

Chapter 15

Mobility of Fallout Radiocesium Depending on the Land Use in Kasumigaura Basin



Shuichiro Yoshida, Sho Shiozawa, Naoto Nihei, and Kazuhiro Nishida

Abstract Although Lake Kasumigaura stores twice as much radiocesium compared to the direct fallout onto the lake surface, the additional source of radiocesium has not been determined. The present study examined the major source of radiocesium deposited in the lake based on surveys of the dry beds of the rivers flowing into the lake. The basin of four rivers, two of which flow through an urbanized region and the other two through a rural region to Lake Kasumigaura, were selected. The radioactivity per unit area of the dry river bed and the top of the river bank was measured. On the dry river beds of the rivers flowing from the urbanized area, the deposition of radiocesium per unit area was found to be much higher than the direct fallout per unit area, revealing a considerable amount of radiocesium had been discharged from the urbanized upstream of the rivers by flooding events. On the other hand, rivers flowing from the rural area stored almost the same amount of radiocesium as the direct fallout. These observations revealed that the urbanized areas located upstream to Kasumigaura Lake were a major additional source of radiocesium contamination in the lake.

Keywords Radiocesium contamination · Watershed · Water source · Land use · GIS

15.1 Introduction

The accident at the Fukushima-Daiichi Nuclear Power Station caused expansive radioactive contamination over farmlands, forests and cities not only in Fukushima Pref. but also in broad areas of eastern Japan. Because cesium is known to be strongly adsorbed by soil minerals, the mobility of the fallout onto the soil surface should be low. However, the fallout onto paved surfaces is less adsorbed and can be carried by the surface water flow. Kakamu et al. (2012) reported that the reduction in the dose rate from April to November 2011 depended highly on ground surface

S. Yoshida (✉) · S. Shiozawa · N. Nihei · K. Nishida
Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo, Japan
e-mail: agyoshi@mail.ecc.u-tokyo.ac.jp

type. The ratios of environmental radiation dose rate of soil and asphalt on 11 November compared with 11 April were 47.9% and 70.7%, respectively. The fallout onto the soil surface could move down to deeper layers with the percolating water, causing a reduction in dose rate. However, the fallout onto the asphalt could not move into the deeper structure of the asphalt but stayed near the surface, causing less change in dose rate during that period. This suggested that most of the fallout onto asphalt was scoured by rainfall soon after the accident, becoming the main source of the contamination in the water system. However, the movement of radiocesium fallout in the water system had not been directly monitored by any studies until the monitoring framework was built. Therefore, indirect evidence was required to prove the difference in the radiocesium mobility depended on the land use. Among the studies, Shiozawa (2016) measured the radiocesium storage density (kBq m^{-2}) in a contrasting pair of irrigation reservoirs, one of which is downstream of a forest and the other located below premises of a factory. The radiocesium storage per unit area (kBq m^{-2}) in the reservoirs depended highly on the land use of the upper basin. The reservoir collecting the water from the factory stored five times as much radiocesium as the direct fallout onto the reservoir surface. However, the reservoir collecting the water from the forest had the same amount of radiocesium as the direct fallout. This study clearly suggested that the paved ground surface adsorbed less radiocesium than the soil, causing an outflow of radiocesium downstream via the rivers or canals.

Lake Kasumigaura is the most important water source for the southern part of Ibaraki Pref., and the major land use of its basins is diverse. The monitoring by the Ministry of the Environment showed that the radiocesium concentration of the mud in the lake bottom gradually increased in the first year after the accident. This suggested not only direct fallout but also the inflow from the rivers caused contamination of the lake. However, the major source of the contamination is not clearly established by the official monitoring. Substantial migration of suspended particles along the river occurs due to heavy rain events when the water level in the rivers rises up to the dry river beds. During these rare events, sediment in the dry river beds can be replaced by the soils or sands flowing down from the upper basin. Because most of the fallout radiocesium attaches to suspended particles, if the amount of radiocesium per unit area of dry river bed is higher than the fallout, radiocesium has probably flowed down from the upper basin. Thus, the ratio of the amount of radiocesium per unit area of dry river bed to the fallout per unit area should be a measure to assess the influence of the upper basin as the source of radiocesium.

