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Predicting the long-term ^{137}Cs distribution in Fukushima after the Fukushima Dai-ichi nuclear power plant accident: a parameter sensitivity analysis

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ABSTRACT

Radioactive materials deposited on the land surface of Fukushima Prefecture from the Fukushima Dai-ichi Nuclear Power Plant explosion is a crucial issue for a number of reasons, including external and internal radiation exposure and impacts on agricultural environments and aquatic biota. Predicting the future distribution of radioactive materials and their fates is therefore indispensable for evaluation and comparison of the effectiveness of remediation options regarding human health and the environment. Cesium-137, the main radionuclide to be focused on, is well known to adsorb to clay-rich soils; therefore its primary transportation mechanism is in the form of soil erosion on the land surface and transport of sediment-sorbed contaminants in the water system. In this study, we applied the Soil and Cesium Transport model, which we have developed, to predict a long-term cesium distribution in the Fukushima area, based on the Universal Soil Loss Equation and simple sediment discharge formulas. The model consists of calculation schemes of soil erosion, transportation and deposition, as well as cesium transport and its future distribution. Since not all the actual data on parameters is available, a number of sensitivity analyses were conducted here to find the range of the output results due to the uncertainties of parameters. The preliminary calculation indicated that a large amount of total soil loss remained in slope, and the residual sediment was transported to rivers, deposited in rivers and lakes, or transported farther downstream to the river mouths. Most of the sediment deposited in rivers and lakes consists of sand. On the other hand, most of the silt and clay portions transported to river were transported downstream to the river mouths. The rate of sediment deposition in the Abukuma River basin was three times as high as those of the other 13 river basins. This may be due to the larger catchment area and more moderate channel slope of the Abukuma River basin than those of the other rivers.

Annual sediment outflows from the Abukuma River and the total from the other 13 river basins were calculated as 3.2×10^4–3.1×10^5 and 3.4×10^4–2.1×10^5 t y^{-1}, respectively. The values vary between calculation cases because of the critical shear stress, the rainfall factor, and other differences. On the other hand, contributions of those parameters were relatively small for ^{137}Cs concentration within transported soil. This indicates that the total amount of ^{137}Cs outflow into the ocean would mainly be controlled by the amount of soil erosion and transport and the total amount of ^{137}Cs concentration remaining within the basin. Outflows of ^{137}Cs from the Abukuma River and the total from the other 13 river basins during the first year after the accident were calculated to be 2.3×10^{11}–3.7×10^{12} and 4.6×10^{11}–6.5×10^{12} Bq y^{-1}, respectively. The former results were compared with the field investigation results, and the order of magnitude was matched between the two, but the value of the investigation result was beyond the upper limit of model prediction.

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1. Introduction

As a result of the Tohoku earthquake and tsunami on 11 March 2011, and the subsequent nuclear accident at the Fukushima Dai-ichi Nuclear Power Plant (NPP), a wide range of terrestrial and freshwater environments in Fukushima underwent heavy contamination (Chino et al., 2011). Radioactive releases occurred of about 10^{18} Bq to the atmosphere and about 10^{16} Bq to the sea. An exclusion zone was established around the site, and a large number of people were evacuated from their houses and are still experiencing difficult situations even today. The radionuclides of most concern at the time of accident were isotopes of cesium, i.e., ^{134}Cs and ^{137}Cs; iodine, ^{131}I; and strontium, ^{90}Sr. Among these, ^{131}I has a radioactive half-life of only 8.02 d. Thus, it was only relevant in the first few weeks following the accident. Strontium-90 has a half-life of 28.79 y and has a high mobility for transport in the environment; however, in the Fukushima case, the release of this radionuclide was limited because the fuel was confined within the reactor, which is different from the Chernobyl accident case. Since ^{134}Cs and ^{137}Cs are the main radionuclides to be considered for health issues (Nagao et al., 2013), in this study, we treat these nuclides and hereafter we especially concentrate on ^{137}Cs.

Predicting the distribution and the fate of radioactive materials released to the atmosphere from the Fukushima Dai-ichi accident that were eventually deposited on the land surface of Fukushima Prefecture is a crucial issue for a number of reasons, including external and internal radiation exposure, and agricultural and aquatic biota impacts. Cesium is an alkali metal with chemical similarity to potassium. In particular, it substitutes for potassium in clay minerals. This can result in substantial sorption of cesium in clay-rich soils, and can lead to fixation of the cesium, i.e., the sorption is effectively irreversible. Therefore its primary transportation mechanism is in the form of soil erosion on the land surface and sediment-sorbed contaminant transport, as well as dissolved transport in the water system, such as rivers.

