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A dynamic model to estimate the activity concentration and whole body dose rate of marine biota as consequences of a nuclear accident

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ABSTRACT

This paper describes a dynamic compartment model (K-BIOTA-DYN-M) to assess the activity concentration and whole body dose rate of marine biota as a result of a nuclear accident. The model considers the transport of radioactivity between the marine biota through the food chain, and applies the first order kinetic model for the sedimentation of radionuclides from seawater onto sediment. A set of ordinary differential equations representing the model are simultaneously solved to calculate the activity concentration of the biota and the sediment, and subsequently the dose rates, given the seawater activity concentration. The model was applied to investigate the long-term effect of the Fukushima nuclear accident on the marine biota using ^{131}I, ^{134}Cs, and, ^{137}Cs activity concentrations of seawater measured for up to about 2.5 years after the accident at two locations in the port of the Fukushima Daiichi Nuclear Power Station (FDNPS) which was the most highly contaminated area.

The predicted results showed that the accumulated dose for 3 months after the accident was about 4–4.5Gy, indicating the possibility of occurrence of an acute radiation effect in the early phase after the Fukushima accident; however, the total dose rate for most organisms studied was usually below the UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation)'s bench mark level for chronic exposure except for the initial phase of the accident, suggesting a very limited radiological effect on the marine biota at the population level. The predicted Cs sediment activity by the first-order kinetic model for the sedimentation was in a good agreement with the measured activity concentration. By varying the ecological parameter values, the present model was able to predict the very scattered ^{137}Cs activity concentrations of fishes measured in the port of FDNPS. Conclusively, the present dynamic model can be usefully applied to estimate the activity concentration and whole body dose rate of the marine biota as the consequence of a nuclear accident.

1. Introduction

A dose assessment of non-human biota is used to investigate if an ecosystem is safe from the radiation risk of radioactivity released into the environment by an accident or during normal operation of a nuclear facility. Two model types, an equilibrium model and dynamic model are usually used to estimate the dose rate of non-human biota. The equilibrium model is generally suitable for the existing and planned exposure situations defined in the ICRP 103 (2007). For the case of an emergency exposure situation such as a nuclear accident, or for the case of planned exposures such as pulsed releases of radioactivity and decommissioning discharges, the dynamic model is more suitable for considering the temporal change in the activity concentration of an environmental medium than the equilibrium model.

A severe nuclear accident occurred at the Fukushima Daiichi Nuclear Power Station (FDNPS) on March 11, 2011. Radioactivity was significantly released into the environment, and a large marine ecosystem in the Pacific Ocean along the eastern coast of Japan was contaminated by the radioactivity. After the accident, the radiation effect on the marine biota as the result of the accident was investigated in a few studies (Garnier-Laplace et al., 2011; Kryshev et al., 2012; Keum et al., 2013, 2014). The initial studies were mostly based on an equilibrium approach, and there have been relatively few dynamic approaches. Kryshev et al. (2012) used a dynamic model to simulate the dose rate for marine biota in the area of the Fukushima NPP in March–May 2011. Tadeda et al. (2013) used a

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dynamic biological compartment model to simulate the transfer of radioactive cesium to biota in the southern Fukushima coastal biota after the accident. The recent study of the UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (UNSCEAR, 2014; Vives i Batlle et al., 2014) also used dynamic models to estimate the impact of Fukushima accident on marine biota. In particular, the D-DAT (first order kinetic model) and ECOMOD models were applied to calculate the doses of biota in the initial phase of the accident, and were compared to the equilibrium CR model. Furthermore, an international comparison study of the dynamic models used to estimate the dose rate and activity concentration of marine biota was launched in the IAEA/MODARIA program (http://www-ns.iaea.org/projects/modaria). Most of the dynamic models differ conceptually and structurally from each other. A sophisticated dynamic model considers the growth and metabolic rate of the biota, but is generally complex and requires many ecological parameter values that are not easily available.

In this study, a dynamic compartment model based on the food chain of marine biota, K-BIOTA-DYN-M, which can be used with easily obtainable ecological parameters, is presented to predict the activity concentration and dose rate of marine biota as a result of a nuclear accident. In particular, the first order kinetic model was introduced to express the sedimentation of radionuclides from seawater to sediment. The dynamic model was applied to investigate the long-term effect of the Fukushima accident on the marine biota using ^{131}I, ^{134}Cs, and ^{137}Cs activity concentrations of seawater measured for up to about 2.5 years after the accident in the port of FDNPS, which was known to be the most severely contaminated. To test the performance of the present model, a comparison study between the predicted and measured activity concentration for fishes captured in the port of FDNPS was carried out. In addition, the impact of the radionuclides and exposure pathway to the total dose rate was discussed.

