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Environmental Monitoring of ^{134}Cs and ^{137}Cs Levels in Namie Town in 2018 and 2019

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The Fukushima Dai-ichi Nuclear Power Plant accident caused a release of radionuclides covering a significant area in Fukushima Prefecture, Japan. In the current work the radio-caesium concentrations observed in some points of Namie Town between 2018. June. and 2019. September in river water, river sediment and aerosol are being presented. The observed concentrations were up to 205.9 ± 9 mBq/L for ^{137}Cs in unfiltered water and less than 4000 μBq/m^3 for ^{137}Cs in air, while the sediment had a maximum of 4041 ± 2 Bq/kg-dry for ^{137}Cs. In many cases the water and aerosol samples had activity concentrations below the detection limit. These values decreased compared to the year 2017 for the same area. The potential yearly committed effective doses were estimated based on the data, with the calculated annual dose rates being well below any regulatory limit.

Key words: Radioactivity in water, radioactivity in sediments, airborne radioactivity, Caesium, Fukushima, Namie

1. Introduction

The accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) released a considerable amount of radionuclides into the environment, which subsequently spread and contaminated neighbouring areas causing concerns about human exposure and the local environment [1]. Radio-caesium, due to the released amount and the half-lives of the released isotopes, is the main concern at this point of time. It has the potential to cause exposure to radiation through multiple pathways, thus the monitoring of radio-caesium levels in various environmental compartments is important for providing information to the local government and the residents, assuring public safety and following the temporal changes in the distribution of the radioisotopes in the area.

One of the closest settlements is Namie Town, which was in the direction of the release of radionuclides from the accident, and which is currently split into two parts,

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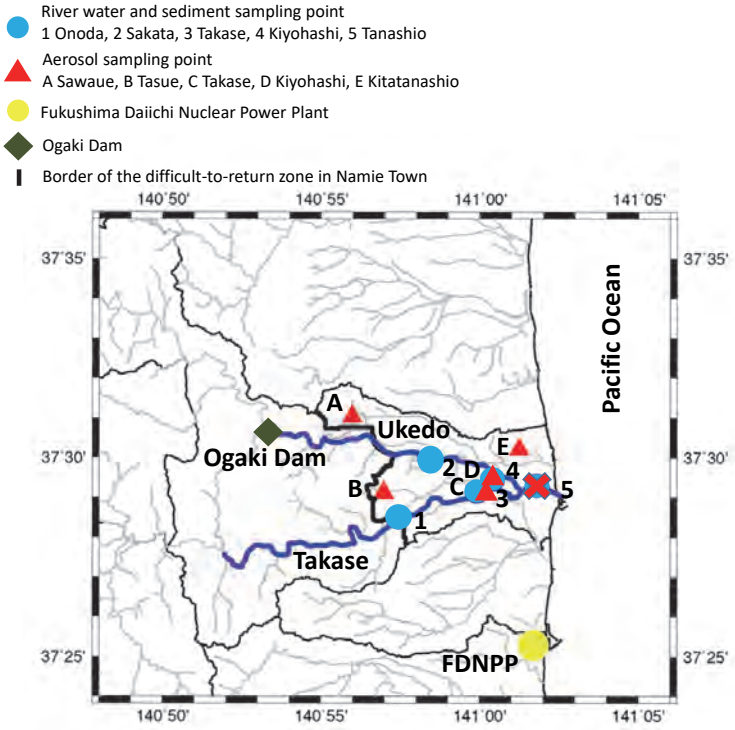

Fig. 1. Map of the experimental area including the river system

the Difficult-to-return zone, which is still contaminated over the permissible levels, and the Evacuation-order-lifted zone where people are allowed to return (observed dose rates below 1 μGy/h by car-born survey)[2]. The difficult to return zone serves as a reservoir for radio-caesium, which can affect the surrounding area by air through radioactive aerosols and by transportation through the waterways. Radioactive aerosol can be generated in a variety of ways, including resuspension, combustion of contaminated materials depending on the technology used[3], and through the lifecycle of plants and fungi through the release spores and pollen.[4, 5]. The contaminated soil and interception of radioactive aerosol can cause elevated concentrations in various plant (for example mushrooms, wild plants, etc.), and through the food-chain this can result in bioaccumulation and significant activity concentrations in animals, for example wild boars and black bears[6, 7].

