Chapter 18
Probabilistic Assessment of Doses to the Public Living in Areas Contaminated by the Fukushima Daiichi Nuclear Power Plant Accident

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Abstract Many residents are exposed to radiation in their daily lives in the areas contaminated by radioactive materials by the Fukushima Daiichi Nuclear Power Plant accident. To protect the people from radiation exposures adequately, dose assessment is necessary. The aim of this study is to provide the scientifically based quantitative information about a range of received doses to the people from the evacuation areas and the deliberate evacuation areas. To achieve this aim, we adopted a probabilistic approach that can provide the information about a range of doses and their likelihood of occurrence taking into account uncertainty and variability of input data. The dose assessment was performed based on the measurement data of the surface activity concentrations of ^{137}Cs and the results of actual survey on behavioral patterns of the population groups living in Fukushima Prefecture. As the result of assessment, the 95th percentile of the annual effective dose received by the inhabitants evacuated was mainly in the 1–10 mSv dose band in the first year after the contamination. However, the 95th percentile of the dose received by some outdoor workers and inhabitants evacuated from highly contaminated areas was in the 10–50 mSv dose band.

Keywords Behavioral pattern • Dose assessment • Exposure pathways • Fukushima Daiichi Nuclear Power Plant Accident • Measurement data • Probabilistic approach • Public exposure

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S. Takahashi (ed.), *Radiation Monitoring and Dose Estimation of the Fukushima Nuclear Accident*, DOI 10.1007/978-4-431-54583-5_18,

18.1 Introduction

After the Tohoku District Pacific Ocean Earthquake, large tsunamis struck the Fukushima Daiichi Nuclear Power Plant (1F Plant), which led to a nuclear accident that released a large amount of radioactive materials into the environment [1]. In the areas contaminated by the accident, many residents are now being exposed to radiation through various exposure pathways in their daily lives. To protect people from radiation exposures and manage the exposure situation appropriately, a suitable dose assessment is necessary [2]. The aim of this study is to provide preliminary results of the assessment of radiation doses received by the inhabitants of Fukushima Prefecture. This assessment is intended to be realistic and comprehensive. For this purpose, the doses are assessed by a probabilistic approach based on environmental monitoring data and realistic lifestyle habits in Fukushima prefecture.

18.2 Method

18.2.1 Scope

In the early phase of the accident, inhabitants were evacuated to prevent and reduce radiation exposure. The National Institute of Radiological Sciences (NIRS) suggested 18 evacuation scenarios according to the Fukushima health management survey [3]. These scenarios are listed in Table 18.1. Figure 18.1 shows the municipalities related to the evacuation scenarios and area classification of Fukushima Prefecture. Most people within the 20 km from the nuclear power plant were rapidly evacuated within a few days after the accident (evacuation scenario no. 1–12). However, some areas including Namie Town, Katsurao Village, Iitate Village, Minami Soma City, and Kawamata Town were later designated as "deliberate evacuation areas" based on environmental monitoring data (evacuation scenario no. 13–18).

Doses were assessed for the inhabitants evacuated, as well as for the inhabitants who continued to live in Fukushima City, Koriyama City, and Iwaki City after the contamination occurred. The doses were assessed for the population living in an urban environment, such as Fukushima City and Koriyama City, whereas the rural environment prevails in some municipalities in Fukushima Prefecture. Further assessments will be needed taking into account both urban and rural environments.

The dosimetric endpoints of the study are the effective doses received by adults in the first year after the contamination and over the inhabitants' lifetimes.[1] The total effective doses were calculated as the summation of those received by inhabitants in the municipalities listed in each evacuation scenario. The present study assumed that other protective actions such as sheltering and stable iodine uptake were not

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[1] The integrated period is 60 years for adults.

Table 18.1 Evacuation scenarios for the population living in the evacuation area or the deliberate evacuation area based on the Fukushima health management survey [3]

Evacuation scenario no.	Municipality where the residence or evacuation facility is located and the length of stay during the period 11 Mar 2011 to 14 Mar 2012[a]		
1	Tomioka Town ~06:00, 12 Mar 2011	Kawachi Village ~10:00, 16 Mar 2011	Koriyama City ~14 Mar 2012
2	Okuma Town ~13:00, 12 Mar 2011	Tamura City ~14 Mar 2012	–
3	Futaba Town ~08:00, 12 Mar 2011	Kawamata Town ~10:00, 19 Mar 2011	Saitama Prefecture ~14 Mar 2012
4	Futaba Town ~16:00, 12 Mar 2011	Kawamata Town ~10:00, 19 Mar 2011	Saitama prefecture ~14 Mar 2012
5	Naraha Town ~13:00, 12 Mar 2011	Iwaki City ~10:00, 31 Mar 2011	Tamura City ~14 Mar 2012
6	Naraha Town ~13:00, 12 Mar 2011	Iwaki City ~10:00, 16 Mar 2011	Aizu Misato Town ~14 Mar 2012
7	Namie Town ~10:00, 15 Mar 2011	Namie Town ~10:00, 16 Mar 2011	Nihonmatsu City ~14 Mar 2012
8	Tamura City ~08:00, 12 Mar 2011	Tamura City ~10:00, 31 Mar 2011	Koriyama City ~14 Mar 2012
9	Minami Soma City ~10:00, 15 Mar 2011	Date City ~10:00, 31 Mar 2011	Fukushima City ~14 Mar 2012
10	Hirono Town ~08:00, 12 Mar 2011	Ono Town ~14 Mar 2012	–
11	Kawachi Village ~10:00, 13 Mar 2011	Kawachi Village ~10:00, 16 Mar 2011	Koriyama City ~14 Mar 2012
12	Katsurao Village ~10:00, 14 Mar 2011	Fukushima City ~14 Mar 2012	–
13	Namie Town ~10:00, 23 Mar 2011	Nihonmatsu City ~14 Mar 2012	–
14	Katsurao Village ~10:00, 21 Mar 2011	Fukushima City ~14 Mar 2012	–
15	Iitate Village ~10:00, 29 May 2011	Fukushima City ~14 Mar 2012	–
16	Iitate Village ~10:00, 21 June 2011	Fukushima City ~14 Mar 2012	–
17	Minami Soma City ~10:00, 20 May 2011	Minami Soma City ~14 Mar 2012	–
18	Kawamata Town ~10:00, 1 June 2011	Kawamata Town ~14 Mar 2012	–

