Modelling the accumulation of ^{137}Cs by age-structured fish population

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Abstract. The dynamic model is presented, which enables one to describe difference types of the size effect in the accumulation of ^{137}Cs by fish. The fish population is represented by a set of discrete age classes characterized by a specific growth rate, diet and activity of metabolic processes. For validation of the model we used the data of observations on the content of ^{137}Cs in fish and other components of the fresh-water ecosystems after Chernobyl accident. The model is applied to the calculation of the dynamics of the ^{137}Cs specific activity in the muscles of different age groups of fish in the Chernobyl NPP cooling pond, and other water bodies. It is shown that the decrease in the specific activity of radiocaesium in fish with age in the first few months following the Chernobyl accident was determined by a more intensive feeding and metabolic activity of young fish. An increase in the specific activity of radiocaesium in fish with age in succeeding months was determined by a slower removal of the radionuclide from the organisms of older generations of fish. The age dependence in the accumulation of radiocaesium shows itself more markedly in predatory fish, which is explained by the effect of trophic levels, as well as by the fact that at a certain time the fish change from a non-predatory to predatory type of feeding. The size effect changes sign from negative to positive smoothly, so the distribution of the ^{137}Cs activity in fish with ages has a maximum during the second year after the accident.

1. INTRODUCTION

A specific phenomenon, called the 'size effect' is observed in many water bodies accidently contaminated with radiocaesium. More often, a 'positive size effect' has been revealed - older fish are more contaminated with ^{137}Cs than younger members of the same species [1]-[5]. More rarely, mostly during the first year following the accident, a 'negative size effect' was observed – the activity concentration of ^{137}Cs in older fish was lower than that in young fish of the same species [6]-[8]. In this paper a mathematical model which enables description of all known types of size effect and the other features of radiocaesium accumulation by fish is presented. The detailed dynamics of ^{137}Cs accumulation by fish, including the size effect and the trophic levels effect, is demonstrated using the results of the model's application to the predatory fish (pike-perch) from the cooling pond of the Chernobyl NPP.

2. MODEL DESCRIPTION

2.1 The general model equations

The main assumptions and derivation of the general model equation were described in the earlier work [5]. We consider the radionuclide as a tracer, which is identical in its properties to a stable (analogous) element participated in the metabolism of hydrobiont [9]. The radionuclide assimilated by an organism goes to the building of new biomass and compensates for the metabolic losses of the analogous bioelement. It was assumed that the major part of ^{137}Cs in freshwater ecosystems enter the fish with the contaminated food.

The basic equation of the model of ^{137}Cs bioassimilation by fish is the following:

$$\frac{dy}{dt} = -(\lambda_r + \varepsilon_A \frac{W}{M} + \frac{1}{M}\frac{dM}{dt})y + \frac{Q_1^A}{Q_0^A}(\varepsilon_A \frac{W}{M} + \frac{1}{M}\frac{dM}{dt}) \cdot y_{food}; \qquad (1)$$

where y is the activity concentration of ^{137}Cs in fish muscles, Bq·kg^{-1}; y_{food} is the activity concentration of ^{137}Cs in the food of the fish, Bq·L^{-1}; λ_r is the radioactive decay constant, year^{-1}; M is the mass of the fish,

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kg; W is the rate of metabolic processes, kg·year^{-1}; Q_1^A is the concentration of potassium in the fish muscles, Q_0^A is the concentration of potassium in the food of the fish. In this model it was assumed that the rate of biological elimination of ^{137}Cs from fish bone is proportional to the rate of overall metabolism and ε_A is the coefficient of proportionality.

