Department of Environment Systems
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Master's Thesis

Discussion on Radiation Protection Approaches in Various Existing Exposure Situations, Especially on Accidentally Contaminated Environments and Technologically Enhanced NORM

(現存する放射線被ばく状況に関する放射線防護アプローチの検討 ー原子力災害後の汚染環境と高自然放射線環境(物質)に着目してー)

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Chapter 1. Introduction

1.1. Background

The Fukushima accident rapidly released radionuclides (above 10^{12} Bq h^{-1} of ^{137}Cs and 10^{13} Bq h^{-1} of ^{131}I within the first ten days) (1). The ambient dose rate measured in Fukushima Prefecture was as high as 2.15 μSv h^{-1} three months after the accident (2). Even nine months after the accident, the concentrations of ^{134}Cs and ^{137}Cs in Fukushima rivers were one to two orders higher than in Gunma Prefecture (3). Indeed, ^{134}Cs, ^{137}Cs, ^{90}Sr, and ^{131}I are the radionuclides of main concern after the Fukushima accident (4). Especially, ^{131}I (160 PBq), ^{134}Cs (18 PBq), and ^{137}Cs (15 PBq) were released much more than ^{90}Sr (0.14 PBq); after considering the half-lives, ^{134}Cs and ^{137}Cs are the main radionuclides of concern (5). The accident also generated 13.3 million m³ of decontaminated soil within the Fukushima Prefecture (6). The decontaminated soil widely exists in the nearby prefectures as well; as of March 2023, a total of 330,000 m³ of decontaminated soil was distributed among Iwate, Miyagi, Ibaraki, Tochigi, Gunma, Saitama, and Chiba Prefecture (7). As shown in Fig. 1 (8), radiocesium was transported from FDNPP to surrounding areas by wind, and the transportation direction was toward the northwestern side.

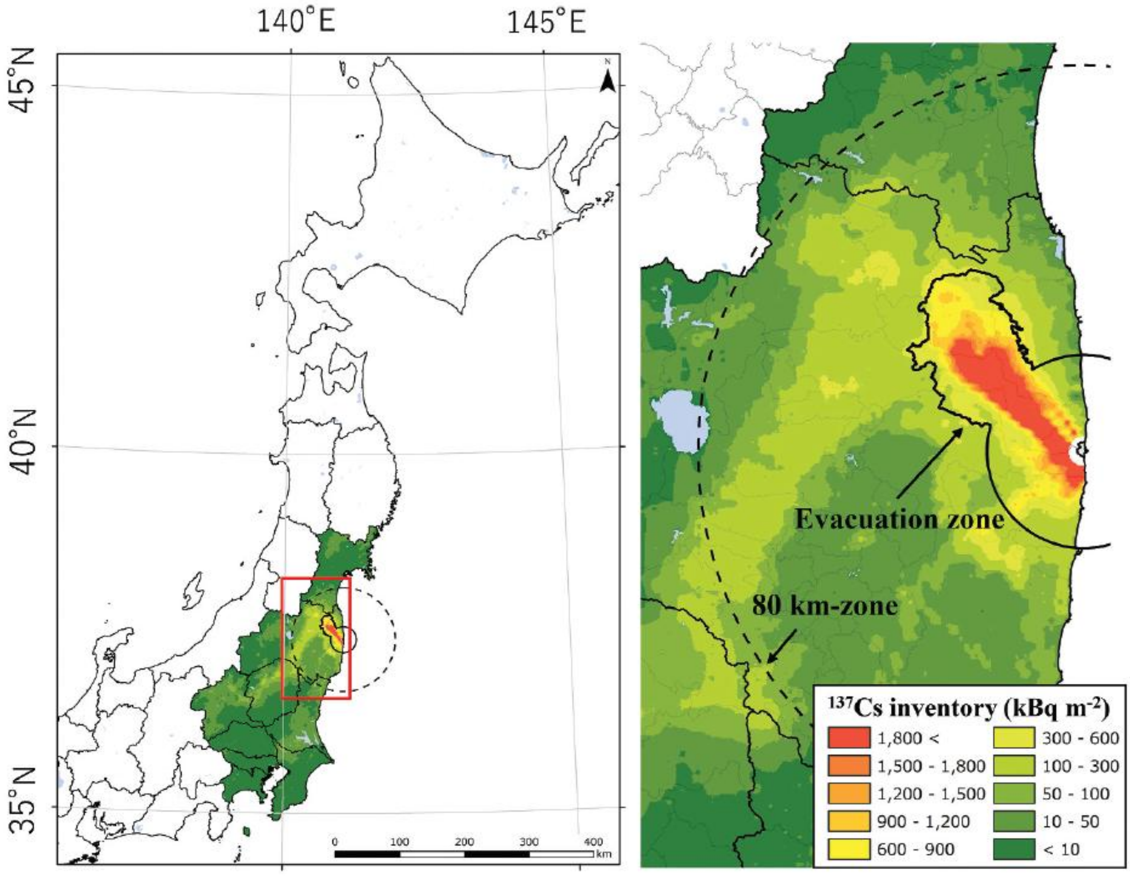

Fig. 1. Migration of radionuclides following the Fukushima accident

1.2. Outline of MS Thesis

In the process of developing radiation protection (RP) strategies, the first crucial step is to conduct dose assessments. These assessments lay the foundation for discussing further RP measures based on the results (9). Consequently, Chapters 3 and 4 of this thesis focus on dose assessments of decontaminated soil situations in Kashiwa City. This city was chosen because it has the second-largest volume of decontaminated soil (approximately 46,000 m^3) among all prefectures neighboring Fukushima, second only to Nasushiobara City with 65,000 m^3 (7). Therefore, conducting further dose evaluations is essential to alleviate local residents' concerns. Additionally, Kashiwa City is located less than 40 km from central Tokyo, making its population potentially vulnerable to radiation exposure. The joint dose (dose per person multiplied by the number of people) could be significant. Moreover, this study was supported by Kashiwa City Hall members, allowing for on-site radiation monitoring of the decontaminated soil.

After the dose assessment, it is vital to discuss RP strategies and regulations. However, current regulations on managing decontaminated soil due to the Fukushima accident are still under discussion (10,11). Thus, this study referred to the regulations for Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) to explore ideas for treating decontaminated soil. Naturally Occurring Radioactive Materials (NORM) refer to radioactive materials containing no significant amounts of radionuclides other than naturally occurring ones. When human activities change their radiation activity concentration, they become known as TENORM (12). This study examined TENORM regulations because TENORM and decontaminated soil share similarities (explained in Chapter 1.3 of this thesis). Unlike the relatively short history of the decontaminated soil issue (only 14 years since the Fukushima accident), the discussion of TENORM regulations has a longer history dating back to the 1990s (13), and thus the regulations are more comprehensive. Consequently, Chapters 5 and 6 in this thesis focus on TENORM regulations. Following the review of TENORM regulations, this study provides recommendations on how to treat decontaminated soil in Kashiwa City, detailed in Chapter 7. Overall, the thesis storyline is illustrated in Fig. 2.

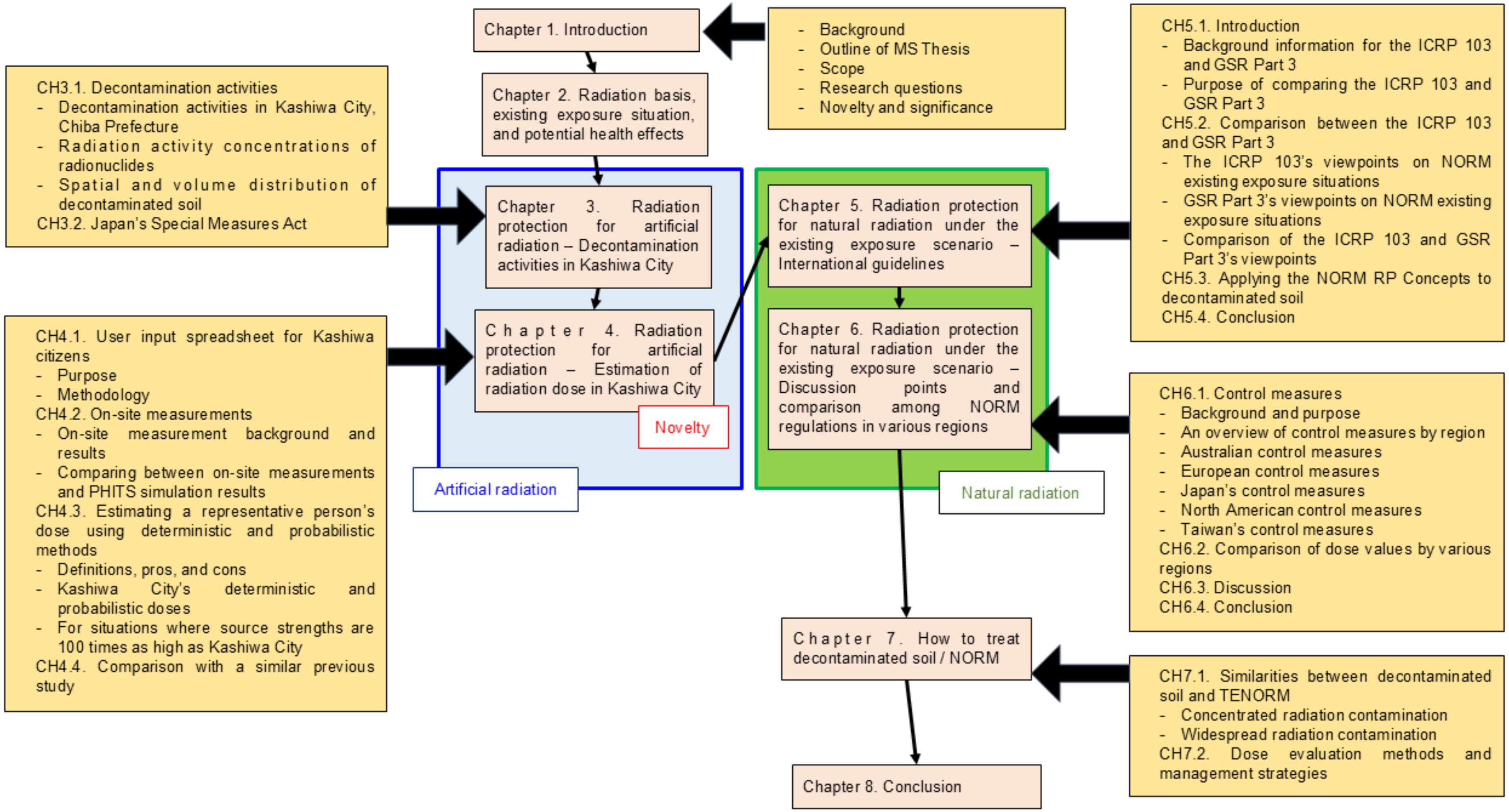

Fig. 2. Storyline of the MS Thesis

1.3. Scope

Following the illustrations in Chapter 1.2, this study discusses the similarities and differences between decontaminated soil and Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) as follows:

Similarities:

1. Widespread Radiation Contamination: Both can be considered widespread radiation contamination situations and evaluated using the unit Bq m^{-2}. For decontaminated soil, based on the JAEA Airborne Survey, it is a widespread contamination phenomenon affecting areas over a 100 km radius from the FDNPP epicenter. The severity of contamination can be quantified using a database measured in Bq m^{-2}. Similarly, certain aspects of (TE)NORM, such as uranium tailings, also represent widespread radiation pollution, and regional differences can be evaluated using Bq m^{-2} (14).

2. Concentrated Radiation Contamination: Both decontaminated soil and TENORM can be viewed as concentrated situations where radiation protection (RP) strategies should be focused, evaluated in Bq g^{-1}. For decontaminated soil, radionuclides accumulate on roofs, are washed down by rain, and concentrate in the backyard. The decontamination process involves removing this surface soil, wrapping it in plastic bags, and burying it underground. Here, radionuclides from large roof areas concentrate into small-volume plastic bags, necessitating RP strategies tailored to manage concentrated soil radiation exposure. Similarly, TENORM situations, such as radionuclide accumulation in water treatment plant pipelines, require focused RP strategies, evaluated using Bq g^{-1}.

Differences:

1. Radionuclide Half-Lives: Decontaminated soil primarily contains ^{134}Cs and ^{137}Cs, with half-lives of 2.06 and 30.17 years, respectively. In contrast, TENORM typically includes radionuclides like ^{238}U, ^{232}Th, ^{226}Ra, ^{222}Rn, and ^{40}K, with half-lives as long as 14 billion years (15). Thus, TENORM's radiation impact duration is much longer, necessitating different RP strategies.

2. Exposure Pathways: While contamination can be present in the air and spread over a wide area on the ground during and immediately after a nuclear accident, it significantly diminishes over time. For instance, 13 years after the Fukushima accident, most radionuclides in the air or on the ground surface have likely been removed through precipitation and decontamination efforts (8). These efforts often involve burying decontaminated soil 30 to 40 cm underground, often wrapped in plastic bags, making internal radiation exposure through inhalation and ingestion unlikely. However, for TENORM, both external and internal exposures need consideration (16). Therefore, different RP strategies are required for TENORM and decontaminated soil based on exposure pathways.

1.4. Research questions

This master's thesis addresses three key research questions:

1. To elucidate the current state of contaminated soil management, using Kashiwa City in Chiba Prefecture—designated as a priority contamination investigation area—as a case study.
2. To propose specific strategies for future protection and provide information that will contribute to ongoing discussions.
3. To assess the current and projected radiation doses to surrounding residents from simply buried decontaminated soil.

1.5. Novelty and significance

This study introduces a novel approach to dose assessments by innovating the life habit data retrieval process. Previous research (17) categorizes individual dose assessment methods into four types, one of which is "Simulation based on ambient dose rates assuming individual lifestyle behavior." Traditionally, lifestyle behavioral data were collected through interviews conducted immediately after an accident.

What sets this study apart is the creation of an Excel spreadsheet that allows local residents to input their lifestyle behaviors themselves. The spreadsheet then automatically calculates the dose and provides the results to the users. This innovative method offers a more efficient way to collect lifestyle data and assess doses.

Another distinctive aspect of this study is its practical application of theory, moving beyond the traditional focus on radiocesium migration mechanisms across various land types (8). Previous research mainly focused on the distribution and migration (radioactivity, in the unit of Bq) of radioactive cesium in the environment, as well as on elucidating its mechanisms. However, it did not necessarily extend to individual dose assessments (in the unit of Sv) for the residents. This research introduces a novel, potentially more efficient dose assessment method compared to the traditional soil sampling and analysis approach. By integrating (i) results from the JAEA Airborne Survey Database to determine radionuclide fallout per unit area (Bq m^{-2}) for each district in the study area; (ii) PHITS Simulation for developing a model to calculate radiation doses (μSv h^{-1}) for different types of residences; and (iii) user input data (address, habits, house dimensions, and date of interest) to calculate radiation doses based on each citizen's lifestyle habits, this method enhances efficiency compared to the previous, more time-consuming experimental process.

This study also considered the interpretation of the assessed doses, such as the application of representative person dose assessment methods (by deterministic and probabilistic approaches).

Significantly, this study lays the groundwork for other prefectures facing similar issues with decontaminated soil. For instance, some areas in Fukushima Prefecture may have radiation levels up to 100 times higher than those in Kashiwa City. Previous studies have indicated that residents in these regions might experience post-traumatic stress disorder (PTSD) (18,19). By adopting a similar spreadsheet, local residents can determine their doses, potentially alleviating PTSD symptoms.

Chapter 2. Radiation basis, existing exposure situation, and potential health effects

2.1. Radiation basis and potential health effects

Becquerel (Bq), sievert (Sv), and gray (Gy) are commonly used units for measuring radiation. The becquerel measures the rate of radionuclide decay, indicating how many decays occur per second. The gray quantifies the absorbed radiation dose, with 1 Gy equaling 1 joule per kilogram (1 J kg^{-1}). The sievert, on the other hand, assesses the biological effects of radiation (20).

Different types of radiation, such as alpha, beta, gamma, and neutron rays, have distinct radiation weighting factors, as detailed in Table 1. Additionally, various tissues and organs have specific tissue weighting factors, as shown in Table 2. The sum of all tissue weighting factors is equal to 1.

Table 1. Radiation weighting factors of various types of radiation (21)

Radiation type	Radiation weighting factor
Photons (the focus of this study)	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, and Heavy nuclei	20
Neutrons	A continuous function of neutron energy

Table 2. Tissue weighting factor (22)

Organs / Tissue	Tissue weighting factor
Bone marrow, colon, lung, stomach, and breast	0.12 each
Gonads	0.08
Bladder, liver, esophagus, and thyroid	0.04 each
Skin and bone surface	0.01 each
Sum of the remaining tissues (such as muscle, brain, and kidney)	0.12 in total

As highlighted in Chapter 1, this study focuses on external exposure to ^{134}Cs and ^{137}Cs, which are gamma emitters with a radiation weighting factor of 1. Assuming homogeneous distribution, this radiation disperses evenly throughout the body, meaning 1 Gy translates to 1 Sv of radiation exposure.

There are two types of exposure: external and internal. External exposure occurs when the radiation source is outside the human body. In contrast, internal exposure involves radionuclides entering the body through inhalation, ingestion, or skin absorption. There are also two types of radiation effects:

deterministic and stochastic (12). Deterministic effects lead to acute radiation disorders such as hair loss and skin injury, while stochastic effects are non-threshold and include risks like cancer and hereditary effects. It is established that cancer risks increase linearly when exposure doses exceed 150 mSv; however, it is unclear if this risk also rises linearly at doses below 150 mSv (22).

2.2. Existing exposure situation

As stated in ICRP 103 Article 253 (22), planned exposure situations allow for the planning of radiological protection before exposures occur, with the magnitude and extent of exposures reasonably predictable. In contrast, ICRP 103 Article 284 defines existing exposure situations as those already present when control decisions must be made. Meanwhile, ICRP 103 Article 274 describes emergency exposure situations as unexpected events that may require urgent protective actions. Therefore, based on these definitions, this master's thesis focuses on decontaminated soil already buried underground, corresponding to an existing exposure situation.

According to ICRP 103 Article 243, a dose limit is defined as "The sum of exposures from sources related to practices that are already justified." Conversely, ICRP 103 Article 261 states that a dose constraint is "a prospective and source-related restriction on the individual dose from a source in planned exposure situations, which serves as an upper bound on the predicted dose in the optimization of protection for that source (ICRP 103, Article 230)." From these definitions, it is clear that the dose limit encompasses various radiation sources, whereas the dose constraint focuses on a single radiation source. Finally, as elaborated in ICRP 103 Article 226, while dose constraint and reference level are conceptually similar, for consistency with earlier publications, the ICRP uses "dose constraint" in planned exposure situations and "reference level" for existing exposure situations. Therefore, the concept of reference level aligns best with the discussion point of this master's thesis. The above-mentioned exposure situations are summarized in Table 3.

Table 3. Radiation exposure definitions and examples of the three categories (22)

Exposure situation	**Definition**	**Examples**
Planned exposure	RP can be planned before exposure occurs	Medical exposures of patients
Existing exposure	Radiation exposure has already existed, but the RP decision has not been taken yet.	• Decontaminated soil due to Fukushima accident • NORM
Emergency exposure	Unexpected situations that require urgent responses	• Chornobyl Nuclear Accident • Fukushima Nuclear Accident

Chapter 3. Radiation protection for artificial radiation – Decontamination activities in Kashiwa City

3.1. Decontamination activities

Following the Fukushima accident, radionuclide fallout affected the surrounding areas. Decontamination efforts were primarily of two types: (i) The soil surface was inverted, so the top 30 to 40 cm consisted of uncontaminated soil, while the underlying layer contained radionuclides. (ii) The contaminated surface soil was removed, wrapped in plastic bags, and buried 30 to 40 cm underground.