Similarly, the originally contaminated area covers a large portion of the catchment area of several rivers, and in case of Namie Town the rivers Takase and Ukedo are able to carry both dissolved and particulate radio-caesium to the already cleaned areas through soil erosion and surface runoff, especially in case of heavy rain events[1, 8]. The Ogaki Dam on the Ukedo river retains some of the particulate faction depending on water levels (especially at high water levels), and can act as a source of dissolved caesium[1, 9].

In order to assure public safety and provide and independent source of information to the public and the local government, the current study is aimed at measuring ^{134}Cs and ^{137}Cs in airborne aerosol, river water and river sediment in the Evacuation-order-lifted Zone in Namie Town. This is a follow up to our previous study in the area[10], presenting two more years of data for the same area.

2. Experimental

Study area

Following up our previous study from 2017 August to 2018 February[10], we are presenting the results for the 2018 June to 2019 September time period. From the five locations selected for sampling of river water and sediments (Onoda, Sakata, Takase, Kiyohashi and Tanashio), one (Tanashio) was closed down due to construction works, and had to be excluded from this current study. The five locations selected to take air samples remained the same (Sawaue, Tasue, Takase, Kiyohashi, Kitatanashio). All sampling points cover local points of interest and were selected together with local authorities.

Figure 2 presents the precipitation data for the area taken from the precipitation data of the Japan

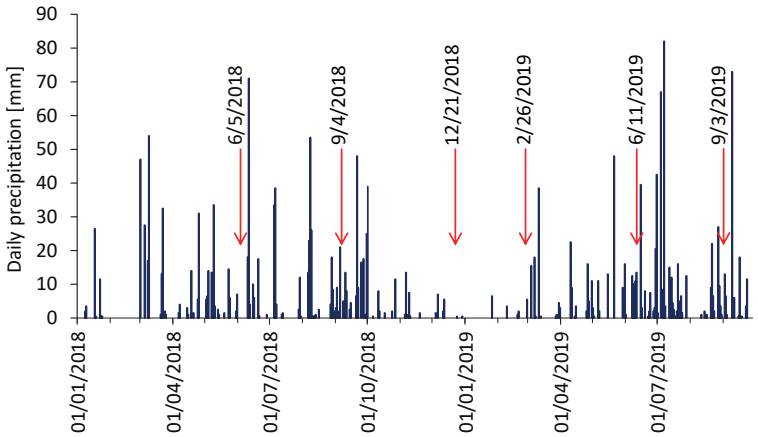

Fig. 2. Precipitation data for the area during the studied period, sampling dates are marked with the red arrows.

Meteorological Agency provided by the Automated Meteorological Data Acquisition System (AMeDAS)[11]. Precipitation influences the surface runoff, and the flow of the rivers in the area. The observed values range from 12/21/2018 with 0 mm precipitation on that day and 0 mm in a 7-day period to 6/11/2019 with 13.5 mm rain on that day and 47.5 mm in a 7-day period. The overall minimum precipitation was 0 mm per day, while the overall maximum was 82 mm on 7/7/2019.

Sampling

As in the previous study sediment sample collection was done by a small metal shovel into a cylindrical plastic container. One sample was taken per sampling location per sampling period[10]. The samples were sent on the same day to the laboratory, after arrival to the lab, the sediment samples were dried at 110°C for 24 h until achieving constant weight, sieved under 2 mm, and transferred into 100 mL cylindrical sample holders (PURATUBO 3-20 type 100 cm^3 sample holder, designated as U-8 type sample holder in Japan). The samples were measured for 80 000 s with a HPGe detector (ORTEC GEM30P4-70 with a 59 mm crystal diameter, 57.2 mm crystal length, 8.8 mm hole diameter, 43.3 mm hole depth and a X-COOLER III electronic cooling system. with a FWHM of 1.68 keV at 1.33 MeV and a relative efficiency of 35.78%. For the evaluation of the spectra, the Gamma Studio (Seiko EG&G, Japan) software was used. The software's inbuilt features were used to calculate the minimum detectable concentration, uncertainties, summing correction and decay correction to the date and time of the sampling; however, it has to be noted that the evaluation software does not consider the calibration uncertainty. Any calculation afterwards was done following the rules of uncertainty propagation. Maintenance is regularly performed by the manufacturer, and calibration is confirmed using standard sources on a regular schedule.