[a] The dose assessment was performed with the assumption that the inhabitants stayed in the same municipality after movement to the final evacuation facility

implemented. Radiation exposure occurs through several pathways. The present study assessed the doses from external exposure to radionuclides deposited on the ground (hereafter referred to as groundshine) and to radionuclides in the radioactive cloud (hereafter referred to as cloudshine) as well as the doses caused by internal exposure through inhalation of radionuclides in the radioactive cloud.

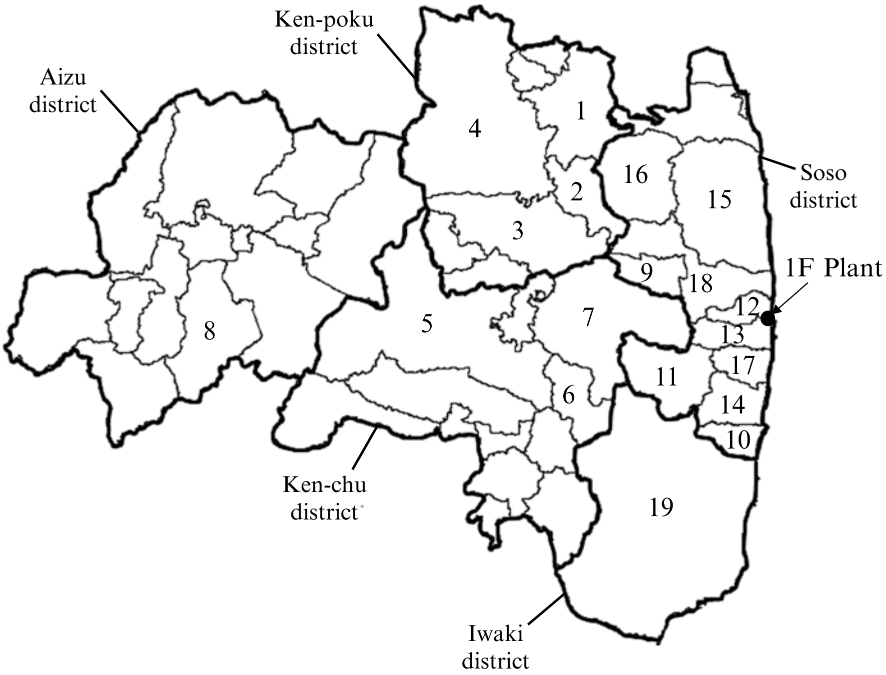

Fig. 18.1 Municipalities related to the 18 evacuation scenarios and area classification of Fukushima Prefecture. The numbers shown in this map represent municipalities listed in Table 18.5

The doses from inhalation of noble gases and radioactive materials resuspended from the ground surface were not included in the assessments. This assumption was adopted according to a World Health Organization (WHO) report [2], which mentions such inhalations are not expected to provide a significant contribution to radiation exposure. Also, the doses from cloudshine caused by noble gases cannot be considered in the present study. In addition, internal radiation doses from ingestion pathways were not included. The measurements of the doses resulting from the ingestion of contaminated food and water are being performed using a whole-body counter. The doses acquired from the ingestion pathway should be assessed with considerations about the results of measurements in the future.

18.2.2 Probabilistic Techniques in Radiation Dose Assessment

In the present study, we used a probabilistic approach to assess the doses to the public living in areas contaminated by radioactive materials released from the 1F Plant. Probabilistic approach in exposure assessments, which are a well-established