From these considerations, the basin of four rivers, two of which flow through an urbanized region and the other two flow through a rural region to Lake Kasumigaura, were selected for this study. The radioactivity per unit area of the dry river bed and the top of the river bank were surveyed to reveal the difference in the migration of radiocesium fallout from the upper stream, and if the migration of radiocesium depended on land use.

15.2 Methods

15.2.1 Characteristics of the Study Area

Four watersheds of Hanamuro (H1~H3), Sakura (S1, S2), Koise (K1, K2) and Bizen (B) rivers were subject to our survey (Fig. 15.1). Most of the watersheds of the rivers were determined with the aid of an elevation map. However, because the upper stream of Hanamuro River functions as the main river for drainage of rainwater from the urbanized area of Tsukuba City, the watershed H3 was determined from the sewage network map provided by the Sewage Management Division of Tsukuba City. The information was introduced to Arc Map10.4 (ESRI Inc.) to facilitate further analyses. Figure 15.2 provides the results of the airborne monitoring in the distribution survey of radioactive cesium performed by The Ministry of Education, Culture, Sports, Science and Technology (MEXT) in July 2011. The inventory values on the map were corrected to those on 21 Oct. 2016.

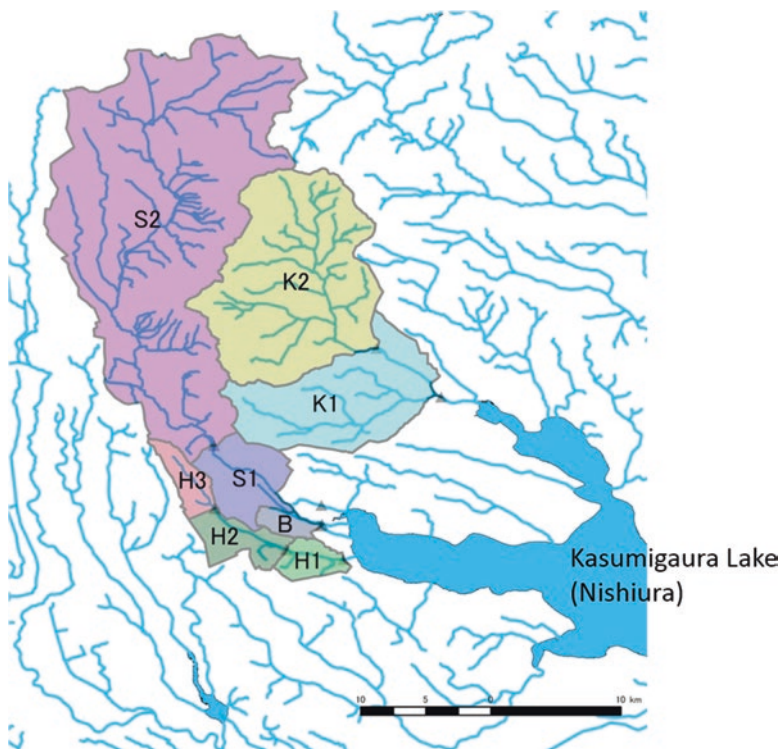


Fig. 15.1 Basins of the rivers for the survey

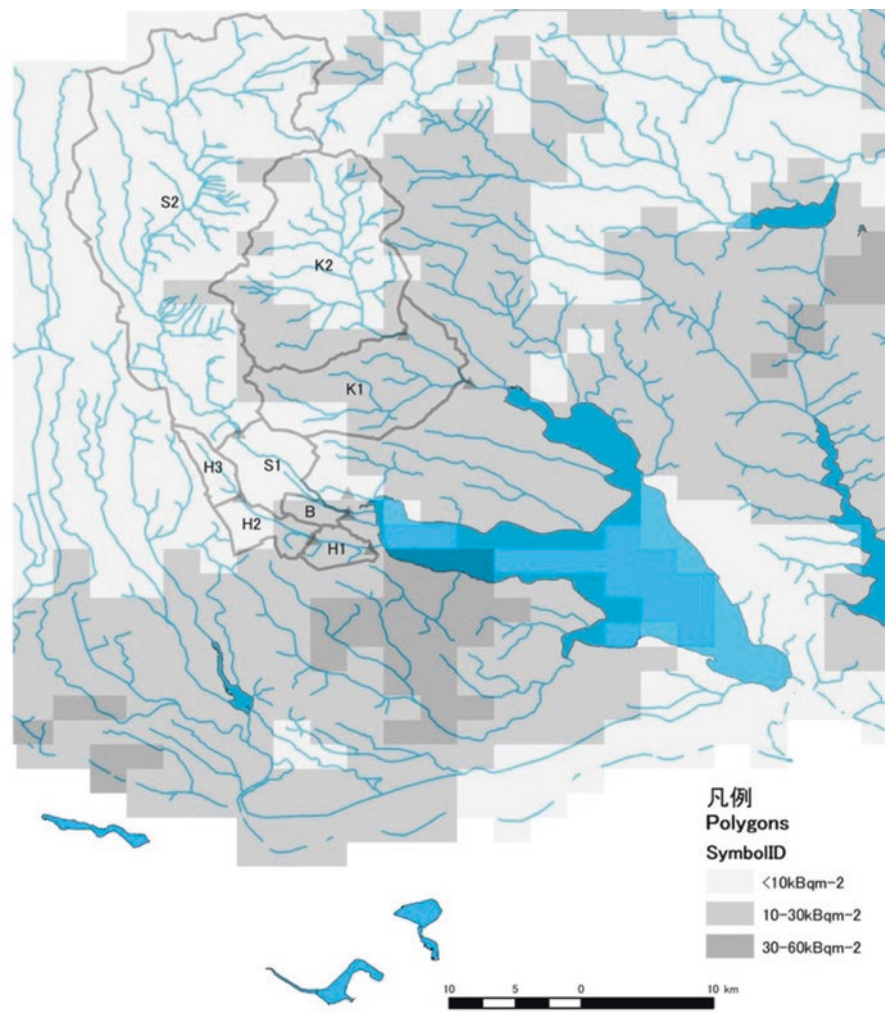


Fig. 15.2 Map of radiocesium inventory measured by airborne survey by MEXT (provided by JAEA 2014)

The land uses of the basins were analyzed using the National Land Numerical Information provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The Land Utilization Segmented Mesh Data (100 m mesh) was introduced to ArcMap10.4 to evaluate the areal proportion of each land use category.

Figure 15.3 illustrates the land use map of the region. Figure 15.4 shows the areal percentage of each land use in the watersheds. Hanamuro River flows through the urbanized area of Tsukuba City and Tsuchiura City. More than 40% of the land is used for buildings. As previously mentioned, the rain falling on roofs and paved ground surfaces are collected by drains that connect to sewers which discharges the rainwater directly to the river. Bizen Riv. also flows through the center of Tsuchiura

