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Modification of the dynamic radionuclide uptake model BURN by salinity driven transfer parameters for the marine foodweb and its integration in POSEIDON-R

R. Heling[1] and R. Bezhenar[2]

[1] *Nuclear Research and Consultancy Group (NRG), PO Box 9034, 6800 ES Arnhem, The Netherlands*
[2] *Ukrainian Center of Environmental and Water Projects, Prospect Glushkova 42, 03187 Kiev, Ukraine*

Abstract. This work is based on the describing a new approach in estimation of Concentration Factor (CF) for marine organisms radionuclides uptake. We considered the dependence of CF from the water salinity (determining the K^+ and Ca^{2+} ions). The radionuclide uptake by the marine biota of Dnieper-Bug Estuary using the numerical compartment-model POSEIDON-R with latest modifications was applied. The levels of radionuclides in the different marine organisms, representing the various types of marine organisms in the different trophic levels of the foodweb, were calculated. The uptake model takes into account both the uptake of radionuclides via food consumption, by describing the predator-prey relations, and the direct uptake of radionuclides from the water via the gills. The influence of the K^+ and Ca^{2+} ions, competitive ions against $^{137}Cs^+$, $^{90}Sr^{2+}$ ions respectively, on the uptake rate was investigated.

1. INTRODUCTION

Radionuclides of anthropogenic origin can be introduced in the marine environment by routine discharges from nuclear sites, by testing of nuclear weapon and by release in the result of accident. In the framework of the developments of the European system RODOS for emergency response to nuclear accident (Real-time On-line DecisiOn support System), the computer code PC-POSEIDON [1], based on the MARINA study [2], was enhanced and adapted to cope with nuclear emergencies such as radioactive fall-out on oceans and seas, sunken ships and containers with nuclear waste, radioactive spills on rivers and estuaries and coastal run-off. The uptake of radionuclides by the marine organisms is modelled by the dynamic foodweb model BURN (Biological Uptake of RadioNuclides) [3]. BURN takes into account both the uptake of radionuclides via the food, and the direct uptake of (dissolved) radionuclides via the gills. The dynamic model BURN takes into account the uptake of radionuclides throughout the foodweb dynamically. By doing this, the radionuclide concentration in marine organisms is not overestimated when the impact of pulse release in small (user-defined) compartments near the source are modelled; in these compartments biological equilibrium will not be reached due to the short hydrological retention time in comparison with the biological half-lives.

Since the marine compartment model POSEIDON-R covers different types of aquatic environments, varying from freshwater environments and estuaries to oceans, the choice of fixed uptake rates and concentration factors for seas will lead to underestimates of predicted radionuclides levels in biota values in inner seas (e.g. east part of the Baltic Sea), in brackish seas (Black Sea), and in estuaries (e.g. the Dnieper – Bug estuary near the Black Sea) since the accumulation in freshwater systems of radioceasium and radiostrontium is higher than in the marine environment. For radioceasium and radiostrontium this difference is caused by the lower concentration of the competitive ions K^+ and Ca^{2+} in freshwater systems. However, to include the effect of these ions, data sets are required for every compartment of the POSEIDON – R model. To avoid this, a relationship is found to correlate these two competitive ions with the total salinity. Salinity levels namely are in general easy to obtain for seas and coastal regions (Atlantic waters, Baltic Sea, North Sea, Mediterranean Sea, and the Black Sea and adjacent river mouths). In the case of lacking measurement data on salinity, calculated salinity data from the POSEIDON-project can be used. The compartment structure of POSEIDON-R namely was refined by using output data on hydrodynamics, temperature, and on salinity of the 3D-hydrodynamical model THREETOX. Since subdivisions were implemented for the Black Sea, Baltic Sea, and Dnieper Bug estuary, the salinity for these compartments are defined [4, 5].

2. MODIFICATIONS OF THE BIOLOGICAL UPTAKE MODEL BURN

2.1 Reasons for salinity-driven submodels

In the previous model release of biological uptake model BURN [3], implemented in POSEIDON-R, all uptake rates had fixed values, independent on the salinity. It is important were to implement the salinity-driven process in the model. Radioceasium and radiostrontium were identified as radionuclides for which knowledge on the effect on the uptake by the competitive ions are well known. The competition takes merely place on the membrane level of the organisms; fish gills and cell membranes of phytoplankton. Eventually high concentration of competitive ions calcium and potassium in the marine environment lowers the direct uptake in the organisms in all trophic levels, and therefore has a lowering effect on the transfer throughout the entire foodchain [6].