3.1.1. Decontamination activities in Kashiwa City, Chiba Prefecture

Starting on February 18th, 2012, decontamination activities in Kashiwa City commenced with the collaboration of the government and local residents. Generally, the decontamination process involves four steps (11). First, a survey of the ambient dose rate is conducted. Next, various decontamination strategies are applied to different locations, including buildings, roads, soil, grass, rivers, and lakes. Third, the decontamination work is carried out, and the decontaminated soil and substances are collected, transported, and stored. Finally, there is ongoing monitoring of the decontaminated soil and substances.

3.1.2. Radiation activity concentrations of radionuclides

According to the Ministry of the Environment of Japan (7), as of March 31st, 2023, 95% of decontaminated soil buried underground across seven prefectures near Fukushima, including Iwate, Miyagi, Ibaraki, Tochigi, Gunma, Saitama, and Chiba, measured below 2 kBq/kg. This study specifically focuses on Kashiwa City in Chiba Prefecture. The JAEA Airborne Survey Database (23) provides the earliest available data for Kashiwa City, dated May 31st, 2012, indicating radionuclide fallout intensities ranging from <1.0E+04 Bq m^{-2} to 3.30E+04 Bq m^{-2} for ^{134}Cs and from <1.0E+04 Bq m^{-2} to 4.60E+04 Bq m^{-2} for ^{137}Cs.

Additionally, on-foot and car-borne surveys have been conducted to investigate ambient dose rates in Kashiwa City, as documented on the Kashiwa City Hall's website (Fig. 3) (24).

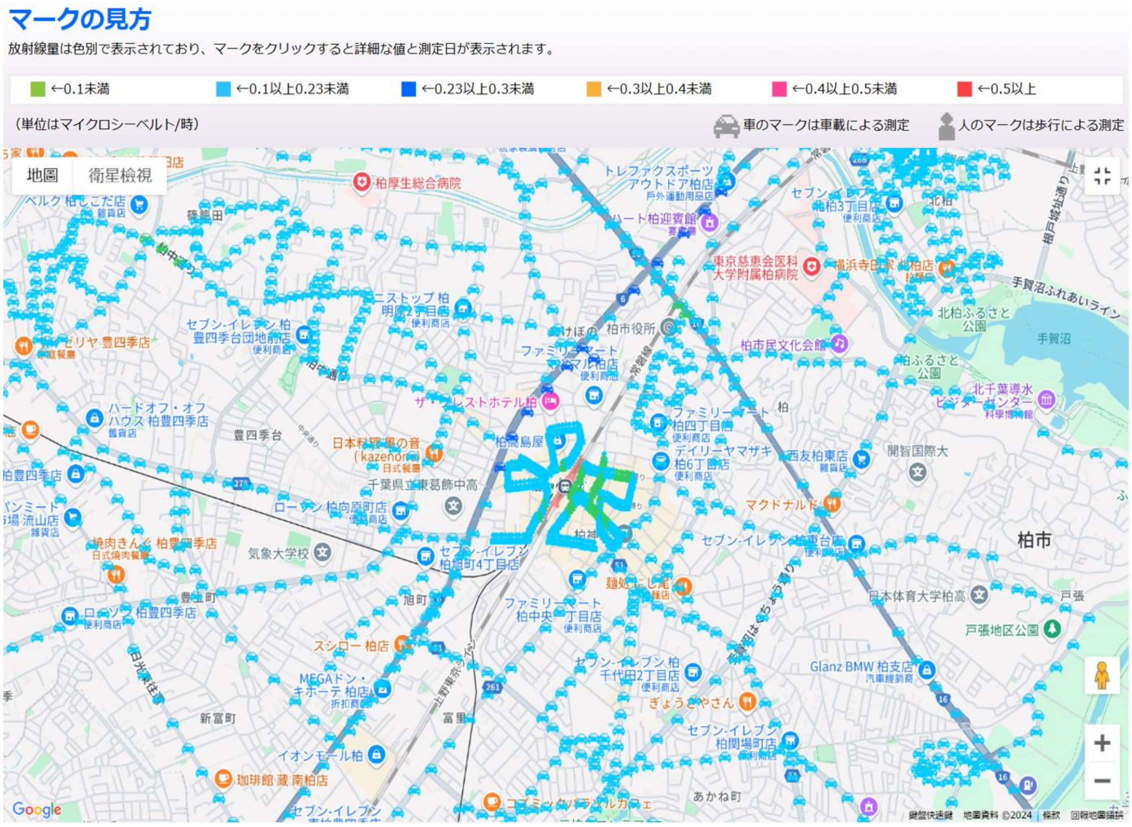

Fig. 3. A map that shows the ambient dose survey results in Kashiwa City (24)

A total of 23 surveys were conducted in Kashiwa City from October 2012 to June 2024. In the initial survey, the ambient dose rate reached up to 0.3 μSv h^{-1}. By the final survey, all measurements were below 0.1 μSv h^{-1}.

3.1.3. Spatial and volume distribution of decontaminated soil

According to the Ministry of the Environment of Japan (7), as of March 2023, Kashiwa City had the second-largest amount of decontaminated soil at 46,447 m^3, surpassed only by Nasushiobara City in Tochigi Prefecture with 64,876 m^3. Across the seven prefectures near Fukushima, the total volume of decontaminated soil amounted to 330,198 m^3. Of this, 234,771 m^3, or 71%, was stored in parks or schoolyards, while approximately 44,073 m^3, or 13%, was kept at individual dwellings. The distribution of decontaminated soil is detailed in Table 4.

Table 4. Distribution of decontaminated soil at various facilities (7)

Decontaminated soil volume (Unit: m³)															
Item	Content	Country	Prefecture			City				Private			Individuals	Other	Total
			Schools	Parks / Green areas	Other	Schools	Kindergartens	Parks / Green areas	Other	Schools	Kindergartens	Companies			
Container	TRUE	1,864	4,109	8,910	1,922	33,651	2,380	32,971	9,869	751	1,589	13,005	16,619	235	127,874
	FALSE	2,138	10,980	2,421	355	59,371	3,774	69,821	16,391	1,932	2,110	5,268	27,454	308	202,324
	TRUE	47%	27%	79%	84%	36%	39%	32%	38%	28%	43%	71%	38%	43%	39%
	FALSE	53%	73%	21%	16%	64%	61%	68%	62%	72%	57%	29%	62%	57%	61%
Total		4,001	15,089	11,331	2,277	93,022	6,155	102,792	26,260	2,683	3,699	18,273	44,073	543	330,198

Number of facilities															
Item	Content	Country	Prefecture			City				Private			Individuals	Other	Total
			Schools	Parks / Green areas	Other	Schools	Kindergartens	Parks / Green areas	Other	Schools	Kindergartens	Companies			
Container	TRUE	13	30	10	15	328	107	640	219	9	71	515	12,045	85	14,087
	FALSE	10	54	12	2	315	97	1,405	208	9	55	706	11,733	35	14,641
	TRUE	57%	36%	45%	88%	51%	52%	31%	51%	50%	56%	42%	51%	71%	49%
	FALSE	43%	64%	55%	12%	49%	48%	69%	49%	50%	44%	58%	49%	29%	51%
Total		23	84	22	17	643	204	2,045	427	18	126	1,221	23,778	120	28,728

3.2. Japan's Special Measures Act

On June 17th, 2022, Japan's Special Measures Act was enacted (25). The act aims to clarify the responsibilities of the central government, local governments, nuclear power plant operators, and the general public in addressing environmental radiation contamination. For the seven prefectures near Fukushima, Japan's government plans to move all decontaminated soil to final disposal by 2045 (26). According to Japan's Nuclear Safety Commission (NSC), the additional dose incurred by the general public due to interim storage facilities should be below 1 mSv y^{-1}, whereas the standard for the final disposal site is 10 µSv y^{-1} (27).

Chapter 4. Radiation protection for artificial radiation – Estimation of radiation dose in Kashiwa City

4.1. User input spreadsheet for Kashiwa citizens

4.1.1. Purpose

This study aims to create a user-input Excel spreadsheet for two main purposes. First, to alleviate the concerns of local residents in Kashiwa City (risk communication). Second, to provide a model for other regions, particularly those more heavily affected, like Fukushima Prefecture, to develop similar spreadsheets. This tool allows residents to input relevant information, such as dwelling dimensions, daily habits, and addresses, to determine the dose from decontaminated soil. This user-input spreadsheet is a versatile risk communication tool designed for a broad audience, making it accessible to a wide range of citizens. Table 5 details the importance of each user input item in the Excel spreadsheet.

Table 5. The importance of each item in the user input spreadsheet is explained

Item	**Reasons of importance**
Address	There are regional differences of radiation intensity from the initial radionuclide fallouts after the Fukushima accident.
Time spent in the backyard per day	Most decontaminated soil outside Fukushima Prefecture (including Kashiwa City) is kept under the backyards of residential houses, parks, or schoolyards (7).
Time spent in the house per day	
Time spent in the park or schoolyard per day	
The roof area of the house	The areas have a positive relationship with the radiation activity concentration of the decontaminated soil buried under the backyard.
The backyard area of the house	
Date of interest	Radiocesium decays over time.

4.1.2. Methodology

4.1.2.1. Calculation flowchart

As shown in Fig. 4, the Excel spreadsheet developed in this study (which allows Kashiwa citizens to input necessary information and learn about the radiation exposure dose) contains three main parts: (i) Data from the JAEA Airborne Survey Database, (ii) PHITS Simulation results, and (iii) Data from user input. After combining these three parts and performing calculations, the spreadsheet will provide the user with information on the maximum dose (in $\mu Sv\ h^{-1}$) and average dose (in $mSv\ y^{-1}$).

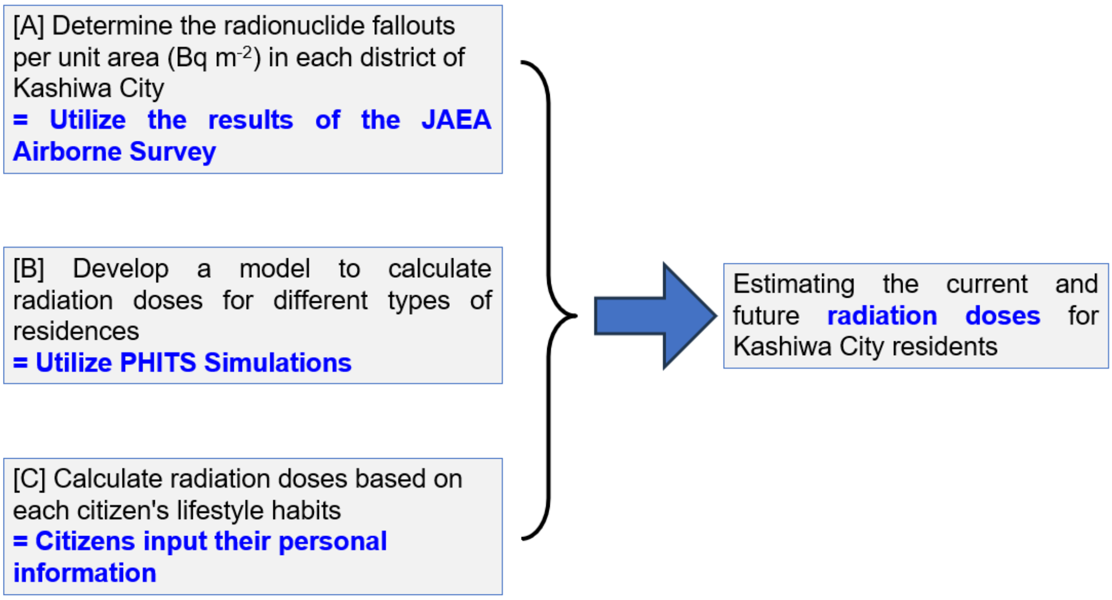

Fig. 4. The calculation flowchart of the Excel input spreadsheet for Kashiwa citizens

4.1.2.2. JAEA Airborne Survey

The original data for the Excel spreadsheet were retrieved from the JAEA Airborne Survey Database (23). The earliest data for Kashiwa City from this database was dated May 31st, 2012. Deposition densities of ^{134}Cs and ^{137}Cs were measured by helicopters cruising at altitudes of 150 to 300 meters. The flight path widths were approximately 1.85 km within 80 km of the Fukushima Daiichi Nuclear Power Plant, 5 km within the 80-100 km range, 5 km for the 120 km area south of the power plant, 3 km for eastern Japan, and 5 km for Hokkaido and western Japan. This study utilized the Kashiwa City data, defined by 3-km flight paths. Air dose rates were obtained after subtracting natural background values. For Kashiwa City, there were a total of 1,719 data points. After excluding 8 data points below the detection limit (<1.00E+04 Bq m^{-2}), 1,711 data points were used for calculations, with radiation source strengths ranging from 1.00E+04 to 3.30E+04 Bq m^{-2} for ^{134}Cs and 1.10E+04 to 4.60E+04 Bq m^{-2} for ^{137}Cs.

To create the user input spreadsheet, this study first divided Kashiwa City into 25 regions, as shown in Fig. 5. From the 1,711 Kashiwa City data points in the JAEA Airborne Survey Database, the data were sorted based on longitude and latitude, and the average values for each grid (in Bq m^{-2}) were calculated for ^{134}Cs and ^{137}Cs.

	ER5	ER4	ER3	ER2	ER1
NT1	5.6E+04	5.4E+04	5.3E+04	5.1E+04	4.5E+04
NT2	5.9E+04	5.6E+04	5.6E+04	5.4E+04	4.8E+04
NT3	5.1E+04	4.9E+04	4.8E+04	4.6E+04	4.1E+04
NT4	5.2E+04	4.9E+04	4.9E+04	4.7E+04	4.1E+04
NT5	5.0E+04	4.8E+04	4.7E+04	4.5E+04	4.0E+04

Fig. 5. In the preliminary step, Kashiwa City was divided into 25 regions. ER1 represents the easternmost longitudes, and NT1 represents the northernmost latitudes from the 1,711 data points in the JAEA Database. The numbers in each region indicate the total (^{134}Cs and ^{137}Cs) source strength (Bq m^{-2}) measured on May 31st, 2012.

Next, this study compared the shape of Kashiwa City with the 25 grids, as shown in Fig. 6. It was determined that some grids were unnecessary due to the city's shape, so these grids were removed. For the remaining 19 grids, the author used Google Maps to assign relevant landmarks that local residents could easily identify. The goal was to assign one landmark per grid. However, in practice, only 16 landmarks were selected. The results are shown in Fig. 7. Generally speaking, two principles guide the selection of the 16 landmarks: firstly, they must cover the entire area of Kashiwa City, and secondly, they should be easily recognizable to local residents, such as train stations or well-known sites.

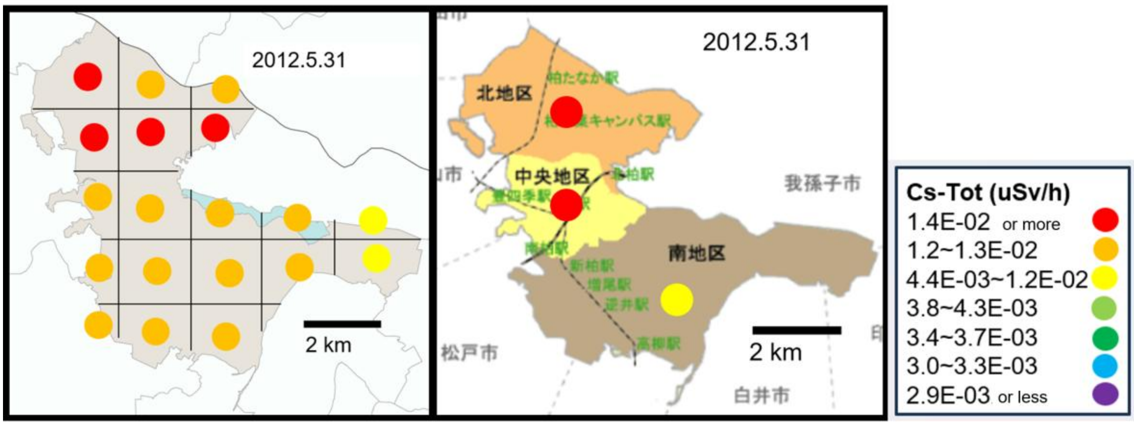

Fig. 6. The figure illustrates the intermediate process of this study, where Kashiwa City doses were compared based on finer separations (19 grids) and coarser separations (three administrative districts). As shown in the left chart, after aligning with the shape of Kashiwa City, 6 of the 25 grids in Fig. 5 were removed.

1. 柏ビレジ水辺公園 (Kashiwa Village Waterfront Park)
2. 柏たなか駅 (Kashiwa-Tanaka Station)
3. 東京大学 (The University of Tokyo)
4. JR北柏駅 (JR Kita-Kashiwa Station)
5. モラージュ柏 (Mallage Kashiwa)
6. 柏の葉キャンパス駅 (Kashiwanoha-campus Station)
7. JR柏駅 (JR Kashiwa Station)
8. 豊四季駅 (Toyoshiki Station)
9. 香取鳥見両神社 (Katori-Tomidokami Shrine)
10. 手賀の丘公園 (Tega no Oka Park)
11. トヨタ勝又グループ 野球場 (Toyota Katsumata Group Baseball Stadium)
12. 増尾城址総合公園 (Masuojoshi General Park)
13. JR南柏駅 (JR Minami-Kashiwa Station)
14. 高柳駅 (Takayanagi Station)
15. 逆井駅 (Sakasai Station)
16. ジーユー (GU) 柏南増尾店 (GU Kashiwa-Minami-Masuo Store)

Fig. 7. The figure illustrates the progression from Fig. 6. The author determined that 16 landmarks would be sufficient to evenly cover most of Kashiwa City's area.

For each landmark, the author calculated the average radiation source strengths (in Bq m^{-2}) for ^{134}Cs and ^{137}Cs within a 2 x 2 km grid, using all available data from the JAEA Airborne Survey. The results of these calculations are presented in Table 6.