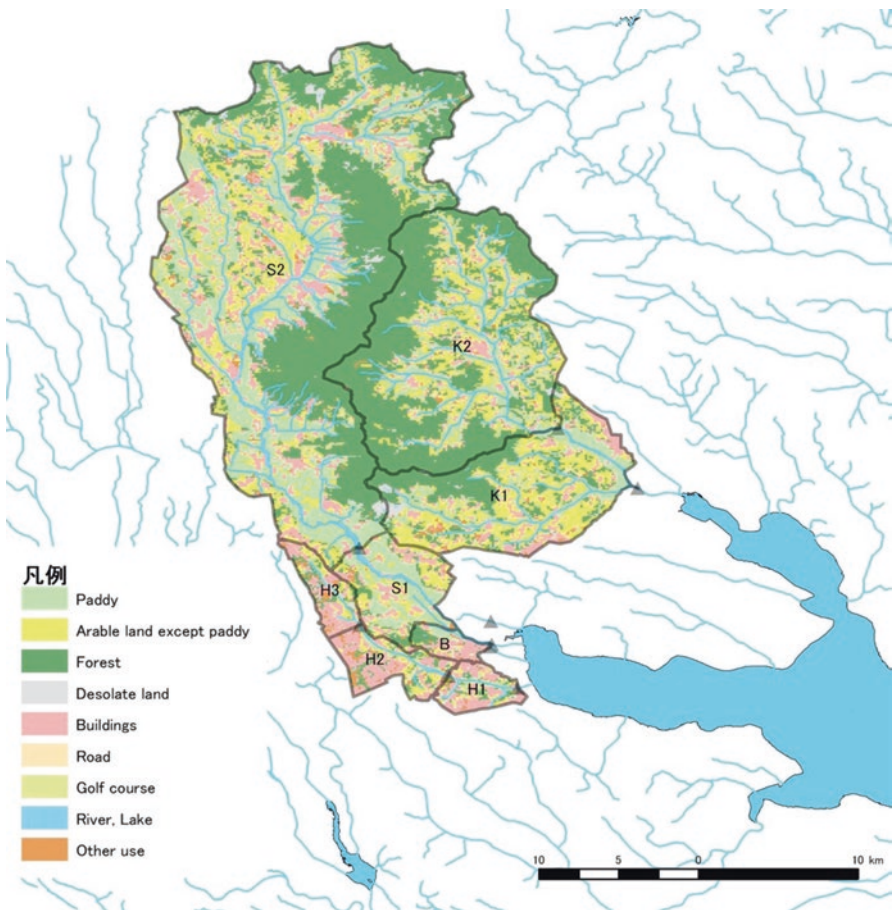


Fig. 15.3 Land use map of the basins

City, where more than 40% of the watershed is used for buildings. In contrast, Sakura Riv. and Koise Riv. flow from the rural areas, and most of the land is used for farming or forestry.

15.2.2 Measurement Apparatus of Deposited Radiocesium per Unit Area (kBq M^{-2})

The radioactivity per unit area (inventory kBq m^{-2}) was measured by the apparatus shown in Fig. 15.5. A commercial NaI scintillation probe and survey meter (Model 5530/5000, National Physical Instrument, USA) was used as the detector. To improve the directionality, the probe was insulated by lead plate except in the

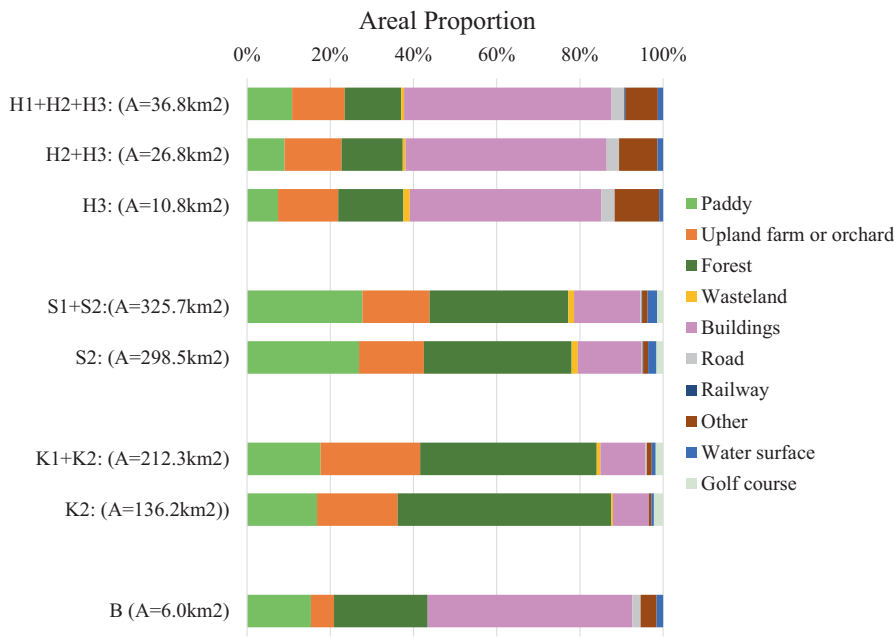


Fig. 15.4 Areal proportions of land use in the basins. (The upper basins are included in the area of the lower basins)