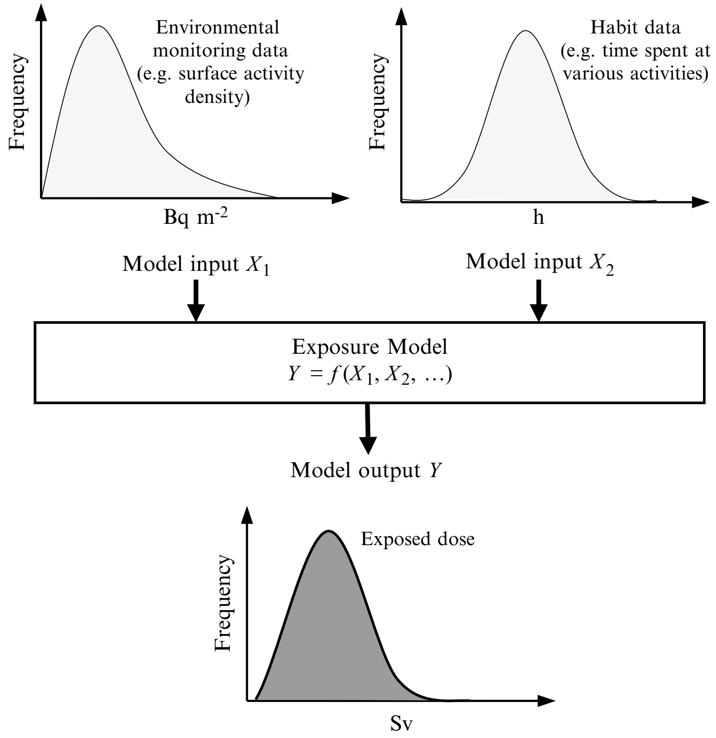

Fig. 18.2 Schematic illustrating the application of probabilistic approach to assess radiation doses

method to describe a diverse set of environmental hazards, can yield a fuller characterization of the information on the dose distributions in the population [4–8]. Application of this approach needs statistically characterized data on the contributors, such as the concentrations of radionuclides in environmental media data and habits data relevant to the exposure pathways [8].

Figure 18.2 illustrates the general process of applying a probabilistic approach to assess radiation doses. One sample from each input distribution is selected based on the statistical characteristics, and the set of samples is entered into the model. The process is repeated until the specified numbers of model iterations have been completed. As a result, it is possible to represent a distribution of the output of a model by generating sample values for the model input. In the present study, we used the probabilistic distributions of surface activity of ^{137}Cs and time the people spent outdoors as input of the calculations of doses.

Table 18.2 Parameters for location factors of cesium for an urban environment [11]

Type of location	$a_{l,1}$	$a_{l,2}$	T_l (years)
Virgin land	0.32	0.68	1.4
Dirt surface	0.50	0.25	2.2
Asphalt	0.56	0.12	0.9

18.2.3 Models for Assessing Doses from External and Internal Exposures

18.2.3.1 External Exposure to Deposited Radionuclides

The effective dose received by population group *j* from groundshine E_j^{gd} in each municipality listed in the evacuation scenarios is represented by

$$E_j^{gd} = \sum_l \left\{ \int f_l\left(t\right) \cdot \left\{ s_{gd} \cdot p_{l,in,j} + p_{l,out,j} \right\} \cdot \dot{E}_{\mathrm{v}}^{gd}\left(t\right) \mathrm{d}t \right\}, \tag{18.1}$$

where *j* is the index for population types; *l* is the index for location types; $\dot{E}_{\mathrm{v}}^{gd}\left(t\right)$ is the effective dose rate from groundshine at locations of virgin land in the urban environment (Sv h^{-1}); $f_l(t)$ is the location factor for urban locations of type *l*, $p_{l,\mathrm{in\ (or\ out)},j}$ is the ratio of time spent indoors (or outdoors) at location type *l* to that of the assessment period; and s_{gd} is the shielding factor for groundshine.

The index *l* for location types represents virgin land, dirt surfaces, and asphalt, which are classified according to the characteristics of the ground surface [9–11]. The location factors are defined by dividing the dose rates at a given location by those at an open undisturbed field [9–11]. The location factors are represented as a function of the time elapsed after the contamination, as follows:

$$f_l\left(t\right) = a_{l,1} \cdot \exp\left(-\frac{\ln 2}{T_l} \cdot t \right) + a_{l,2}, \tag{18.2}$$

where $a_{l,1}$, $a_{l,2}$, and T_l are fitting parameters for the location factors of cesium. The values of these parameters are listed in Table 18.2; they were determined from data obtained from the Chernobyl accident [11].

The ratio of time spent at location type *l* for the assessment period was defined as a fraction of the average time spent in a day at location *l*, as follows:

$$p_{l,in(or\,out),j} = \frac{t_{l,in(or\,out),j}}{24}, \tag{18.3}$$

where $t_{l,\mathrm{in(or\ out)},j}$ is the time spent indoors (or outdoors) in a day at location *l* by an individual of population group *j*.

In the present study, the calculations were performed for indoor workers, outdoor workers, and pensioners on the assumption that they live in the urban areas. It is assumed that indoor workers and pensioners spend all day in areas paved with asphalt. However, it is assumed that outdoor workers spend their working hours in areas classified as dirt surfaces in an urban environment.

The values of $t_{l,\mathrm{in(or\ out)},j}$ were determined by generating random numbers in accordance with the probabilistic distribution functions obtained from the surveys in Fukushima Prefecture. In the survey we measured time spent indoors and outdoors for the three population groups of indoor workers, outdoor workers, and pensioners. The indoor workers surveyed were from the Fukushima City office and the outdoor workers were from the Northern Fukushima affiliate of Contractors Association and Japan Agricultural Cooperatives. In the present study, data surveyed for the month of February, March, and April 2012 were used.

