30. Simulation of Radiocesium Discharge from the Catchment Area of Abukuma River after Fukushima Daiichi Nuclear Accident.

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This study attempted to simulate numerically the discharge of radiocesium from Abukuma River to the Pacific Ocean after Fukushima Dai-ichi Nuclear Power Plant Accident. Wash-off process of radiocesium from the river catchment surface due to surface run-off (liquid wash off) and erosion (solid wash off), which is represented by wash-off coefficient, was used as a basic concept of this simulation. In order to simulate the wash off process, the catchment area was divided into three types of landuse (Forest, Urban, Agriculture), the value of wash off coefficient was obtained from the post Chernobyl research, and the amount of surface run-off and erosion were provided by utilizing SWAT model. By comparing the result of the model and the measured data, the value of R^2 of 0.98 and 0.97 for ^{134}Cs and ^{137}Cs respectively shows that the model could predict the seasonal variation. The discharge of radiocesium for the next 25 years was also estimated in this study. It was estimated 1.9×10^{14} Bq and 1.2×10^{14} Bq of ^{137}Cs and ^{134}Cs respectively would be released from Abukuma River basin into the Pacific Ocean within 25 years after the accident.

Key Words : *radiocesium, wash-off, Abukuma catchment, Pacific Ocean, simulation*

1. Introduction

The Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident had released a huge amount of radionuclide substances into environment. Right after the accident, it was estimated that 10^4-2.25×10^6 Bq.m^{-2} of radiocesium was deposited on the catchment area of the river[1)]. Moreover, due to weathering effect, the radionuclide is expected to be transported into the receiving water body. This was confirmed by the detection of 0 - 14,000 Bq.kg^{-1} of ^{134}Cs and 0 - 16,000 Bq.kg^{-1} of ^{137}Cs in the bottom sediment of Abukuma River[2)]. A Field observation carried out by Yamashiki et al.[3)] shows about 5.74 TBq of ^{137}Cs and 4.74 TBq of ^{134}Cs were discharged into the Pacific Ocean from Abukuma River during August 2011 to May 2012. In addition, the amount of the discharge was equal to only 1.13% of the total deposited radiocesium in the catchment area. The study also indicates that the amount of discharged radiocesium from Abukuma River during the period was in the same order of magnitude estimated for direct leakage from the FDNPP site between 1 June 2011 to 30 September 2012(estimated as 17 TBq) and for the Level 3 Scale Leakage incident occurring in August 2013(estimated as 24 TBq). As the amount of the discharge from the river is extremely high and a significant amount of radiocesium still remains in the catchment area, the future projection of Radiocesium Flux to the ocean from Abukuma River is deemed necessary to be carried out.

Transport of radiocesium from the ground surface is mainly driven by wash off process. The process is defined by the amount of the radionuclides in the carrying media of the remaining radionuclide in the ground surface. The quantification of wash-off process is usually represented by the value of wash off coefficient, which was measured in several previous studies[4),5)]. Based on the carrying media, wash off process is divided into two types namely solid and liquid. The former type involves the movement of soil particle due to erosion as a carrying media whereas in the later type, surface run-off plays as a carrying media. The value of the wash-off coefficient was derived based on data from rivers in Europe after the Chernobyl accident. It is yet to be determined if the value is applicable to other locations, for example in Japan with respect to the Fukushima accident.

The future projection of radiocesium discharge from Abukuma River had been examined by several studies with various approaches such as computational of the water flow and the associated washload and suspended load transport and the Universal Soil Loss Equation and simple sediment discharge formulas[6),7)]. This study attempted to estimate the total discharge of radiocesium from Abukuma River into the Pacific Ocean by utilizing the wash off coefficient, which is simpler than the method performed by the mentioned previous studies. This study also examined the reliability of the application of the value of wash-off coefficient for application in FDNPP case.