If the fish feeds on relatively small organisms, for example zooplankton, zoobenthos, mollusks, y_{food} can be estimated using the constant equilibrium concentration factor CF_{food}. This simplification is justified since an equilibrium in the exchange of radiocaesium between such hydrobionts and the water is established rapidly [5], [10]. Then $y_{food} = CF_{food} \cdot C_w(t)$, where $C_w(t)$ is the activity concentration of the radionuclide in water, and equation (1) takes the form

$$\frac{dy}{dt} = -a \cdot y + G \cdot C_w(t); \qquad (2)$$

where $a = \lambda_r + \varepsilon_A \cdot (W/M) + (dM/Mdt)$, $G = (Q_1^A/Q_0^A) \cdot (\varepsilon_A \cdot (W/M) + (dM/Mdt)) \cdot CF_{food}$. The concentration factors of ^{137}Cs in zooplankton, zoobenthos, mollusks and aquatic plants can be estimated by the formula: $CF_{food} = Q_0^A/Q_0$, where Q_0^A is the concentration of potassium in the organism, Q_0 is the concentration of potassium in the lake water.

The equations (1)-(2) can be rewritten to describe the migration of ^{137}Cs in the 'predatory fish – prey fish' trophic chain in the following form:

$$\frac{dy_{prey}}{dt} = -(\lambda_r + (\varepsilon_A \frac{W}{M})_{prey} + (\frac{dM}{Mdt})_{prey}) y_{prey} + \\ + (\frac{Q_1^A}{Q_0^A})_{prey} \cdot ((\varepsilon_A \frac{W}{M})_{prey} + (\frac{dM}{Mdt})_{prey}) CF_{food} \cdot C_w(t) \qquad (3)$$

$$\frac{dy_{pred}}{dt} = -(\lambda_r + (\varepsilon_A \frac{W}{M})_{pred} + (\frac{dM}{Mdt})_{pred}) y_{pred} + \\ + (\frac{Q_1^A}{Q_0^A})_{pred} \cdot ((\varepsilon_A \frac{W}{M})_{pred} + (\frac{dM}{Mdt})_{pred}) y_{prey}(t) \qquad (4)$$

where index *prey* is related to the prey fish, index *pred* is related to the predatory fish, CF_{food}, is the average concentration factor for organisms which are consumed by the prey fish.

2.2 Determination of the model parameters

The fish growth rate is an important parameter of the model. The logistic growth model provided very good results by approximating the growth of all fish age groups by a single formula:

$$M = \frac{M_{max}}{1 + \alpha \cdot \exp(-\beta \cdot \tau)}; \qquad (5)$$

where M is the fish weight, g; τ is the fish age, years; M_{max}, α, β are the constant parameters. The numerical values of parameters in formula (5) can be determined for every fish species by the least-squares method on the basis of the available ichthyological data on the specific or analogous water body.

The method for estimation of the value of rate of metabolic processes for freshwater fish was described in [5], [11], [12]. The value of the fish metabolic rate W (g·day^{-1}) was estimated with the simple formula:

$$W = 0.0359 \cdot \alpha_1 \cdot M^{\alpha_2} \cdot \exp(0.093 \cdot TEMP); \qquad (6)$$

where M is the mass of the fish, g; α_1 and α_2 are the constant parameters, $TEMP$ is the temperature in °C. The numerical values of the constant parameters were determined in [11], [12].

The coefficient of proportionality between the fish overall metabolism and bioelimination of radiocaesium ε_A is one of the most important parameters of the model. An analysis of the data of different authors who have investigated the biological elimination of radiocaesium from fish together with measurements of fish weight and temperature was conducted. The results of such analysis are shown in Table 1. The values of the metabolic rate (Table 1) were estimated with the equation (6) on the basis of the reported data of measurements of fish weight and average temperature in every experiment. The analysis of Table 1 let us to conclude that the values of the proportionality coefficient ε_A fall within the range ε_A=0.3±0.1 for every fish species.

Table 1. The dependence between the experimentally detected rates of ^{137}Cs biological elimination from fish $\varepsilon_p = \ln 2/T_{1/2biol}$ ($T_{1/2biol}$ is the half-time of radiocaesium bioelimination) and the fish overall metabolic rate (W/M).