To determine the distribution form of time spent outdoors of each population group, normality tests were performed for time spent outdoors in a day and its logarithmic values. When the normality was examined for the logarithmic values of that of indoor workers, the results of the *p* values were more than 5 %. Log-normal distribution was thus assumed for the time spent outdoors by indoor workers. Hereafter, the significance level of 5 % is used to determine whether the null hypothesis is rejected. The results of similar analyses performed for time spent outdoors of the other population groups indicated that the distribution was normal for outdoor workers and log-normal for pensioners. The statistical values to determine the probabilistic distribution functions of $t_{l,\mathrm{in(or\ out)},j}$ are listed in Table 18.3.

The shielding factor s_{gd} for gamma radiation from deposited radionuclides is defined as the ratio of ambient doses inside a house to those outside. Figure 18.3 shows the correlation between the ambient dose rate measured inside and outside houses. The dosimetric surveys were made for 130 households in Fukushima Prefecture during a period between October 2 and November 11, 2012. The breakdown of building types is as follows: 124 one- or two-story wood frame houses, and 6 concrete houses with one or more stories. The calculations were performed using a shielding factor s_{gd} of 0.4. This value were determined conservatively based on the ratio of the ambient dose rate measured inside and those measured outside (Fig. 18.3).

The effective dose rate from groundshine at locations of virgin land is given by the following form:

$$\dot{E}_{\mathrm{v}}^{gd}(t) = r(t)\sum_{i}\left\{k_{gd,i}\cdot C_i \cdot A_{Cs137}(0)\cdot \exp(-\lambda_i \cdot t)\right\}, \tag{18.4}$$

where $r(t)$ is the attenuation function of dose rate from migration of ^{137}Cs into the soil; C_i is the ratio of the surface activity density of radionuclide i to that of ^{137}Cs; A_{Cs137} (0) is the initial value of the surface activity density of ^{137}Cs (Bq m^{-2}); λ_i is the decay constant for radionuclide i (h^{-1}); and $k_{\mathrm{gd},i}$ is the effective dose coefficient from surface density activity ((Sv h^{-1})/(Bq m^{-2})).

Table 18.3 Statistical values to determine the probabilistic distribution functions of time spent outdoors for each population group

Population group[a]	Distribution form	Mean (h)	Deviation
Indoor worker	Log-normal	0.57[b]	3.28[d]
Outdoor worker	Normal	6.97[c]	2.90[e]
Pensioner	Log-normal	1.27[b]	3.37[d]

[a] Indoor worker means Fukushima City office workers; outdoor worker includes construction workers and farmers

[b] GM

[c] AM

[d] GSD

[e] SD

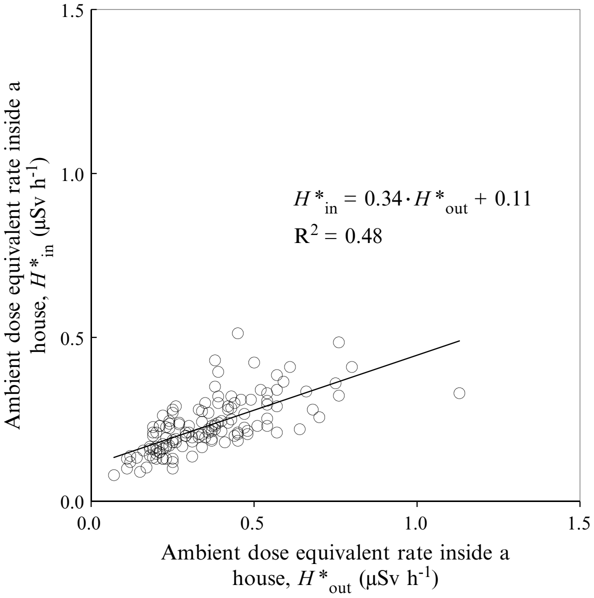

Fig. 18.3 Correlation between ambient dose equivalent rates measured inside and outside houses

The attenuation function $r(t)$ is given by the following equation [2, 9–12]:

$$r(t) = p_1 \cdot \exp\left(-\frac{\ln 2}{T_1} \cdot t\right) + p_2 \cdot \exp\left(-\frac{\ln 2}{T_2} \cdot t\right). \tag{18.5}$$

The parameter values were $p_1 = 0.34$, $p_2 = 0.66$, $T_1 = 1.5$ years, and $T_2 = 50$ years [2, 12].

Radioactive fallout and contamination in most of the contaminated areas of Fukushima Prefecture were estimated to have occurred on March 15 or 16, 2011 because the gamma dose rate in air suddenly increased over the background radiation rates during these days [13]. In the present study, the doses were assessed

Table 18.4 Composition of radionuclides deposited on March 15, 2011 [2]

Radionuclides	Deposited activity normalized by ^{137}Cs
^{131}I	11.7
^{132}I	–[a]
^{132}Te	8.0
^{134}Cs	0.94
^{136}Cs	0.2
^{137}Cs	1.0
^{140}Ba	0.1
^{140}La	–[a]
^{110m}Ag	0.01
^{129m}Te	1.5

[a] Activity of ^{132}I and ^{140}La was derived from that of the parent nuclide, i.e., ^{132}Te and ^{140}Ba, assuming radioactive equilibrium

with the assumption that the contamination occurred at 00:00 on March 15, 2011.[2] The ratio of the surface activity density of each radionuclide i to that of ^{137}Cs was determined according to the report of WHO [2]. The relative isotopic composition of deposited radionuclides is listed in Table 18.4.

