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Development and evaluation of a regression-based model to predict cesium-137 concentration ratios for saltwater fish

John E. Pinder III [a, *], David J. Rowan [b], Jim T. Smith [c]

[a] Department of Radiological and Environmental Health Sciences, Colorado State University, 305 W. Magnolia, PMB 231, Fort Collins, CO 80521, USA
[b] Canadian Nuclear Laboratories, Chalk River Laboratories, Chalk River, Ontario K0J 1J0, Canada
[c] School of Earth and Environmental Science, University of Portsmouth, Portsmouth P01 3 QL, United Kingdom

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ABSTRACT

Data from published studies and World Wide Web sources were combined to develop a regression model to predict ^{137}Cs concentration ratios for saltwater fish. Predictions were developed from 1) numeric trophic levels computed primarily from random resampling of known food items and 2) K concentrations in the saltwater for 65 samplings from 41 different species from both the Atlantic and Pacific Oceans. A number of different models were initially developed and evaluated for accuracy which was assessed as the ratios of independently measured concentration ratios to those predicted by the model. In contrast to freshwater systems, were K concentrations are highly variable and are an important factor in affecting fish concentration ratios, the less variable K concentrations in saltwater were relatively unimportant in affecting concentration ratios. As a result, the simplest model, which used only trophic level as a predictor, had comparable accuracies to more complex models that also included K concentrations. A test of model accuracy involving comparisons of 56 published concentration ratios from 51 species of marine fish to those predicted by the model indicated that 52 of the predicted concentration ratios were within a factor of 2 of the observed concentration ratios.

1. Introduction

The ratio of the mean concentration of a radionuclide in a fish to its mean concentration in the water, when measured under equilibrium conditions, is an important parameter used to assess the bioavailability of radionuclides such as ^{134}Cs and ^{137}Cs in aquatic environments. This ratio may alternatively be termed the concentration ratio (hereafter, C_r), the concentration factor, or bioaccumulation factor and has units of L kg^{-1}. Numerous compilations of previously observed C_r for Cs isotopes have been developed (*e.g.*, Vanderploeg et al., 1975; Blaylock, 1982; Fesenko et al., 2011; Yankovich et al., 2012; Psaltaki et al., 2013; Tagami and Uchida, 2013) for use in accident assessments, and models have also been developed to predict C_r for Cs isotopes in fish using aspects of fish biology (*e.g.*, diet) and water quality parameters such as K concentrations (*e.g.*, Rowan and Rasmussen, 1994), Maximum Entropy Methods of analyses of previously compiled C_r (Hosseini et al., 2008), and Residual Maximum Likelihood extrapolations of known C_r among similar species (Beresford et al., 2016).

Rowan and Rasmussen (1994) developed a predictive model applicable to both freshwater and saltwater systems that has been shown to predict C_r for ^{137}Cs within a factor of 2 for a majority of cases (Smith et al., 2000). The model is based on 1) a classification of fish as either piscivorous or nonpiscivorous and 2) measures of K and suspended sediment concentrations in the water column. The model predicts 1) greater C_r for piscivorous fish, 2) smaller C_r in waters with greater K concentrations and 3) smaller C_r in waters with greater suspended sediment concentrations. This model is most appropriately applied to predict C_r when equilibrium conditions exist between the fish and the water.

Recently, an alternative form of the Rowan and Rasmussen (1994) model (hereafter referred to as the "freshwater fish model") was developed and evaluated (Pinder et al., 2014) that predicts C_r for ^{137}Cs in freshwater fish using the data from Rowan and Rasmussen (1994) but replaces their nonpiscivorous and piscivorous classification with a species-specific, numerical trophic level (hereafter, TL) obtained from the online database *fishbase.org* (Froese and Pauly, 2011). Information compiled in this database on

* Corresponding author.
E-mail addresses: jepinder@uga.edu (J.E. Pinder), djrowan@bell.net (D.J. Rowan), jim.smith@portac.uk (J.T. Smith).

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fish diets and food items are used to compute numeric estimates of mean (±Standard Error, hereafter SE) TL. These TLs range from 2, which indicates an herbivorous diet, through 3, which indicates a primarily carnivorous diet composed of herbivorous species, and to 4 and above that indicates a diet composed primarily of other carnivorous species. An advantage of this alternative, model using a continuous range of TL is that it predicts a separate C_r for each species rather than predictions for only the two discrete groups of piscivorous species and nonpiscivorous species.

This alternative, predictive model considered only freshwater fish. It did not include saltwater species, and it is the purpose of this analysis is to 1) extend the approaches used in Pinder et al. (2014) to develop a predictive model of C_r for saltwater species (hereafter termed the saltwater fish model) and 2) to test this model using two sources of independent data. The first source involves published data not incorporated into the Rowan and Rasmussen (1994) analysis. The second source involves those data that are appropriate for estimating C_r from the releases of Cs isotopes at the Fukushima Daiichi Nuclear Power Plant (hereafter, FDNPP). An ability to predict C_r for saltwater species based on their TLs may become a useful asset as the FDNPP ^{137}Cs releases continue to be dispersed across the northern Pacific Ocean (Buesseler et al., 2012; Kamenik et al., 2013; Otosaka and Kato, 2014; Povinec et al., 2013; Kawamura et al., 2014; Ramzaev et al., 2014).