Table 6. The table shows the average radiocesium deposition source strengths (arithmetic mean) in Kashiwa City as of May 31st, 2012, as well as the standard deviations (SD) in Bq m^{-2}, for the 16 landmarks (Note: For data below 1.0E+04 Bq m^{-2}, this study rounded the values to 1.0E+04 Bq m^{-2} to maintain a conservative perspective on radiation dose assessment)

NO.	Name	Data	^{134}Cs (Bq m^{-2})	^{134}Cs (SD)	^{137}Cs (Bq m^{-2})	^{137}Cs (SD)
1	柏ビレジ水辺公園(Kashiwa Village Waterfront Park)	63	2.30E+04	2.94E+03	3.21E+04	4.23E+03
2	柏たなか駅(Kashiwa-Tanaka Station)	63	2.57E+04	2.22E+03	3.59E+04	3.04E+03
3	東京大学(The University of Tokyo)	56	2.38E+04	2.05E+03	3.33E+04	2.67E+03
4	JR 北柏駅(JR Kita-Kashiwa Station)	44	2.28E+04	1.24E+03	3.19E+04	1.56E+03
5	モラージュ柏(Mallage Kashiwa)	56	2.50E+04	1.21E+03	3.50E+04	1.68E+03
6	柏の葉キャンパス駅(Kashiwanoha-campus Station)	72	2.70E+04	8.46E+02	3.76E+04	1.32E+03
7	JR 柏駅(JR Kashiwa Station)	56	2.26E+04	1.22E+03	3.16E+04	1.72E+03
8	豊四季駅(Toyoshiki Station)	26	2.55E+04	1.27E+03	3.57E+04	1.69E+03
9	香取鳥見両神社(Katori-Tomidokami Shrine)	60	1.44E+04	1.96E+03	2.02E+04	2.73E+03
10	手賀の丘公園(Tega no Oka Park)	48	1.38E+04	1.85E+03	1.94E+04	2.65E+03
11	トヨタ勝又グループ 野球場(Toyota Katsumata Group Baseball Stadium)	72	2.00E+04	1.89E+03	2.80E+04	2.70E+03
12	増尾城址総合公園(Masuojoshi General Park)	64	2.30E+04	1.49E+03	3.22E+04	2.08E+03
13	JR 南柏駅(JR Minami-Kashiwa Station)	38	2.02E+04	7.18E+02	2.84E+04	1.03E+03
14	高柳駅(Takayanagi Station)	45	1.70E+04	9.03E+02	2.38E+04	1.18E+03
15	逆井駅(Sakasai Station)	63	2.05E+04	1.65E+03	2.88E+04	2.35E+03
16	ジーユー (GU) 柏南増尾店(GU Kashiwa-Minami-Masuo Store)	40	1.82E+04	9.03E+02	2.55E+04	1.34E+03

Alternatively, to minimize uncertainty, this study divided Kashiwa City into 38 grids, each measuring 2 x 2 km, as illustrated in Fig. 8. This grid system encompasses the entire area of Kashiwa City. Consequently, in the user-input spreadsheet, citizens can select either from the 16 landmarks or from the 38 grids. The representative values of radiation intensity and the standard deviations for each of the 38 grids are presented in Table 7.

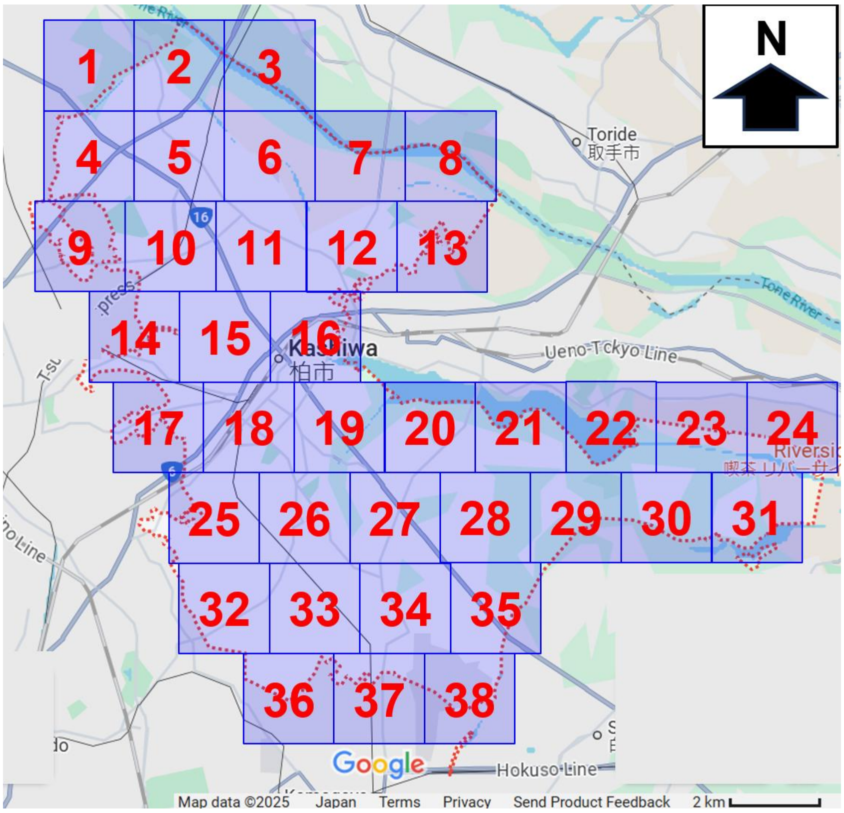

Fig. 8. Kashiwa City is divided into 38 grids that cover the entire city area

Table 7. The average radiation intensity (arithmetic mean) values and standard deviations (SD, in Bq m^{-2}) of each of the 38 grids are shown (decay correction as of May 31st, 2012)

Grid NO.	Data points	^{134}Cs (Bq m^{-2})	^{134}Cs (SD)	^{137}Cs (Bq m^{-2})	^{137}Cs (SD)
1	5	2.18E+04	8.37E+02	3.08E+04	8.37E+02
2	40	2.33E+04	2.52E+03	3.26E+04	3.51E+03
3	20	1.98E+04	2.33E+03	2.79E+04	3.24E+03
4	46	2.15E+04	1.09E+03	3.03E+04	1.56E+03
5	63	2.62E+04	1.91E+03	3.66E+04	2.62E+03
6	63	2.22E+04	3.34E+03	3.11E+04	4.69E+03
7	44	2.02E+04	2.51E+03	2.81E+04	3.55E+03
8	30	1.94E+04	1.99E+03	2.72E+04	2.70E+03
9	26	2.19E+04	1.52E+03	3.07E+04	2.04E+03
10	61	2.65E+04	1.18E+03	3.70E+04	1.64E+03
11	63	2.57E+04	1.02E+03	3.60E+04	1.43E+03
12	68	2.49E+04	2.12E+03	3.49E+04	2.93E+03
13	30	2.33E+04	1.66E+03	3.24E+04	2.36E+03
14	25	2.60E+04	6.11E+02	3.63E+04	8.02E+02
15	72	2.50E+04	8.95E+02	3.51E+04	1.14E+03
16	62	2.25E+04	1.25E+03	3.14E+04	1.63E+03
17	36	2.19E+04	1.55E+03	3.08E+04	2.17E+03
18	63	2.15E+04	7.79E+02	3.01E+04	1.01E+03

19	69	2.08E+04	1.08E+03	2.92E+04	1.50E+03
20	48	1.99E+04	3.19E+03	2.80E+04	4.53E+03
21	37	1.40E+04	2.81E+03	1.92E+04	4.44E+03
22	20	1.19E+04	8.13E+02	1.66E+04	1.15E+03
23	32	1.24E+04	1.81E+03	1.74E+04	2.67E+03
24	18	1.31E+04	8.02E+02	1.82E+04	1.06E+03
25	64	2.05E+04	7.97E+02	2.88E+04	9.79E+02
26	63	2.30E+04	1.74E+03	3.22E+04	2.39E+03
27	86	2.10E+04	1.75E+03	2.95E+04	2.44E+03
28	40	1.85E+04	1.52E+03	2.58E+04	2.19E+03
29	46	1.51E+04	1.10E+03	2.11E+04	1.52E+03
30	42	1.54E+04	1.62E+03	2.15E+04	2.16E+03
31	56	1.56E+04	2.06E+03	2.19E+04	2.82E+03
32	46	1.84E+04	9.06E+02	2.57E+04	1.36E+03
33	63	1.85E+04	1.37E+03	2.58E+04	1.84E+03
34	63	1.78E+04	9.98E+02	2.50E+04	1.31E+03
35	57	1.68E+04	1.02E+03	2.35E+04	1.44E+03
36	15	1.56E+04	5.07E+02	2.17E+04	7.04E+02
37	13	1.64E+04	6.50E+02	2.29E+04	9.54E+02
38	24	1.68E+04	1.63E+03	2.36E+04	2.32E+03

The overlapping relationship between the 16 landmarks and the 38 grids is illustrated in Fig. 9. In the uncertainty analysis, it is important to note that if a resident selects one of the 38 grids, there may be an underestimation or overestimation of the radiation dose. This is because the representative value (arithmetic mean) of each grid may differ from the actual radiation intensity at the specific location of the residential dwelling. Similarly, if a resident selects one of the 16 landmarks, the uncertainty may arise from the difference between the representative value (arithmetic mean) of the nearest landmark and the actual radiation intensity at the specific location of the residential dwelling. To quantify this, the corresponding relationship between the 16 landmarks and the 38 grids is shown in the "possible nearest grid" column in Table 8. In other words, residents may choose the corresponding landmark as the nearest representative place from their homes based on the possible nearest grids in the list. The minimum and maximum radiation intensities (^{134}Cs + ^{137}Cs in Bq m^{-2}, decay calibrated as of May 31, 2012) for all the grids are shown in the "Minimum" and "Maximum" columns, respectively. Meanwhile, the "landmark representative value (LM Rep. Val.)" column displays the arithmetic mean of ^{134}Cs + ^{137}Cs for each landmark. The "Minimum %" and "Maximum %" columns show the values of "Minimum/LM Rep. Val." and "Maximum/LM Rep. Val.," respectively.

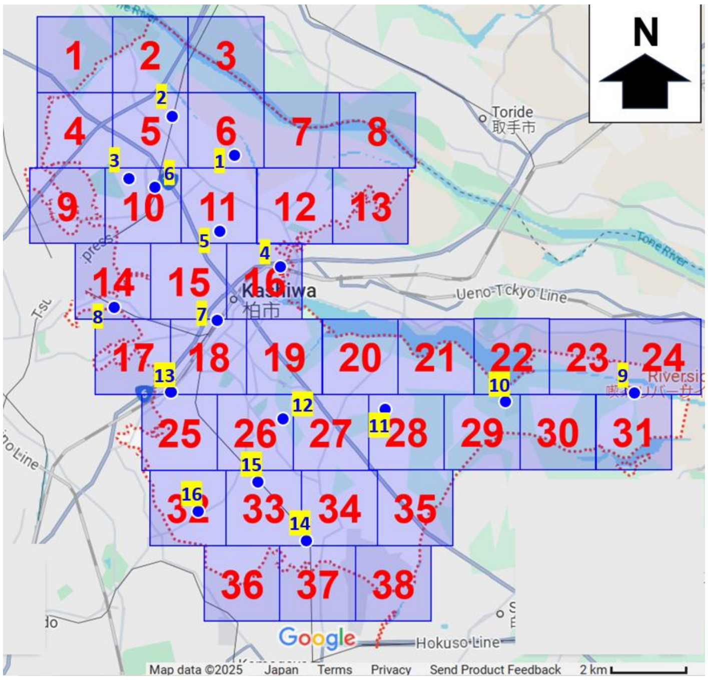

Fig. 9. The overlapping relationship between the 16 landmarks and 38 grids

Table 8. The uncertainty analysis of the 16 landmarks

Landmark	Possible nearest grid	LM Rep. Val. (Bq m^{-2})	Minimum (Bq m^{-2})	Maximum (Bq m^{-2})	Minimum %	Maximum %
1	3, 6, 7, 8, 11, 12, 13	5.51E+04	2.70E+04	7.20E+04	49	131
2	1, 2, 3, 4, 5, 6	6.15E+04	2.70E+04	7.90E+04	44	128
3	4, 5, 9, 10, 14, 15	5.71E+04	4.80E+04	7.90E+04	84	138
4	11, 12, 13, 16, 19, 20	5.47E+04	2.40E+04	7.20E+04	44	132
5	10, 11, 12, 15	6.00E+04	4.60E+04	7.20E+04	77	120
6	5, 6, 10, 11, 14, 15	6.46E+04	2.70E+04	7.90E+04	42	122
7	15, 16, 17, 18, 19	5.42E+04	4.30E+04	6.50E+04	79	120
8	9, 10, 14, 15, 17	6.12E+04	4.50E+04	7.20E+04	73	118
9	23, 24, 30, 31	3.45E+04	2.20E+04	5.30E+04	64	154
10	21, 22, 23, 28, 29, 30, 35	3.31E+04	2.00E+04	5.10E+04	60	154
11	20, 21, 27, 28, 29	4.80E+04	2.00E+04	6.30E+04	42	131
12	18, 19, 20, 26, 27, 34	5.52E+04	2.40E+04	6.50E+04	43	118
13	17, 18, 25, 26	4.86E+04	4.50E+04	6.50E+04	93	134
14	33, 34, 35, 36, 37, 38	4.08E+04	2.90E+04	5.00E+04	71	123
15	25, 26, 27, 32, 33, 34	4.93E+04	3.60E+04	6.50E+04	73	132
16	25, 26, 32, 33, 36	4.36E+04	3.60E+04	6.50E+04	83	149

Similarly, this study has analyzed the uncertainty of the 38 grids, and the results are shown in Table 9.

Table 9. The uncertainty of the 38 grids

Grid	Cs-tot	Minimum	Maximum	Minimum %	Maximum %
1	5.26E+04	5.10E+04	5.50E+04	97	105
2	5.59E+04	3.80E+04	6.70E+04	68	120

3	4.77E+04	3.30E+04	5.70E+04	69	119
4	5.18E+04	4.80E+04	5.70E+04	93	110
5	6.28E+04	5.10E+04	7.90E+04	81	126
6	5.33E+04	2.70E+04	6.50E+04	51	122
7	4.83E+04	3.50E+04	6.00E+04	72	124
8	4.66E+04	3.40E+04	5.30E+04	73	114
9	5.26E+04	4.80E+04	5.80E+04	91	110
10	6.35E+04	5.60E+04	7.20E+04	88	113
11	6.18E+04	5.50E+04	6.50E+04	89	105
12	5.98E+04	4.60E+04	7.20E+04	77	120
13	5.57E+04	4.60E+04	6.20E+04	83	111
14	6.23E+04	6.00E+04	6.50E+04	96	104
15	6.02E+04	5.50E+04	6.50E+04	91	108
16	5.39E+04	4.60E+04	6.20E+04	85	115
17	5.28E+04	4.50E+04	6.00E+04	85	114
18	5.16E+04	4.80E+04	5.70E+04	93	111
19	5.01E+04	4.30E+04	5.50E+04	86	110
20	4.80E+04	2.40E+04	6.30E+04	50	131
21	3.32E+04	2.00E+04	4.60E+04	60	138
22	2.84E+04	2.40E+04	3.10E+04	85	109
23	2.98E+04	2.20E+04	3.80E+04	74	127
24	3.13E+04	2.90E+04	3.60E+04	93	115
25	4.93E+04	4.60E+04	5.50E+04	93	112
26	5.52E+04	4.60E+04	6.50E+04	83	118
27	5.05E+04	3.60E+04	5.70E+04	71	113
28	4.43E+04	3.80E+04	5.10E+04	86	115
29	3.62E+04	3.30E+04	4.80E+04	91	133
30	3.69E+04	3.10E+04	4.60E+04	84	125
31	3.74E+04	2.90E+04	5.30E+04	77	142
32	4.41E+04	4.00E+04	5.10E+04	91	116
33	4.43E+04	3.60E+04	5.00E+04	81	113
34	4.28E+04	3.90E+04	4.80E+04	91	112
35	4.02E+04	3.40E+04	4.60E+04	85	114
36	3.73E+04	3.60E+04	3.90E+04	96	104
37	3.93E+04	3.60E+04	4.10E+04	92	104
38	4.04E+04	2.90E+04	4.60E+04	72	114

Comparing the results between Table 8 and Table 9, it is evident that dividing Kashiwa City into 38 grids reduces uncertainties. Unlike the 16 landmarks, which have a range of 42% to 154%, the range between the minimum and maximum percentages for the grids is smaller, at 50% to 142%. Additionally, none of the 16 landmarks fall within the 80% to 120% range, whereas over half of the 38 grids (23 out of 38) fall within this range.

4.1.2.3. PHITS Simulation

There are numerous nuclear engineering software systems, each designed for specific applications.

For example, SCALE (Standardized Computer Analyses for Licensing Evaluation) focuses on criticality safety and radiation shielding in nuclear reactors (28). Meanwhile, MCNP (Monte Carlo N-Particle) is versatile and suitable for a broad range of applications (29). PHITS (Particle and Heavy Ion Transport code System) is a Monte Carlo particle transport code capable of simulating various types of radiation across different energy ranges. Its simulation results are continuously calibrated against experimental data (30,31). These functionalities made PHITS suitable for radiation dose assessment in this study.

To calculate the total dose for a local resident, one factor to consider is exposure from decontaminated soil at home. For the dwelling scenario, the dimensions of the house and backyard for the PHITS simulation are shown in Fig. 10. The wall was assumed to be wooden with a thickness of 20 cm. The cement foundation of the house was assumed to be 1 m thick. The decontaminated soil (from the roof drainage system and backyard surface decontamination) was assumed to have a volume of 10 liters and be buried 30 cm underground in the backyard, adjacent to the wall outside the house. One important aspect of the PHITS program design is that the axis orientations differ from traditional conventions; in PHITS, the horizontal direction is the z-axis and the vertical direction is the x-axis. Additionally, while the figures presented in the thesis are in two dimensions, the actual PHITS simulations were conducted in three dimensions.

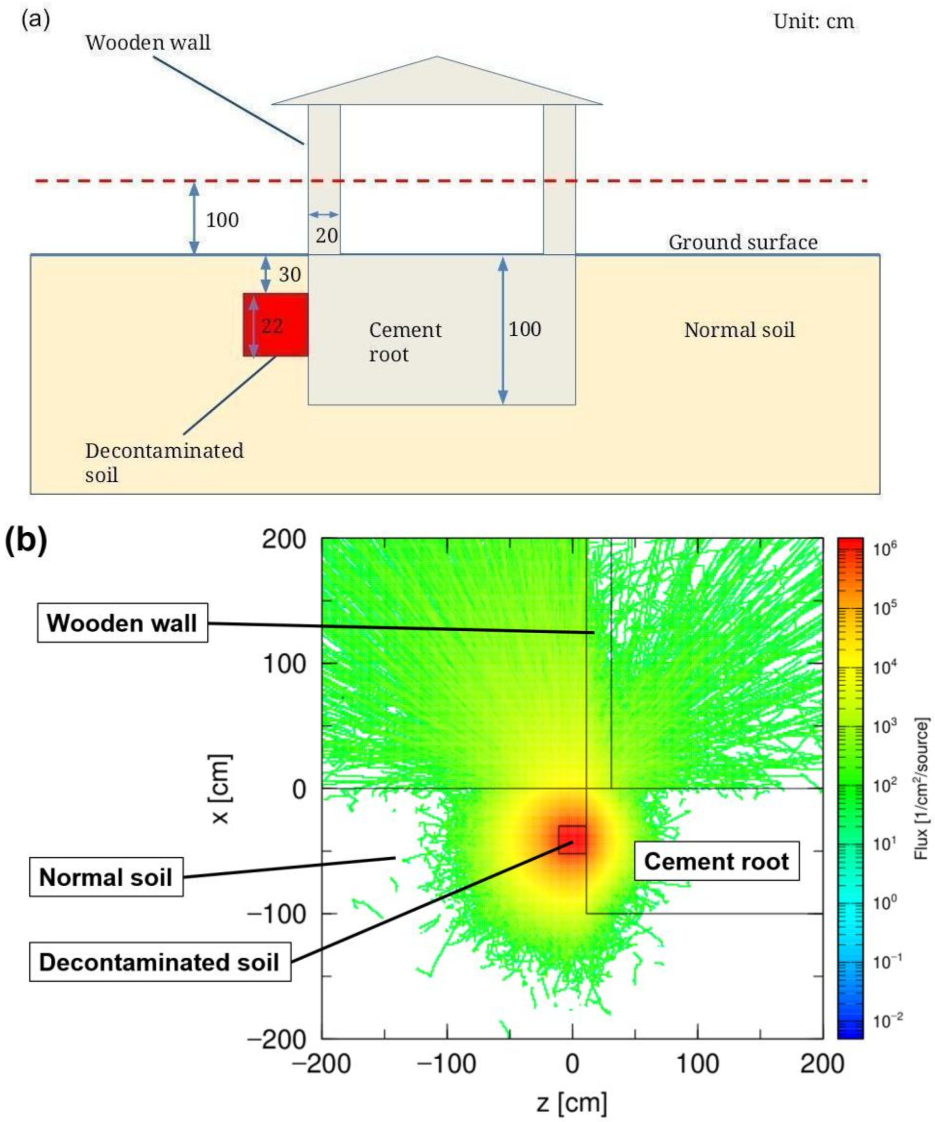

Fig. 10. (a) Dimensions of the dwelling situation; (b) PHITS Simulation results

The results of the PHITS Simulation are presented in Table 10. The source strength in PHITS was set to 1 GBq for both ^{134}Cs and ^{137}Cs. User input data will be calculated based on the ratio between the actual radiation strength and 1 GBq to determine the dose. Further details will be provided in Chapter 4.1.2.5.