Equation (18.4) was calculated using values of $A_{\mathrm{Cs137}}(0)$ produced by the random number generator according to the distributions of the measured surface density of ^{137}Cs for each municipality listed in the evacuation scenarios. The distributions of the surface activity density of ^{137}Cs on March 15, 2011 were derived from the monitoring data measured by MEXT[3] [14]. The soil samples were collected from a 5-cm surface layer within 80 km of the 1F Plant.[4] In principle, the measurements were conducted at a single location per 2×2 km^2 grid for these areas. The details of the surface density of ^{137}Cs are discussed in Sect. 18.2.4. The effective dose coefficients were obtained from a U.S. Environmental Protection Agency (EPA) report [16].

18.2.3.2 External Exposure to the Radioactive Cloud

The effective dose received by population group j from cloudshine E_j^{cd} is represented by

$$E_j^{cd} = p_{in,j} \cdot s_{cd} \cdot E_{out}^{cd} + p_{out,j} \cdot E_{out}^{cd}, \tag{18.6}$$

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[2] The data presented in this paper used Japan Time [i.e., Greenwich mean time (GMT) plus 9 h].

[3] MEXT is the abbreviation for the Ministry of Education, Culture, Sports, Science and Technology of Japan.

[4] The soil samples had been collected prior to the rainy season in Japan, from June 6 to June 14 and from June 27 to July 8, 2011, so that the level of contamination could be observed before any changes occurred on the soil surface [15].

where $p_{\mathrm{in},j}$ is the ratio of time spent indoors; $p_{\mathrm{out},j}$ is the ratio of time spent outdoors; $E_{\mathrm{out}}^{\mathrm{cd}}$ is the effective dose from cloudshine outdoors (Sv); and s_{cd} is shielding factor for cloudshine from radionuclides in the radioactive cloud.

The ratio of time spent indoors or outdoors was calculated as the total time spent indoors or outdoors in various locations per day. To calculate the external doses from the radioactive cloud, $E_{\mathrm{out}}^{\mathrm{cd}}$, it was necessary to convert the surface density of radionuclides to time-integrated activity concentrations in air. Noble gases, which do not deposit on the ground surfaces, were not included in the calculations.

The effective dose from cloudshine outdoors, $E_{\mathrm{out}}^{\mathrm{cd}}$, is represented as follows:

$$E_{out}^{cd} = \sum_i \left(\frac{C_i \cdot A_{Cs137}(0)}{V_i} \right) \cdot k_{cd,i}, \tag{18.7}$$

where V_i is the bulk deposition velocity of radionuclide i (m s^{-1}) and $k_{\mathrm{cd},i}$ is the effective dose coefficient for air submersion of radionuclide i (Sv/(Bq s m^{-3}).

The deposition velocity V_i is determined according to the method in the WHO preliminary report [2]. The areas in which the surface density of ^{137}Cs, A_{Cs137}, is higher than or equal to 30 kBq m^{-2} were treated as being contaminated through wet deposition, with deposition velocities of $V_{\mathrm{I\text{-}131}} = 0.07$ m s^{-1} for ^{131}I and $V_{\mathrm{other}} = 0.01$ m s^{-1} for other radionuclides. If the surface density A_{Cs137} is less than 30 kBq m^{-2}, then the contamination originated from dry deposition with deposition velocities of $V_{I\text{-}131} = 0.01$ m s^{-1} for ^{131}I and $V_{\mathrm{other}} = 0.001$ m s^{-1} for other radionuclides. The doses from cloudshine and inhalation were calculated using the surface densities of ^{137}Cs in the municipality where the inhabitants stayed while the radioactive plumes passed.

The value of 0.6 was used as the shielding factor s_{cd} for gamma radiation from the radioactive plume [17]. The effective dose coefficients $k_{\mathrm{cd,i}}$ were obtained from an EPA report [16].

18.2.3.3 Internal Exposure Through Inhalation of Radionuclides

The effective dose received by the population group j from internal exposure through inhalation of radionuclide i in the radioactive cloud E_j^{inh} is represented by

$$E_j^{inh} = p_{l,in,j} \cdot f \cdot E_{out}^{inh} + p_{l,out,j} \cdot E_{out}^{inh}, \tag{18.8}$$

where $E_{\mathrm{out}}^{\mathrm{inh}}$ is the effective dose from inhalation of radionuclide i in the radioactive cloud (Sv); f is the filtering factor for a house.

To prevent underestimation of doses in the calculation, the value of 1 was adopted for the filtering factor f. $E_{\mathrm{out}}^{\mathrm{inh}}$ is given as

$$E_{out}^{inh} = \sum_i \left(\frac{C_i \cdot A_{Cs137}(0)}{V_i} \right) \cdot B \cdot k_{inh,i}, \tag{18.9}$$

where B is the breathing rate for adults (L day^{-1}) and $k_{\mathrm{inh},i}$ is the effective dose coefficient for inhalation of radionuclides i (Sv Bq^{-1}).

