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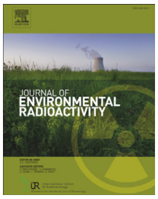

Characteristics of radio-cesium transport and discharge between different basins near to the Fukushima Dai-ichi Nuclear Power Plant after heavy rainfall events

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ABSTRACT

This paper describes watershed modeling of catchments surrounding the Fukushima Dai-ichi Nuclear Power Plant to understand radio-cesium redistribution by water flows and sediment transport. We extended our previously developed three-dimensional hydrogeological model of the catchments to calculate the migration of radio-cesium in both sediment-sorbed and dissolved forms. The simulations cover the entirety of 2013, including nine heavy rainfall events, as well as Typhoon Roke in September 2011. Typhoons Man-yi and Wipha were the strongest typhoons in 2013 and had the largest bearing on radio-cesium redistribution. The simulated ^{137}Cs discharge quantities over the nine events in 2013 are in good agreement with field monitoring observations. Deposition mainly occurs on flood plains and points where the river beds broaden in the lower basins, and within dam reservoirs along the rivers. Differences in ^{137}Cs discharge ratios between the five basins are explained by differences in the initial fallout distribution within the basins, the presence of dam reservoirs, and the input supply to watercourses. It is possible to use these simulation results to evaluate future radioactive material distributions in order to support remediation planning.

1. Introduction

The magnitude 9.0 earthquake and subsequent tsunami on 11 March 2011 instigated the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident followed by the release of radionuclides into the environment (Katata et al., 2012; Terada et al., 2012; Kobayashi et al., 2013; Buesseler, 2014). Substantial endeavors have been paid to monitoring the distribution and fate of the radionuclides in the environment in order to comprehend human exposures to radiation and the effects on agriculture, forests, rivers and oceans in the region (Chartin et al., 2013; Gonze et al., 2014; Saito et al., 2014; Yoshimura et al., 2014; Takahashi et al., 2015).

Radioactive material was deposited on a wide range of land types after the accident. Based on learning after the Chernobyl accident, Onishi et al. (2007) recommended predicting contamination migration in the environment using simulations to assist in the design of countermeasures. In particular they recommended simulating the transport of radionuclides both dissolved in surface water flows and via transport in the soil-sorbed form by erosion and sediment redistribution. The results can then input into considerations for remediation and recovery, decisions to resume agricultural activities and reutilize irrigation systems, and for radiation protection purposes.

Previously some watershed scale simulations of soil erosion, sediment movement, and radio-cesium migration in Fukushima Prefecture were reported (Yamaguchi et al. (2014); Kitamura et al. (2014); Kinouchi et al. (2015); Mori et al. (2015)). Yamaguchi et al. (2014) and Kitamura et al. (2014) calculated soil loss and ^{137}Cs discharge for 14 river basins in eastern Fukushima using an

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empirical model, the Soil And Cesium Transport (SACT) model, which can cover broad areas (5432 km^2 in Kitamura et al., 2014). Kinouchi et al. (2015) simulated the Kuchibuto River catchment (140 km^2) using a physically-based distributed hydrological and sediment erosion model, and Mori et al. (2015) studied the 15 km^2 Hokkawa Dam catchment using integrated watershed modeling.

Two complementary modeling approaches for watersheds include using simple, empirical models with minimal parameters to describe the data, or employing complex approaches capturing the underlying physical processes of the watershed. A risk of the former approach is that the model may lack sufficient complexity to describe the watershed dynamics, and physical interpretation of empirically fitted parameters can be difficult (Abbott et al., 1986). An issue with the latter however is that over-parameterization can lead to equifinality, creating uncertainty in the results (Beven, 1989). Our approach to these issues in our studies of Fukushima basins has been to employ both empirical (Kitamura et al., 2014) and physics-based models (Kitamura et al., 2016), coupled with targeted field monitoring (Saegusa et al., 2016), to deduce the dynamics of radio-cesium redistribution within the basins.

We previously developed a 3D model for five basins surrounding FDNPP in order to simulate water and sediment transport using a complex physics-based watershed simulation code (Kitamura et al., 2016). The five catchments studied comprise of forest, farmland and surface water systems such as rivers, lakes, dam reservoirs and ground water systems. In this paper we extend our previous study to calculate quantities of radio-cesium migration.

The key features of this study are that it covers five of the most highly contaminated catchments in terms of radio-cesium deposition density in Fukushima Prefecture. The catchments surround FDNPP and total 674 km^2 in area. We employed a fine resolution simulation mesh to determine the local areas with high radio-cesium accumulation. By considering five basins together, we could contrast each basin to determine the important factors controlling radio-cesium redistribution within each basin. The main results are datasets of cesium discharge information for each basin under floods with varying intensity. The datasets could be used to evaluate future radioactive cesium distributions, re-evaluate of the amount of radio-cesium dispersed and deposited on the land surface following the FDNPP accident, or to provide boundary conditions for more detailed river simulations or ocean models.