Table 10. PHITS Simulation results (dose at 1 m above the ground) for the dwelling scenario

Conditions \ Positions	Normal conditions		Soil excavation	
	^{134}Cs: 1 GBq ^{137}Cs: 0 Bq	^{134}Cs: 0 Bq ^{137}Cs: 1 GBq	^{134}Cs: 1 GBq ^{137}Cs: 0 Bq	^{134}Cs: 0 Bq ^{137}Cs: 1 GBq
Indoors	4.64E-01 μSv h^{-1}	1.89E-01 μSv h^{-1}	Indoors	4.64E-01 μSv h^{-1}
Outdoors	4.39E+00 μSv h^{-1}	2.09E+00 μSv h^{-1}	Outdoors	4.39E+00 μSv h^{-1}

4.1.2.4. Determining the park/schoolyard areas

For the park/schoolyard scenario, this study assumed that decontamination involved flipping the top layer of contaminated soil with the uncontaminated soil beneath. The outcome of this process is illustrated in Fig. 11.

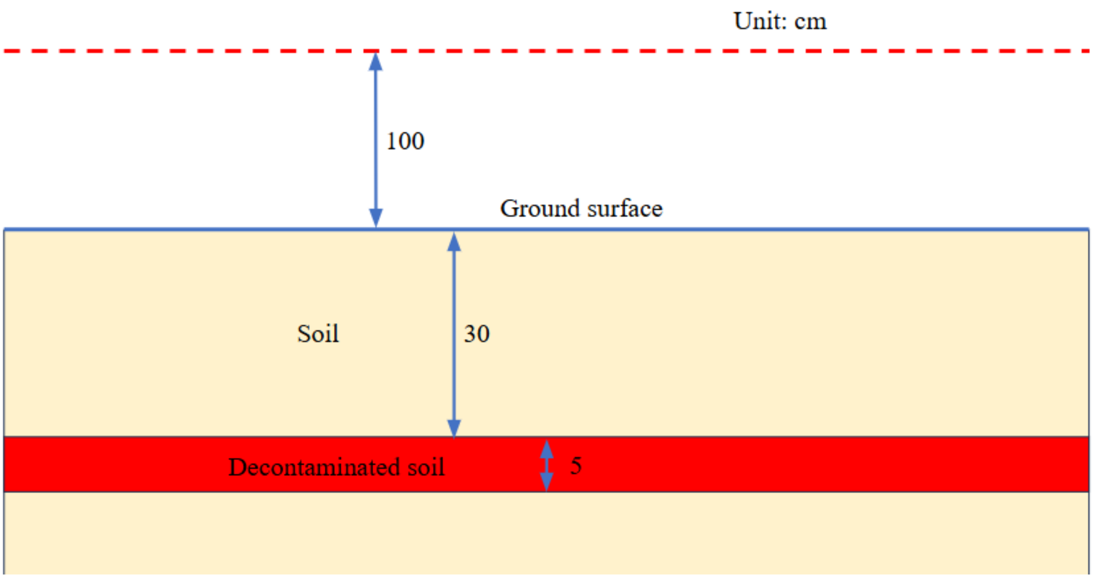

Fig. 11. The outcome after flipping the soil in parks/schoolyards (as indicated by the red dashed line) was to determine the ambient dose at 1 m above the ground.

The simulation result is presented in Table 11. It is important to note that in the simulation, the radius of the radiation source was set to 5 m. According to previous studies (32), the relationship between the radius of the radiation source and the dose contributed by the radiation source is illustrated in Fig. 12. By selecting a 5 m source radius, the circular radiation source contributes more than 60% of the total dose, while the remainder (less than 40%) is contributed by the assumed infinitely extended plane source.

Table 11. The PHITS Simulation results for the parks/schoolyards scenario (1 GBq was distributed homogeneously within the 5-m radius, resulting in a radiation activity concentration of 1.27E+07 Bq m⁻². In the row of infinitely wide plain, the 5-m radius values were divided by 0.62 due to the calibration factor shown in Fig. 12).

Conditions \ Process	Normal conditions		Soil excavation	
	^{134}Cs: 1.27E+07 Bq m^{-2} ^{137}Cs: 0 Bq m^{-2}	^{134}Cs: 0 Bq m^{-2} ^{137}Cs: 1.27E+07 Bq m^{-2}	^{134}Cs: 1.27E+07 Bq m^{-2} ^{137}Cs: 0 Bq m^{-2}	^{134}Cs: 0 Bq m^{-2} ^{137}Cs: 1.27E+07 Bq m^{-2}
5m radius	4.21E-01 μSv h^{-1}	1.99E-01 μSv h^{-1}	6.73E+00 μSv h^{-1}	3.48E+00 μSv h^{-1}
Infinitely wide plain (calibrated)	6.79E-01 μSv h^{-1}	3.21E-01 μSv h^{-1}	1.09E+01 μSv h^{-1}	5.62E+00 μSv h^{-1}

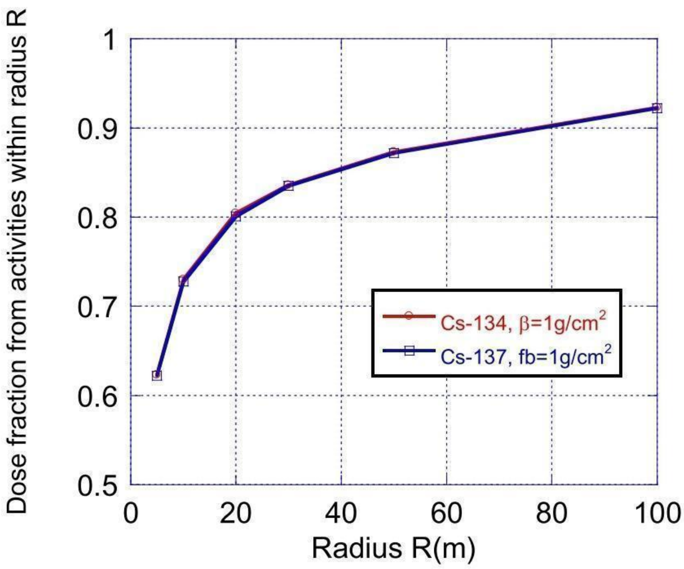

Fig. 12. The relationship between the radius of the radiation source and the contribution of dose from the source (32).

The detailed calibration process is explained as follows, as shown in Fig. 13. The "soil excavation scenario" serves as an example in the following explanations. First, the dose contributed by the 5-m circular source was 6.73E+00 μSv h^{-1} for 1 GBq of ^{134}Cs and 3.48E+00 μSv h^{-1} for 1 GBq of ^{137}Cs, as shown in Table 11. However, these values were obtained under simulation conditions where 1 GBq of radiocesium was distributed only within the 5-m-radius circle (with an average radiation activity concentration of 1.27E+07 Bq m^{-2}). In reality, most parks and schoolyards are likely much larger than the 5-m-radius circle. Therefore, by conservatively assuming that parks and schoolyards are infinitely wide plains, the dose assessment results might be closer to reality. Based on Fig. 12, if the radiation source is an infinitely wide plain, only 62% of the dose is contributed from within the 5-m radius, necessitating a calibration factor to divide the values by 0.62. After calibration, the data in the row "Infinitely wide plain (calibrated)" in Table 11 were obtained.

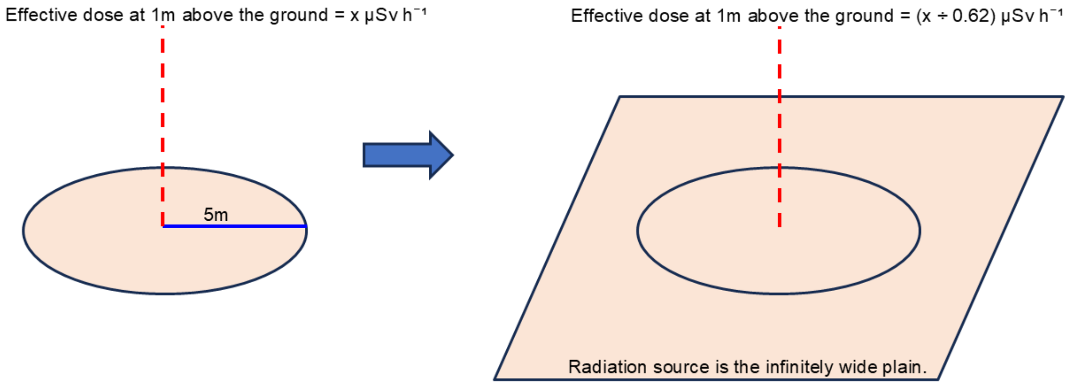

Fig. 13. The calibration process for the park and schoolyard scenario

4.1.2.5. Using real data as an example

The result of the user input spreadsheet is shown in Fig. 14. In the first line, Kashiwa citizens select the location nearest to their house. For example, if a citizen chooses "Kashiwanoha Campus Station," the Excel spreadsheet automatically retrieves all available data within the 2 x 2 km grid near Kashiwanoha Campus Station and calculates the average values. The decay calibration is also performed based on the user input date, as shown in the bottom line of Fig. 14. In this example, the average radiation source strength is 2.70E+04 Bq m^{-2} for ^{134}Cs and 3.77E+04 Bq m^{-2} for ^{137}Cs (before decay calibration), as shown in Fig. 15.

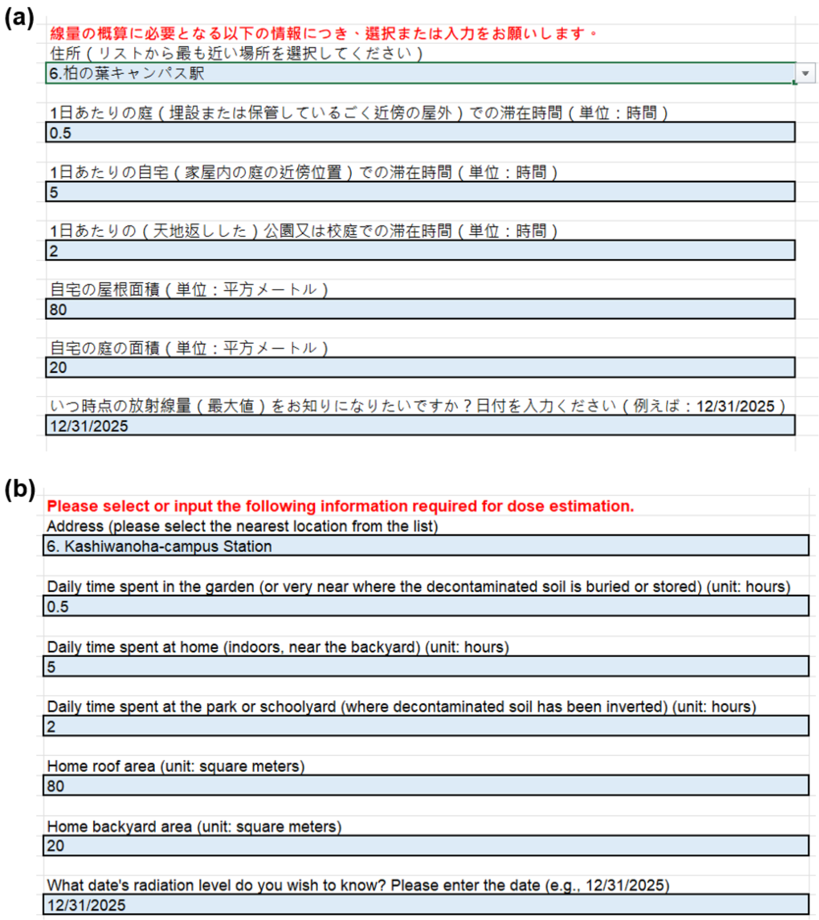

Fig 14. (a) The user interface of the input spreadsheet; **(b)** The English translation of (a)

Time: 2012/05/31

Cs-134 (Bq/m^2)	Cs-137 (Bq/m^2)
2.70E+04	3.77E+04

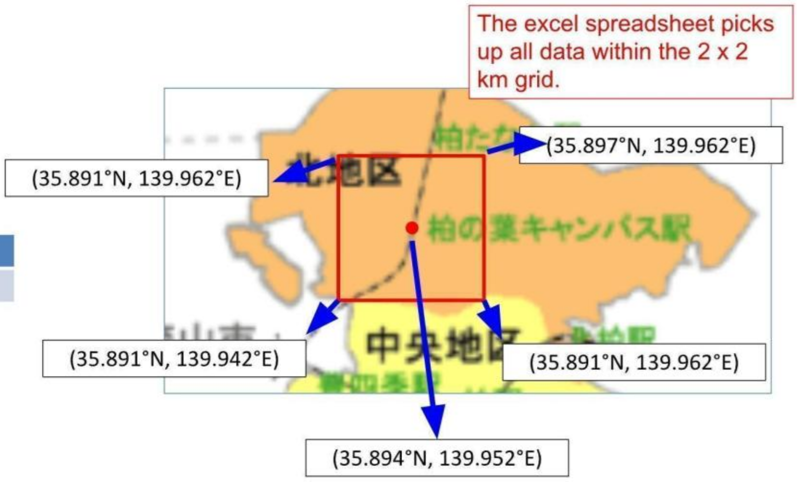

Fig 15. This figure depicts how the spreadsheet converts from the user input address and date into the average radiation source strength

Next, in lines 5 and 6 of the user input spreadsheet (Fig. 14), assuming the user inputs are 80 and 20 m^2 for the roof and backyard area, respectively, the result from Fig. 15 is multiplied by the sum of these areas, calculated as follows:

^{134}Cs: 2.70E+04 Bq m^{-2} * (80 + 20) m^2 = 2.70E+06 Bq . . . [a]
^{137}Cs: 3.77E+04 Bq m^{-2} * (80 + 20) m^2 = 3.77E+06 Bq . . . [b]

Next, since the user input the date of interest as Dec. 31, 2025 (bottom line in Fig. 14), decay calibration is needed (from May 31, 2012). The calibration results are as follows:

(^{134}Cs, ^{137}Cs) = (2.70E+04 Bq, 2.75E+06 Bq) . . . [c]

The results of [c] will be compared with the PHITS Simulation results shown in Chapter 4.1.2.3. For the situation in the backyard near where decontaminated soil is buried, since 1 GBq of ^{134}Cs and ^{137}Cs contributes to 4.39E+00 and 2.09E+00 µSv h^{-1}, respectively, the actual doses can be calculated as follows:

For ^{134}Cs: 2.70E+04 Bq / 1 GBq * 4.39E+00 µSv h^{-1} = 1.19E-04 µSv h^{-1} . . . [d]
For ^{137}Cs: 2.75E+06 Bq / 1 GBq * 2.09E+00 µSv h^{-1} = 5.75E-03 µSv h^{-1} . . . [e]

Thus, the total dose (both ^{134}Cs and ^{137}Cs) in the backyard is 5.87E-03 µSv h^{-1}. Likewise, the total dose (both ^{134}Cs and ^{137}Cs) in the house near the wall where decontaminated soil is buried is calculated to be 5.35E-04 µSv h^{-1}.

In lines 2 and 3 of Fig. 14, the user inputs the time spent in the backyard and in the house (near the position where decontaminated soil is buried) as 0.5 and 5 hours per day, respectively. Thus, the doses per day are calculated as follows:

In the backyard: 5.87E-03 µSv h^{-1} * 0.5 h d^{-1} = 2.94E-03 µSv d^{-1} . . . [f]
In the house: 5.35E-04 µSv h^{-1} * 5 h d^{-1} = 2.68E-03 µSv d^{-1} . . . [g]

Similarly, for the park/schoolyard scenario, the average radionuclide fallout in the 2 x 2 km grid surrounding Kashiwanoha Campus Station was as follows:

(^{134}Cs, ^{137}Cs) = (2.70E+04 Bq m^{-2}, 3.77E+04 Bq m^{-2}) . . . [h]

In this example, as shown in Fig. 14 (bottom line), the user inputs the date of interest as December 31, 2025. After decay calibration, the results of [h] become:

(^{134}Cs, ^{137}Cs) = (2.70E+02 Bq m^{-2}, 2.75E+04 Bq m^{-2}) . . . [i]

Next, the spreadsheet calculates the ratio between the actual source strengths [i] and theoretical dose (in PHITS Simulation shown in Table 11 under normal conditions). The process is as follows:

For ^{134}Cs: 2.70E+02 Bq m^{-2} ÷ 1.27E+07 Bq m^{-2} * 6.79E-01 µSv h^{-1} = 1.44E-05 µSv h^{-1} For ^{137}Cs: 2.75E+04 Bq m^{-2} ÷ 1.27E+07 Bq m^{-2} * 3.21E-01 µSv h^{-1} = 6.95E-04 µSv h^{-1}

Thus, the total dose (due to both ^{134}Cs and ^{137}Cs) is 7.09E-04 µSv h^{-1}.

In this example, the user inputs the time spent in the park/schoolyard as 2 hours per day, as shown in Fig. 14 (line 4). Thus, the dose incurred in the park/schoolyard is: (7.09E-04 µSv h^{-1})(2 h d^{-1}) = 1.42E-03 µSv d^{-1} . . . [j]

Finally, the spreadsheet provides the user with the highest dose incurred in the backyard (as shown in the top row in Fig. 16). It also returns the value of annual total exposure (as shown in the bottom row in Fig. 16) by the following calculation:

(Backyard dose, µSv d^{-1} + in-house dose, µSv d^{-1} + park/schoolyard dose, µSv d^{-1}) * 365 d y^{-1} * (0.001 mSv µSv^{-1})

In this example, the dose is calculated as follows:

(Backyard dose, 2.94E-03 µSv d^{-1} + in-house dose, 2.68E-03 µSv d^{-1} + park/schoolyard dose, 1.42E-03 µSv d^{-1}) * 365 d y^{-1} * (0.001 mSv µSv^{-1}) = 2.57E-03 mSv y^{-1}

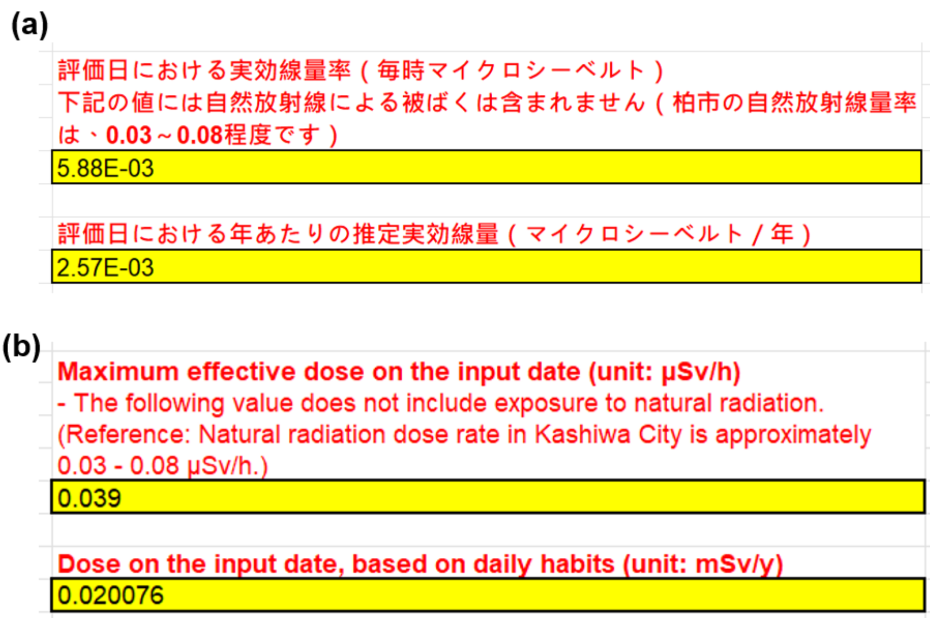

Fig. 16. (a) The figure shows the returning image of the spreadsheet, displaying the maximum dose (in terms of µSv h^{-1}) and average annual dose (mSv y^{-1}) **(b)** The English translation for (a)

4.1.2.6. Uncertainties of the dose assessment

In this study, this study used the pre-defined conversion coefficients in PHITS to convert from Gy to Sv. As shown in the PHITS Manual in Fig. 17, there are 12 different multiplier IDs to choose from (33). The concept of various multiplier IDs is briefly illustrated in Fig. 17 (34). Theoretically, the CAU irradiation geometry shown in Fig. 18 is most suitable for this study because the radiation comes from underground (as decontaminated soil is buried 30 to 40 cm underground). However, since CAU conversion coefficients are absent in PHITS (as shown in Fig. 17), this study followed the recommendation received during the JAEA Internship and used ISO irradiation geometry to convert from Gy to Sv. ISO was suggested to be the second-best irradiation geometry for the circumstances of this study. Nonetheless, it might be worthwhile to conduct further research to evaluate the uncertainties between using the CAU and ISO irradiation geometries.