Similarly, as in the previous study, water samples were directly collected into 10 L collapsible plastic containers from the center of flow[10]. Each sample was divided into two 4 L subsamples, one measured without filtration, and one filtered by a 0.45 µm membrane filter (47 mm diameter Advantec cellulose acetate filter from Toyo Roshi Kaisha Ltd.) according to a procedure described by Ueda *et al.*[12]. Each subsample was passed through a 60 mm inner diameter ion-exchange column with a mixed bed of 40 g POWDEX PAO and 40 g POWDEX PCH type resin (Graver Technologies) at a flow rate of 20 mL per minute. The column was disassembled, the resin was dried until constant weight, was powdered by a metal spoon, and transferred to 100 mL cylindrical sample holders (U-8 type, as before). These samples were measured by the same HPGe detector for 80 000 s.

Air sampling was carried out by battery operated low volume air samplers (SIBATA LV-40BR type with 47 mm diameter Whatman glass microfibre filters set to 30 L/min sampling approximately 42 m^3 per day) at three locations, where electricity was not available, while the high volume air samplers (SIBATA HV-500R type with 110 mm diameter SIBATA PTFE filters set to 500 L/min sampling approximately 720 m^3 per day) were set up at two locations, where the local authorities provided a source of electricity. Both systems used pre-weighed filters. After the samples arrived back to the laboratory the filters were cleaned of foreign objects, mainly small flying insects. The filters were dried until achieving constant weight, and their weight was measured to be able to calculate the mass of the filtered material. The low volume filters were transferred directly to U-8 type sample holders, and were measured for 604 800 s, while the high-volume filters were folded to fit into the U-8 type

sample holders, and were measured for 80 000 s by the same HPGe detector.

Statistical analysis

Correlation between the observed ^{137}Cs activity concentration values of river sediment and the filtered and unfiltered water samples was evaluated using the Pearson correlation coefficient, which shows the measure of linear correlation between two values. This value can be obtained by the "PEARSON" function in Microsoft Excel.

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - x)^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (1)$$

The test statistics for the Pearson correlation coefficient is calculated as,

$$T = r * \sqrt{(N-2)/(1-r^2)} \quad (2)$$

The P value then is calculated using the T value, N–1 as the degrees of freedom, two tailed hypothesis and α = 0.05 significance level. This value can be obtained by the "TDIST" function in Microsoft Excel or the appropriate table can be used from a statistical handbook.

Dose assessment

To put the measured radionuclide concentration values in context the potential dose contribution was calculated making the same considerations as our previous study[10]. This could be informative for showing the relative risk carried by each environmental compartment, which could be used for risk management and communication purposes.

Based on Minato findings for in-situ gamma spectrometry, the gamma dose rate could be calculated as follows[13]:

$$D = \frac{C_{^{137}Cs}}{1000} * f_{^{137}Cs} * \rho_A + \frac{C_{^{134}Cs}}{1000} * f_{^{134}Cs} * \rho_A \quad (3)$$

where C is the concentration of the respective caesium isotopes in Bq/kg, f is the conversion factor in μGy/h per kBq/m^2, and ρ_A is the surface density in kg/m^2. The coefficients used for the calculations are 0.00268 μGy/h per kBq/m^2 for ^{137}Cs and 0.00685 μGy/h per kBq/m^2 for ^{134}Cs based on the ICRU53 report.

River water is unlikely to be directly consumed, but that is an easy way for placing the measured values in a frame of reference. The three water intake points of Namie Town are located next to the Ukedo and Takase rivers, however they use the bed of the river as a filter, and use wells to extract water from the water table.

The yearly committed effective dose (D_{water}) from the water consumption can be calculated by the following equation:

$$D_{water} = 365 * I * \sum C_i * f_{ci} \quad (4)$$

where, I is the consumption rate in L/day, C_i is the concentration of the respective caesium isotope in Bq/L, and f_{ci} is the committed effective dose coefficient for ingestion of the respective caesium isotope in Sv/Bq[14]. The coefficients used for the calculations are presented in the supplementary data.

