Migration and Accumulation of Radioactive Cesium in the Upstream Region of River Watersheds Affected by the Fukushima Daiichi Nuclear Power Plant Accident: A Review

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Abstract

Huge amounts of radioactive cesium (Cs) were released by the accident at the Fukushima Daiichi Nuclear Power Plant into the environment and widely contaminated the Tohoku and Kanto regions, especially mountainous area of Fukushima Prefecture. Much research on the migration and accumulation of radioactive Cs in the heavily contaminated upstream region mainly consisting of forested catchments and water bodies has been conducted to understand the current status and process of the contamination from the Fukushima accident. This paper organizes the scientific knowledge about the migration and accumulation of deposited radioactive Cs in contaminated upstream regions after the Fukushima accident, especially regarding the runoff characteristics from forest catchments, accumulation characteristics in bottom sediment of dam reservoirs and ponds, and the behavior of bioavailable radioactive Cs. It then highlights future research issues for providing local residents safe and secure lives based on the above knowledge.

Key words: bioavailable radioactive Cs, dam reservoir, forest, irrigation pond, recontamination

1. Introduction

A severe accident familiarly known as “the Fukushima accident” occurred in March 2011 at the Fukushima Daiichi Nuclear Power Plant (FDNPP) operated by the Tokyo Electric Power Company (TEPCO), releasing a large amount of radioactive Cs into the atmosphere (Chino *et al*., 2011; Thakur *et al*., 2013). About 20 percent of the fallout from this atmospheric release was deposited over the area of Japan, and about 70 percent of this deposition severely contaminated the vast area of Fukushima Prefecture, in which the FDNPP operated (Morino *et al*., 2011).

Forest covers about 62 percent of the area fully evacuated by local residents by order of the Japanese government on April 23, 2011, due to this severe radioactive contamination. Since most of the forested area is in the upstream mountainous part of Fukushima Prefecture, the runoff of the deposited radioactive Cs is causing concern about increased risk of external exposure due to recontamination of water bodies and floodplains in the downstream region. The northern part of the downstream coastal region of Fukushima, in particular, is less contaminated than the heavily contaminated upstream mountainous region, so radioactive Cs runoff from the upstream region is causing strong concern among local residents in the populated downstream area with regard to maintaining a safe living environment.

On the other hand, from the viewpoint of water use, there are over 90 water supply dams and about 3,700 agricultural irrigation ponds in Fukushima Prefecture, where agriculture is well developed as a main industry but has less sufficient precipitation (1,366 mm/ year) compared to the national average (1,757 mm/ year). Generally, the sediment produced in the catchment area during a rain runoff event or snow melt period flows into and accumulates at the bottom of reservoirs and ponds. Water storage operations at dams for irrigation and flood protection in particular strongly promote the deposition of inflow sediment at the bottom of the reservoir. Some studies after the Chernobyl Nuclear Power Plant accident (the Chernobyl accident) reported that a large part of the radioactive Cs associated with inflow of soil particles was captured in the sedimentation process at the bottom of a dam reservoir (Sansone & Voitsekhovitch, 1996;

Brittain *et al*. 1997). Since radioactive Cs, specifically, Cs-137 with a long half-life (30.2 years) that is associated with inflow sediment will continue to accumulate at the bottom of reservoirs and agricultural ponds in the area contaminated by the Fukushima accident over the long term, various properties like accumulation states and processes, resuspension, and remobilization in bottom sediment should be clarified to facilitate risk evaluation and management of aquatic ecosystem contamination of as well as water use.

The objective of this paper is, given the situation five years after the Fukushima accident, to organize scientific knowledge about the migration and accumulation of deposited radioactive Cs in the contaminated upstream region, runoff properties from forested areas and the behavior of Cs in water bodies, reservoirs and ponds by reviewing published reviewed papers. In particular, this review attempts to summarize scientific knowledge about bioavailable Cs, which consists of dissolved Cs and Cs associated with organic compounds, as well as about radioactive Cs associated with inorganic soil particles, which is considered the dominant type for the dynamics in terrestrial water environments. Moreover, in addition to highlighting future issues based on this review, research activities by the National Institute for Environmental Studies (NIES) related to these issues are introduced.