Multiplier ID	Data information
-200	$H^*(10)$[90]
-201	Effective dose based on ICRP60 (AP irradiation)[91]
-202	Effective dose based on ICRP103 (AP irradiation)[92]
-203	Effective dose based on ICRP103 (ISO irradiation)[92]
-204	New operational quantity H^* (Maximum effective dose among the all irradiation conditions[92]
-210	Sex-averaged effective dose equivalent (ISO irradiation)[93]
-211	Effective dose equivalent for male (ISO irradiation)[93]
-212	Effective dose equivalent for female (ISO irradiation)[93]
-213	Dose equivalent for male red-bone marrow (ISO irradiation)[93]
-214	Dose equivalent for female red-bone marrow (ISO irradiation)[93]
-215	Dose equivalent for male skin (ISO irradiation)[93]
-216	Dose equivalent for female skin (ISO irradiation)[93]
-299	Soft error rate on semiconductor device (ISO irradiation)[94]

Fig. 17. The page of PHITS Manual that shows various types of pre-defined conversion coefficients that convert Gy to Sv (33)

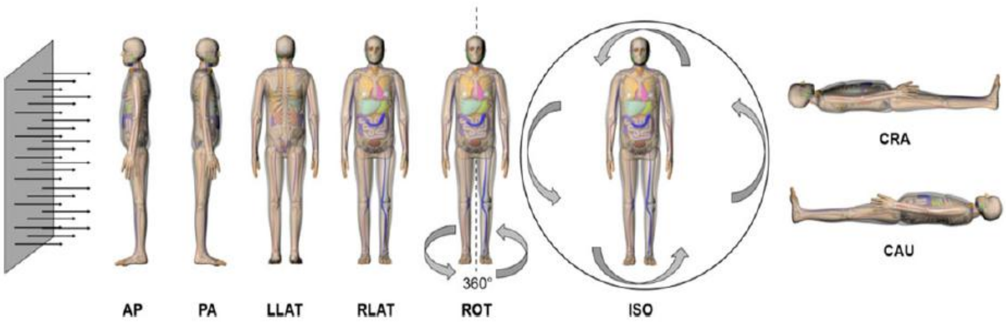

Fig. 18. The schematic illustrations of several different types of irradiation geometries (34)

In addition to the uncertainties due to the irradiation geometries, further uncertainties might arise from the JAEA Airborne Survey itself. The JAEA Airborne Survey calculated the radiation activity concentration data (in Bq m^{-2}) by measuring the ambient dose rate (in μSv h^{-1}) at 150 to 300 m above the ground and then converting the values using specific formulas (23). However, this conversion process might introduce some uncertainties. As shown in Fig. 19, the correlation (R^2) between the ambient dose rate (measured at 1 m above the ground) and the actual radiation activity concentration (measured by soil sampling) was 0.76 (2). Given that the JAEA Airborne Survey was conducted at higher altitudes (150 to 300 m), the uncertainties might be even larger. However, due to the limitation that soil sampling data were only available within 100 km of the FDNPP, the JAEA Airborne Survey Database might be a practical source for conducting dose assessments in regions beyond the 100 km radius, including Kashiwa City.

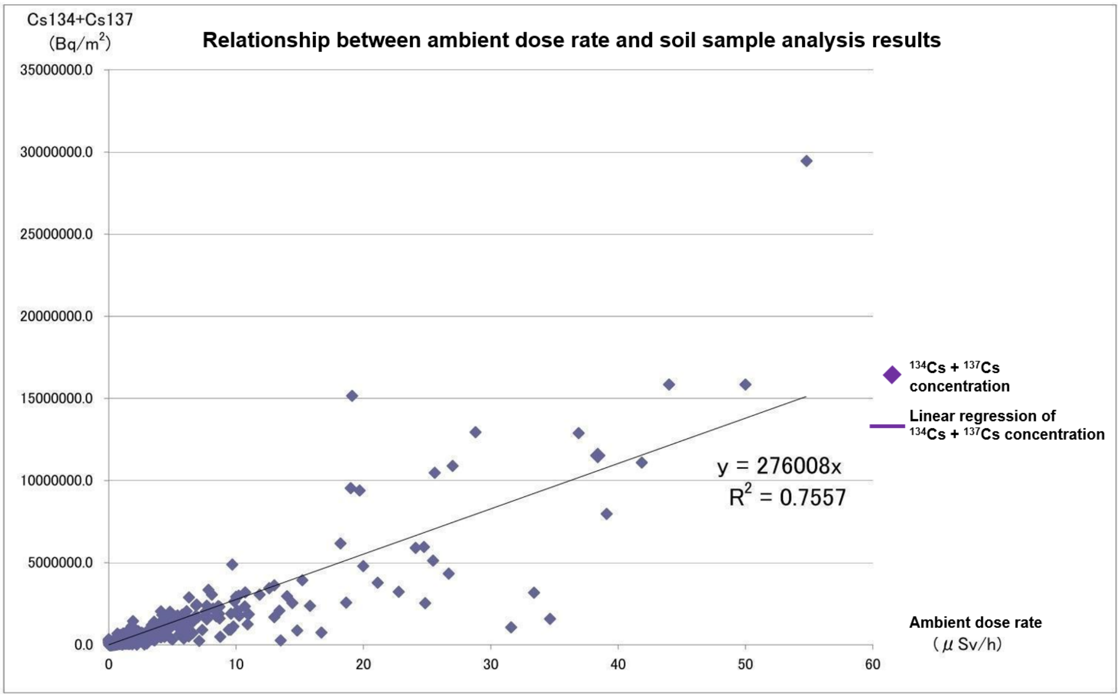

Fig. 19. A graph illustrating the correlation between radiation activity concentration (from direct soil sampling within 100 km of the FDNPP) and ambient dose rate (measured at 1 m above the ground) (2)

4.2. On-site measurements

4.2.1. On-site measurement background and results

To compare the calculation method with the real data, this study conducted on-site measurements with the support of Kashiwa City Hall members. The measurements were taken from 9:00 to 12:30 on November 19, 2024. The main detector used was the Scintillation Survey Meter ALOKA TCS-172 (calibrated), and the auxiliary detector was the Environmental Gamma-Ray Monitor (環境ガンマ線測定器) FUJI PEGASUS-Pro (not calibrated). The weather conditions from November 16 to 19 were dry, with no precipitation. Measurements were taken at four locations: 少年補導センター (Juvenile Guidance Center), 南増尾小鳥の森 (Minami-Masuo Bird Forest), 柏市民文化会館 (Kashiwa Citizen's Cultural Hall), and 大堀川レクリエーション公園 (Ohorigawa Recreation Park). The on-site measurement procedure is shown in Fig. 20. The basic information and measurement results for these four locations are shown in Table 12.

Fig. 20. On-site measurement procedures

Table 12. Background information and measurement results for the four locations in Kashiwa City (Remarks: [A] 12 m by 12 m; [B] 144 x 0.6 = 86.4 m², 2 of the 5 drainage pipes drain into the river; 3 of the 5 pipes drain into backyard soil surface; [C] measured by the auxiliary detector; [D] 60 x 40 + 30 x 40 = 3,600 m²; [E] Assume all rainwater is drained to the surface soil; [F] For some areas in the backyard where they were likely not decontaminated yet, the 0-cm background dose was 0.10-0.20 μSv h⁻¹; [G] No dose detected; one possible reason was that the soil surface was covered with leaves (the decontamination area was 4.5 by 4.5 m); [H] The decontamination area was approximately 15 by 15 meters).

Location	少年補導センター（柏市柏5-8-32） Juvenile Guidance Center (5-8-32 Kashiwa, Kashiwa City)	南増尾小鳥の森（柏市南増尾 3-40） Minami-Masuo Bird Forest (3-40 Minami-Masuo, Kashiwa City)	柏市民文化会館（柏市柏下107） Kashiwa Citizen's Cultural Hall (107 Kashiwashita, Kashiwa City)	大堀川レクリエーション公園（柏市篠籠田字初音 13-1） Ohorigawa Recreation Park (13-1 Shinogoda Aza-Hatsune, Kashiwa City)
Type	Dwelling	Park	Dwelling	Park
Roof area (m^2)	144 [A]	No roof	3600 [D]	No roof
Rain drainage basin area (m^2)	86.4 [B]	No roof	3600 [E]	No roof
Soil coverage (cm)	30	40	40	40
Plastic bag wrapping	Yes	Yes	Yes	Yes

Background dose - 0cm (μSv h⁻¹)	0.03-0.05	0.03-0.05 [C]	0.06-0.08 [F]	0.07-0.08
Background dose - 100cm (μSv h⁻¹)	0.03-0.05	0.03-0.05 [C]	0.06-0.08	0.07-0.08
Pre-excavation dose - 0cm (μSv h⁻¹)	0.10-0.12	0.08	0.08	0.05-0.06
Pre-excavation dose - 100cm (μSv h⁻¹)	Not measured	0.06	0.10-0.12	0.04
Excavation window (cm x cm)	7x7	7x7	7x7	7x7
Post-excavation dose - 0cm (μSv h⁻¹)	0.70-0.80	0.06-0.08 [G]	0.53-0.55	0.18-0.19 [H]
Post-excavation net dose - 0cm (μSv h⁻¹)	0.71	0.03	0.47	0.11

Among the four locations, two of them (Juvenile Guidance Center and Kashiwa Citizen's Cultural Hall) correspond to the dwelling scenario described in Chapter 4.1.2.3. In these locations, roofs collected radionuclide fallouts, and rainwater was directed toward the surface of the backyard, as illustrated in Fig. 21. The decontamination process involved removing the top layer of the backyard soil, wrapping the decontaminated soil in a plastic bag, and burying the bag below the ground.

The Juvenile Guidance Center and Kashiwa Citizen's Cultural Hall differ significantly. The former resembles an actual residential house, with a smaller building volume and a backyard filled with flat soil. In contrast, the latter is a large-volume building surrounded by an asphalt yard.

Regarding Minami-Masuo Bird Forest and Ohorigawa Recreation Park, both are parks with soil coverage. However, the former is located near the foot of a mountain, while the latter is a flat, wide area. The decontamination process involved removing the top layer of soil, wrapping it in plastic bags, and burying the bags underground. Unlike the previous residential scenarios, the decontaminated soil in these large parks was not concentrated in one place. Instead, the soil was buried in over 20 different locations.

Fig. 21. A photo taken outside the Juvenile Guidance Center showing the rainwater drainage pipe

One thing to note is that, for the Juvenile Guidance Center, there are five groups of rainwater drainage pipes, but only three groups drain toward the backyard's surface, while the other two groups drain directly into the river. Therefore, although the roof area measured on Google Maps was 144 m², this study multiplied this number by 0.6 and determined the rainwater drainage basin area (into the backyard) to be 86.4 m².

Another thing to note is that, in the Kashiwa Citizen's Cultural Hall, there were various background values before soil excavation. The value was measured as high as 0.10-0.20 μSv h⁻¹. It is possible that part of the backyard near the Kashiwa Citizen's Cultural Hall was not decontaminated. The value chosen to display in Table 12 was the lower value measured at another corner of the backyard.

4.2.2. Comparing between on-site measurements and PHITS Simulation results

Table 13 presents the PHITS simulation process, results, and instances of overestimation for four on-site measurement locations. The detailed simulation process for each location will be discussed later.

Table 13. Comparison of on-site measurement and theoretical dose values

Location	**Juvenile Guidance Center**	**Minami-Masuo Bird Forest**	**Kashiwa Citizen's Cultural Hall**	**Ohorigawa Recreation Park**
Type	Dwelling	Park	Asphalt	Park
Post-excavation net dose - 0cm (μSv h⁻¹)	0.71	0.03	0.47	0.11
Reference position	7. JR Kashiwa Station	16. GU Kashiwa-Minami-Masuo Store	7. JR Kashiwa Station	7. JR Kashiwa Station

^{134}Cs (Bq m^{-2}) Date: 20120531	2.22E+04	1.79E+04	2.22E+04	2.22E+04
^{137}Cs (Bq m^{-2}) Date: 20120531	3.12E+04	2.49E+04	3.12E+04	3.12E+04
^{134}Cs (Bq) Date: 20120531	1.92E+06	3.63E+05	8.00E+07	5.00E+06
^{137}Cs (Bq) Date: 20120531	2.69E+06	5.04E+05	1.12E+08	7.01E+06
^{134}Cs (Bq) Date: 20241119	2.88E+04	5.45E+03	1.20E+06	7.50E+04
^{137}Cs (Bq) Date: 20241119	2.02E+06	3.78E+05	8.41E+07	5.26E+06
Simulation: ^{134}Cs (μSv h^{-1} GBq^{-1})	1.14E+03	3.13E+03	3.13E+03	3.13E+03
Simulation: ^{137}Cs (μSv h^{-1} GBq^{-1})	6.16E+02	1.53E+03	1.53E+03	1.53E+03
Theoretical ^{134}Cs (μSv h^{-1})	3.29E-02	1.70E-02	3.76E+00	2.35E-01
Theoretical ^{137}Cs (μSv h^{-1})	1.24E+00	5.79E-01	1.29E+02	8.05E+00
Theoretical ^{134}Cs + ^{137}Cs (μSv h^{-1})	1.28E+00	5.96E-01	1.32E+02	8.29E+00
Ratio (calculated / measurement)	1.80E+00	1.99E+01	2.82E+02	7.54E+01

To compare the on-site measurement results with the PHITS Simulation, this study operated the simulations as follows:

For the Juvenile Guidance Center, the nearest reference location among the 16 landmarks was JR Kashiwa Station. The average radionuclide fallout at JR Kashiwa Station (within the 2 x 2 km grid) was 2.22E+04 Bq m^{-2} for ^{134}Cs and 3.12E+04 Bq m^{-2} for ^{137}Cs as of May 31, 2012. The rain drainage basin area is 86.4 m^2. Thus, the radiation source strength as of May 31, 2012, is:

^{134}Cs: (2.22E+04 Bq m^{-2}) * (86.4 m^2) = 1.92E+06 Bq . . . [k]
^{137}Cs: (3.12E+04 Bq m^{-2}) * (86.4 m^2) = 2.70E+06 Bq . . . [l]

The on-site measurement day was November 19, 2024. Taking into account the decay of radiocesium, [k] and [l] become:

(^{134}Cs, ^{137}Cs) = (2.88E+04 Bq, 2.02E+06 Bq) . . . [m]

Additionally, during the on-site measurement, this study removed the top 30 cm of soil coverage and exposed the plastic bag wrapping the decontaminated soil, as shown in Fig. 22. Once the plastic bag was visible, used a small plastic shovel to gently remove the soil coverage, creating an opened window approximately 7 x 7 cm. These dimensions were replicated in our PHITS Simulation, as shown in Fig. 23.

Fig. 22. A photo taken at Juvenile Guidance Center showing the exposure of the plastic bag that wrapped decontaminated soil

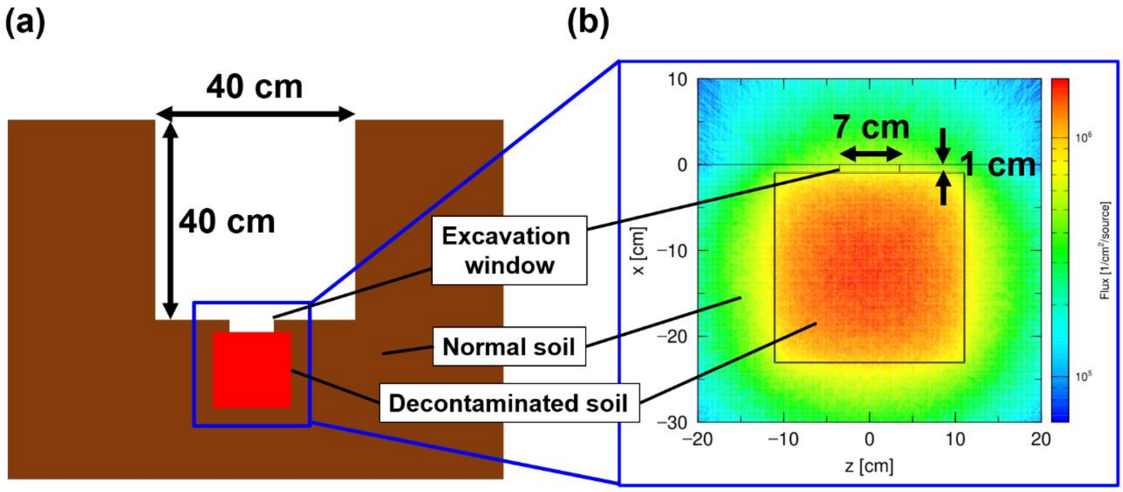

Fig. 23. (a) Dimensions of PHITS Simulation for the Juvenile Guidance Center; (b) Simulation results

In the simulation result, the maximum dose measured at the center on top of the decontaminated soil is shown in Table 14. The method used was the same as in Chapter 4.1, utilizing 1 GBq of ^{134}Cs and ^{137}Cs as the standard sources. This study then calculated the theoretical doses based on the ratio between the actual radiation source strength. After decay calibration, the resulting dose (for the sum of ^{134}Cs and ^{137}Cs) is 3.18 μSv h^{-1}. Meanwhile, in the on-site measurement, the actual dose measured was 0.71 μSv h^{-1} (after deducting the background value), indicating a 4-fold overestimation (ratio between calculated and measurement results).