The airborne radioactivity can be similarly assessed for the yearly committed effective inhalation dose (D_{Air}), but as previously there are some presuppositions. The aerosol is assumed respirable, and the shielding effect of buildings is not taken into account to keep the estimation conservative yielding an upper estimate[15].

$$D_{Air} = 365 * 24 * 3600 * \sum v_i * C_i * f_{ci} \quad (5)$$

where v_i is the inhalation rate in m^3/s, C_i is the concentration of the respective caesium isotope in Bq/L, and f_{ci} is the committed effective dose coefficient for the inhalation of the respective caesium isotope in Sv/Bq[15]. The coefficients used for the calculations are presented in the supplementary data.

The real values could be significantly lower, the reported decontamination factors in the Fukushima prefecture could be as low as 0.08, with the average of 0.58 and 0.52 in March and April in 2011, respectively. However this value shows great variability based on the type of the building and the particle size distribution of aerosols[16].

3. Results and discussion

Caesium concentration in sediment

Table 1 below presents the measured ^{137}Cs and ^{134}Cs concentrations in river sediment corrected to the sampling date.

The average activity concentration observed in river sediment was 992.8 Bq/kg for ^{137}Cs and 89.4 Bq/kg for ^{134}Cs, while the median activity concentration was 645.8 Bq/kg for ^{137}Cs and 60.1 Bq/kg for ^{134}Cs, respectively. The maximum concentration of 4040.6 ± 2.3 Bq/kg for ^{137}Cs and 404.1 ± 2.0 Bq/kg for ^{134}Cs were evaluated according to the method described by Minato[13] for *in-situ* gamma spectrometry. The originating estimated absorbed dose rates in air were calculated to be a maximum of 271.9 ± 0.4 nGy/h combined, while the average translates to 65.5 nGy/h combined and the median to 42.8 nGy/h combined. If compared to the actual values being measured in the area, these values are higher than those observed in the repopulated area[2], and the values reported by the

Table 1. Caesium activity concentrations in river sediment

Sampling date	Onoda ^{137}Cs (Bq/kg)	Takase ^{137}Cs (Bq/kg)	Ikusebashi ^{137}Cs (Bq/kg)	Sakata ^{137}Cs (Bq/kg)
6/5/2018	681.7 ± 1.1	1075.6 ± 13	467.1 ± 1.1	4040.6 ± 2.3
9/4/2018	590.8 ± 1.1	415.2 ± 1.0	353.5 ± 1.0	1641.9 ± 1.6
12/21/2018	951.7 ± 1.4	361.8 ± 1.0	610.0 ± 1.0	1539.2 ± 1.5
2/26/2019	819.2 ± 1.2	403.4 ± 1.0	538.6 ± 1.1	1659.7 ± 1.5
6/11/2019	387.0 ± 1.0	334.7 ± 1.0	562.0 ± 2.0	1926.8 ± 1.5
9/3/2019	413.0 ± 1.0	338.0 ± 1.0	419.0 ± 1.0	2002.8 ± 3.9
Sampling date	Onoda ^{134}Cs (Bq/kg)	Takase ^{134}Cs (Bq/kg)	Ikusebashi ^{134}Cs (Bq/kg)	Sakata ^{134}Cs (Bq/kg)
6/5/2018	69.5 ± 0.8	111.5 ± 1.0	46.1 ± 0.7	404.1 ± 2.0
9/4/2018	54.6 ± 0.7	39.0 ± 0.6	32.8 ± 0.6	149.7 ± 1.1
12/21/2018	82.2 ± 0.9	30.5 ± 0.5	53.3 ± 0.7	129.2 ± 1.0
2/26/2019	65.6 ± 0.8	32.8 ± 0.6	43.2 ± 0.6	133.3 ± 1.0
6/11/2019	29.4 ± 0.6	25.1 ± 0.5	40.7 ± 0.6	141.7 ± 1.0
9/3/2019	27.4 ± 0.5	22.6 ± 0.5	28.2 ± 0.5	135.7 ± 1.1