2. Model

The K-BOTA-DYN-M is a dynamic compartment model used to assess the activity concentration and whole body dose rate of marine biota when the seawater activity concentration varies with time, likely for the early phase after an accident. The model consists of seven marine biota compartments including phytoplankton, zooplankton, prey fish, benthic fish, crustacean, mollusc, and macroalgae, and one sediment compartment (Fig 1).

Buesseler et al. (2012) reported that even for zooplankton the measured CR value of the Fukushima-derived ^{137}Cs was comparable to the equilibrium CR value of the IAEA, while there is another study that states that the biological half-lives of iodine for phytoplankton are in the range from hours to a few days (Kuenzler, 1967). In the present model, phytoplankton is assumed to be in equilibrium with seawater, which is based on the existence of the huge amount of phytoplankton in seawater that allows reaching equilibrium quickly. It was noted that the equilibrium assumption would be able to result in an overestimated activity concentration of phytoplankton in the initial phase after an accident. The other marine animals intake the radioactivity from both water and diet, and simultaneously lose the radioactivity through the biological elimination and radioactivity decay. Macroalgae takes the radioactivity from only seawater. For the biological elimination process, a two-step biological kinetic model (fast-slow model) is often used (Vives i Batlle et al., 2008a). Despite the two-step kinetic model being scientifically sound for any marine organism; the full application of the model is sometimes limited owing to the lack of parameter values, particularly data on the "fast" rate. Based on this situation, a single biological kinetic model with one parameter is adopted in the present study for the simplicity of the model.

The transfer equations of radioactivity between biota through the food chain are expressed as follows;

Phytoplankton:

$$A_o(t) = CR_{w-phytoplankton} A_W\left(t\right) \tag{1}$$

Zooplankton

$$\frac{dA_1(t)}{dt} = FP_{w1}(t) + FP_0(t) - (R_d + R_{b1})A_1(t) \tag{2}$$

Prey fish:

$$\frac{dA_2(t)}{dt} = FP_{w2}(t) + FP_1(t) - (R_d + R_{b2})A_2(t) \tag{3}$$

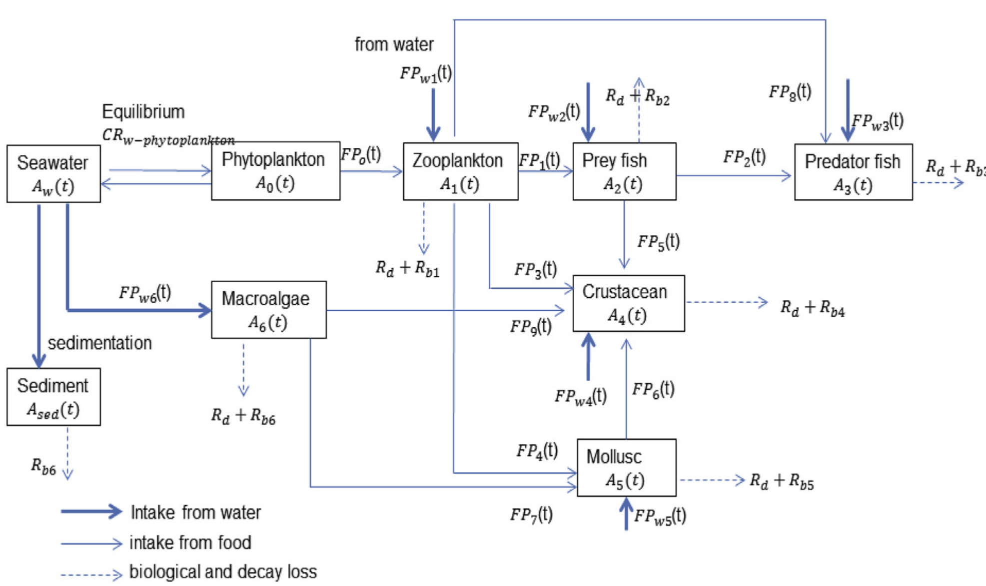

Fig. 1. Structure of food chain considered in the present dynamic model (K-BIOTA-DYN-M).