The dynamic uptake model BURN is basically a target-tissue driven uptake model; the tissue in which the accumulation is expected determines the retention time of the radionclide in the organism. Caesium accumulates in the flesh of marine organisms, and is therefore accumulating in the foodchain. Therefore a salinity-driven submodel for the uptake in the lowest trophic level (phytoplankton) is of importance, since caesium enters the foodweb via phytoplankton. For strontium however, accumulation in the foodchain hardly occurs [7]; direct uptake via the gills of marine fish contributes to a higher extent to concentration in fish, than it does in the case of caesium. At the higher trophic levels, the reason is that radiostrontium accumulates in the bones (target tissue) of prey fish and is diluted by the not contaminated flesh of the prey in the stomach of the predator.

For strontium therefore it important to include a salinity-driven uptake rate for the fish gill uptake to avoid underpredictions in brackish regions. Although it is for strontium less important to include a salinity-driven submodel for planktonic uptake, it has its significance for the lower trophic level to calculate the strontium concentration in the invertebrates. So for strontium it is of importance not to overpredict the gill uptake in the marine environment, and therefore this uptake rates should be governed by the salinity level.

The improved POSEIDON foodchain model contains the description of the effect of potassium and calcium on the uptake of radioceasium and radiostrontium. By relating the calcium and potassium to salinity, easy-to-obtain salinity data can be used. For other radionuclides in POSEIDON-R, the model will be same as in the previous release.

Summarising, the modifications of the BURN-model are:

- Submodel for planktonic uptake as a function of the salinity for caesium and strontium.
- Submodel for gill uptake for strontium as function of the salinity.
- Submodel relating salinity with the potassium and calcium concentration in the water.

2.2 Description of the submodels for planktonic uptake and gill uptake

The concentration in the marine organisms can be described by the following differential equation:

$$\frac{dC}{dt} = aK_f C_f + bK_w C_w(t) - K_{0.5}C \tag{1}$$

where C – radionuclide concentration in the marine organism, C_f – concentration activity in food, C_w – activity concentration water, a – food extraction coefficient, b – water extraction coefficient (gills), K_l – food uptake rate, K_w – water uptake rate, $K_{0.5}$ – elimination rate fish body.

The concentration in the food of a predator can be expressed by equation:

$$C_f = \sum_{i=1}^{n} C_{prey,i} P_{prey,i} \frac{drw_{pred}}{drw_{prey,i}} \quad (2)$$

where $C_{prey,I}$ – activity concentration in prey (i), $P_{prey,I}$ – preference for prey (i) (ranging between 0–1), drw_{pred} – dry weight fraction predator, drw_{prey} – wet weight fraction prey (i).

Predator-prey relationships are shown on the Figure 1. The food preferences for marine organisms as applied in the POSEIDON – BURN model for the marine environment is set on 100% for all predators except for crustaceans and molluscs; it is assumed that molluscs and crustaceans predate 90% on zooplankton, and 10% on phytoplankton.

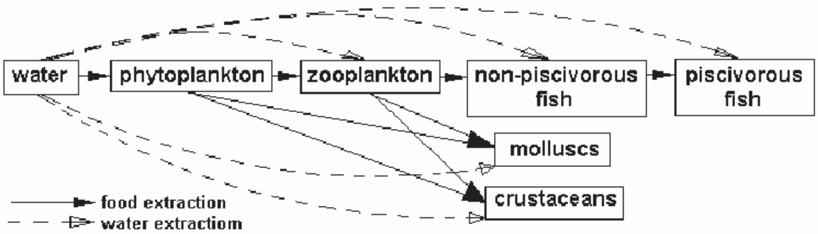

Figure 1. The foodweb structure of BURN-POSEIDON for the marine environment.