2. Radioactive Cs Runoff from Forested Areas

2.1 Migration Properties of Radioactive Cs on Hill Slopes

The vertical profile of deposited radioactive Cs dynamically changed in forested land during the first year after the Fukushima accident. A significant proportion of the deposited radioactive Cs captured in the canopy and on stems soon after the accident migrated to forest floor through washout or leaching by precipitation (throughfall) and litterfall in forests of evergreen conifers like Japanese cypress and cedars that had been foliating at the time of the accident (Kato *et al*. 2012; Teramage *et al*., 2014a; Kato & Onda, 2014). On the other hand, most of the radioactive Cs deposited on the forest floor, including the secondary migrated Cs described above, remained stored in the organic (litter) layer and the surface portion of the inorganic layer even several years after the accident due to the very strong action of adsorption or fixation (Teramage *et al*., 2014b; Takahashi *et al*., 2015). This situation eventually implies that forest floors may act as a potential runoff source of radioactive Cs associated with soil erosion during storm events and snow melt periods.

Several field surveys have been conducted by creating experimental plots to evaluate wash-off of radioactive Cs from a hillslope in contaminated forest land (Yamamoto *et al*. 2014; Yosimura *et al*., 2015a; Nishikiori *et al*., 2015; Niizato *et al*., 2016). Table 1 gives a summary of those experiments and the measured runoff ratio of Cs-137 to deposition amount on the forest floor at each experimental site. Although Nishikiori *et al*. (2015) reported a relatively higher migration ratio in the experimental plots on steep slopes in Japanese cypress and deciduous forests in Marumori Town, Miyagi Prefecture, the migration of radioactive Cs was found generally to be limited in the installed plots in each survey. For a comparison with other land-use types, an experiment using USLE standard plots in Kawamata Town, Fukushima Prefecture found the contribution of the fine soil fraction in forest land to be much lower than in farmland or grassland (Yoshimura *et al*., 2015a). Moreover, an experiment by Niizato *et al*. (2016) conducting a quantitative evaluation of radioactive Cs input and output associated with surface wash-off, througfall, stemflow and litterfall processes in Japanese cedars and deciduous Konara oaks, reported that radioactive Cs input was 4 to 50 times higher than the output during the summer monsoon in Fukushima. This shows that the radioactive Cs stored in the forest floor tends to be preserved within the forest ecosystem.

Table 1 Migration rate of Cs-137 associated with soil erosion from experimental plots on forested hill slope.

Site	Forest type	Period	Migration rate (%)	Average deposition (kBq/m^2)	Plot size W. × S.L (m)	Slope (degree)	Source
Yamakiya, Fukushima	Deciduous broad-leaved	Jul. 2 – Dec. 1, 2013	0.08	490	9 × 35	31	Yamamoto *et al*. (2014)
Kawamata, Fukushima	Japanese cedar	Jul.17, 2011 – Nov. 18, 2012	0.07	442	5× 22.1	27.5	Yoshimura *et al*. (2015a)
Hippo, Miyagi	Deciduous broad-leaved Japanese Red Pine Japanese cedar Japanese cypress	May 24 – Oct. 16, 2013	1 0.16 0.08 0.87	110 170 200 160	1.5× 2	37 39 39 39	Nishikiori *et al*. (2015)
Sakashita, Fukusima Ogi, Fukushima	Deciduous broad-leaved Deciduous broad-leaved Japanese cedar	Apr. 7 – Oct. 20, 2014 Apr. 7 – Oct. 20, 2014 Apr. 11 – Oct. 8, 2014	0.06 0.12 0.04	487 487 497	6 × 11 6 × 10 4 × 11	11 – 15 27 – 30 28 – 31	Niizato *et al*. (2016)