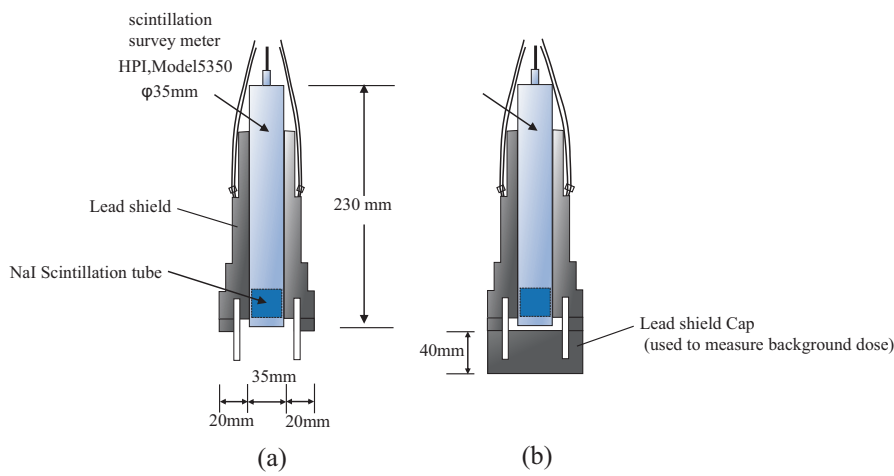


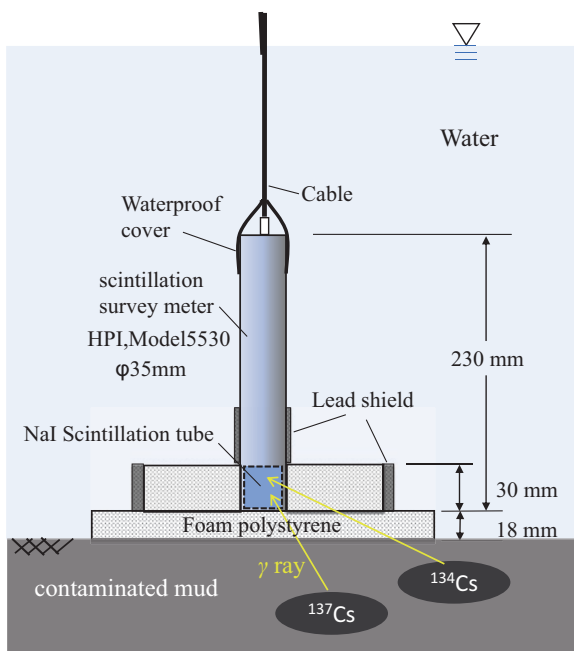
Fig. 15.5 Apparatus for measuring radioactivity per unit area (inventory) in soil. (a) To measure the gamma beam radiation from the radiocesium deposited to the ground surface. (b) To measure the background radiation alone

direction the measurements were taken (Fig. 15.5a). Radioactivity (counts of gamma beam) was measured three times from 1 m above the ground at each location. Measurements were also conducted when the opening was closed with a lead cap to eliminate background radiation (Fig. 15.5b).

The radioactivity per unit area of the submerged bottom of the river (kBq m^{-2}) was measured by the apparatus shown in Fig. 15.6. The same commercial NaI scintillation survey probe (Model 5530, National Physical Instrument, USA) was covered by a rubber cap to waterproof it. Because the attenuation of a gamma beam in water is a thousand times higher than in air, round foamed polystyrene boards were attached to the tip of the rod to avoid attenuation of the gamma beam by the water between the probe and the bottom mud. Meanwhile, the insulation against the background radiation was not necessary due to the attenuation by water. The measurements were conducted by hanging the apparatus from the middle of pedestrian and vehicle bridges and lowering it to the bottom of the river. Radioactivity was measured three times at each location.

Undisturbed soil samples (diameter = 50 mm, length = 100 mm) were collected at the river beds of Hanamuro Riv. (H1, H2, H3) to compare the radioactivity with the aforementioned method. The vertical profiles of radiocesium concentration were determined by measuring the samples with a NaI scintillation analyzer on Jan 8 and 10, 2017.

Fig. 15.6 Apparatus for measuring radioactivity per unit area (inventory) in the submerged river bottom



15.2.3 Measurement and Analysis of Radioactivity

The amount of deposited radiocesium per unit area was measured along the cross sections of the rivers on 27 Sept. and 21 Oct. 2016. All the measured cross sections were located near bridges, above which the corresponding watersheds spread. Radiocesium in the river water did not reach the unpaved top of the river bank, and only direct fallout radiocesium was captured by the soil. The dry river bed is the domain where the river water flows exclusively during flooding events, in which suspended particles can deposit. The river bottom is always under water which carries in contaminated particles but also carries contaminated particles out.

