ABSTRACT

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

－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－)

Graduation year: March 2025, Department of Environment Systems,

47-236659; Changting GUH

Supervisor: Takeshi IIMOTO (Professor)

[Keywords] Fukushima accident, Kashiwa City, Decontaminated soil, External radiation dose, Standardized dose assessment procedures

1. Introduction

The Fukushima accident released vast quantities of radionuclides, especially ^{134}Cs and ^{137}Cs, which were transported by wind and deposited on the ground via precipitation (1). This event impacted regions far beyond Fukushima Prefecture, reaching as distant as 200 km away, including Kashiwa City in Chiba Prefecture. In the aftermath, local governments and residents collaborated on decontamination efforts, which involved encasing decontaminated soil, containing radio cesium, in plastic bags, and burying it underground. Assessing the potential radiation risks from this buried soil is crucial from both scientific and risk communication perspectives (2). This study focuses on Kashiwa City, located less than 40 km from central Tokyo, a significant area for radiation protection (RP) research. The initial step in RP is to conduct dose assessments, and this study uses Kashiwa City as a case study for such assessments. Given that managing decontaminated soil from the Fukushima nuclear accident is a relatively new challenge (less than 15 years), with limited experience in designing RP strategies, this study looked at TENORM (technically enhanced naturally occurring radioactive materials) regulations from the 1990s for guidance on decontaminated soil management (3). Based on dose assessment results and TENORM reviews, the study proposes a standardized dose assessment procedure applicable to various radiation-contaminated environments. While previous studies primarily examined the migration mechanisms of radio cesium across different types of land (4) or used more sophisticated, time-consuming methods for dose assessments (5), this study offers a scientific, practical, and efficient approach. The objectives of this study are: (a) To elucidate the current state of contaminated soil management using Kashiwa City as a case study. (b) To propose specific strategies for future protection and contribute to ongoing discussions. (c) To assess the current and projected radiation doses to surrounding residents from buried decontaminated soil.

2. Methodology

2.1. Calculation flowchart of radiation dose assessment

This study developed an Excel spreadsheet that allows users to input relevant information and determine the radiation exposure dose from buried decontaminated soil. The calculation flowchart is depicted in Fig. 1, which integrates regional radionuclide fallout data, model calculations for various residence types, and an assessment of lifestyle habits. To account for regional differences in radionuclide fallouts (Bq m^{-2}), Kashiwa City was divided into 16 landmarks and 38 grids (as shown in Fig. 2). Average radio cesium concentrations were calculated for each 2 x 2 km mesh of these landmarks. Subsequently, PHITS Simulations (as shown in Fig. 3) were used to calculate radiation doses (converting from Bq m^{-2} to μSv h^{-1}) for different locations within the house, backyard, and park or schoolyard. Finally, this study considers user input information, such as address, lifestyle habits, house dimensions, and radio cesium decay correction, to calculate the average dose (mSv y^{-1}).

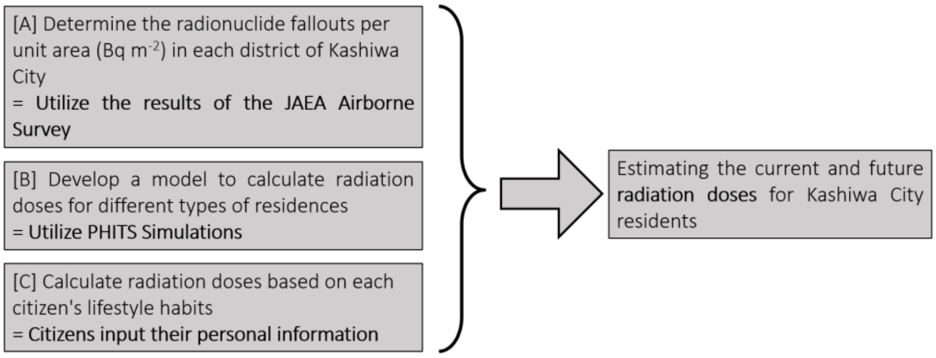


Fig 1. Calculation flowchart of dose assessment

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)