Reported data of observations					Calculated values	
Reference	Fish species	Fish mass, g	TEMP, °C	ε_p, day^{-1}	(W/M), day^{-1}	ε_A
[13]	Carp (*Cyprinus carpio)*	250	20	0.0045	0.0178	0.253
		250	12.5	0.0020	0.0089	0.225
[14]	Bluegill (*Lepomis macrochirus*)	90	20	0.0047	0.0191	0.246
[15]	Bluegill (*Lepomis macrochirus*)	100	15.5	0.0038	0.0123	0.308
		80	15.6	0.0037	0.0130	0.282
		80	14.5	0.0032	0.0117	0.270
[16]	Arctic char (*Salvelinus alpinus)*	250	12.5	0.0045	0.0178	0.253
[17]	Trout (*Salmo trutta*)	23	15.5	0.0067	0.0177	0.378
		416	4.4	0.0018	0.00315	0.390
[18]	Carp (*Cyprinus carpio)*	200	11	0.0026	0.0081	0.321
		350	11	0.0021	0.0072	0.292
		450	11	0.0019	0.0069	0.275
		550	11	0.0018	0.0066	0.281
		1000	11	0.0025	0.0058	0.430
	Goldfish (*Carassius auratus gibelio)*	40	22.5	0.0082	0.0339	0.241
		70	22.5	0.0073	0.0318	0.229
		100	22.5	0.0069	0.0306	0.227

3. APPLICATION OF THE MODEL TO THE CHERNOBYL NPP COOLING POND

The Chernobyl NPP cooling pond was highly contaminated with radiocaesium in 1986 as a result of the Chernobyl accident. Pike-perch (*Stizostedion lucioperca*), the predatory fish from this water body, was selected for model testing because for predatory fish the size-effect is more pronounced. The dynamics of the ^{137}Cs activity concentrations in water of the cooling pond and in non-predatory fish were estimated earlier [5], [19]. Pike-perch are piscivorous predators from the second year of their life onwards.

The 'weight-age' dependence for pike-perch from the Chernobyl NPP cooling pond was calculated using the equation (5) with the parameters: M_{max}=3500 g, α=216.2, β=0.96 year^{-1}. The value of metabolic rate was estimated using the equation (6) with the parameters: α_1=0.446, α_2=0.83 [12].

Fig. 1 shows the calculated dynamics of the activity concentration in the muscles of the pike-perch of different generations. In the first year following the accident, a negative size effect is enhanced by the fact that pike-perch of the first year of life feed as non-predatory fish. After their change to a predatory type of feeding the secondary maximum of contamination takes place. The smooth change from a negative size effect to a positive one occurs beginning in the second year after the accident.

Each curve in Fig. 1 is the relationship between the activity y and the time of the accident t with a fixed fish age τ_0 at the time of the accident. The size effect can be conveniently illustrated by showing in the figure the results of calculations for a definite fixed moment of time t and different τ_0. Since the dependence between the fish weight and the fish age for the cooling pond of the Chernobyl NPP is known, the activity of ^{137}Cs in the fish can be presented as a function of fish weight rather than fish age. Fig. 2 (a) shows the calculated activity concentrations of ^{137}Cs in the muscles of pike-perch in April, 1989 as a function of their weights together with the measurements data. It is seen that the model describes the size-effect quantitatively as well as qualitatively. Fig. 2 (b) shows the calculated dynamics in the population of pike-perch weighted-averaged by all age classes and the data of observations. The high range of uncertainity in the observed data could be explained by the size-effect (see Fig. 1). It is seen that the model predictions of the levels of radiocaesium contamination of pike-perch population in the Chernobyl NPP cooling pond are in good agreement with the test data.

It is interesting to note, that in the period from the 250th to the 900th day after the accident the age distribution of ^{137}Cs activity has a maximum. Fig. 3 shows the age distribution of activity concentration of ^{137}Cs in pike-perch for the cooling pond of the Chernobyl NPP on the 180th, 270th, 540th and 900th day after the accident. It can be seen that the size effect changes sign progressively, as the contamination maximum for pike-perch moves from younger to older ages. The presence of such a maximum during the second year after the accident was reported in several experimental studies [6], [7], [20].