Instead of incorporating freshwater and saltwater fish into a common model, a separate model was developed for saltwater fish. The use of separate, independent models for fresh and salt waters was suggested by the differing relative ranges of variation in the important predictor variables of TL and K concentrations between fresh and saltwater. The TLs of *fishbase.org* range over a factor of approximately two from somewhat >2 to somewhat >4 in both fresh and salt waters. In contrast, the ranges of maximum to minimum K concentrations in these environs range over factors of approximately 1.2 for the ocean (*i.e.*, from 8783 to 10,058 μM L^{-1}; Rowan and Rasmussen, 1994) but over a factor of approximately 30 in freshwaters (8–249 μM L^{-1}; Rowan and Rasmussen, 1994). These relative ranges suggest that K concentrations may be a more important predictor of C_r in freshwater but that TL may be a more important predictor of C_r in saltwater.

2. Materials and methods

Separate data sources were employed in model development and model evaluation.

2.1. Model development

Four data sources were employed in model development including: 1) the TL estimates from *fishbase.org*; 2) C_r data from Rowan and Rasmussen (1994) for saltwater fish; 3) concentrations of K in salt waters from Rowan and Rasmussen (1994); and 4) assessments of fish species as being primarily pelagic species or primarily demersal species in *fishbase.org*.

2.1.1. TL data

The TL estimates were obtained from *fishbase.org* where data on fish biology and ecology have been compiled for >30,000 species from >45,000 references. Several alternative methods are used in *fishbase.org* to estimate a mean ± SE TL depending on the type of available data. Where only lists of the food items consumed are available, the TL is estimated using a randomized resampling of those items to produce a mean ± a SE TL (see Pinder et al., 2014 and *fishbase.org* for details of this resampling process). In those cases where data are available on the proportions of food items consumed, an additional estimate of the TL is also computed using these proportions. For both methods, the TL of the fish is computed as 1 plus the mean TL computed for its diet (*i.e.*, a fish whose diet has a mean TL of 2.5 would have a TL of 3.5). These estimations of TLs have been shown to agree with those computed from stable isotopic ratios (Kline and Pauly, 1988; Vander Zanden, 1997). Where data are lacking on diets, a fish's TL is inferred from taxonomically related species of a similar size. Because TL estimates from the random resampling procedures were available for the majority of the species involved in this study, they have been used in the models to predict most C_r. Where random resampling estimates were not available, the taxonomically related estimates were used instead.

2.1.2. The ^{137}Cs data for fish and their environment

The development of the predictive model was based on the ^{137}Cs data for saltwater fishes compiled by Rowan and Rasmussen (1994; Table 1) which included: 1) the fish's scientific name; 2) the 0 or 1 nonpiscivorous or piscivorous classification; 3) the location of the study; 4) the K concentration in the water (μM K L^{-1}); 5) the ^{137}Cs concentration (mBq L^{-1}) in the water; and 6) the wet mass ^{137}Cs concentration (Bq kg^{-1}) in either the fish's whole body or its muscle. The K concentrations in saltwater reported by Rowan and Rasmussen (1994) were interpolated from salinities using the conversion factor of 283.3 μM K L^{-1} per g kg^{-1}of salinity (Broecker and Peng, 1982). The Rowan and Rasmussen (1994) study included 71 measures of C_r for 42 species from 18 open ocean locations which included seas such as the Irish Sea, the North Sea and the Sea of Japan which are open to flow through circulation of ocean waters. Data from the more enclosed Baltic Sea and the Gulf of California were not used because of known variation in K concentrations in gradients of freshwaters to salt waters in the Baltic Sea and the possibility for similar gradients in other similarly enclosed waters. In the estimation of C_r from the data of Rowan and Rasmussen (1994) it was assumed that the concentrations in fish and water were at or near equilibrium, and this assumption of equilibrium is reasonable because the principal source of the ^{137}Cs in the oceans was global fallout from past weapons testing.

Concentration ratios were computed from these data as the ratio of concentrations in fish to those in water did not (and in some cases could not) differentiate between concentrations for whole fish and those for only muscle tissue. As a consequence, no distinctions with regard to muscle versus whole-body concentrations have been made in the use of these data to predict C_r in fish.

2.1.3. Classification of fish species as either demersal or pelagic species

Fish species were classified as either pelagic or demersal species based on descriptions in *fishbase.org*. Although the classification of species as pelagic or demersal may be a subjective classification, demersal species 1) have been documented to accumulate greater ^{137}Cs concentrations than co-occurring pelagic species (Rowan et al., 1998), 2) have sometimes had their ^{137}Cs concentrations ratios underestimated by predictive models (*e.g.*, Pinder et al., 2014). Moreover, it has been suggested that rates of decline of ^{137}Cs

Table 1
Spearman rank correlation coefficients (r_s) among the variables TLs (TL), K concentrations, and ^{137}Cs concentration ratios for 65 samples of fish from 41 species from 18 open ocean locations. * = P ≤ 0.05.

Variables	Spearman rank correlations for the variables	
	K Concentrations	Concentration ratios
TLs	0.060	0.261*
K concentrations	–	0.229