The value of 22.2 L day^{-1} was adopted as the breathing rate of adults from the recommendation of the International Commission on Radiological Protection (ICRP) Publication 71 [18]. The effective dose coefficients for inhalation were also obtained from the same publication [18].

18.2.4 Input Monitoring Data of the Surface Activity Density of ^{137}Cs

To determine the distribution form of the surface density of ^{137}Cs, normality tests were performed for the logarithmic values of the surface density for each municipality. The data measured by MEXT [14] were used for the tests, which decay corrected to 0:00 on March 15, 2011. The p values of the tests for municipalities other than Fukushima City, Koriyama City, Nihonmatsu City, Tamura City, and Namie Town were higher than the significance level of 5 %, so the null hypothesis was not rejected.[5] The normality tests for Fukushima City and Namie Town yielded p values of 0.044 and 0.036, respectively. Because the values were close to 5 %, these two municipalities were treated in the same manner as those without normality rejection. Therefore, log-normal distribution was assumed for the surface density of ^{137}Cs for these municipalities.

The p values of the tests for the distributions for Koriyama City, Nihonmatsu City, and Tamura City were considerably lower than the significance level of 5 %. Thus, the null hypothesis for these tests was rejected. Although the following calculations assume log normality in the surface density distributions for municipalities including Koriyama City, Nihonmatsu City, and Tamura City, attention should be paid to the limitations already mentioned.

The geometric mean (GM) and geometric standard deviation (GSD) of the surface densities for each municipality of Fukushima Prefecture are listed in Table 18.5. Futaba Town, Okuma Town, and Namie Town are the most highly contaminated areas, and the values of the GM for the surface densities of ^{137}Cs are 1.53, 1.23, and 0.97 MBq m^{-2}, respectively. The next most highly contaminated municipalities are Iitate Village, Tomioka Town, and Katsurao Village, whose surface densities are 0.61, 0.60, and 0.26 MBq m^{-2}, respectively. The surface density levels of ^{137}Cs for the other municipalities of the Soso area, that is, Hirono Town, Kawauchi Village, Naraha Town, and Minami Soma City, are comparable to the levels for the municipalities in the Ken-poku and Ken-chu districts.

The surface densities of ^{137}Cs in municipalities in the Ken-poku and Ken-chu districts are about 0.1 and 0.02–0.07 MBq m^{-2}, respectively. The surface density of ^{137}Cs for the Iwaki City was the lowest among the values for the municipalities listed in the evacuation scenarios.

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[5] In other words, it concludes that the surface density data for these municipalities are from a lognormal-distributed population.

Table 18.5 Surface density of ^{137}Cs for each municipality of Fukushima Prefecture

Area	Municipality		Sample size	GM (Bq m^{-2})	GSD
Ken-poku District	1	Date City	60	1.29E+05	1.94E+00
	2	Kawamata Town	38	1.40E+05	1.87E+00
	3	Nihonmatsu City	82	1.20E+05	2.00E+00
	4	Fukushima City	94	1.25E+05	2.13E+00
Ken-chu District	5	Koriyama City	118	6.76E+04	2.71E+00
	6	Ono Town	31	2.16E+04	1.48E+00
	7	Tamura City	109	3.78E+04	2.81E+00
Aizu District	8	Aizu Misato Town	2	1.22E+04	1.34E+00
Soso District	9	Katsurao Village	18	2.56E+05	1.94E+00
	10	Hirono Town	14	6.79E+04	1.77E+00
	11	Kawauchi Village	37	1.01E+05	2.42E+00
	12	Futaba Town	9	1.53E+06	3.67E+00
	13	Okuma Town	14	1.23E+06	3.90E+00
	14	Naraha Town	16	9.18E+04	2.61E+00
	15	Minami Soma City	78	1.06E+05	2.81E+00
	16	Iitate Village	53	6.08E+05	1.77E+00
	17	Tomioka Town	16	5.98E+05	2.90E+00
	18	Namie Town	38	9.66E+05	4.02E+00
Iwaki District	19	Iwaki City	266	2.15E+04	2.14E+00

18.3 Results and Discussion

18.3.1 Estimated Effective Doses

18.3.1.1 Effective Dose in the First Year After the Contamination Event

To assess doses, the set of values for time spent outdoors, $t_{l,\mathrm{out},j}$, and initial value of the surface activity density of ^{137}Cs, A_{Cs137} (0), was selected based on the statistical characteristics using the global sensitivity analysis code GSALab [19], which was developed by the Japan Atomic Energy Agency (JAEA). The calculations of doses were performed by 10,000 sets of sample values. Relative errors of these calculations were less than 0.05.

Table 18.6 lists the 50th and 95th percentiles of the effective doses in the first year after the contamination, which were obtained from the probabilistic assessment. The following discussions are based on the 95th percentile.