2.2 Runoff Flux of Radioactive Cs Associated with SS from Forested Catchments

While significant contamination from the Fukushima accident in a forested area was confirmed, not many field surveys have considered quantitative evaluation of radioactive Cs runoff from a forest catchment (Shinomiya *et al*., 2014, Iwagami *et al*., 2016; Tsuji *et al*., 2016). The reported runoff ratios of Cs-137 to catchment-averaged deposition are summarized in Table 2, including the results measured in river watersheds mainly covered by forest (Ueda *et al*., 2013). Although the spatially averaged depositions of Cs-137 have ranged from (113 – 1,900 kBq/m^2) among the observed catchments, the annual runoff ratios of Cs-137 have been very small, at 0.05 – 0.5%, in every observation. This is consistent with the results for migration on hillslopes described in the previous section. As for temporal changes in the concentration of Cs-137 associated with suspended solids (SS) (Bq/kg), no significant decrease has been confirmed yet among these observed catchments, except in one case in which the rate of decrease was far faster than the natural decay rate in one of the small catchments of the Kuchibuto River (Iwagami *et al*., 2016; Hayashi *et al*., 2016). The observed limited runoff of radioactive Cs with no apparent decrease in its concentration reflects the control of sediment runoff during storm events by the formation of understory vegetation and a litter layer on the soil surface, causing most of the deposited radioactive Cs to be retained in the forest floor. The runoff of radioactive Cs was also reported to be very limited from the contaminated forest catchment after the Chernobyl accident (Bonnett & Appelby, 1994; Nylén & Grip, 1997; Burrough *et al*. 1999). Although it brought concerns that more runoff of Cs associated with SS would occur in the forest area contaminated by the Fukushima accident with steeper terrain and a larger amount of precipitation than in the area contaminated by the Chernobyl accident, these observed results suggest that contaminated forest areas contribute little to the recontamination of the downstream region as a source of radioactive Cs at this time. On the other hand, concerns about the effect of forest management on radioactive Cs still remain. Planted forest accounts for 35 percent of the forest area in Fukushima Prefecture (Forest Agency, 2012). Forest management represented by thinning and clear-cutting which are needed for plantation cultivation is well known to be accompanied by sediment runoff (e.g., Grant and Wolff, 1991; Lewis *et al*., 2001). However, since research based on field surveys has not reported the effects of forest management on radioactive Cs runoff, organization of scientific knowledge is needed based on many case studies available to develop adequate management methods for controlling radioactive Cs runoff.

2.3 Runoff Behavior of Bioavailable Cs

Although the amount of runoff from contaminated forest catchments has been found to be limited, the runoff behavior of radioactive Cs, especially, bioavailable Cs consisting of dissolved and soluble fractions and an organic-matter-bound fraction, should be precisely understood due to concerns about water use in the downstream region and transfers to aquatic ecosystems. The dissolved fraction is generally defined as compounds that can pass through a 0.45 μm membrane filter. The soluble fraction and organic-matter-bound fraction are indicated as compounds able to generate a dissolved fraction by ion exchange and biological decomposition. As for the properties of dissolved radioactive Cs runoff from forest catchments contaminated by the Fukushima accident, an increase in concentration in stream water has been reported during the summer period (Tsuji *et al*., 2016 and higher concentrations were noted during a runoff event than during the low-flow conditions before the event (Shinomiya *et al*., 2014; Iwagami *et al*., 2015; Tsuji *et al*., 2016). On the other hand, the quantitative contribution of dissolved forms to the total amount of radioactive Cs runoff is generally small, since the proportions of radioactive Cs associated with SS dominate during flooding with high turbidity conditions,

Table 2 Runoff rate of Cs-137 associated with suspended soils (SS) from forested catchments.

Site	Catchment area (km^2)	Period	Runoff rate (%)	Average deposition (kBq/m^2)	Source
Hiso and Wariki Rivers, Fukushima	4.5 3.2	Mar. 2011 – Dec. 2011	0.5 0.3	100 300	Ueda *et al*. (2013)
Tadano, Fukushima	0.012	During typhoon Guchol	0.07	113	Shinomiya *et al*. (2014)
Yamakiya, Fukushima	0.54 0.017 0.075	Aug. 2012 – Sep. 2013	0.019 0.3 0.098	916 544 298	Iwagami *et al*. (2016)
Upper region of Ohta River, Fukushima	21	May 2014 – May 2015	0.052	1900	Tsuji *et al*. (2016)