2. METHOD

The model developed in this study is divided into two sub-model, "basin" and "river". Sub-model Basin simulates the wash-off process from the ground surface into the receiving model whereas Sub-model River calculates the transport process of the radiocesium in the river body. Sub-model basin divides the catchment area into 29 sub-basins. Each sub-basin contains three compartment which are forest, agriculture and urban. The governing equation of each sub-basin is written as follows:

$$M_{mobile(t)} = M_{mobile(t-1)} + (D - F_{fix} - F_{heavy-rain} - F_{decay})dt \quad (1)$$

$$M_{fixed(t)} = M_{fixed(t-1)} + (F_{fix} - F_{washoff} - F_{decay})dt \quad (2)$$

Where M_{mobile} and M_{fixed} are the mass of radionuclide in mobile form and fixed form respectively for each compartment (Bq). Time step is represented by t (month). D is flux of deposition of radionuclide on ground surface (Bq.month^{-1}), F_{fix} is the flux of radionuclide fixated into fixed form (Bq.month^{-1}), $F_{heavy-rain}$ is flux of mobile radionuclide removed by the first heavy rain. $F_{wash-off}$ is the flux of radionuclide as a result of the wash off process. The flux is the sum of solid wash off and liquid wash off. Solid wash off is only calculated in the soil component in the forest compartment, un-built component in urban and agriculture compartment. F_{decay} is the flux of radionuclide removed by the decay process.

The wash off process for each compartment is governed by the following equations

$$F_{liquid\ wash\ off(t)}. = C_l \,.\, Q_r.\, M_{fix(t-1)}$$
$$F_{solid\ wash\ off(t)}. = C_s \,.\, E.\, M_{fix(t-1)}$$

Table 1. The value of wash off coefficient for various type of land cover.

No	Parameter	Unit	Value
1	liquid washed off rate for tree	mm^{-1}	0.0004
2	liquid washed off rate for soil	mm^{-1}	0.00012
3	solid washed off rate for soil	m^2.g^{-1}	0.00067
4	liquid washed off rate for built area	mm^{-1}	0.001
5	liquid washed off rate for unbuilt area	mm^{-1}	0.00012
6	solid washed off rate for unbuilt area	m^2.g^{-1}	0.00067
7	liquid washed off rate	mm^{-1}	0.00012
8	solid washed off rate	m^2.g^{-1}	0.00067

Where C_l is liquid wash off coefficient for (mm^{-1}), Q_r is depth of surface run-off (mm), C_s is solid wash off coefficient (m^2/g) and E is amount of erosion per unit area (g/m^2). The value of liquid and solid wash off coefficient for various type of land cover is presented in table 1.

The quantification of solid and liquid wash off depends on the amount of surface run-off and soil erosion. The quantification process used Soil Water Assessment Tool (SWAT) which is integrated into the ArcMAP10.0(ESRI) interface. By using meteorological data provided by Automated Meteorological Data Acquisition System (AMeDAS), soil type data provided by world soil map, landuse data provided by landsat8 image and digital elevation model provided by ASTER GDEM, the calculation of surface run-off and soil erosion was carried out.

Based on the location of each sub-basin outlet, sub-model River divides Abukuma River into nine sections. The governing equation for each Section is written as follows:

$$FIN_i = FOUT_{i-1} + FLW_i + FSW_i$$
$$FOUT_i = FIN_i - SED_i \quad (3)$$

Where, FIN_i is the flux of the radionuclide entering the Section i (Bq.day^{-1}). $FOUT_{i-1}$ represents the flux of radionuclide exiting the previous Section (Bq.day^{-1}). FLW_i and FSW_i represent the flux of radionuclide from the sub-basins which have their outlet located in the Section i (Bq.day^{-1}). $FOUT_i$ is the flux of radionuclide exiting the Section i (Bq.day^{-1}) and SED_i represents the amount of radionuclide removed from the stream due to sedimentation process.

3. RESULTS AND DISCUSSION

In order to test the accuracy, the result of the model was compared to the measured data obtained from study conducted by Bulgakov et al.[4)] The values of R^2 of 0.98 and 0.97 for ^{134}Cs and ^{137}Cs respectively were obtained indicating the model could predict the seasonal variation well. The discharge of radiocesium was highly affected by meteorological factor. It could be seen in figure 1(left) and 1(right), the discharge dramatically high during September 2011 since heavy storm and high intensity rain occurred during that time. The discharge reached minimum level during December 2011-February 2012 periods due to the ground surface of the catchment area was covered by snow layer. The overestimation of the modeled data was observed. As some important factors such as decontamination activity and sedimentation in intermediate storage have not considered yet in this model, it leads to overestimation. Other factor that leads to overestimation might come from the value of wash off coefficient is too high for application in Japan. Thus further adjustment of the value in order to make it applicable in japan is needed to be done.