Table 14. PHITS Simulation results of Fig. 23

Source \ Activity	Effective dose (μSv h^{-1})
^{134}Cs (1 GBq)	3.13E+03
^{137}Cs (1 GBq)	1.53E+03
^{134}Cs (2.88E+04 Bq)	9.02E-02
^{137}Cs (2.02E+06 Bq)	3.09E+00

For 南増尾小鳥の森, the nearest reference location is GU Kashiwa-Minami-Masuo Store, where the average radionuclide fallouts for ^{134}Cs and ^{137}Cs are 1.79E+04 Bq m^{-2} and 2.49E+04 Bq m^{-2}, respectively. In the on-site measurement, Kashiwa City Hall members provided information that the decontamination area of the park was 4.5 x 4.5 m, resulting in the following theoretical source strengths as of May 31, 2012:

^{134}Cs: 1.79E+04 Bq m^{-2} x 4.5 m x 4.5 m = 3.62E+05 Bq . . . [n]
^{137}Cs: 2.49E+04 Bq m^{-2} x 4.5 m x 4.5 m = 5.04E+05 Bq . . . [o]

After decay calibration to the on-site measurement date (November 19, 2024), the results of [n] and [o] became:

(^{134}Cs, ^{137}Cs) = (5.45E+03 Bq, 3.78E+05 Bq) . . . [p]

The values of [p] were used as input parameters for our PHITS Simulation. After soil excavation, the geometry at Minami-Masuo Bird Forest (as well as the other two sites) was similar to Fig. 23, so this study conducted the same PHITS Simulation, adjusting the source strength to 5.45E+03 Bq for ^{134}Cs and 3.78E+05 Bq for ^{137}Cs. Based on this ratio, the theoretical dose (for the sum of ^{134}Cs and ^{137}Cs) was 0.60 μSv h^{-1}, representing a 20-fold overestimation.

One possible reason for the overestimation is that Minami-Masuo Bird Forest has a significant amount of leaves on the surface, as shown in Fig. 24. This may have significantly decreased the dose; the measured dose before and after soil excavation was approximately the same on the measurement date.


Fig 24. Photo taken at Minami-Masuo Bird Forest on the measurement date

At Kashiwa Citizen's Cultural Hall, a rough estimation on Google Maps suggests the roof area is approximately 3,600 m^2. Out of the 16 reference positions, Kashiwa Citizen's Cultural Hall is closest to JR Kashiwa Station, where ^{134}Cs and ^{137}Cs concentrations were 2.22E+04 Bq m^{-2} and 3.12E+04 Bq m^{-2}, respectively (as of May 31, 2012). Thus, the theoretical source strengths can be calculated as follows:

^{134}Cs: 2.22E+04 Bq m^{-2} * 3,600 m^2 = 7.99E+07 Bq . . . [q]
^{137}Cs: 3.12E+04 Bq m^{-2} * 3,600 m^2 = 1.12E+08 Bq . . . [r]

Taking decay calibrations into account, ^{134}Cs and ^{137}Cs were adjusted to the following values on the on-site measurement day (Nov. 19, 2024):

(^{134}Cs, ^{137}Cs) = (1.20E+06 Bq, 8.41E+07 Bq) . . . [s]

Using the same method mentioned above, the theoretical dose (sum of ^{134}Cs and ^{137}Cs) was calculated to be 1.32E+02 μSv h^{-1}, which is a 300-fold overestimation. One possible reason for this overestimation could be the extremely large roof area (3,600 m^2) used in the calculation. It is possible that only a small part of the roof drained rainwater to the backyard; For other parts, the radiocesium in the rainwater was lost due to the asphalt coverage. In this case, the overestimation in the calculation might be significantly smaller, which will be discussed later.

For Ohorigawa Recreation Park, the nearest reference location among the 16 reference positions is JR Kashiwa Station, where the average radionuclide fallout as of May 31, 2012, was 2.22E+04 Bq m^{-2} for ^{134}Cs and 3.12E+04 Bq m^{-2} for ^{137}Cs. Considering the dimensions of the decontamination area at Ohorigawa Recreation Park (15 x 15 m), the source strengths were calculated as follows:

^{134}Cs: 2.22E+04 Bq m^{-2} * 15 m * 15 m = 5.00E+06 Bq . . . [t]
^{137}Cs: 3.12E+04 Bq m^{-2} * 15 m * 15 m = 7.02E+06 Bq . . . [u]

After decay calibration, the source strengths become the following values as of the measurement day (Nov. 19, 2024):

(^{134}Cs, ^{137}Cs) = (7.50E+04 Bq, 5.26E+06 Bq) . . . [v]

Using the same calculation method as above, the theoretical dose (sum of ^{134}Cs and ^{137}Cs) is 8.29E+00 μSv h^{-1}, which is a 75-fold overestimation compared with the actual measurement result. Fig. 25 is a photo taken at the Ohorigawa Recreation Park on the measurement day.

Fig. 25. A photo taken at the Ohorigawa Recreation Park

From the discussion above, it is evident that the PHITS Simulation led to overestimations for all four locations. Some identified reasons (such as leaf coverage at Minami-Masuo Bird Forest and the extremely large roof area assumption at Kashiwa Citizen's Cultural Hall) contributed to the overestimation. Additionally, other reasons might include assumptions in the PHITS Simulation, such as plastic bag thickness and density. In this study, plastic bags were assumed to be 0.1 cm thick with a density of 1.3 g cm^{-3}. However, it is possible that the actual thickness and density were larger. By adjusting these two parameters, the overestimation might be reduced. Another possible reason for the overestimation at Kashiwa Citizen's Cultural Hall is that radiocesium might have been lost during the transportation from the rooftop to the backyard, where the measurements were conducted. Additionally, for all four locations, the exact shape and volume of the plastic bags were unknown, which might also contribute to the overestimation.

To test this study's hypothesis, this study changed the input parameters as follows (38-40): Plastic bag thickness = 0.3 cm, plastic density = 1.5 g cm^{-3}, and soil density = 1.4 g cm^{-3}. The PHITS Simulation for Juvenile Guidance Center resulted in 3.10E+00 μSv h^{-1} (compared to the original 3.18 μSv h^{-1}), which was a 4.4-fold overestimation (compared to the original 4.5-fold overestimation). From this perspective, the impact of plastic bag thickness, plastic bag density, and soil density appears to be quite limited.

Alternatively, another hypothesis suggests that the measurement was not taken from the center of the plastic bag. Instead, it is possible that the study measured a corner of the bag, as most of it was buried under the soil and out of sight. To test this hypothesis, another PHITS simulation was conducted, as illustrated in Fig. 26.

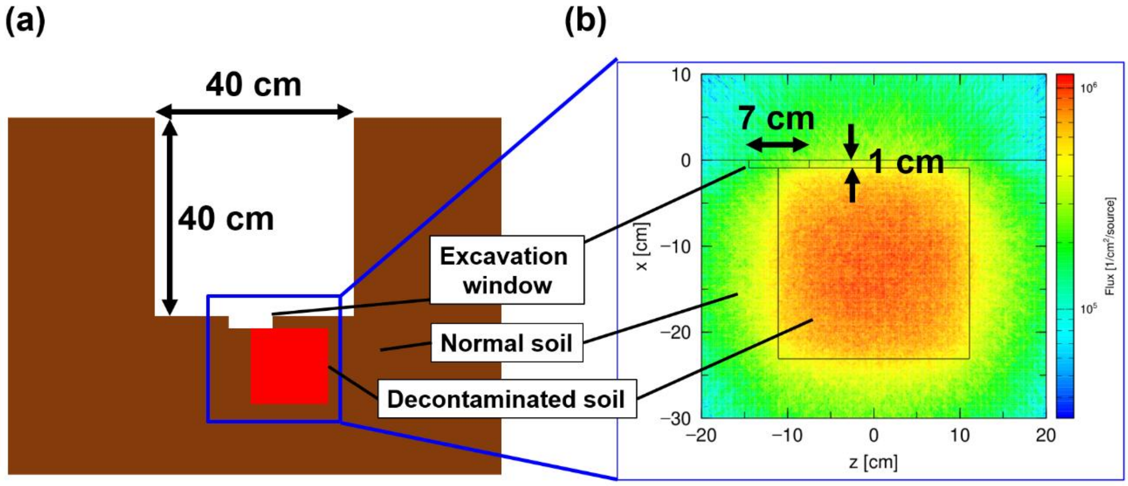

Fig. 26. (a) The figure illustrates the hypothetical positions of the soil excavation window and the buried decontaminated soil. **(b)** The figure presents the PHITS simulation results corresponding to (a).

Regarding the simulation results, the new theoretical dose was calculated to be 1.28 μSv h^{-1}, with an overestimation of 1.8 times. The above discussion indicates that, for the dwelling scenario, the simulation results might closely align with measurement outcomes. In either case, the overestimation of the dwelling scenario is a zero-order (10^0) overestimation.

Conversely, in the park and schoolyard scenario, both Minami-Masuo Bird Forest and Ohorigawa Recreation Park show a one-order (10^1) overestimation. One possible explanation might be the distribution of decontaminated soil. According to Kashiwa City Hall members, decontaminated soil in the parks was distributed across 20 or more different locations, though exact numbers were uncertain (the concept is shown in Fig. 27). However, this study calculated the theoretical dose by assuming all decontaminated soil was concentrated in a single location. If the theoretical values were divided by a factor of 20 or more, the overestimation would be significantly reduced. Additionally, as mentioned in the Juvenile Guidance Center, the overestimation for the parks could also be largely reduced due to the fact that the decontaminated soil was not measured at the center position. Considering the above factors, the overestimation of the park and schoolyard scenario is a zero-order (10^0) overestimation.

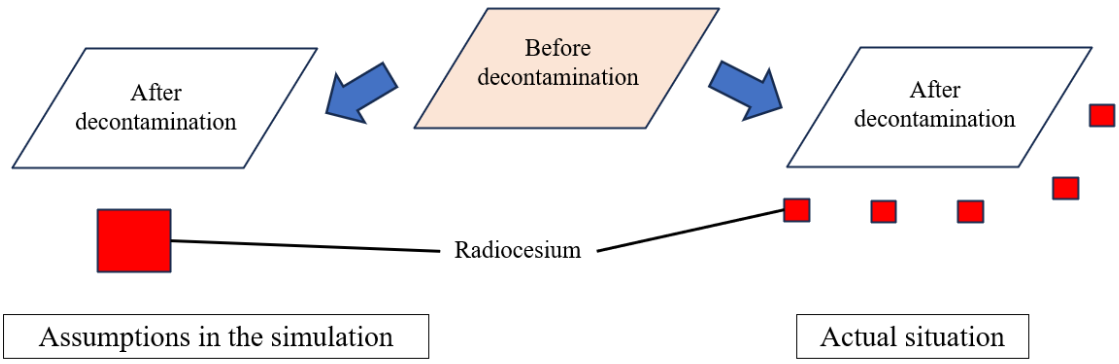

Fig. 27. A conceptual figure illustrating why the park scenario might result in a 10^1-fold overestimation.

Additionally, this study aims to further discuss the significant overestimation at Kashiwa Citizen's Cultural Hall, where the discrepancy was the largest (approximately 300-fold). The main reason might be the asphalt coverage, as depicted in Fig. 28.

Fig. 28. A photograph taken on the day of measurement, highlighting the asphalt coverage surrounding Kashiwa Citizen's Cultural Hall.

As mentioned in a previous study (8), when the ground surface is covered by asphalt, rainwater carrying radiocesium deposits will quickly drain horizontally, with minimal penetration into the ground (the concept is shown in Fig. 29). This study demonstrates that in such asphalt-covered scenarios, the calculation's overestimation can be two orders of magnitude (10^2). In summary, Table 15 presents the degrees of overestimation for the method used in this study.

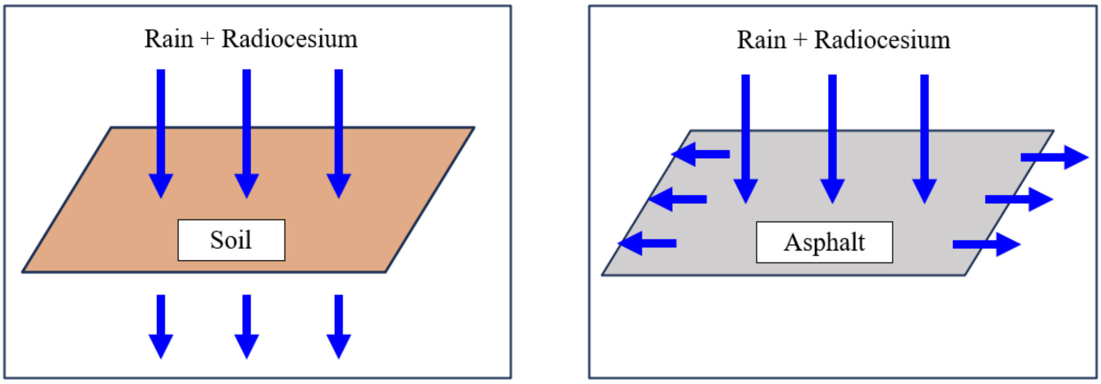

Fig. 29. Conceptual figures illustrating why the asphalt-coverage scenario might result in a 10^2-fold overestimation

Table 15. Degrees of overestimation for various scenarios in the method proposed by this study

Scenario	Dwelling	Parks and schoolyards	Asphalt
Overestimation	10^0	10^0	10^2

Based on the discussions above, this study encourages future research to enhance the user-input spreadsheet by accounting for uncertainties due to various land types. One approach could be to allow users to enter specific addresses or park names in addition to the 16 landmarks set in Kashiwa City. By incorporating actual data on the distribution of decontaminated soil burial sites, it may be possible to correct overestimations in the spreadsheet's calculation formulas.

4.3. Estimating a representative person's dose using deterministic and probabilistic methods

4.3.1. Definitions, pros, and cons

As shown in Table 16 (35), the dose to the representative person can be evaluated using two methods: probabilistic and deterministic calculation methods. More specifically, ICRP Publication 101, Table 3.2., summarizes the methods used for determining the dose to the representative person. For the probabilistic calculation method, the environmental concentration data are distributions of estimated or measured concentrations. In contrast, for the deterministic calculation method, the environmental concentration data are single values for parameters.

Regarding habit data, the probabilistic calculation method uses a range or fixed values for habit data, while the deterministic calculation method uses the average value for the group that is more highly exposed or the 95th percentile of national or regional data. As for the dose coefficient, a fixed value based on age is used in both the probabilistic and deterministic calculation methods.

For the dose to the representative person, the probabilistic calculation method identifies it in a way that the probability is <5% that a person selected at random from the population would receive a higher dose. For the deterministic calculation method, the dose to the representative person is the product of the environmental concentration data values, habit data values, and the dose coefficient.

Table 16. Definitions of the probabilistic and deterministic calculation method (simplified from the ICRP 101 Table 3.2.) (35)

Aspect \ Method	**Probabilistic**	**Deterministic**
Environment	Distribution of concentration	Single values
Habit	Range of fixed values	95th percentile of the data
Coefficient	A fixed value based on the age	
Dose	Top 5% of the dose distribution	The product of the above values

From the viewpoint of a previous study (36), it might be interpreted that the probabilistic method might be "The most appropriate way to take into account safety without having to resort to very conservative assessments;" however, it might be "difficult to prepare the database." On the other hand, for the deterministic method, "Data are easier to be gathered," making it "more efficient to evaluate radiological exposure;" however, this method might be "very conservative." In the above passage, the original statements from the publication by Nelson et al. (2013) are quoted in quotation marks. In simple terms, the pros and cons of the probabilistic and deterministic methods can be summarized in Table 17.

Table 17. Pros and cons of the probabilistic and deterministic methods

Aspects \ Methods	**Probabilistic**	**Deterministic**
Pros	Not too conservative	Very conservative
Cons	Less efficient	More efficient

4.3.2. Kashiwa City's probabilistic and deterministic doses

To calculate Kashiwa City's probabilistic and deterministic doses, this study used the following conditions and assumptions. First, Kashiwa City's population is projected to be approximately 435,000 in the year 2025 . Due to the lack of habit data, this study assumed normal situations where residents spend 0.5, 5, and 2 hours per day in the backyard (outside the house), in the house, and in the park or schoolyard, respectively, near the position where decontaminated soil is buried. The decay calibration time was set for December 31, 2025. There are no specific reasons for selecting this date; however, it was considered suitable to choose a near-future date so readers of this master's thesis can have a glimpse into Kashiwa City's current radiation dose.

Following Table 16, this study selected three environmental factors for evaluating the representative person's dose: (i) Regional differences in radionuclide fallouts, (ii) Total area (roof + backyard) of the house, and (iii) Soil coverage thickness on top of decontaminated soil. For (i) Regional differences in radionuclide fallouts, Kashiwa City is divided into 38 areas, with each area assumed to have the same population (due to the lack of data on population distribution in Kashiwa City). While the probabilistic dose assumed a homogeneous population distribution, the deterministic dose utilized the data from the region with the highest radiation activity concentration (Bq m^{-2}) among the 38 grids. For (ii) Total area (roof + backyard) of the house, based on Google Maps observations, this study assumed that $30m^2$ is 4.4%, $40m^2$ is 4.4%, $50m^2$ is 13%, $60m^2$ is 13%, $70m^2$ is 22%, $80m^2$ is 8.7%, $90m^2$ is 4.4%, $100m^2$ is 17%, $110m^2$ is 4.4%, and $150m^2$ is 4.4%. While the probabilistic dose considered the distribution in the house area, the deterministic dose used only the largest house area ($150m^2$). For (iii) Soil coverage thickness on top of decontaminated soil, based on observations of on-site measurements and safety concerns (sufficiently shielding gamma rays), it is assumed that most situations (99%) have 30 cm soil coverage. However, there are very rare cases (1%) where soil coverage is accidentally excavated. While the probabilistic dose assumes that most scenarios (99%) are covered with soil, the deterministic dose considers only the soil excavation scenario. Regarding the dose coefficient, since the focus of this study is on decontaminated soil buried underground, it is unlikely to have internal exposure; thus, age-dependent dose coefficients for inhalation and ingestion are not within the scope of discussion. This study utilized the built-in ISO function in PHITS to determine the external exposure dose coefficient. Based on the above passage, the conditions for evaluating the probabilistic and deterministic doses of Kashiwa City are compared in Table 18.

Table 18. A comparison of the probabilistic and deterministic conditions for Kashiwa City's evaluation

Aspect \ Method	**Probabilistic**	**Deterministic**
Environment	(i) Distribution of regional differences; (ii) Distribution of house areas; (iii) Distribution of soil coverage thickness	(i) Single value for the highest polluted region; (ii) Single value for the largest house area; (iii) Single value for the soil excavation scenario
Habit	0.5, 5, and 2 h d^{-1} in the backyard, in the house, and in the park/schoolyard, respectively	

Dose coefficient	A fixed value based on the age	
Final dose	Top 5% in the dose distribution	Single value of the environmental factors (μSv h^{-1}) multiplied by the habit data (h d^{-1})

The calculation results are shown in Table 19 and Fig. 30. Based on the above illustrations, Kashiwa City's probabilistic and deterministic doses were calculated to be 2.49E-03 and 2.50E-02 mSv y^{-1}, respectively.

Table 19. The table displays various ranges of doses, the corresponding population amounts in each range in Kashiwa City, and the accumulated ratio (below a certain dose) among the entire population.