as presented by the reported high solid– liquid distribution coefficient (Kd) of radioactive Cs associated with SS (Yoshimura *et al*., 2015b). Iwagami *et al*. (2016) reported that the annual proportion of Cs-137 discharged by the dissolved form was 0.73 – 3.7% in the three headwater catchments in Yamakiya District, Fukushima Prefecture. However, in the heavily contaminated forest catchment in the upper regions of the Ohta River flowing through Namie Town and Minamisoma City, Tsuji *et al*. (2016) reported that dissolved Cs-137 was found in about 30 percent of the total annual runoff based on calculations using an equation defining the regression between dissolved Cs-137 and hydrometeorological items (flowrate and air temperature), determined from observed data throughout the year, including flooding periods. Additionally, dissolved Cs-137 concentrations increased logarithmically with specific runoff or SS concentration in this catchment. Conversely, Cs-137 concentrations associated with SS showed almost no change with runoff intensity. These results suggest that the process of generating dissolved radioactive Cs depends little on solid-liquid distribution (adsorption-desorption) processes with SS and is governed by another process. While the results from some field experiments suggest the contribution of highly contaminated organic matter (leaf litter) to the generation of dissolved radioactive Cs (Sakai *et al*., 2015; Nakanishi *et al*., 2014), more detailed investigations are needed in terms of the seasonal fluctuation in concentrations and the generation mechanisms at runoff events to understand future trends.

There is little field research on radioactive Cs runoff with organic-matter-bound fractions from forest catchments. Iwagami *et al*. (2016) only reports that the annual proportion of Cs-137 discharge through coarse particulate organic matter (CPOM), defined as particulate organic matter over 1 mm in size, was 0.0092 – 0.069% in the case of quantitative evaluation. But then, as for fine particulate organic matter (FPOM), defined as under 1 mm in size, which is an important feed source for aquatic organisms, although Eyrolle-Boyer *et al*. (2016) suggest that there could be a significant transfer of highly contaminated detrital biomass from forest litter to downstream areas based on results with relatively high radioactive Cs concentrations recorded in sandy samples possibly including contaminated micrometric litter debris collected from river beds in the coastal region of the Fukushima Prefecture, the direct involvement of FPOM in radioactive Cs discharge has yet to be specified. Though a large amount of SS would be needed as a test material, one way to clarify the contribution of FPOM would be to measure the organic-matter-bound fraction directly by fractionating the SS with different bond strengths, using a sequential extraction procedure (Tessier *et al*. 1979; Tsukada *et al*., 2008), as has been the case with its application to irrigation water for paddy fields (Yoshikawa *et al*., 2014).

3. Radioactive Cs Behavior in Dam Reservoirs and Ponds

3.1 Accumulation of Radioactive Cs in Bottom Sediment

It is known that the ratio of radioactive Cs runoff to that deposited by the Fukushima accident is very low (less than one percent per annually at most) in the catchments of the Abukuma River and other rivers in the coastal region of Fukushima Prefecture as well as in forested catchments, as described above (Nagao *et al*., 2013; Yamashiki *et al*., 2014; Hayashi *et al*., 2016). On the other hand, in water bodies such as reservoirs and irrigation ponds with from several times to tens of times larger catchment areas than their own water surface area, even if the runoff ratio of the deposited radioactive Cs from the catchment is limited, the accumulation rate might be not negligible in the long-term radioactive contamination of their bottom sediments. Also, direct deposition and initial inflow from washable areas such as urban areas are suggested to be the main cause of radioactive Cs contamination of lake beds from field surveys after the Chernobyl accident (Smith *et al*., 2005). As for the effort to comprehend the state of radioactive contamination of the reservoirs and irrigation ponds in the area influenced by the Fukushima accident, the Ministry of the Environment has been using grab samplers to conduct periodical monitoring of the concentrations of radioactive Cs in the surface part of bed sediment in natural lakes, dam reservoirs and irrigation ponds at a total of 164 points in Fukushima and its surrounding prefectures from October 2011. The measured data are released as needed on its website (Ministry of the Environment, 2016). Currently, there are a few studies, limited to irrigation ponds (Aoi *et al*., 2014; Yoshimura *et al*., 2014), that have reported on investigations to get a detailed grasp of the state of radioactive Cs accumulation by measuring vertical profiles of radioactive Cs concentration and sediment properties in undisturbed core samples. In lakes, however, only studies on the radioactive Cs concentration have been performed in the surface part of the bed sediment collected by a grab sampler to investigate the relationship to the contamination of fish (Fukushima & Arai, 2014; Matsuda *et al*., 2015).