4. CONCLUSIONS

The dynamic model, which takes into account the characteristic features of the metabolism, feeding and behaviour of the fish, enables a description of all known types of size effect in the radiocaesium accumulation by fish. The model parameters can be easily determined on the basis of biological and ichthyological data. The major factor responsible for a size effect in radiocaesium contamination of fish in the early period after the accidental contamination of water body is the dependence of the metabolism intensity in fish and the feeding of fish from its weight (age). In the later period the most important factor determined the positive size-effect is the decrease of radiocaesium activity in water because of its uptake by sediments.

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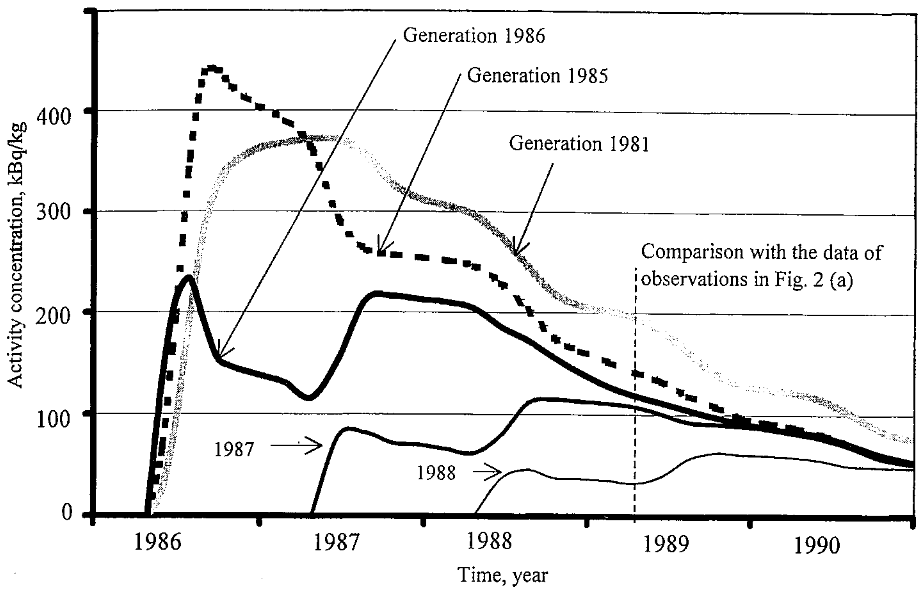

Fig. 1. The dynamics of Cs-137 activity concentration in the muscle of pike-perch of different generations, Chernobyl NPP cooling pond (model calculations).

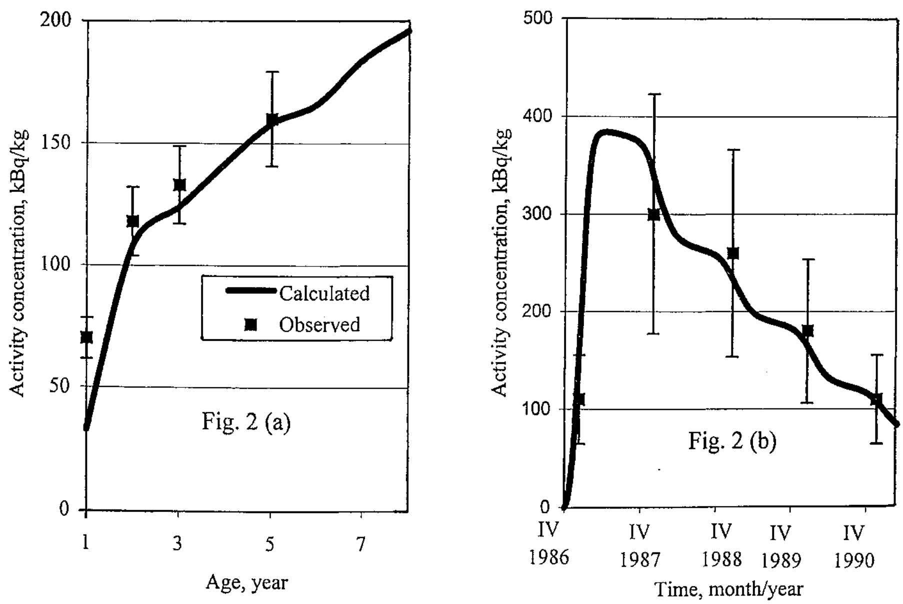

Fig. 2 (a). Cs-137 activity concentration in the muscle of pike-perch from the Chernobyl NPP cooling pond in dependence from their age, April 1989. Continious line represents the model calculations, squares - the data of observations [5].