When the measured amounts of radiocesium per unit area at the top of the bank, dry river bed and submerged river bottom are denoted by M_a , M_b and M_c , respectively, the ratios M_b/M_a and M_c/M_b probably reflect the migration of radiocesium from the upper basin along the rivers. If M_b/M_a is larger than one, radiocesium must have migrated from the upper stream of the river when the discharge of the river increased. Because the water level does not frequently reach the upper river bed, sediment on the dry river bed is thought to remain for more than a few years. Thus, high radioactivity of the dry river bed is expected to remain for many years after the migration of radiocesium. If M_c/M_a is larger than one, radiocesium must have migrated from the upper stream of the river as well. However, even if it is close to one, it does not necessarily mean the absence of migration from the upper stream, because the contaminated sediment at the river bottom does not stay for long but moves down stream continuously. Therefore, M_b/M_a rather than M_c/M_a should clearly reflect the mobility of radiocesium along the streams.

15.3 Results and Discussion

Table 15.1 shows the M_b/M_a and M_c/M_a depending on the land use of the upper basin. The results clearly show that the urbanized middle and upper watershed of Hanamuro Riv. (H2, H3) and Bizen Riv. (B) have released much radiocesium into the rivers. On the other hand, no clear evidence was found that the watershed of Sakura Riv. (S1, S2) and Koise Riv. (K1, K2) have supplied radiocesium to the downstream. These results suggest that the urbanized area where the ground surface is highly paved or covered with buildings cannot adsorb nor hold radiocesium, causing rapid migration to the water system. However, the migration of radiocesium from farmland and forest to the rivers was much less, because the soil strongly held radiocesium. Yoshioka et al. (2013) started to monitor the outflow of radiocesium from a paddy field in Fukushima on 28 April 2011, showing 3.3% of the inventory was released in the first year after the accident. Eguchi (2017) summarized the reports on radiocesium balance in paddy fields from 2011 to 2015. The balance relative to the radiocesium inventory ranged between +0.24 and -2.96% and the mean was -0.52% . On the other hand, the radiocesium outflow from urbanized regions

Table 15.1 Measured radioactivity at the end of basin of the rivers

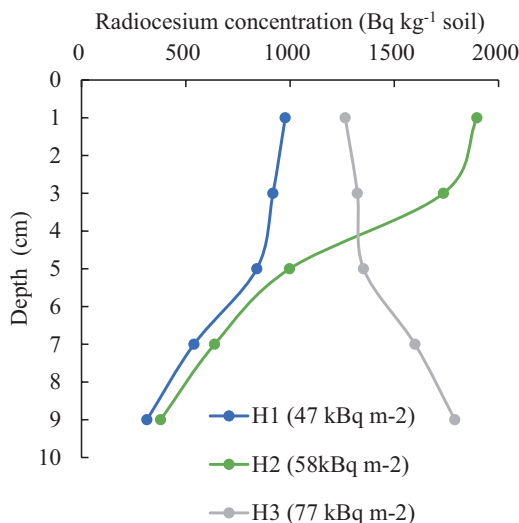
Basin	Areal proportion of building site and road/Total area of the basin	M_a : Top of the bank kBq m ⁻²	M_b : Dry river bed kBq m ⁻²	M_c : Submerged river bottom kBq m ⁻²	M_b/M_a	M_c/M_b
H1: Downstream of Hanamuro Riv.	53%/36.8km ²	40.2	41.9	65.3	1.0	1.6
H2: Middle stream of Hanamuro Riv.	51%/26.8km ²	22.9	76.6	—	3.3	—
H3: Upper stream of Hanamuro Riv.	49%/10.8km ²	36.5	94.3	—	2.6	—
S1: Downstream of Sakura Riv.	16%/325.7km ²	30.0	29.5	32.9	1.0	1.1
S2: Upper stream of Sakura Riv.	16%/298.5km ²	31.7	23.2	—	0.7	—
K1: Upper stream of Koise Riv.	11%/136.2km ²	35.8	37.7	35.8	1.1	1.0
K2: Middle stream of Koise Riv.	9%/212.3km ²	31.5	35.8	31.0	1.1	1.0
B: Bizen Riv.	51%/6.0km ²	(30.0) ^a	—	91.7	—	(3.1)

^aThe measured radioactivity at S1 is shown instead, because the locations are very close to each other

had not been directly monitored. We have measured the dose rate at 1 cm above a paved road and at an uncultivated neighboring paddy field in Fukushima on February 2012 by insulating the scintillation detector with a lead block having a thickness of 30 mm. Only 50% of dose rate was recorded on the road compared to the paddy soil surface. Because the measured dose rates included the effect of the background radiation, more than 50% of fallout onto the paved road was probably scoured by water. Even if the land use is categorized to ‘building’, not all the ground is covered by buildings or pavement. Thus, the percentage of outflow of radiocesium might have been less. However, it is highly plausible that the radiocesium outflow from urbanized regions should have been much higher than that from the farmlands and forests.