The effective doses received by the population groups of Namie Town and Iitate Village in the first year after the contamination were estimated to be in the 10–50 mSv dose band. Namie Town had two evacuation scenarios, nos. 7 and 13. In evacuation scenario 7, the inhabitants were rapidly evacuated on March 16, 2011. On the other hand, the evacuation of Namie Town according to scenario 13 was implemented 7 days after evacuation scenario 7. The difference in the annual effective doses

Table 18.6 Effective doses in the first year after the contamination[a] (mSv)

	Evacuation scenario no.		Pensioner	Indoor worker	Outdoor worker	WHO[b]
Tomioka Town	1	50th–95th percentile	1.3–5.4	1.3–5.0	1.8–8.1	–
		Groundshine (%)	91	90	94	
		Cloudshine (%)	1	1	0	
		Inhalation (%)	8	9	6	
Okuma Town	2	50th–95th percentile	0.74–3.3	0.71–3.0	1.0–4.8	–
		Groundshine (%)	89	88	92	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	10	11	7	
Futaba Town	3, 4	50th–95th percentile	0.45–1.2	0.43–1.2	0.54–1.5	–
		Groundshine (%)	65	64	71	
		Cloudshine (%)	2	2	2	
		Inhalation (%)	33	34	27	
Hirono Town	10	50th–95th percentile	0.55–0.81	0.53–0.75	0.72–1.1	–
		Groundshine (%)	69	68	76	
		Cloudshine (%)	2	2	2	
		Inhalation (%)	29	30	22	
Naraha Town	5	50th–95th percentile	0.72–2.6	0.69–2.3	0.98–4.0	1–10
		Groundshine (%)	87	86	91	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	12	13	8	
	6	50th–95th percentile	0.34–0.53	0.33–0.50	0.44–0.68	
		Groundshine (%)	63	61	71	
		Cloudshine (%)	3	3	2	
		Inhalation (%)	34	36	27	
Namie Town	7	50th–95th percentile	4.3–18	4.1–17	5.7–21	10–50
		Groundshine (%)	61	60	69	
		Cloudshine (%)	3	3	2	
		Inhalation (%)	36	37	29	
	13	50th–95th percentile	6.2–39	6.0–37	8.4–52	
		Groundshine (%)	79	78	84	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	20	21	15	
Minami Soma City	9	50th–95th percentile	2.5–6.1	2.4–5.7	3.5–9.3	1–10
		Groundshine (%)	94	93	96	
		Cloudshine (%)	0	1	0	
		Inhalation (%)	6	6	4	
	17	50th–95th percentile	1.9–9.9	1.8–9.2	2.7–15	
		Groundshine (%)	93	93	95	
		Cloudshine (%)	1	0	0	
		Inhalation (%)	6	7	5	

(continued)

Table 18.6 (continued)

	Evacuation scenario no.		Pensioner	Indoor worker	Outdoor worker	WHO[b]
Iitate Village	15	50th–95th percentile	6.7–16	6.5–14	9.3–22	10–50
		Groundshine (%)	90	89	92	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	9	10	7	
	16	50th–95th percentile	7.3–17	6.9–16	9.9–24	
		Groundshine (%)	90	90	93	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	9	9	6	
Tamura City	8	50th–95th percentile	1.2–4.5	1.2–4.1	1.7–6.8	–
		Groundshine (%)	92	92	95	
		Cloudshine (%)	1	1	0	
		Inhalation (%)	7	7	5	
Kawamata Town	18	50th–95th percentile	2.5–6.8	2.3–6.3	3.5–9.5	–
		Groundshine (%)	94	93	95	
		Cloudshine (%)	0	1	0	
		Inhalation (%)	6	6	5	
Kawachi Village	11	50th–95th percentile	1.4–5.5	1.3–5.0	1.9–8.3	–
		Groundshine (%)	91	90	94	
		Cloudshine (%)	1	1	0	
		Inhalation (%)	8	9	6	
Katsurao Village	12	50th–95th percentile	2.2–7.5	2.0–6.5	3.1–11	1–10
		Groundshine (%)	94	93	96	
		Cloudshine (%)	0	1	0	
		Inhalation (%)	6	6	4	
	14	50th–95th percentile	3.0–7.2	2.8–6.7	4.1–11	
		Groundshine (%)	90	89	93	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	9	10	6	
Fukushima City	–[c]	50th–95th percentile	2.2–7.5	2.1–6.9	3.1–11	–
		Groundshine (%)	94	94	95	
		Cloudshine (%)	0	0	0	
		Inhalation (%)	6	6	5	
Koriyama City	–[c]	50th–95th percentile	1.2–5.5	1.1–5.4	1.7–8.6	–
		Groundshine (%)	92	91	94	
		Cloudshine (%)	1	1	1	
		Inhalation (%)	7	8	5	
Iwaki City	–[c]	50th–95th percentile	0.55–1.3	0.53–1.2	0.72–1.9	1–10
		Groundshine (%)	78	77	84	
		Cloudshine (%)	2	2	1	
		Inhalation (%)	20	21	15	

[a] Contributions of exposure pathways were calculated using the arithmetic mean of the distributions of each pathway

[b] It is noted that the estimated values by WHO include contributions of internal exposures from ingestion of radionuclides in food and water

[c] The calculations of doses were performed with the assumption that the inhabitants had lived continuously in these cities during the first year after the contamination occurred

Table 18.7 Effective lifetime doses (60 years) (mSv)

	Pensioner 50th–95th percentile	Indoor worker 50th–95th percentile	Outdoor worker 50th–95th percentile
Fukushima City	5.2–18	4.9–16	9.3–34
Koriyama City	2.8–14	2.7–13	5.0–26
Iwaki City	1.1–3.0	1.1–2.8	1.8–5.8

between the rapid evacuation (scenario 7) and the deliberate evacuation (scenario 13) is almost double for each population group. This result indicates that the doses received by the population living in the highly contaminated area were significantly influenced by the delayed evacuation at the early phase after the contamination.