Japanese Nuclear Regulation Authority's monitoring information published for Namie Town. Furthermore, if compared to the previous data reported for the same area for the August 2017 to February 2018 period in the previous survey (maximum 3142.3 ± 2.4 nGy/h, average 288 nGy/h and median 132 nGy/h for ^{137}Cs and ^{134}Cs combined)[10], there is an observable decrease. The values measured at Sakata are higher than those measured at Onoda, Takase and Ikusebashi, the reason for this is that Sakata is located on the Ukedo river, while the other three are located on the Takase river. The Ogaki Dam is located upriver from our measurement point on the Ukedo river and it has been previously reported to be a reservoir for both particulate and dissolved caesium[9]. It is worth mentioning, that the calculation assumes a uniform plane source with a 2 g/cm^3 surface density, which is probably not the case, the calculated dose values are good for comparison purposes only. On the other hand, this calculation could be useful for evaluating the risk posed by the bulk deposition of sediment removed by civil engineering works, such as dredging, in advance. As in our previous study[10], it is worth mentioning that the sediment can be deposited outside the riverbed during flooding, which might pose a source of a radioactive aerosol in the area. This is not the only potential source, since the neighbouring Difficult-to-return-zone also poses the risk of dust and bio-aerosol containing radio-caesium[4, 5]. Fortunately, this is mentioned only as a possibility and one of the reasons for the monitoring, since as it can be seen on Table 4 below the measured airborne caesium concentrations are near the detection limit by our current setup and the resulting doses pose no significant risk, especially if compared to the natural background radiation.

At the time of closing down the Fukushima Dai-ichi Nuclear Power Plant the ^{134}Cs/^{137}Cs activity ratio of Unit 1 was calculated to be 0.941, while those of Unit 2 and Unit 3 were 1.082 and 1.046, respectively[17, 18]. Namie Town lies in the direction of the plume from the hydrogen explosion at Unit 1. Our observed ratios follow the expected curve from the physical radioactive decay, are in fairly good agreement with other reports on the area, including our previous observations at the same points[10]. Based on Figure 3, a large portion of the observed contamination seems to come from Unit 1, however it is worth mentioning that further measurements would be required for a more exact determination.

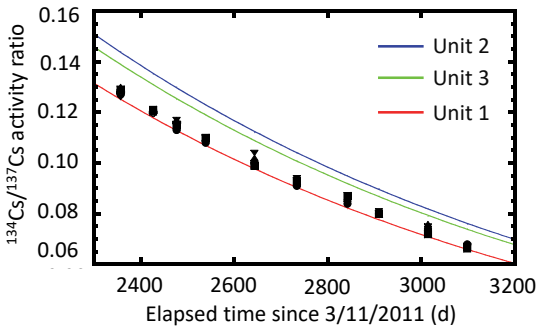

Fig. 3. ^{134}Cs/^{137}Cs activity ratio in river sediment, the coloured lines show the activity concentration ratios for material originating from the respective reactor units based on the radioactive decay[17, 18]

Caesium concentration in unfiltered water

Table 2 below shows the observed radionuclide concentrations in unfiltered river water. To put the values in perspective the limit for $^{134+137}$Cs in drinking water under the Japanese regulation is of 10 Bq/kg. All of our values are well below that limit (by two orders of magnitude).

Because of the differences in the half-lives of ^{134}Cs and

Table 2. Caesium activity concentrations in unfiltered river water

Sampling date	Onoda ^{137}Cs (mBq/L)	Takase ^{137}Cs (mBq/L)	Ikusebashi ^{137}Cs (mBq/L)	Sakata ^{137}Cs (mBq/L)
6/5/2018	< 14.7	32.4 ± 6.2	37.5 ± 6.1	171.5 ± 7.8
9/4/2018	39.8 ± 6.1	30.5 ± 6.0	24.9 ± 5.3	141.2 ± 7.0
12/21/2018	20.6 ± 6.0	<18.6	< 17.0	151.0 ± 8.2
2/26/2019	< 16.5	< 16.6	22.1 ± 5.5	65.8 ± 6.3
6/11/2019	19.0 ± 5.5	21.0 ± 5.7	20.4 ± 6.1	93.3 ± 7.1
9/3/2019	103.3 ± 6.8	87.5 ± 7.0	87.5 ± 7.0	205.9 ± 8.7
Sampling date	Onoda ^{134}Cs (mBq/L)	Takase ^{134}Cs (mBq/L)	Ikusebashi ^{134}Cs (mBq/L)	Sakata ^{134}Cs (mBq/L)
6/5/2018	< 15.8	< 21.5	< 20.8	< 22.0
9/4/2018	< 19.9	< 20.3	< 20.7	< 18.1
12/21/2018	< 20.2	< 20.8	< 20.1	< 20.8
2/26/2019	< 19.6	< 19.2	< 16.5	< 19.0
6/11/2019	< 16.2	< 18.5	< 18.5	< 17.4
9/3/2019	< 18.1	< 18.5	< 18.5	< 19.3