Fig. 2 (b). Cs-137 activity concentration in the muscle of pike-perch from the Chernobyl NPP cooling pond (average contamination of the population). Continious line represents the model calculations, squares - the data of observations [21].

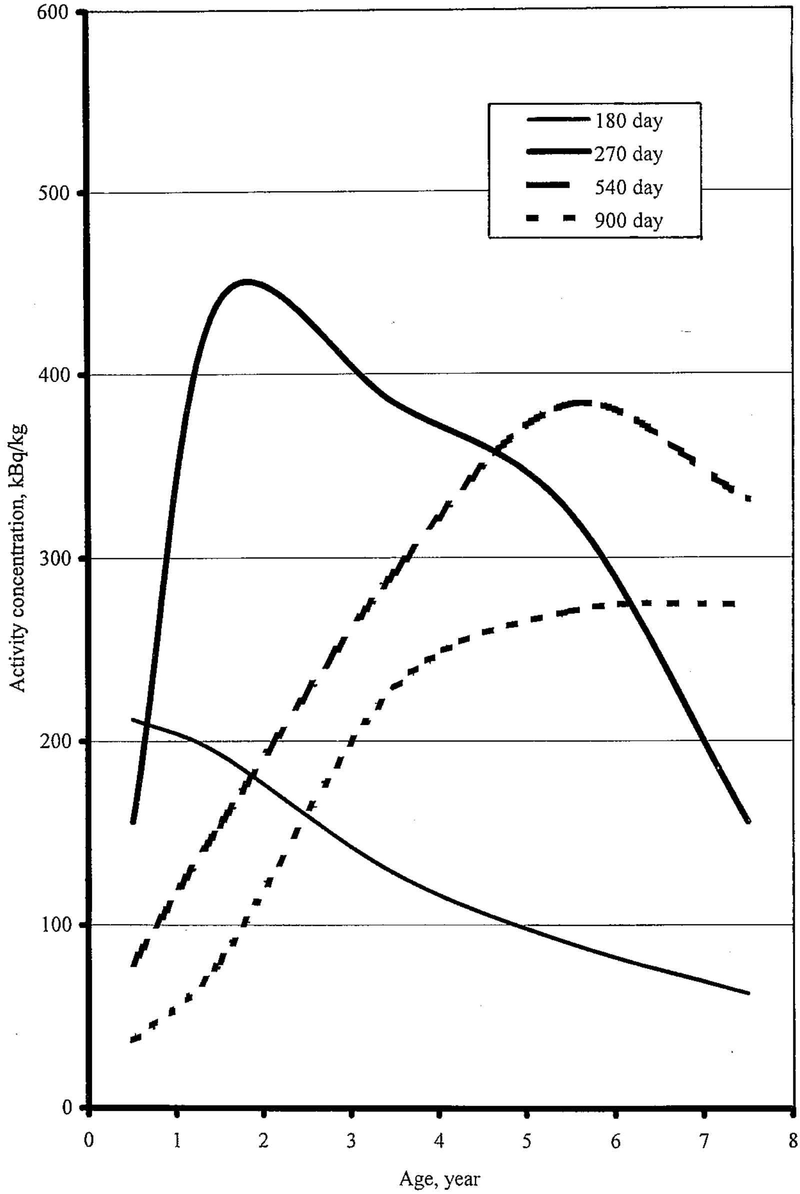

Fig. 3. The distribution of Cs-137 activity in pike-perch from the Chernobyl NPP cooling pond by age at the different time points: 180, 270, 540 and 900 days after the accident (different types of size effect)