Numerous watershed models on erosion and sediment transport have been formulated and are in progress. For example, prominent models such as the Agricultural Non-Point Source model (AGNPS, Young et al., 1989), the Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS, Beasley et al., 1980), the Chemical Runoff and Erosion from Agricultural Management System model (CREAMS, Knisel, 1980), the Griffith University Erosion System Template (GUEST, Misra and Rose, 1996), the Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques (PERFECT, Littleboy et al., 1992), the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998), and the Watershed Erosion Production Project (WEPP, Laflen et al., 1991; NSERL, 1995) already exist and various others are being modified or improved (such as the ANSWERS 2000, Dillaha et al., 2001; the Groundwater Loading Effects of Agricultural Management Systems, GLEAMS, Ball and Trudgill, 1995, Connolly et al., 1999). A comprehensive review can be found elsewhere (Merritt et al., 2003).

However, these models tend to require numerous parameters and/or input data for simulations. Even today in many places in Fukushima, especially in the exclusion zone, entry is limited and therefore it is difficult to obtain appropriate data for simulations. Even if such data were available, removing the overall uncertainties in the model predictions is unachievable because it is impossible to determine all the parameters necessary for simulations. In fact, it is very difficult to collect and assemble all the data with good accuracy due to the cost aspects as well as to the measuring capabilities. For example, measurements of diffusion coefficients are very difficult both in time and technical aspects (Churakov and Gimmi, 2011). Instead, a simulation model with minimum parameters may provide fair order of magnitude estimates for large-scale and long-term prediction.

Therefore, we intend to develop a model that can calculate a large-scale, long-term future cesium distribution using simple governing equations for sediment with public open data already available. Since sedimentation and transportation mechanisms of sediment depend on the sediment sizes, we introduced well-known physical equations for sand, silt, and clay separately, and because the values needed for these physical equations are available in existing literature, and values for estimating soil erosion potential are accessible as factors in the Universal Soil Loss Equation (USLE), we used these open-source data primarily. We also accounted for the ease of connectivity of other specific codes such as the river calculation module and the estuary calculation module. Novelties of the present model are the inclusion of a minimum number of hydraulic equations with minimum input data and complementarities with other modules. Fourteen river basins located within 100 km of Fukushima Dai-ichi NPP were selected in the present calculation.

2. Methodology

We have developed a simple, novel and fast simulation model, Soil and Cesium Transport (SACT), to predict the long-term distribution of a radioactive material, especially ^{137}Cs, on the Fukushima area, based on the USLE and simple sediment discharge formulas (Yamaguchi et al., 2013). The model consists of calculating schemes of soil erosion, transportation and deposition, ^{137}Cs transport, and the resulting future distribution of ^{137}Cs. The model conservatively predicts (with the intent to overestimate) the long-term transport of ^{137}Cs due to soil erosion and transport. In order to produce a conservative prediction, we simply assumed that the total volume of ^{137}Cs fallout was instantly absorbed into surface soil. We applied the SACT model to predict long-term ^{137}Cs transport and distribution in the terrestrial environments in Fukushima. Since not all data on parameters have been acquired to date and some of the parameters vary annually, we conducted a number of "sensitivity analyses" to estimate the upper and lower bounds of predicted results due to uncertainties in parameters.

According to the official survey of ^{137}Cs inventory (MEXT and MAFF, 2012), areas with relatively high contamination exceeding 1.0×10^5 Bq m^{-2} were observed within an approximately 100 km radius of the Fukushima Dai-ichi NPP. Therefore we covered the area shown in Fig. 1 (which includes the catchment basins of the Abukuma River (area: 5432 km^2), Uta River (area: 180 km^2), Mano River (area: 168 km^2), Niida River (area: 261 km^2), Ota River (area: 79 km^2), Odaka River (area: 67 km^2), Ukedo River (area: 420 km^2), Maeda River (area: 48 km^2), Tomioka River (area: 63 km^2), Ide River (area: 40 km^2), Kido River (area: 260 km^2), Natsui River (area: 685 km^2), and Same River (area: 593 km^2)).

Modeling of soil erosion, transport, and deposition and ^{137}Cs transport was carried out to calculate ^{137}Cs transport and its future distribution based on a 100 m grid system covering 14 river basins shown in Fig. 1. The raster-based calculation was carried out using ArcEditor (v.10.0) by developing a geographic information system (GIS) toolbox for the calculation. In this section, we describe the SACT model which we developed using the USLE and the GIS, based on the methodology already introduced by Yamaguchi et al. (2013). Fig. 2a schematically shows the model simulation steps; we outline these steps first followed by details of each step.

In the first step, we calculated the soil erosion potential for each cell using the USLE to predict the annual amount of soil eroded from land per unit area. The USLE predicts the long-term average annual rate of erosion from a field based on rainfall pattern, soil type, topography, crop system and management practices