The results of measurement by both Aoi *et al*. (2014) and Yoshimura *et al*. (2014) with undisturbed sediment core samples in irrigation ponds in Fukushima Prefecture indicate radioactive Cs concentrations peak in the surface layer and are particle-size dependent: finer particles exhibit higher concentrations. They also found that the radioactive accumulation process tended to depend on hydraulic conditions in the pond. Their results showed that the Cs-137 inventory in the bottom sediment was almost identical to that in the pond catchment area immediately after accident, but was significantly higher than that in the core sampling period 19 months after the Fukushima accident, and this suggests that the pond serves as a sink for radioactive Cs (Aoi *et al*., 2014), whereas fine sediments containing high concentrations of Cs-137 were reported to be removed from the system by hydraulic flushing from some ponds (Yoshimura *et al*., 2014). It is predicted that the effect of direct deposition on radioactive Cs concentration in bottom sediment will be more obvious in a dam reservoir with a generally much longer retention time than an irrigation pond. Progress is needed in studies on the behavior of sediment with high concentrations of radioactive Cs by direct deposition and initial inflow to clarify the actual state of bottom sediment contamination in dam reservoirs.

3.2 Effects of Dams on Migration of Radioactive Cs in a River Watershed

Dams are constructed for various purposes such as water use, electric power generation, flood protection, and so on. Therefore, water storage management and discharge operations are conducted according to their purposes in general. Water use for irrigation, industry and drinking is the main purpose of most dams in the area radioactively contaminated by the Fukushima accident. These dams are managed to take water with less turbidity from the surface or upper layer with a sediment storage capacity sufficient for causing inflow sediment to accumulate. This capacity for accumulating not only inflow sediments but also radioactive Cs associated with the sediment in a lake, is thought to play an important role in protecting against the spread of radioactive Cs from the heavily contaminated upstream region to the relatively lightly contaminated downstream farmland and urban areas in the coastal region of Fukushima Prefecture.

Several studies after the Chernobyl accident have qualitatively evaluated this storage effect by comparing the concentrations of SS and radioactive Cs associated with SS between the inflow and outflow of dams in the contaminated area (Sansone & Voitsekhovitch 1996; Brittain *et al*. 1997). As for evaluating this role of dams in Fukushima Prefecture after the Fukushima accident, a study using a numerical simulation model has been conducted mainly by the Japan Atomic Energy Agency (JAEA) to examine the quantitative effect of dams on the Cs inflow storage function through water storage control. For the Ogaki Dam Reservoir, one of the main irrigation reservoirs of Fukushima Prefecture, Kurikami *et al*. (2014) found the predicted values of sediment and Cs-137 associated with SS discharged from the dam satisfactorily reproduced the observed data. Moreover, by raising the height of the dam exit, Yamada *et al*. (2015) simulated the amount of clay exiting the reservoir, finding it could be reduced by a factor of three. This indicates that the dam could be operated to buffer radioactive Cs discharge and limit the contamination spreading into lowland areas of the Ukedo River basin. the A balance calculation of SS and Cs-137 associated with SS based on observed data in the Uda River Basin in the coastal region of the Fukushima Prefecture, the Matsugabo Dam on the Uda River estimated that over 90 percent of Cs inflow associated with SS accumulated in the lake through water storage control, even during the extremely heavy rainfall event of Tropical Storm Etau in September 2015 (Hayashi *et al*., 2016). In addition to utilizing this function to protect against radioactive contamination of the environment, it is also suggested that predicting the impacts of future climate change on sediment and Cs-137 fluxes from dams will be crucial to environmental planning and management (Mouri *et al*., 2014).