^{137}Cs, ^{134}Cs activity concentration values became less than the detection limit for all of the samples in both filtered and unfiltered river water samples. For both the filtered and the unfiltered river water the Ukedo river (Sakata) had the higher activity concentration values compared to the Takase River. The maximum value observed was at Sakata on 9/3/2019 (205.9 ± 8.7 mBq/L for ^{137}Cs and less than 19.3 mBq/L for ^{134}Cs), and if it were to be evaluated for drinking water consumption, it would equal to approximately 2.2×10^{-3} mSv/y for adults, 8.5×10^{-4} mSv/y for 10-year old children and 7.6×10^{-4} mSv/y for infants. This value serves only as a base for comparison, since river water is unlikely to be consumed directly, and because the conversion ratios for dissolved and bound caesium species are different[19]. In addition, if compared to the natural background dose, this is multiple orders of magnitude lower than the 2.1 mSv/y Japanese average annual effective dose from background radiation or the estimated 1.9 mSv/y average annual effective dose from background radiation for the evacuees from Namie Town [20].

Figure 4 shows multiple things, first the majority of the observed values are fairly low, second, Sakata has the highest concentrations both in sediment and in unfiltered river water. The Pearson Correlation Coefficient indicated a weak positive linear correlation for the Sakata sampling point (r = 0.37, P = 0.4668), a weak negative linear correlation for the Ikusebashi sampling point (r = -0.38, P = 0.5123), and a moderate positive correlation for the whole dataset (r = 0.71, P = 0.0006) between the observed sediment and unfiltered river water values. This amount of data however is not enough to draw a well-grounded conclusion.

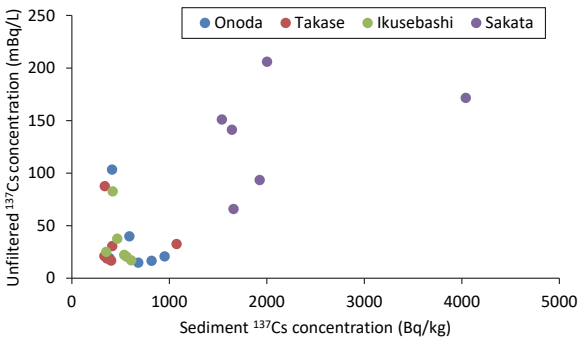

Fig. 4. Radiocaesium activity concentrations in unfiltered river water plotted against those in river sediment

Caesium concentration in filtered water

Table 3 shows the data for filtered river water. Compared to the unfiltered data the dissolved amount ranges from less than 16% to a 100 %, making even more of the data points fall under the detection limit.

The maximum activity concentration in filtered river water was 123.8 ± 7.1 mBq/L for ^{137}Cs and less than 16.8 mBq/L for ^{134}Cs, which would, if it were to be evaluated for drinking water consumption, equal to approximately 1.4×10^{-3} mSv/y for adults, 5.4×10^{-4} mSv/y for 10-year old children and 4.8×10^{-4} mSv/y for infants, which is even less than the values for unfiltered river water, and similarly, pales in comparison with the natural background radiation. The filtration process can lead to the formation of a filter cake or spent ion-exchanger cartridges rich in caesium which might, which could possibly require the attention of the local authorities. In case of Namie the riverbed is used as a filter, and the water is taken out by wells out of the water table, so the problem of filter cakes does not emerge. The two highest precipitation days have shown different behaviour, the 6/11/2019 sampling round had the most precipitation both on the day and the week while having relatively

