90	2.0E1				Present study. Suolanen, 2021
	Sr-90	2.3E1				ERICA, 2019; Brown et al., 2008
Coastal predator	Am-241	3.2E2	1.9E2	1.7E1	1.5E3	IAEA, 2014
	Am-241	1.0E2				IAEA, 2004
	Am-241	4.0E1				Present study. Suolanen, 2021

Table A1. The concentration rates (continued).

Organism	Radionuclide	AM	GM	Min	Max	References
Coastal predator	Co-60	5.3E3	1.8E3	2.8E1	7.8E4	IAEA, 2014
	Co-60	7.0E2				IAEA. 2004
	Co-60	5.6E3				ERICA, 2019; Brown et al., 2008
	Co-60	3.0E2				Present study. Suolanen, 2021
	Cs-137	8.4E1	4.8E1	5.0E0	1.8E3	IAEA, 2014
	Cs-137	1.0E2				IAEA. 2004
	Cs-137	3.0E2				Present study. Suolanen, 2021
	Cs-137	8.6E1				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	3.0E2				IAEA, 2004
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	2.50E1				Present study. Suolanen, 2021
	Ni-63, Ni-59	2.5E2	2.0E2	5.5E1	6.7E2	IAEA, 2014
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	1.0E3				IAEA, 2004
	Ni-63, Ni-59	1.0E2				Present study. Suolanen, 2021
	Pu-238; Pu-239; Pu-240; Pu-241	1.5E3	3.6E2	1.0E0	4.5E4	IAEA, 2014

Table A1. The concentration rates (**continued**).

Organism	Radionuclide	AM	GM	Min	Max	References
Coastal predator	Pu-238; Pu-239; Pu-240; Pu-241	1.0E2				IAEA, 2004
	Pu-238; Pu-239; Pu-240; Pu-241	3.5E3				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	4.0E1				Present study. Suolanen, 2021
	Sr-90	2.5E1	1.4E1	1.5E-1	1.9E2	IAEA, 2014
	Sr-90	3.0E0				IAEA, 2004
	Sr-90	2.3E1				ERICA, 2019; Brown et al., 2008
	Sr-90	2.0E1				Present study. Suolanen, 2021
Seal /mammals	Co-60	5.0E2	1.7E2			IAEA, 2014; ERICA, 2019; Brown et al., 2008
	Cs-137	2.1E2				ERICA, 2019; Brown et al., 2008
	Cs-137	2.2E2	8.4E1	8.7E0	8.2E2	IAEA, 2014
(muscle)	Cs-137	4.0E2		3.1E1	1.0E3	IAEA, 2004
(liver)	Cs-137	3.0E2				IAEA, 2004
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
(liver)	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.1E3	9.2E2	1.0E2	4.0E3	IAEA, 2014
	Pu-238; Pu-239; Pu-240; Pu-241	2.8E2				ERICA, 2019; Brown et al., 2008

Table A1. The concentration rates (**continued**).

Sea mammals (liver)	Pu-238; Pu-239; Pu-240; Pu-241	8.0E0		3.0E0	2.0E1	IAEA, 2004
	Sr-90	1.4E0				ERICA, 2019; Brown et al., 2008
	Sr-90	1.6E2	6.8E1	1.4E0	1.0E3	IAEA, 2014
Sea Bird	Co-60	5.0E2	1.7E2			ERICA, 2019; Brown et al., 2008
	Cs-137	4.8E2	2.9E2	5.0E1	3.5E3	IAEA, 2014
	Cs-137	4.4E2				ERICA, 2019; Brown et al., 2008
	Eu-152, Eu-154, Eu-155	4.4E2				ERICA, 2019; Brown et al., 2008
	Ni-63, Ni-59	1.7E2				ERICA, 2019; Brown et al., 2008
	Pu-238; Pu-239; Pu-240; Pu-241	1.5E2				ERICA, 2019; Brown et al., 2008
	Sr-90	1.4E0				ERICA, 2019; Brown et al., 2008

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Title	Evaluation of the bioaccumulation processes for a wide set of radionuclides under accidental releases by biota
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Abstract max. 2000 characters	It was shown that it is impossible to use two approaches for the bioaccumulation process at the same time: (i) bioaccumulation based on the concentration rate approach and (ii) kinetic modelling of the bioaccumulation process. Simultaneous use of these two approaches provides a wrong description of the bioaccumulation process and concentration of radionuclides in biota, especially during the first period of exposure. In this connection, the evaluation of the kinetic parameters for bioaccumulation process for a wide set of radionuclides and biota has been provided. Preliminary evaluation of the kinetic parameters has been provided based on literature review and the extraction from existing databases. The selected kinetic parameters have been further improved based on mathematical experiments, including the successive simulations of bioaccumulation processes during increasing trophic levels. The sub-model with the modified kinetic parameters for bioaccumulation process has been used based on simulations from the compartmental model, which uses the non-instantaneous dispersion of radioactivity in the marine environment. The selected release scenario corresponds to a potential accident with nuclear submarine reactor in the Gulf of Finland. Concentrations of radionuclides in biota, doses to humans and dose rates to the marine organisms have been evaluated. The results of the present study can be used to improve the ability to evaluate the consequences to humans and biota after a

radioactive release into marine environment. It was shown that the methodology, which was used in the present study allows to find a suitable set of kinetic parameters.

Key words

Radionuclides, bioaccumulation, kinetic modelling, consequences to humans and biota

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