2. 3D hydrogeological structure model

The simulations are conducted on a 3D hydrogeological model of the study area, which covers the Odaka, Ukedo, Maeda, Kuma and Tomioka River basins (Kitamura et al., 2016, Fig. 1). The dominant land uses in the area are forests, rice paddies, crop fields and buildings, covering 60%, 22%, 7%, and 5% of the area, respectively. The physical characteristics, land use and ^{137}Cs contamination level of each basin are summarized in Table 1. The Ukedo basin consists two main rivers, the Ukedo and the Takase, and a large dam reservoir, the Ogaki Dam, which lies 22 km upstream of the Ukedo River mouth.

The model divides the region using a 3D mesh into different grid-blocks. Water, sediment and radio-cesium flows are evaluated between the different blocks in the model. The spacing of the mesh varies to account for topographical features. The mesh takes a fine structure around rivers and their neighboring grid regions, which are important areas to resolve sediment and fluid transport. The mesh is coarser over the forests, and locations far from rivers, for computational efficiency. The horizontal resolution of the mesh cells varies between 10 and 250 m (average 70 m). The mesh structure is shown in Fig. 2.

The ground was discretized into 28 layers of varying thickness to account for variations between geological strata of the subsurface. At ground level three surface soil layers can be eroded by rainfall impact or surface water flows, or added to by sediment deposition. The upper surface soil layer is 2 cm thick, with a 10 cm layer followed by an 18 cm layer beneath. In the initial state of the simulation all of the radio-cesium inventory is spread homogenously within the top 2 cm surface soil layer. This represents a reasonable approximation to the true depth distribution of radio-cesium within soil, which is typically exponential (Matsuda et al., 2015) with around 60–95% of the inventory within 2 cm from the surface.

Overland water flows occur in a layer termed the surface layer, which lies above the top surface soil layer. Eroded sediment is transported suspended within the overland flows in the surface layer. Likewise radio-cesium is transported within the surface layer in both the sediment-sorbed and dissolved forms. An air layer above tops the model. The total number of grid-blocks created was 4,224,000.

The hydrogeological structure of the 3D grid-block system (geology/deposit type, etc.) was assigned based on geological maps produced by the Geological Survey of Japan (2012) (see Kitamura et al., 2016). These data were used to initiate various parameters in the model, such as bedrock effective porosity and intrinsic permeability (Supplementary Table 1) for the subsurface layers.

Each grid-block in the surface soil layers was assigned a land use type (e.g. urban, paddy field) or land cover (e.g. forest) based on data published by the Ministry of the Environment (1986) and Ministry of Land, Infrastructure, Transport and Tourism (2006). The intrinsic permeability and effective porosity parameters for these grid-blocks are shown in Supplementary Table 2.

The soils within each grid-block of the surface soil layers were modeled with grain diameters of 0.001 mm, 0.01 mm, 0.1 mm, 0.3 mm, 1.0 mm, and 5.0 mm, respectively. We developed the grain size distribution for each type of land use and land cover (Supplementary Table 3) based on previous studies of basins in Japan (Mori et al., 2015).

Supplementary Fig. 1 shows how the relative permeability and the capillary pressure of the surface soil layers and subsurface grid blocks changes as a function of the water saturation within the grid block. Both these factors affect the flow of air and water underground in the model. The curves are based on van Genuchten's formulation (van Genuchten, 1980). The parameters in this model were fitted based on experimental data from the Japan Nuclear Cycle Development Institute (1999), Kinouchi and Watanabe (2011) and the Japan Institute of Construction Engineering (2012).

3. Simulation method and parameters

In order to simulate ^{137}Cs redistribution within surface water flows, subsurface fluid flows (air and water), we utilized the General-purpose Terrestrial fluid-Flow Simulator (GETFLOWS) code (Mori et al., 2014, 2015). Papers by Tosaka et al. (2000, 2010) and Mori et al. (2014, 2015) describe the details of GETFLOWS simulation code. The governing equations this code solves for fluid, sediment and radio-cesium transport are given in Mori et al. (2015).

The code models the effects of precipitation and evapo-transpiration on surface water flows (Hamon, 1961). The boundary conditions for the simulations were informed by meteorological data, including precipitation quantities measured by radar and at 8 weather stations over the periods simulated. During periods of heavy rain, we used radar AMeDAS data as precipitation inputs (JMA, 2011; 2013). Air temperature (5 stations), sunshine hours (5 stations), average wind velocity (5 stations) and relative humidity (3 stations) data were used to calculate evapo-transpiration. Manning's roughness coefficients, describing the resistance of the ground surface against surface water flows, are listed for each land