Table 3. Caesium activity concentrations in filtered river water

Sampling date	Onoda ^{137}Cs (mBq/L)	Takase ^{137}Cs (mBq/L)	Ikusebashi ^{137}Cs (mBq/L)	Sakata ^{137}Cs (mBq/L)
6/5/2018	< 13.6	22.6 ± 5.5	< 18.2	93.7 ± 6.4
9/4/2018	< 16.9	10.6 ± 2.5	< 18.2	41.5 ± 3.1
12/21/2018	< 18.0	< 19.5	25.7 ± 5.9	91.8 ± 7.1
2/26/2019	< 17.3	< 18.1	< 19.9	66.9 ± 6.3
6/11/2019	< 18.2	< 15.8	19.6 ± 5.4	94.2 ± 7.0
9/3/2019	< 16.1	< 17.6	< 17.6	123.8 ± 7.1
Sampling date	Onoda ^{134}Cs (mBq/L)	Takase ^{134}Cs (mBq/L)	Ikusebashi ^{134}Cs (mBq/L)	Sakata ^{134}Cs (mBq/L)
6/5/2018	< 14.8	< 20.1	< 20.9	20.0 ± 5.9
9/4/2018	< 21.4	< 11.2	< 19.5	< 11.6
12/21/2018	< 19.2	< 20.8	< 18.8	< 20.0
2/26/2019	< 18.2	< 19.7	< 21.7	< 19.5
6/11/2019	< 19.1	< 17.4	< 18.4	< 17.1
9/3/2019	< 19.4	< 19.5	< 19.6	< 18.6

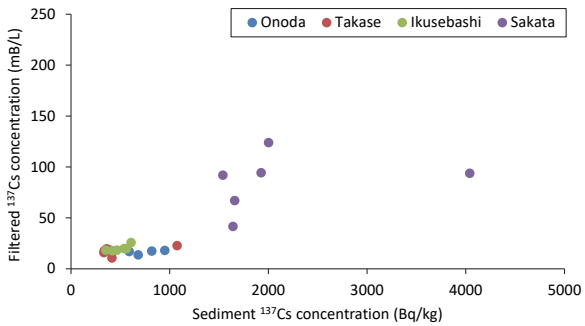

Fig. 5. Radiocaesium activity concentrations in filtered river water plotted against those in river sediment

high amounts of dissolved radio-caesium, while the second highest precipitation on and the week leading up to 9/3/2019 had one of the lowest rates of dissolved radio-caesium observed. Even the days which had no precipitation for a week prior to the sample collection show a wide range of suspended solid ratios.

Figure 5, especially compared to Figure 4, shows some additional information. Most of the data-points on the Takase river were near or below the detection limit, while Sakata on the Onoda river has comparatively higher amounts of dissolved caesium, probably due to the effects of the Ogaki Dam upriver[1, 9]. The Pearson Correlation Coefficient indicated a weak positive linear correlation for the Sakata sampling point (r = 0.27, P = 0.6038), and a moderate positive correlation for the whole dataset (r = 0.71, P = 0.0180) between the observed sediment and filtered river water values. This amount of data however is not enough to draw a well-grounded conclusion. Comparing the two Figures, both the Takase and the Ukedo rivers transport radio-caesium bound to suspended solids on occasion, with the Ukedo river being more proliferous in this regard.[1, 9]. The Pearson Correlation Coefficient indicated a moderate positive linear correlation for the Sakata sampling point (r = 0.52, P = 0.1560), and a moderate to strong positive correlation for the whole dataset (r = 0.81, P = 0.0045) between the observed unfiltered and filtered river water values. This amount of data however is not enough to draw a well-grounded conclusion.