To modify the present uptake model BURN, the model is enhanced with salinity dependent uptake rates for caesium and strontium. Functions are introduced to relate the potassium and calcium concentrations with the salinity of the coastal and sea waters. Instead of using fixed concentration factors (CF) for phytoplankton, and strontium [3], the CF for phytoplankton is related to potassium via the electrochemical competition (Nernst equation) for which the parameters are based on laboratory experiments with marine plants (equation (3)). The CF (Cs-137) for phytoplankton can be expressed by

$$CF = \frac{1}{\mathrm{EXP}\left(0.73\ln(K^+/39.1) - \dfrac{1.22\ 10^3}{(T+273)}\right)} \quad (3)$$

Using the river- sea range for potassium, which ranges from the typical value for rivers of 0.5 mg/L till the typical value in the marine environment of 400 mg/L. By using extreme boundaries of this range, the potassium could be linked to the salinity in the following way by the linear relationship:

$$K^+ = 11.6 \cdot S - 4.28 \quad (\mathrm{K}^+ > 1.5\,\mathrm{mg/L}, \mathrm{S} > 0.14) \quad (4)$$

For Sr-90 the CF for phytoplankton is governed by calcium by means of an empirical equation (6):

$$CF = -116\log(Ca^{2+}) + 378 \quad (5)$$

This equation (5) is of importance to predict the concentrations in the lower trophic levels (zooplankton crustaceans, molluscs) adequately. Due to the lack of bioaccumulation in the predatory fish, direct gill uptake is more important. The reduction with increasing salinity is given in equation (7). As stated, for the gills the uptake rate for Cs-137 is not modified for the marine environment, since it has a relatively minor contribution. Although some reduction of the intake will occur at higher salinity, this process is dominated by the uptake via the food.

Based on a range for calcium concentration for rivers of 15 mg/L and 400 mg/L in seas:

$$Ca^{2+} = 11.6 \cdot S + 9.5 \quad (\mathrm{Ca}^{2+} > 15, \mathrm{S} > 0.5) \tag{6}$$

where S – salinity in g/L.
For the gill extraction b based on combining BURN on measured equilibrium levels in the seas:

$$b = 0.1 \cdot (11.16 * S + 9.5)^{-1.35} \tag{7}$$

where *b* is the gill extraction coefficient, and S the salinity in g/L.

In Table 1 the calculated values for CF (phytoplankton) for ^{137}Cs and ^{90}Sr and for the gill extraction coefficient *b* for three different seas are given.

Table 1. Implications of the use of the new submodels on CF (phytoplankton) for Sr-90 and Cs-137, and of the gill extraction coefficient b (Sr-90).

Location (salinity, mg/L)	CF (phytoplankton) L/kg		Gill extraction coefficient *b* [-]
	Sr-90	Cs-137	Sr-90
Baltic Sea (10-17)	119	4.3	1.0 10^{-4}
Black Sea (15-18)	109	2.6	0.8 10^{-4}
North Sea (32-34)	77	1.6	0.3 10^{-4}

3. APPLICATION OF THE MODEL *BURN* ON THE DNIEPER-BUG ESTUARY

To test the modified salinity-driven uptake model, POSEIDON – R with the newly included BURN model, was applied to simulate the radionuclide concentrations in the abiotic and biotic phase of the Dnieper-Bug Estuary (DBE), an estuary connection the two rivers with the Black Sea (see Figure 2). For this aim, the existing DBE compartment in POSEIDON – R was divided into seven planar boxes (Figure 3). Three deep compartments were subdivided into two deep layers if the depth was exceeding 6 meter (box 11, 12, and 16). Salinity is ranging from 1.0 g/L in box 10, up to 11 g/L in box 16. The list of compartments, and their physical characteristics and salinity are given in Table 2. The planar structure of the Black Sea and the adjacent Dnieper-Bug estuary is given in Figure 1 and Figure 2 respectively.

Table 2. Characteristics of the boxes of the Dnieper-Bug Estuary.

Compartment	**Depth of the compartment, m**	**Volume m^3**	**Salinity**
10	7.7	6.79E + 08	1
11	8.3	9.45E + 08	3
12	8.7	3.16E + 09	5
13	3.8	9.47E + 08	1
14	4.4	6.01E + 08	7
15	2.3	4.10E + 08	7
16	9.5	1.13E + 09	11

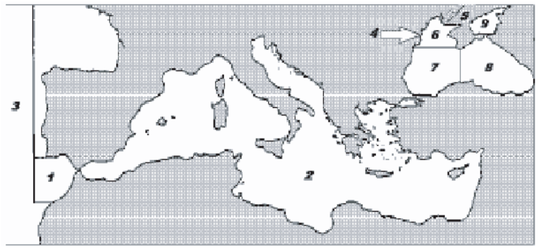

Figure 2a. The planar structure of Black See subdivision. 1 – Gulf of Cadiz; 2 – Mediterranean Sea; 3 – North-East Atlantic; 4 – Danube; 5 – Dnieper (added are DBE boxes: from 10 to 16); 6 – Black Sea North West Shelf; 7 – Black Sea West; 8 – Black Sea East; 9 – Azov Sea.