Figure 15.7 shows the vertical profiles of radiocesium measured by the undisturbed soil samples taken at the river beds of Hanamuro Riv. At the measured points of the watershed H1 and H2, the thickness of the contaminated sediment was approximately 10 cm. The total amounts of radiocesium per unit area were estimated to be 47 and 58 kBq m⁻², respectively, which were close to the radioactivity per unit area (inventory) measured by the scintillation detector. At the measured

Fig. 15.7 Vertical profile of radiocesium concentration measured in the dry river beds of Hanamuro river



points of the watershed H3, the whole radioactivity per unit area (inventory) should have been higher because radiocesium was distributed deeper than 10 cm; the total amount of radiocesium to 10 cm was estimated to be 77 kBq m⁻². The vertical profile of the radiocesium concentration at the measured points of the watershed H3 also suggests that the observed higher radioactivity per unit area (inventory) than the fallout was not caused by the lateral flow from the slope of the bank, but by the accumulation of contaminated mud due to flooding; the vertical profile of radiocesium formed by the percolation of water had hardly extended to deeper layers (e.g. Honda et al. 2015; Koarashi et al. 2012). Finally, the influence of the radiocesium outflow from the basin on the contamination of Kasumigaura Lake was analyzed. Neither the total amount of radiocesium accumulating in Lake Kasumigaura nor the total fallout onto the lake has been accurately estimated because airborne monitoring does not work on the water surface. Tanaka (2015) began surveying the sediment of Kasumigaura Lake in 2011 at a spatial interval of a minute (1') mesh to reveal the inflow of radiocesium and its horizontal movement within the lake. From a map in that report, the authors estimated the total amount and the mean inventory of radiocesium in Nishiura portion of Kasumigaura Lake. Because only the categorized range of the inventory of each polygon was shown on the map, the mean of the categorized range was used for the representative inventory of the polygon. The inventory on the ground surrounding the lake was also cited from the airborne survey conducted by MEXT in 2011 (JAEA 2014). The domain was determined by forming a 500 m buffer from the lake shore by GIS software. Table 15.2 shows the areal percentage of the inventory in the lake and the lake shore. The comparison suggested that Lake Kasumigaura has almost the same amount of radiocesium from the upstream basin as the direct fallout onto the lake, assuming the amount of direct fallout per unit area of the lake was the average in the surrounding ground. The area of the lake (Nishiura Lake portion of the whole Kasumigaura Lake system) and its

Table 15.2 Estimated radioactivity per unit area of the lake bottom and the surrounding ground of Kasumigaura Lake

Inventory class	Lake Kasumigaura ^b (%)	Surrounding ground ^a (%)
<10 kBq m ⁻²	6%	30%
10–30 kBq m ⁻²	57%	61%
30–60 kBq m ⁻²	26%	8%
60–100 kBq m ⁻²	11%	0%
Estimates of the mean	32.2 kBq m ⁻²	17.3 kBq m ⁻²

^aEstimated from the data of the airborne survey conducted by MEXT in 2011 (JAEA 2014)^bCompiled from the distribution map estimated by Tanaka (2015)

basin is 170 km² and 1400 km², respectively. If 12% of the fallout on the basin was scoured and flowed out to the rivers, the observed accumulation of radiocesium in the lake can be accounted for. However, since most of the basin was used for agriculture or forestry, only a small proportion of fallout was released to the water system from the soil surface. Thus, the urbanized areas, which are located at the western edge of Lake Kasumigaura, were probably the main additional source of radiocesium to the bottom of the lake.

15.4 Conclusions

On the dry river beds of the rivers flowing from the urbanized area to Kasumigaura Lake, the deposition of radiocesium per unit area was found to be much higher than the direct fallout per unit area at each surveying point. On the other hand, the dry river beds of the rivers flowing from the rural area stored almost the same amount of radiocesium as the direct fallout. These observations revealed that the urbanized areas located at the upstream of Kasumigaura Lake were a major additional source of radiocesium contamination in the lake.

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