3.3 Radioactive Cs Remobilization Properties in Bottom Sediment

Remobilization of accumulated radioactive Cs might not actively occur in the bottom sediments of lakes and ponds, considering the reported Kd values (mainly 10^5 – 10^6, unit: kg/L) for SS in rivers in Fukushima Prefecture (Yoshimura *et al*., 2015b). Some studies on the sorption of radioactive Cs into sediments, however, have shown that NH_4^+ in anaerobic sediment and bottom waters can make radioactive Cs leach from contaminated sediment (Evans *et al*., 1983). Also, Kd is inversely proportional to the content of competing ions (specifically K^+ and NH_4^+) in sediment pore water (Comans *et al*. 1989), and sediment containing much organic matter and sand is suggested to boost radioactive Cs mobility because it lacks strong radioactive Cs fixation ability (Smith *et al*., 2005). On the other hand, no studies have yet reported on leaching of radioactive Cs from bottom sediment in a lake or a pond after the Fukushima accident. Dam reservoirs and irrigation ponds are essential for agricultural use. Since the duration of radioactive contamination conditions in a freshwater ecosystem depends on the level of dissolved Cs-137 concentration in the water system, an investigation is needed into whether or not these reservoirs in the contaminated area act as a source of dissolved radioactive Cs, and this should be done as rapidly as possible.

4. NIES' Approach to Understanding Radioactive Cs Behavior in a River Watershed

In order to quantitatively evaluate the migration and accumulation of radioactive Cs not only associated with SS but in bioavailable forms in a river watershed, the National Institute for Environmental Studies (NIES), Japan has been conducting field measurements in watersheds of the main rivers (Uda, Mano and Ohta rivers) of the northern coastal region of Fukushima Prefecture since 2012.

As for the evaluation of radioactive Cs flows and stocks, migration of radioactive Cs associated with SS was examined in the Uda River watershed during the super heavy rain event of Tropical Storm Etau (Hayashi *et al*., 2016). The estimated total runoff volumes of Cs-137 from the small forest catchment, Matsugabo Dam (Udagawa Lake; an upstream reservoir) and the entire river watershed during the event were 1.4 to 5.3 times greater than the annual total runoff volumes in

2014, respectively. The sizes of Cs-137 runoff, however, fell much below those of the SS runoff from the Matsugabo Dam reservoir and the entire Uda River basin due to decreasing concentrations of Cs-137 associated with SS, possibly due to the effects of decontamination operations in the watershed.

Also to elucidate radioactive Cs accumulation in the bottom sediment of reservoirs, sediment core samples were collected in 2012 and 2013 from the Matsugabo Dam reservoir. Analysis of these samples showed that the sedimentation of SS containing relatively low Cs-137 concentrations that currently flow into the dam during storm events shields the sediment layer that was highly contaminated with Cs-137 near the dam wall (Fig.1). The contaminated layer was formed because of direct deposition onto the lake surface at the time of the Fukushima accident and inflow of radioactive Cs from areas with impervious ground cover soon after the radioactive Cs had been deposited into those areas. As a future effort to understand radioactive Cs migration and accumulation in a river watershed, field measurements are underway to evaluate the positive and negative effects of the decontamination operations conducted over wide areas of the contaminated upstream region.

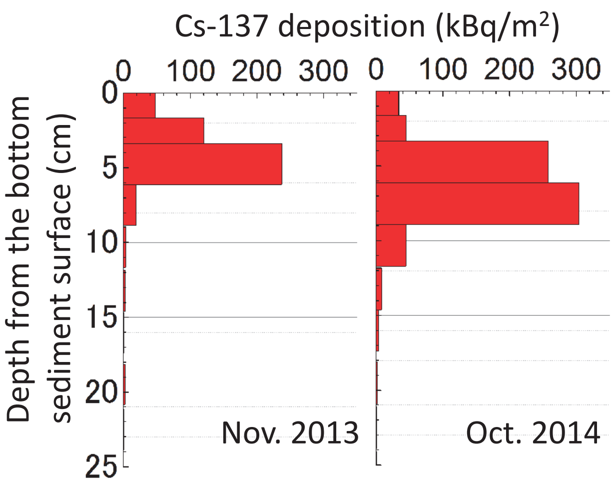

Fig. 1 Annual change in the accumulation of Cs-137 in the bottom sediment near the dam wall of Matsugabo Dam on the Uda River.