Population	Accumulated (%)	Dose (mSv y^{-1})
10341	2.49	4.96E-04 – 7.34E-04
75262	20.60	7.34E-04 – 1.09E-03
177581	63.32	1.09E-03 – 1.61E-03
122174	92.71	1.61E-03 – 2.38E-03
26128	99.00	2.38E-03 – 3.52E-03
0	99.00	3.52E-03 – 5.21E-03
209	99.05	5.21E-03 – 7.71E-03
1282	99.36	7.71E-03 – 1.14E-02
2212	99.89	1.14E-02 – 1.69E-02
453	100.00	1.69E-02 – 2.50E-02

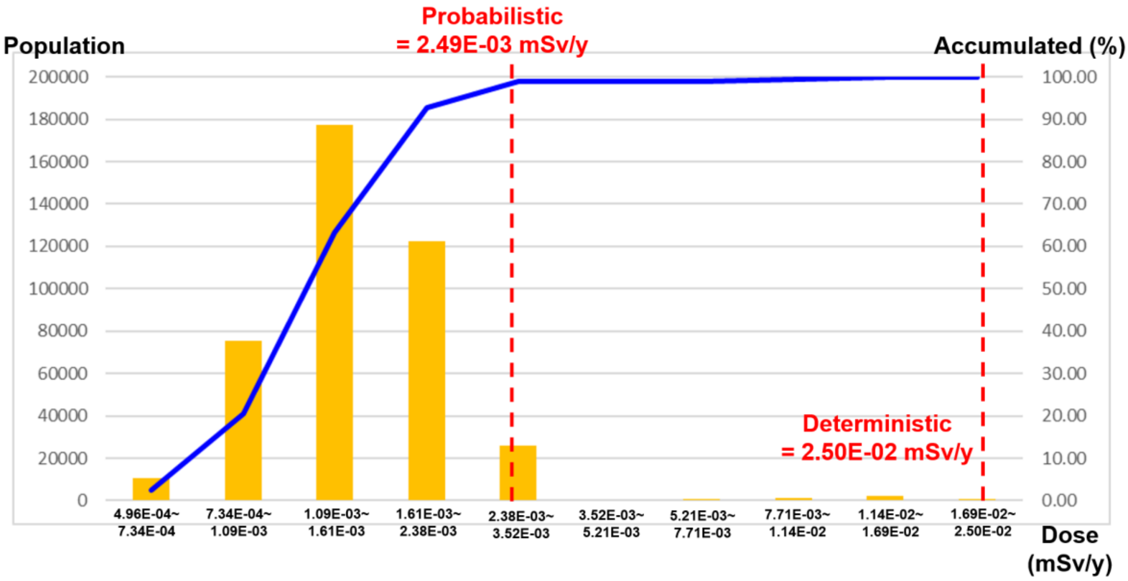

Fig. 30. This figure visualizes the data presented in Table 19. Specifically, the dose column is represented on the horizontal axis, the population column is depicted as a bar chart, and the accumulated ratio is illustrated as a line chart.

4.3.3. For situations where source strengths are 100 times as high as Kashiwa City

From Kashiwa City's deterministic and probabilistic evaluation results, it is evident that the doses are low, making it sufficient to use only the deterministic dose to ensure radiation safety. However, our evaluation showed that the deterministic dose was an order of magnitude higher than the probabilistic dose. In highly polluted areas, the dose might be over 100 times higher than in Kashiwa City (37). In such situations, the deterministic dose may exceed 1 mSv y^{-1} (the lower boundary of the reference level for existing radioactive residues in human habitats). Therefore, it is essential to evaluate both the deterministic and probabilistic doses in these circumstances.

In other words, in low-dose environments, assessing the maximum dose for a representative person using deterministic methods can encompass the protection policies for other residents. However, as doses increase, considering dose distribution and other factors, more meticulous estimation of exposure doses is desirable. This means that while 95% of the population might be considered safe (under the probabilistic dose), the most extreme 5% may need to consider some form of radiation protection strategy intervention, such as changes in habits or the use of engineering controls.

4.4. Comparison with a similar previous study

This study is similar to a previous one (38), which utilized the results of the JAEA Airborne Survey Database and other relevant data sources to evaluate the doses of individual residents in the difficult-to-return zone within Fukushima Prefecture. Table 20 provides a comparison between this study and the previous one.

Table 20. Comparison of this study with another similar previous study

Aspects \ Study	This study	Previous study
Methodology	[A] Determine the radionuclide fallouts per unit area (Bq m^{-2}) in each district of the study area **= Utilize the results of the JAEA Airborne Survey Database** [B] Develop a model to calculate radiation doses for different types of residences **= Utilize PHITS Simulations to simulate various exposure models (at home, in the backyard, and in the park or schoolyard where decontaminated soil was buried)** [C] Calculate radiation doses based on each citizen's lifestyle habits **= Citizens input their personal information into the Excel spreadsheet**	[A] Determine the radionuclide fallouts per unit area (Bq m^{-2}) in each district of the study area **= Integrate the results of the JAEA Airborne Survey Database, on-foot survey results, and car-borne survey results** [B] Develop a model to calculate radiation doses for different types of residences **= Assign various dose reduction factors (at home and during transportations) based on in-situ measurements and existing values (from previous studies)** [C] Calculate radiation doses based on each citizen's lifestyle habits **= Use a smartphone app (with the GPS function) to record the location and time information**
Study area	Kashiwa City, Chiba Prefecture	Difficult-to-return zones in the Fukushima Prefecture
Accuracy	Relatively lower	Relatively higher

	• **For dwellings: uncertainty = 10^0 order** • **For parks and schoolyards (covered with soil): uncertainty = 10^0 order** • **For areas covered by asphalt: uncertainty = 10^2 order**	• **Geometric mean of "estimated dose / personal dose" = 0.81** • **Geometric standard deviation of "estimated dose / personal dose" = 1.50**
Natural background radiation	Not considered	Considered
Efficiency	Relatively higher **(Procedures are relatively easier and less time-consuming)**	Relatively lower **(Procedures are relatively complicated and more time-consuming)**

As shown in Table 20, compared to the previous study, the novelty of this study stems from a more efficient dose assessment method. This method is less time-consuming and suitable for radiation-contaminated areas where smartphone availability is low and dosimeters are scarce. This new approach can significantly aid in designing dose assessment and radiation protection strategies for these areas.

In other words, the method introduced in this study serves as a complementary and cost-effective precursor to the previous approach. When evaluating a radiation-contaminated environment, this method should be implemented first due to its speed and simplicity. If the dose assessment indicates that the reference level might be exceeded for certain critical groups (considering uncertainties), then the previous method should be applied exclusively to those critical groups. In the meantime, it is important to note that when using the new dose assessment method proposed by this study, further verifications of land types and decontaminated soil distributions might be necessary. Without these verifications, the dose assessment results could be conservative.

Chapter 5. Radiation protection for natural radiation under the existing exposure scenario – International guidelines

5.1. Introduction

5.1.1. Background information for the ICRP 103 and GSR Part 3

According to the "aim and scope" in ICRP 103 (22), the ICRP provides radiation protection (RP) guidance associated with ionizing radiation, which includes naturally occurring sources. Additionally, in ICRP 103 "CH2.3. The scope of the Recommendations," it is mentioned that "the Commission's Recommendations cover exposures to both natural and man-made sources," which include Naturally Occurring Radioactive Material (NORM). In this regard, ICRP 103 is suitable for discussion in this study (comparing NORM and decontaminated soil).

In GSR Part 3 (39), it is mentioned that "the IAEA safety standards establish fundamental safety principles, requirements, and measures to control the radiation exposure of people and the release of radioactive material to the environment." Article 1.43 states that "These Standards establish requirements to be fulfilled in all facilities and activities giving rise to radiation risks," which include NORM. Therefore, GSR Part 3 is suitable for discussion in this study.

5.1.2. Purpose of comparing the ICRP 103 and GSR Part 3

From Chapter 5.1.1 of this master's thesis, it is evident that both ICRP 103 and IAEA GSR Part 3 are closely related to NORM issues. The ICRP 103 provides more general guidance and principles, while GSR Part 3 offers more specific control measures. By comparing ICRP 103 and GSR Part 3, it is possible to develop comprehensive ideas for treating decontaminated soil from the NORM perspective. These ideas would encompass both general principles and specific control measures.

5.2. Comparison between the ICRP 103 and GSR Part 3

5.2.1. The ICRP 103's viewpoints on NORM existing exposure situations

According to the abstract of ICRP 103, the principles of the ICRP 103 include "optimization, justification, and the use of dose limits."

From the optimization perspective, Article 225 mentions that for the concept of the reference level, "the initial intention would be to not exceed, or to remain at, these levels, with the ambition to reduce all doses to levels that are as low as reasonably achievable, considering economic and societal factors."

From the justification perspective, the ICRP 103 glossary states that "justification" can refer to "a proposed remedial action in an existing exposure situation where the benefits to individuals and society (including the reduction in radiation detriment) from introducing or continuing the remedial action outweigh its cost and any harm or damage it causes."

In terms of the use of reference levels, ICRP 103 "CH6.5. Comparison of Radiological Protection Criteria" mentions that the reference level for NORM existing exposure situations is 1 - 20 mSv y^{-1}.

5.2.2. GSR Part 3's viewpoints on NORM existing exposure situations

Corresponding to the guidelines of ICRP 103, the IAEA GSR Part 3 provides more specific control methods for managing radiation exposure situations based on the principles of optimization, justification, and the use of dose values.

Optimization Principle: According to Article 5.9, "The regulatory body or other relevant authority shall periodically review the reference levels to ensure that they remain appropriate in light of the prevailing circumstances." This implies that the reference level might need to be continuously reduced to optimize radiation protection, following the ALARA (As Low As Reasonably Achievable) concept.

Justification Principle: In accordance with Article 5.7, "The government and the regulatory body or other relevant authority shall ensure that the protection strategy for the management of existing exposure situations is commensurate with the radiation risks associated with the existing exposure situation; and that remedial actions or protective actions are expected to yield sufficient benefits to outweigh the detriments associated with taking them, including detriments in the form of radiation risks."

Use of Reference Levels: Article 5.2 states that "The government shall ensure that, when an existing exposure situation is identified, responsibilities for protection and safety are assigned and appropriate reference levels are established." Additionally, Article 5.8 specifies that the reference level should be chosen within the 1 - 20 mSv y^{-1} range, and the dose to the representative person should not exceed the reference level.

5.2.3. Comparison of the ICRP 103 and GSR Part 3's viewpoints

The comparison of the ICRP 103 and GSR Part 3 viewpoints is summarized in Table 21. Generally, ICRP 103 provides the fundamental concepts for the principles of optimization and justification, while GSR Part 3 offers specific details on actions that the government and regulatory bodies should take to reinforce these principles.

Optimization Perspective: From a previous study (40), it was suggested that during the decommissioning of a NORM facility, several aspects should be considered when judging optimization:
(i) Legislation and regulations,
(ii) Technological availability,
(iii) Public exposure during the execution of the strategy,
(iv) Public exposure after the execution of the strategy.
Additionally, GSR Part 3's Requirement 48 states that, as the regulatory body optimizes protection for all individuals, those who exceed the reference level should be prioritized, and periodic reviews might be necessary.

Justification Perspective: Enlightened by GSR Part 3's Article 3.61, when conducting a NORM RP practice, the government and regulatory body should consider:
(i) The benefits and detriments of implementing the RP practice,
(ii) The benefits and detriments of not implementing the RP practice,
(iii) Any legal or ethical issues associated with introducing the RP practice,
(iv) The availability of sufficient resources to conduct the RP practice safely throughout its intended period.

Use of Reference Levels: Both ICRP 103 and GSR Part 3 set the reference level band for NORM existing exposure situations to be 1 - 20 mSv y^{-1}.

Table 21. Comparison of the ICRP 103 and GSR Part 3's viewpoints

Publications / Principles	ICRP 103	GSR Part 3
Optimization	The initial intention would be to not exceed the reference level, and the ambition is to reduce all doses that are as low as reasonably achievable, economic and societal factors being taken into account.	The regulatory body shall periodically review the reference levels to ensure that they remain appropriate in the light of the prevailing circumstances.
Justification	The remedial action for an existing exposure situation should be in a way that its benefits outweigh its cost.	The government and the regulatory body shall ensure that the protection strategy / remedial actions are expected to yield sufficient benefits to outweigh the detriments.
The use of reference levels	For the existing exposure due to NORM, the reference level is the band of 1 - 20 mSv y^{-1}.	The reference level should be chosen within the 1 - 20 mSv y^{-1} band, and the representative person's dose shall not exceed the reference level.

5.3. Applying the NORM RP Concepts to decontaminated soil

Based on the discussions in Chapters 5.1 and 5.2, this study offers recommendations on managing decontaminated soil, as shown in Table 22.

Optimization Principle: The GSR Part 3 categorizes optimization into three aspects. This study focuses on the third aspect: public exposure during and after the radiation protection (RP) practice. The recommended management strategy for decontaminated soil includes the following:
Evaluation of Dose During Decontamination: Following the procedure in Fig. 4, it is worthwhile to evaluate the dose during the decontamination process, from when radionuclides are on the ground's surface until the soil's top layer is wrapped in a plastic bag and buried underground.
Whole-Process Dose Evaluations: If the strategy involves moving decontaminated soil from temporary storage (buried underground) to permanent storage facilities, whole-process dose evaluations should also be conducted. This approach allows the optimization of RP strategies based on various exposure pathways and doses.

Justification Principle: The GSR Part 3 highlights three discussion points in Table 22. While points (ii) and (iii) are beyond this study's scope, the management strategy for decontaminated soil can be discussed based on point (i). Specifically, for low-dose decontaminated soil outside Fukushima Prefecture, given the limited final disposal storage space (48), the following countermeasures may be considered:

- Reuse of Decontaminated Soil: As building materials for bridges, levees, and roads.
- Permanent Storage Decision: Leaving low-dose decontaminated soil as it is (buried underground).

Preliminary evaluations regarding the benefits and detriments (both social and economic) are necessary to determine if the decision can be justified.

Use of Reference Levels: Both ICRP 103 and GSR Part 3 recommend using the 1 – 20 mSv y^{-1} band. GSR Part 3 further recommends prioritizing those who exceed the reference level in RP strategies.

Further discussions might be needed regarding the current strategy. Currently, Japan's authority sets the reference level for decontaminated soil at 1 mSv y^{-1} (41). However, regional differences might need to be considered; for areas near the FDNPP, it may not be practical to immediately apply the 1 mSv y^{-1} reference level. Instead, the value might need to be selected within the 1 – 20 mSv y^{-1} range based on prevailing circumstances.

Table 22. Comparison of the concepts in the ICRP 103 and GSR Part 3, and the corresponding recommendations on decontaminated soil made by this study

ICRP 103	GSR Part 3	Decontaminated soil
Optimization (ALARA)	The government and regulatory body should conduct periodic reviews in view of (i) Legislation / regulations, (ii) Technological availability, and (iii) Public exposure during and after the RP practice.	With the dose assessment procedure demonstrated in this study, it may be beneficial to evaluate the radiation dose both during the decontamination process and after the decontaminated soil has been buried to certain depths.
Justification (Benefit > cost)	The government and regulatory body should ensure justification of the RP practice in view of (i) The benefits and detriments with / without the RP practice, (ii) Legal and ethical issues, (iii) Resource availability	For areas outside Fukushima Prefecture, given the vast amount of decontaminated soil (14 million m^3) and its generally low radiation activity concentration (76% below 8 kBq kg^{-1}), discussions may be necessary to determine whether it is justifiable to reuse this soil as building material for bridges, levees, and roads (41).
The use of reference levels (1 – 20 mSv y^{-1})	Those who exceed the reference level should be prioritized in the RP.	Currently, Japan's authority has set the goal that the additional dose (excluding natural background radiation) due to decontaminated soil should be less than 1 mSv y^{-1} (42). However, based on the concepts in ICRP 103 and GSR Part 3, further discussions might be necessary. The reference level might need to be selected within the 1 – 20 mSv y^{-1} band, considering regional differences.

5.4. Conclusion

Based on the above discussions, the recommendations from this study are as follows:

For Optimization: It may be beneficial to conduct a comprehensive dose evaluation process (such as the one demonstrated in this study) to evaluate the dose over time and across different locations in order to optimize RP strategies.

For Justification: It might be necessary to evaluate the social and economic benefits and detriments for:

- Reusing decontaminated soil for practical purposes.
- Leaving in-situ burial as the permanent treatment method for decontaminated soil.

For the Use of Reference Levels: Rather than selecting a single value (1 mSv y^{-1}) for all affected areas, it may be more pragmatic to consider various reference levels based on the prevailing circumstances.

Chapter 6. Radiation protection for natural radiation under the existing exposure scenario – Discussion points and comparison among NORM regulations in various regions

6.1. Control measures

6.1.1. Background and purpose

The purpose of the NORM-law review is to provide suggestions for current and future management of decontaminated soil in light of the Kashiwa City situation. Therefore, aspects of NORM related to building materials, food, water, and consumer products are not discussed, as they are not directly relevant to the decontaminated soil situation in this study.

For the regional NORM recommendation discussions, this study examines Japan, Taiwan, Australia, Europe, and North America for the following reasons: In our preliminary literature review (unpublished article), North America, Europe, and Australia were found to have some of the best recommendations for NORM management. Japan's Special Measure Act, which addresses the treatment of decontaminated soil from the Fukushima accident, might provide an interesting comparison to domestic NORM recommendations. In Taiwan, NORM-related regulations are divided into various administrative regulations, each focusing on a specific aspect of NORM, making it particularly insightful to review Taiwan's NORM regulations.

6.1.2. An overview of control measures by region

After conducting the literature review, several control measures were identified, as shown in Table 23. These criteria were selected because they were relevant to the discussion points of this study. By creating the table, it becomes apparent whether a world region sufficiently covers various aspects of NORM management, particularly those relevant to decontaminated soil.

It is important to note that most control measures in Table 23 relate to occupational exposure. Therefore, the review's results might provide more insights into how to implement radiation protection (RP) measures for workers handling decontaminated soil following a nuclear accident. On the other hand, for public exposure, the results of the international NORM recommendations review (discussed in Chapter 5 of this master's thesis) might be more informative.

Table 23. An overview of NORM control measures by region

	Australia	Europe	Japan	North America	Taiwan
Workplace categorization: Categorizing workplaces into various areas based on the potential doses	O	O	O		O

Dose values by work categories: Assigning various dose values on radiation and non-radiation workers	O	O			O
Investigation levels: Set threshold values for more precise investigation and record-keeping	O			O	O
Disseminating work procedures: Educate workers the safe operational procedures for handling radiological substances.		O	O	O	
Recording personal dose: Operating a personal dosimetric program for record-keeping	O	O		O	O
Engineering controls: Providing shielding, barriers, and ventilation systems	O	O	O	O	
Work time limitations: Allocating radiation workers at various positions and sectors to reduce the annual dose	O		O		

6.1.3. Australian control measures

The control measures of Australia, summarized in Table 24, focus on NORM activities, particularly in mining and mineral processing.

Workplace Categorization: The threshold values of 5 and 15 mSv y^{-1} are used to define controlled areas and restricted areas (43). In controlled areas, workers are generally not allowed to eat, drink, or smoke. Additionally, laundry facilities may need to be provided to prevent contaminated clothing from being removed from the area. Good housekeeping and regular clean-ups are required to minimize unnecessary radiation exposures. Restricted areas, part of the controlled areas, have minimized work times to reduce exposure, and work procedures must be carried out by experienced staff under supervision.

Dose Values by Work Categories: The dose constraint for non-radiation workers is 1 mSv y^{-1}, the threshold for a "designated employee" is > 5 mSv y^{-1}, and the dose limit for radiation workers is 20 mSv y^{-1}. Designated employees must receive personal dose monitoring and records.

Investigation Levels and Personal Dose Recordings: The threshold is 5 mSv y^{-1}, and records of monitoring results should be kept for at least 30 years (44).

Engineering Controls: When necessary, ventilation and enclosed cleaning equipment should be used (45).