The future prediction of the discharge was estimated and presented in Figure 2. The figure shows that even after 25 years, the discharge of the radionuclide into the Pacific Ocean still in the order of magnitude of 10^{11} Bq/year. The decreasing of ^{134}Cs discharge occurs in higher rate than ^{137}Cs due to its half live value. The sum up of the radiocesium discharge within 25 years after the accident shows 1.9 x 10^{14} Bq and 1.2 x 10^{14} Bq of ^{137}Cs and ^{134}Cs respectively would be released from Abukuma River basin into the Pacific Ocean. These huge amounts have some uncertainties as decontamination activity and sedimentation in intermediate storage are not considered in this model, however the projection of the discharge shows that river could be a significant source of contamination of radiocesium after the nuclear power plant accident beside direct discharge from the nuclear power plant itself.

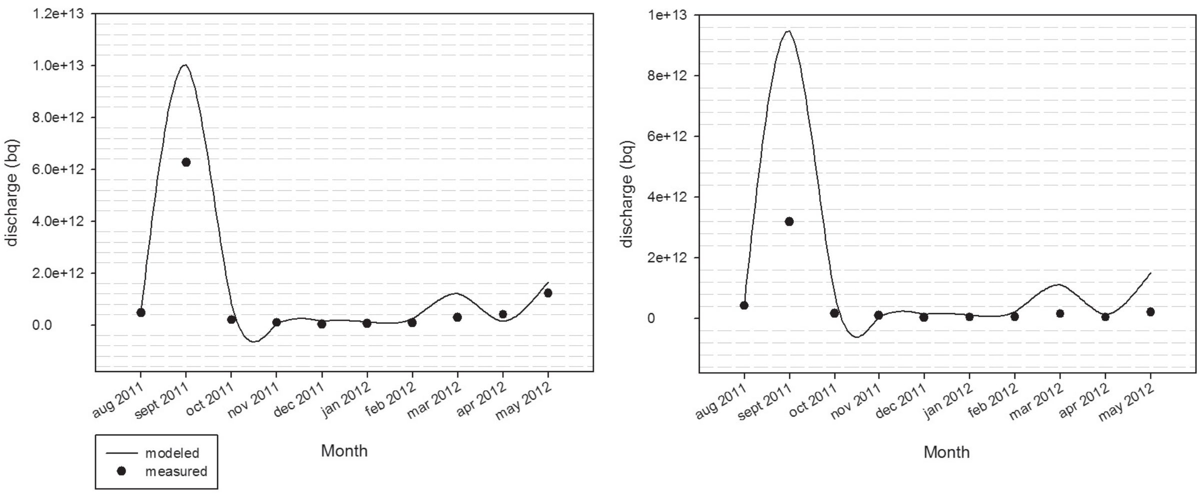

Figure 1. The comparison of modeled data and measured data for August 2011-May 2012 for ^{137}Cs (left) and ^{134}Cs (right).

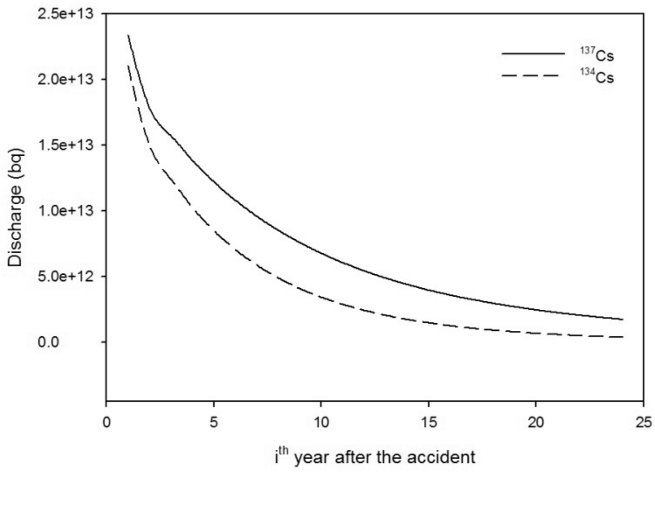

Figure 2. The projection of radiocesium discharge from Abukuma River basin into the Pacific Ocean within 25 years after the accident.

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