As part of the effort to understand the behavior of bioavailable radioactive Cs in a river watershed, concentrations and fluxes of dissolved radioactive Cs are being investigated in the upstream part of the Ohta River watershed, which is covered with a high-dose-rate forested area, under base flow conditions and during storm events (Tsuji *et al.*, 2016). Under base flow conditions, an increase in dissolved Cs-137 concentrations in the water [Bq/L] was confirmed in summer as compared to in winter, and these levels in both seasons were higher than those of particulate Cs-137 concentrations in the same seasons [Bq/L]. On the other hand, during storm events, the particulate Cs-137 concentration became dominant as the SS concentration increased. Throughout the monitoring period, dissolved Cs-137 concentrations in the water [Bq/L] were higher during storm events than base flow conditions and were positively correlated with runoff intensity (Fig. 2). The factors influencing changes in dissolved Cs-137 concentrations are also being investigated by measuring the Cs-137 concentrations associated with SS [Bq/ kg] and dissolved Cs-137 concentrations in unsaturated soil water, throughfall and rainfall, together with other main solute concentrations. The Cs-137 concentration per unit weight of SS in river water was not strongly correlated with runoff intensity. Additionally, dissolved Cs-137 concentrations were not detected in soil water, groundwater or rainfall, whereas higher dissolved Cs-137 concentrations were detected in

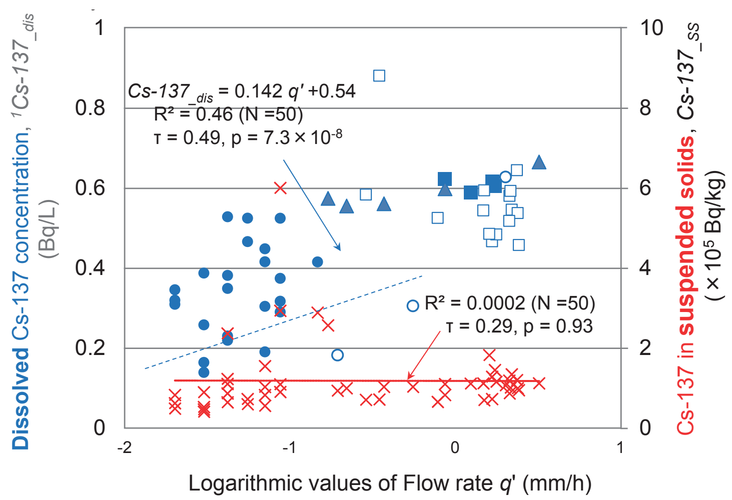

Fig. 2 Relationships between specific runoff rate (mm/h) and dissolved Cs-137 (Bq/L) or Cs-137 in suspended solids (Bq/kg) in the upstream part of the Ohta River.

Dissolved Cs-137 at ● base flow, ■ 6 October 2014, ▲ 14 October 2014, □ 16 July 2015, ○ other events, and × ^{137}Cs in SS throughfall than in river water. K+ concentrations were higher during storm events than base flow conditions, and dissolved organic carbon concentrations increased toward the peak flow rate. These findings suggest that one major factor influencing the generation of dissolved Cs-137 in river water is leaching from organic material in flooded areas. In addition to finding the detailed mechanisms of dissolved radioactive Cs generation in water, some targets are currently being addressed such as quantitative evaluation of the migration and accumulation of radioactive Cs associated with organic compounds and remobilization from the bottom sediment in dam reservoirs for a sound understanding of bioavailable radioactive Cs behavior leading to correct assessment of the risk to local residents' living environments.

5. Summary

Huge amounts of radioactive Cs released by the Fukushima nuclear accident have seriously contaminated the mountainous part of Fukushima Prefecture. From several research activities for understanding the behavior of radioactive Cs, it was confirmed that the migration of radioactive Cs from the mountainous region to the downstream lowlands and the coastal area was fully controlled by the inhibition of runoff from forested areas and the storage function of dams. On the other hand, it is still unknown how the retained or accumulated radioactive Cs acts in the generation and dynamics of bioavailable Cs in forest soil or lake bed sediments. Scientific knowledge about the behavior of bioavailable Cs in terrestrial water environments needs to be organized to enable evaluation of future effects on water use and freshwater ecosystems.

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(Received 16 November 2016, Accepted 16 December 2016)