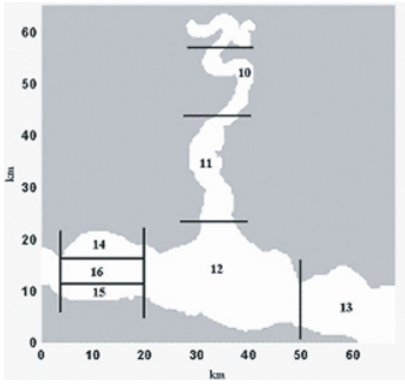

Figure 2b. The planar structure of DBE subdivision.

4. RESULTS AND CONCLUSION

For ^{137}Cs, the results of the application of the modified model BURN model are shown for two compartments of the DBE, 11 and 16. In Figure 3 and 4, the calculation results for a 10-years period for ^{137}Cs levels are shown for compartment 11 and 16 for water and prey fish respectively.

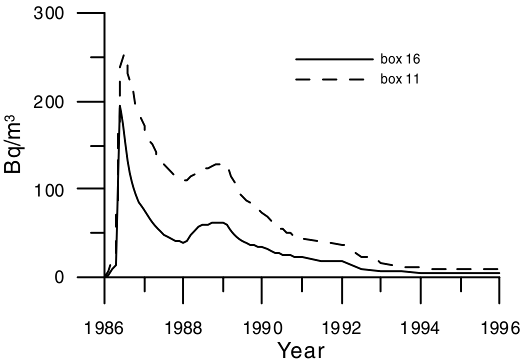

Figure 3. Concentration of Cs-137 in the water.

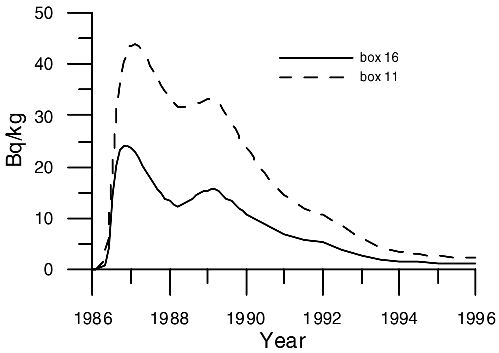

Figure 4. Concentration of Cs-137 in fish.

Ceasium-137 in the DBE is originating from the Black Sea [6] since the cesium from the upstream region of the River Pripyat is deposited in the subsequent artificial reservoirs of the River Dnieper. From these figures the effect of salinity driven uptake it is clearly visible, about two times higher in compartment 16, whereas the difference between the radionuclides concentration in the water is smaller (Figure 3). The reason is the higher potassium concentration in compartment 16.

For ^{90}Sr, the calculation results for water and zooplankton are given in Figures 4 and 5. Strontium originates from the Chernobyl region, and is transported downstream via the River Dnieper. The model results have shown the effectiveness of the new submodels in combination with the relationships between potassium and calcium, and salinity. In the near future, the predicted values will be compared

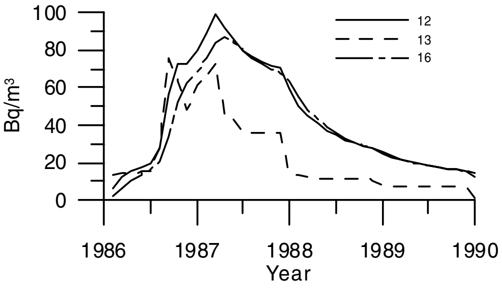

Figure 5. Concentration of Sr-90 in the water.

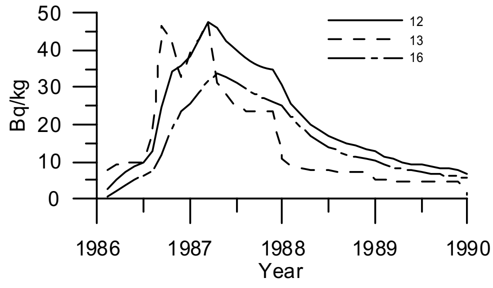

Figure 6. Concentration of Sr-90 in the zooplankton.

with measurement data on aquatic organisms for the DBE and in the Black Sea for caesium and strontium and other radionuclides.

Acknowledgments

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