Table 24. An overview of Australian control measures on NORM (49-51)

Control measures	Description	Source
Workplace categorization	If there is an area where employees could receive > 5 mSv y^{-1}, it should be designated as a "controlled area." If the potential exposure is > 15 mSv y^{-1}, it should be designated as a "restricted area."	Australian NORM-1 CH 2.4.1.
Work time limitations		
Dose values by work categories	For office staff, the dose constraint is 1 mSv y^{-1} (5-year average). For all work categories, the dose limit is 20 mSv y^{-1} (5-year average).	Australian NORM-1 CH 2.4.2.
Investigation levels	If an employee has the potential to receive > 5 mSv y^{-1}, he/she should receive personal dose monitoring.	RPS-9 CH3.8.1.
Recording personal dose		
Engineering controls	Ventilate NORM workplaces and equipment; Use glass bead blasters to clean the NORM equipment	RPS-15 A1.5.1.

6.1.4. European control measures

The European control measures are summarized in Table 25 (46). Particularly, regarding each aspect, the details are as follows.

Workplace Categorization: It is recommended that each Member State delineate workplaces into controlled and restricted areas based on potential exposure doses.

Dose Values by Work Categories: It is advised that Member States set the dose limit for students and apprentices aged 16 to 18 at 6 mSv y^{-1}.

Disseminating Work Procedures: It is suggested that all Member States establish an adequate legislative and administrative framework to ensure sufficient education and training for all individuals whose jobs require specific competencies in radiation protection (RP).

Recording Personal Dose: Category A refers to workers who receive > 6 mSv y^{-1}, while Category B includes all other workers outside Category A. Each Category A worker must receive individual dose monitoring, and dosimetry records should be kept until the worker is 75 years old and for at least 30 years after the termination of work.

Engineering Controls: When planning new radiation installations, it is recommended that the advice of an RP expert be sought regarding engineering controls.

Table 25. Summary of European control measures (46)

Control measures	Description	Source
Workplace categorization	Controlled and supervised areas	Article 36
Dose values by work categories	Lower doses for apprentices and students	Article 11
Disseminating work procedures	RP education and training are required	Chapter IV
Recording personal dose	Recording and reporting the dose of each Category A worker is mandatory	Article 43
Engineering controls	Must consult RP experts regarding the engineering controls	Article 82

6.1.5. Japan’s control measures

Japan’s control measures are detailed in Table 26. The specifics of each measure are as follows:

Workplace Categorization: If the estimated occupational dose exceeds 1 mSv per year, the workplace may be subject to additional controls, such as engineering measures and work time limitations.

Work Time Limitations: This measure is specifically applied to individuals whose exposure exceeds 1 mSv per year.

Engineering Controls: When the estimated dose surpasses 1 mSv per year, engineering controls, such as building shields, must be implemented.

Disseminating Work Procedures: In cases where the dose is estimated to exceed 1 mSv per year, educational programs must be conducted.

Table 26. Japan’s control measures (47–50)

<table>
<tr><th>Control measures</th><th>Description</th><th>Source</th></tr>
<tr><td>Workplace categorization</td><td rowspan="3">If the occupational dose is estimated to be > 1 mSv y^{-1}, the following measures should be taken:
1. Store NORM wastes at several places while reducing the amount in each storage.
2. Shorten the work time.
3. Build shields.

If the resident's dose on the site boundary is estimated to be > 1 mSv y^{-1}, the following measures should be taken:
1. Store NORM wastes at several places while reducing the amount in each storage.
2. Move the storage places farther away from the site boundary.
3. Build shields.</td><td rowspan="3">Japan’s NORM Guidelines CH5.2</td></tr>
<tr><td>Work time limitations</td></tr>
<tr><td>Engineering controls</td></tr>
<tr><td>Disseminating work procedures</td><td>In the case where the exposure doses of workers are estimated to be > 1 mSv y^{-1}, education programs should be provided (regarding the methods of exposure reduction and the handling of U/Th-bearing matters), and the records of education should be kept for three years.</td><td>Japan’s NORM Guidelines CH5.4</td></tr>
</table>

6.1.6. North American control measures

North American control measures are detailed in Table 27. The specific aspects are as follows:

Investigation Levels: Under the Canadian framework, an investigation level of 5 mSv y^{-1} is designated. If this threshold is exceeded, a formal Radiation Protection (RP) program is implemented. Additionally, the Canadian framework provides lower investigation levels: if potential exposure exceeds 0.3 mSv y^{-1}, a NORM management program and periodic reviews are initiated; if it exceeds 1 mSv y^{-1}, a dose management program is implemented. Detailed information on these programs is available in the Canadian NORM Recommendations.

Disseminating Work Procedures: In the dose management program (for situations where the estimated dose exceeds 1 mSv y^{-1}), workers must be informed about the radiation sources and receive training on work procedures.

Recording Personal Dose: The formal RP program (for workers expected to receive more than 5 mSv y^{-1}) includes monitoring and recording personal doses.

Engineering Controls: For both the dose management program (estimated dose > 1 mSv y^{-1}) and the RP program (estimated or measured dose > 5 mSv y^{-1}), engineering controls must be considered or applied.

Table 27. North American control measures (51,52)

Control measures	Description	Source
Investigation levels	If >5 mSv y^{-1}, a formal RP program (similar to the NPP workers) must be implemented.	Canadian NORM Recommendations CH3.3.3.4
Disseminating work procedures	If > 1 mSv y^{-1}, workers must receive trainings.	Canadian NORM Recommendations CH3.3.3.3
Recording personal dose	If > 5 mSv y^{-1}, personal dose monitoring and recording are mandatory.	Canadian NORM Recommendations CH3.3.3.4
Engineering controls	If > 1 mSv y^{-1}, engineering controls must be considered or applied.	Canadian NORM Recommendations CH3.3.3

6.1.7. Taiwan's control measures

Taiwan's control measures are detailed in Table 28. The specific aspects are summarized as follows:

Workplace Categorization: According to Article 7 of Taiwan's NORM Act (53), "After a naturally occurring radioactive material (NORM) is regulated by the competent authority, if the radiation dose assessment results in an annual dose of less than 6 mSv y^{-1} for workers, the owner, holder, or manager must conduct operational and environmental monitoring and implement access control for personnel at the work site." This means that based on these conditions, a workplace may be classified as a "NORM Workplace" and subject to specific controls.

Investigation Levels and Recording Personal Doses: As stated in Article 6, "After a naturally occurring radioactive material (NORM) is regulated by the competent authority, if the radiation dose assessment results in an annual dose greater than 6 mSv y^{-1} for workers, the owner, holder, or manager must conduct individual dose monitoring for the workers and submit a radiation protection plan for approval by the competent authority before implementation." Thus, the investigation level for NORM workers is set at 6 mSv y^{-1}, and recording personal doses becomes mandatory if this threshold is exceeded.

Table 28. NORM Control measures in Taiwan (53)

Control measures	Description	Source
Workplace categorization	For the regulated NORM material and the workplace that is < 6 mSv y^{-1}, access restrictions must be conducted.	Taiwan's NORM Act Article 7

Investigation levels	For NORM workers, if the estimated dose is > 6 mSv y^{-1}, individual dose monitoring and RP Plan must be conducted.	Taiwan's NORM Act Articles 6 and 8
Recording personal doses		

6.2. Comparison of dose values by various regions

Table 29 consolidates the dose values discussed in Chapter 6.1 of this study, along with additional values relevant to this research.

Occupational Dose (Targeting People):

- 1 mSv y^{-1}: Dose limit for non-radiation workers; if exceeded, work time must be reduced, and educational training reinforced.
- 5 mSv y^{-1}: If exceeded, personal dose monitoring and recording are required.
- 6 mSv y^{-1}: Dose limit for students and apprentices.
- 20 mSv y^{-1}: Occupational dose limit averaged over 5 years.
- 50 mSv y^{-1}: Occupational dose limit for a single year.

Occupational Dose (Targeting the Environment):

- 0.3 mSv y^{-1}: Workplace surveys by gamma and airborne dose are required.
- 1 mSv y^{-1}: Radiation protection (RP) arrangements, such as distributing NORM wastes at several locations and applying engineering controls, must be made.
- 5 mSv y^{-1}: If exceeded, the area must be designated as a controlled area.
- 6 mSv y^{-1}: If below, environmental dose monitoring must be conducted.
- 15 mSv y^{-1}: If exceeded, the area must be designated as a restricted area.

Public Exposure (Targeting People):

- 0.3 mSv y^{-1}: Site boundary surveys by gamma and airborne doses are required.
- 1 mSv y^{-1}: Dose limit at the site boundary and for authorized NORM practices. If below, former NORM facilities can be repurposed.
- 1-20 mSv y^{-1}: Reference level band for existing exposure situations.

Public Exposure (Targeting the Environment):

- 0.3 mSv y^{-1}: If below, NORM activities are unrestricted.
- 1 mSv y^{-1}: If below, the site can be released from regulatory controls.

Table 29. Comparison of dose values by region (Remark: [A] Targeting people; [B] Targeting the environment)

Regions / Categories	**Australia**	**Europe**	**Japan**	**North America**	**Taiwan**
Occupational exposure - dose [A]	>5mSv y^{-1}: Requiring personal dose monitoring >1mSv y^{-1}: Requiring work group average dose assessments <1mSv y^{-1}: Required for non-radiation workers	< 6 mSv y^{-1}: Dose limit for students and apprentices	>1mSv y^{-1}: The work time must be shortened <20mSv y^{-1}: The occupational dose limit for the 5-year average <50mSv y^{-1}: The occupational dose limit for the one-year maximum value	>1mSv y^{-1}: Training and engineering controls are required > 5mSv y^{-1}: The personal dosimetric program is required	>6mSv y^{-1}: individual dose monitoring must be conducted
Occupational exposure - dose [B]	>5mSv y^{-1}: Defined as the controlled area >15mSv y^{-1}: Defined as the restricted area	> 1 mSv y^{-1}: RP arrangements shall be made	>1mSv y^{-1}: NORM wastes must be distributed at several different locations. Engineering controls (such as building shields) should be applied. >1.3mSv / 3 months: The area should be assigned as a controlled area.	>0.3mSv y^{-1}: Workplace surveys by gamma and airborne dose are required	<6mSv y^{-1}: environmental dose monitoring must be conducted
Public exposure - dose [A]	<1mSv y^{-1}: The value of the public dose limit on the NORM site boundary	<1 mSv y^{-1}: Dose limit for public exposure due to authorized NORM practices	Not specified	>0.3mSv y^{-1}: Site boundary surveys by gamma and airborne doses are required	<1mSv y^{-1}: Former NORM facility can be used for other purposes

		1-20 mSv y^{-1}: Band for the reference level of the existing exposure situation			
Public exposure - dose [B]	<1mSv y^{-1}: The site can be released from the regulatory control	Not specified		<0.3mSv y^{-1}: The NORM activities are unrestricted	Not specified
Radiation activity concentrations	<1Bq/g: Transportation exemption value for each radionuclide <10kBq/kg: The value of the modified exemption limit for NORM (non-extraction purpose)	Exemption or clearance of materials: ^{134}Cs < 0.1 kBq kg^{-1} ^{137}Cs < 0.1 kBq kg^{-1}	When the NORM material contains U or Th that is > 74 Bq/g, the notification is required.	Scale (rare earth extraction): ^{226}Ra, ^{228}Th < 1000 Bq g^{-1}	Not specified

6.3. Discussion

The control measures used in NORM management—such as workplace categorization, dose values by work categories, investigation levels, dissemination of work procedures, personal dose recording, engineering controls, and work time limitations—could indeed be effectively applied to develop radiation protection strategies for workers and residents handling decontaminated soil. These measures ensure comprehensive safety by addressing both occupational and environmental exposure, and implementing them could help manage radiation risks effectively in similar contexts.

The NORM regulations highlighted above indicate that when targeting people, radiation workers directly handling NORM were assigned relatively high dose values, while administrative staff and the general public were assigned relatively low dose values. Similar concepts should be applied to decontaminated soil issues.

When targeting the environment, restricted areas were assigned relatively high dose values, controlled areas were assigned intermediate dose values, and site boundaries were assigned relatively low dose values. Meanwhile, low dose values were set, below which NORM facilities could be repurposed, and NORM activities could be exempted. These concepts might also be applied to the management of decontaminated soil, particularly in determining whether some burial sites can be treated as in-situ permanent storage if the dose is low enough.

6.4. Conclusion

As mentioned in Chapter 6.1.1, the purpose of the NORM-law review is to provide recommendations for the current and future management of decontaminated soil, specifically in light of the Kashiwa City situation. Following the review, this study provides the following recommendations:

- Control Measures: The control measures used in NORM management should be considered for radiation protection (RP) strategies for decontaminated soil.
- Dose Values: A similar trend of dose values used in NORM management, targeting both people and the environment, should be considered for RP strategies for decontaminated soil.
- Permanent In-Situ Disposal: Just as NORM can be exempted under certain conditions, decontaminated soil might also be considered for permanent in-situ disposal if specific conditions are met.

Chapter 7. How to treat decontaminated soil / NORM

7.1. Similarities between decontaminated soil and TENORM

7.1.1. Concentrated radiation contamination

Decontaminated soil and Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) share several similarities. Both can be considered concentrated radiation contamination situations. For decontaminated soil, radionuclides settle on rooftops and are washed down through rainwater drainage pipelines to the backyard surface, leading to concentrated radiation activity. Similarly, in the case of TENORM, certain circumstances, such as scaling in water treatment plants, result in concentrated radionuclides (45). In both cases, the intensity of radiation activity concentration can be evaluated using the unit Bq g^{-1}.

7.1.2. Widespread radiation contamination

From other perspectives, both decontaminated soil and TENORM can be considered widespread radiation contamination. In the case of decontaminated soil, it represents a widespread radiation contamination situation, where regional differences can be quantified using the unit Bq m^{-2}, as demonstrated in the case study of Kashiwa City. Similarly, for some TENORM situations, such as uranium tailings, it also represents widespread contamination, and regional differences can be evaluated using the unit Bq m^{-2}.

7.2. Dose evaluation methods and management strategies

Due to the aforementioned similarities, the dose evaluation methods and management strategies proposed in this study can be applied to various kinds of radiation-polluted environments. This includes both past and future scenarios, whether artificial or natural. These methods are not limited to the case study of Kashiwa City but can be extended to other radiation-polluted environments.

From the case study in Kashiwa City, this study has established a standardized procedure for evaluating doses due to radiation contamination events, as illustrated in Fig. 31. This flowchart can be followed for dose assessments and discussing RP strategies for any radiation contamination events, whether past or future.

The first step involves collecting data and identifying regional differences. As demonstrated in the case study, although in-situ soil sampling data might be the most accurate source, the limitation of availability (2) means that airborne survey data might be a practical alternative.

In the second step, it is essential to identify all possible radiation exposure pathways and conduct simulations or dose calculations accordingly. In this case study, since the decontaminated soil is buried underground (at 30 to 40 cm below the surface), internal exposure might be negligible. However, for other situations (such as before the burial of contaminated soil), internal radiation exposures might also need to be evaluated.

The third step involves combining user-input data with the results from the first two steps. This allows the user to learn about their own dose, while the national database can collect user input data to calculate deterministic and probabilistic doses. In this case study, this study has yet to collect user input data, so the deterministic and probabilistic doses were calculated based on general assumptions about the habits of the citizens. Future studies are encouraged to collaborate with the government and launch a national database to collect abundant user input data and evaluate deterministic and probabilistic doses comprehensively.

Finally, in the fourth step, RP strategies should be designed differently based on the concepts of optimization, justification, and the use of reference levels (10), adjusted according to the dose evaluation results.

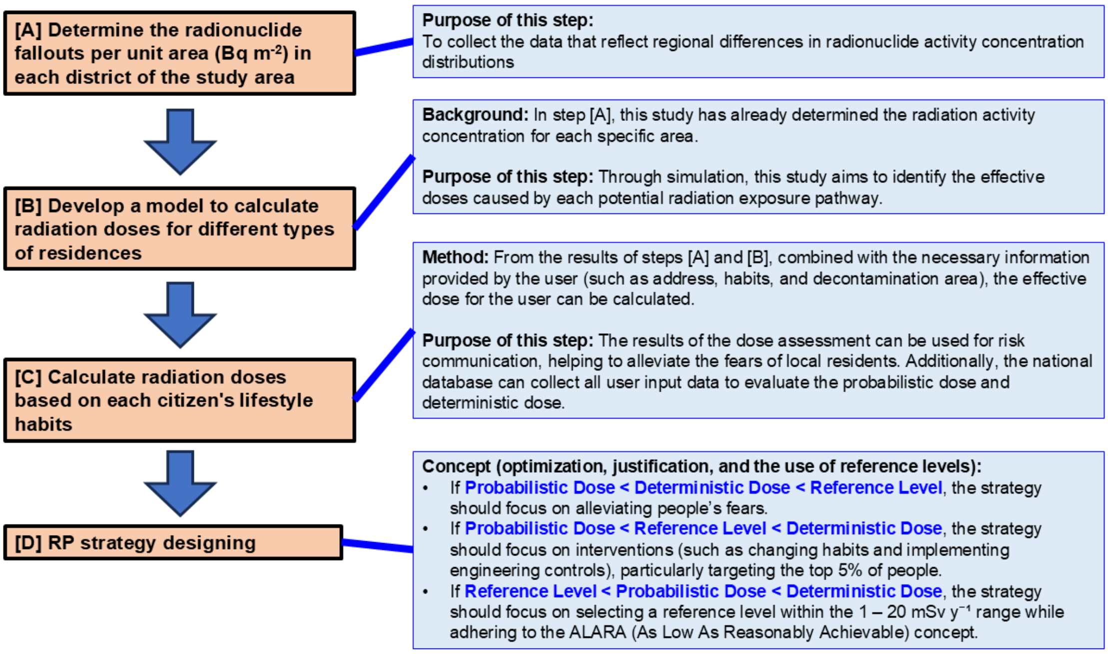

Fig. 31. Standardized procedures for evaluating the dose due to radiation contamination events

Chapter 8. Conclusion

This master's thesis addresses three key research questions:

1. To elucidate the current state of contaminated soil management, using Kashiwa City in Chiba Prefecture—designated as a priority contamination investigation area—as a case study.
2. To propose specific strategies for future protection and provide information that will contribute to ongoing discussions.
3. To assess the current and projected effective radiation doses to surrounding residents from simply buried decontaminated soil.

For research question #1:
An on-site investigation revealed that decontaminated soil is buried 30-40 cm underground, stored, and maintained in a stable condition. At all four locations in the on-site survey, the decontaminated soil was wrapped in plastic bags, and the radiation dose measured directly above the soil (before excavation) matched the background dose value.

For research question #2:
A dose assessment procedure was provided to address future circumstances resulting from radiation-contaminated environments. Using Kashiwa City as an example, the study offers a method for assessing residential doses after various past and potential future radiation contamination incidents. The standardized dose assessment consists of four steps: (i) determining the radionuclide fallouts per unit area (Bq m^{-2}) in each district of the study area, (ii) developing a model to calculate radiation doses for different types of residences, (iii) calculating radiation doses based on each citizen's lifestyle habits, and (iv) designing a radiation protection strategy based on the concepts of optimization, justification, and the use of reference levels.

For research question #3:
A user input spreadsheet was created, allowing residents to enter their address, habits, house dimensions, and dates to determine their dose. This spreadsheet integrates scientific information, including the results of the JAEA Airborne Survey Database (which reflects regional differences in radiation activity concentration distributions, Bq m^{-2}), the utilization of PHITS Simulation (which calculates radiation doses for different types of residences, converting Bq m^{-2} to μSv h^{-1}), and inputs from citizens (enabling dose calculations based on average lifestyle habits, converting μSv h^{-1} to mSv y^{-1}). Deterministic and probabilistic dose calculations were also made.

As for the future step, further research into dose assessment methods and protection policies related to artificial radiation environments resulting from accidents is recommended. Additionally, studying the natural radiation environment, which serves as a background radiation environment, is encouraged.

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