However, there was no significant difference among the evacuation scenarios for inhabitants living in Iitate Village. The entire population of Iitate Village was evacuated 2–3 months after the accident onset. Thus, most of the inhabitants had already been exposed to radiation before they were evacuated to Fukushima City. In our estimations, about 80 % of the effective doses received by the inhabitants living in Iitate Village throughout the first year were delivered before the evacuation was implemented.

In addition, the effective doses received by outdoor workers had the potential to be above 10 mSv for 1 year after the contamination in Minami Soma City, Katsurao Village, and Fukushima City. The effective doses received by the inhabitants evacuated according to scenarios 1–5, 8–12, 14, and 18 and to the inhabitants living in Koriyama City and Iwaki City were assessed to be in the 1–10 mSv dose band. The contributions to the annual effective dose from the doses received in the final evacuation facilities in the municipalities ranged from 60 % to 75 % for each scenario.

The effective doses reported by WHO [2] are shown in Table 18.6. The effective doses received by inhabitants living in Iitate Village and Namie Town in the first year after the accident are estimated to be in the 10–50 mSv dose band. At other locations considered in Fukushima Prefecture, the effective doses are estimated to be in the 1–10 mSv dose band. The range of the assessed values in this chapter corresponds approximately to that of the results reported by WHO [2]. In addition, NIRS [3] reported the external doses received by the evacuees during the 4 months after the accident. The results reported by NIRS cannot be compared directly with the assessed values in this chapter because the period subject to assessment is different. The results of this chapter, however, are consistent with the results reported by NIRS [3].

18.3.1.2 Effective Lifetime Doses

The lifetime doses received by the inhabitants of Fukushima City, Koriyama City, and Iwaki City are listed in Table 18.7. The values of the 95th percentile of the effective doses to the three population groups are 16–34, 13–26, and 2.8–5.8 mSv in Fukushima City, Koriyama City and Iwaki City, respectively. For each city, 20–30 % of the lifetime effective dose was delivered during the first year.

18.3.2 Contributions of Different Exposure Pathways

For evacuation scenarios 10, and the continuously living scenario of Iwaki City, the contributions of doses through inhalation range from 15 % to 30 %. Because the doses for these evacuation scenarios were calculated under the condition that radionuclides were deposited on dry property, the deposition velocities are less than those for average scenarios with a wet property. Thus, the dose contributions through inhalation are larger than those in average scenarios.

For evacuation scenarios 3 and 4, the inhabitants of Futaba Town were evacuated to Saitama Prefecture on March 19, 2011. The contamination level in Saitama Prefecture is considerably lower than that in Fukushima Prefecture. Therefore, the prolonged doses from groundshine after the evacuation to Saitama Prefecture are small. Consequently, the dose contributions through inhalation are larger than those in the other average scenarios.

The inhabitants of Namie Town were evacuated according to evacuation scenarios 7 and 13. These inhabitants received doses through internal exposure before evacuation from the highly contaminated area. Therefore, the doses through this pathway are larger than those through external exposure to groundshine in Nihonmatsu City after evacuation.

Contributions of the doses from groundshine and inhalation to the annual effective dose are 85–95 % and 5–15 %, respectively. The contributions from cloudshine are much less than those from groundshine and inhalation. For several evacuation scenarios, the contribution of inhalation is larger than that already mentioned.

18.4 Conclusions

The present study assessed radiation doses in the first year after the contamination and over inhabitants' lifetimes caused by external exposure to groundshine and cloudshine as well as those from internal exposures through inhalation. To assess the doses realistically and comprehensively, a probabilistic approach was employed using data that reflected realistic environmental trends and lifestyle habits in Fukushima Prefecture.

The 95th percentile of the estimated annual effective dose for most of the population living in the municipalities listed in the evacuation scenarios was in the 1–10 mSv dose band. However, the doses received by some outdoor workers living in Minami Soma City, Katsurao Village, and Fukushima City could exceed 10 mSv. In addition, the inhabitants of Namie Town and Iitate Village were exposed to radiation doses in the 10–50 mSv dose band. These results suggest that the doses received by the population living in the highly contaminated area were significantly influenced by the delay in evacuation in the early phase after the contamination.

Contributions of the groundshine and inhalation doses to the annual effective dose are about 85–95 % and 5–15 %, respectively. However, the contributions from these pathways vary depending on deposition conditions, timing of evacuations, and differences in the contamination level of the ground surface.

In addition, the values of the 95th percentile of the lifetime effective doses received by the inhabitants of Fukushima City, Koriyama City, and Iwaki City are 16–34, 13–26, and 2.8–5.8 mSv. For each city, 20–30 % of the lifetime effective dose was delivered during the first year after the contamination.

It is noted that these calculations were performed on the basis of some important assumptions regarding the input data, assessment model, and model parameters. The doses must be assessed by iterative processes that reflect site-specific and realistic information derived from further investigations.

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