Airborne caesium concentration

As it can be seen on Figure 6, the results for the airborne radio-caesium monitoring can be split into two categories, Tasue and Sawaue being high volume and Kiyohashi, Kiatatanashio and Takase being low volume sampling points. During the measurements there has been two equipment malfunctions, Kiyohashi on the 2/26/2019 sampling trip had a battery connection failure, and Tasue on the 6/11/2019 sampling trip had a blower error failure, both resulting in less air passed through the filter. Most of the ^{137}Cs, and all of the ^{134}Cs values were below the detection limit. Even if we were to estimate the annual committed effective doses for different age groups based on the maximum values derived from the 2/26/2019 sample from Kiyohashi (less than 4 000 μBq/m^3 for ^{137}Cs and less than less than 5 000 μBq/m^3 for ^{134}Cs), which is one order of magnitude higher than all other data, the resulting dose values would be less than 4.8 $\times 10^{-4}$ mSv/y for outdoor workers, 4.2 $\times 10^{-4}$ mSv/y for indoor workers, 2.3 $\times 10^{-4}$ mSv/y for 10-year olds and 1.1 $\times 10^{-4}$ mSv/y for infants respectively, without taking into account the shielding effects of buildings. In spite of some concerns about the possibility radioactive aerosol coming from difficult-to-return, the current survey shows that the potential contribution of the aerosol to the annual committed effective dose through inhalation is miniscule.

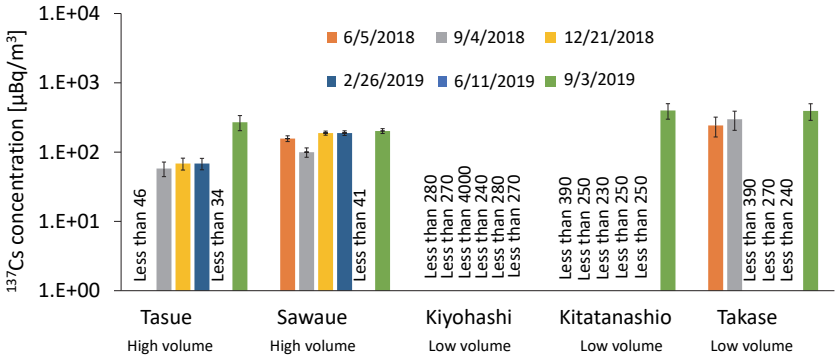

Fig. 6. Radiocaesium activity concentrations in airborne aerosol

Even the most conservative value is approximately four orders of magnitude lower than the natural background of the 2.1 mSv/y Japanese average annual effective dose from background radiation or the estimated 1.9 mSv/y average annual effective dose from background radiation for the evacuees from Namie Town[20].

4. Conclusions

The sediment has the greatest potential to cause excess radiation dose, on a similar scale to the natural background. The estimated doses were maximum of 271.9 ± 0.4 nGy/h combined, with an average of 65.5 nGy/h combined and a median of 42.8 nGy/h combined. This is an overestimation compared to the actual dose rates measurable in the area. Compared to the previous survey (average of 288 nGy/h and a median of 132 nGy/h) the observed values had decreased considerably[10].

The observed radio-caesium concentrations in unfiltered river water were maximum 205.9 ± 8.7 mBq/L for ^{137}Cs and less than 19.3 mBq/L for ^{134}Cs), and if it were to be evaluated for drinking water consumption, it would equal to approximately 2.2×10^{-3} mSv/y for adults, which pales in comparison with the natural background. This would be further reduced by filtration, the dissolved amount ranges from less than 16 % to a 100 %. The observed radio-caesium concentrations in filtered river water were maximum 123.8 ± 7.1 mBq/L for ^{137}Cs and less than 16.8 mBq/L for ^{134}Cs, which would, if it were to be evaluated for drinking water consumption, would at most equal to approximately 1.4×10^{-3} mSv/y for adults. To further put the values in perspective, the limit for $^{134+137}$Cs in drinking water under the Japanese regulation is of 10 Bq/kg, which is 2 orders of magnitude higher than the values observed in the current survey. The concentrations observed in air are near or below the detection limit of our current experimental setup. Even if the highest value (less than 4000 μBq/m^3 for ^{137}Cs and less than less than 5000 μBq/m^3 for ^{134}Cs) obtained during an equipment malfunction were to be evaluated for inhalation, the resulting dose values would be less than 4.8×10^{-4} mSv/y for any age group, which is quite small compared to the natural background. It should be noted that the calculated dose rates are just estimations based on assumptions, and should be used only as a basis for comparing the relative risks.

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Conflict of Interest

All the authors report no conflicts of interest.

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