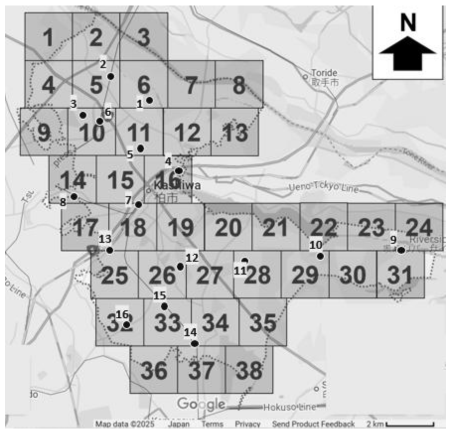


Fig 2. Division of Kashiwa City into 16 landmarks

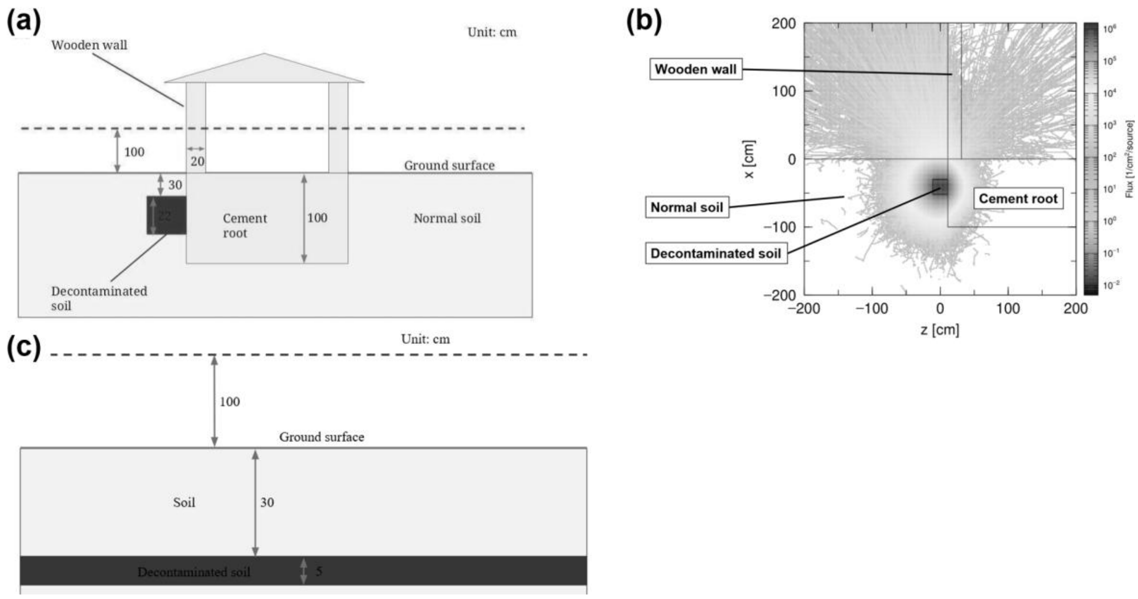


Fig 3. (a) PHITS Simulation dimensions for house (b) PHITS Simulation results for house (as an example) (c) PHITS Simulation dimensions for parks and schoolyards

2.2. Probabilistic and deterministic dose assessment methods

This study referred to the ICRP 101 guidelines to assess radiation doses for Kashiwa residents due to buried decontaminated soil, using both probabilistic and deterministic methods. According to ICRP

101, three key aspects must be considered in such evaluations: environmental factors, lifestyle habits, and dose coefficients (6). Table 1 outlines the conditions utilized in this study for evaluating doses to Kashiwa residents.

Table 1. Conditions used by this study when evaluating Kashiwa citizen's probabilistic and deterministic doses

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	Out of the scope of this study	
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})

3. Results and discussions

3.1. Dose assessment results

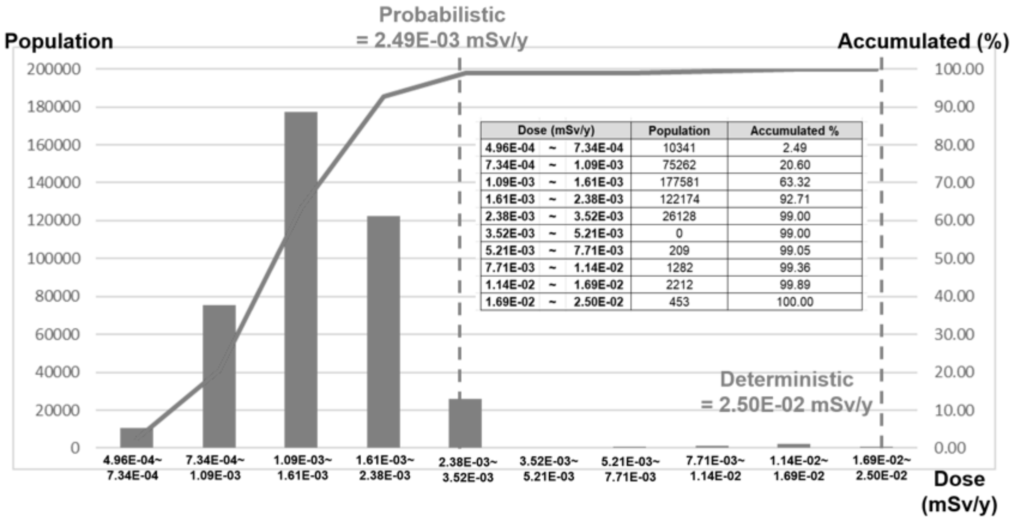
The probabilistic and deterministic doses for citizens of Kashiwa have been calculated and are presented in Fig. 4. The results indicate that the deterministic dose is an order of magnitude higher than the probabilistic dose. Therefore, it can be concluded that in low-dose environments, determining the maximum dose for a representative individual using deterministic methods can effectively cover radiation protection strategies for other residents. However, as doses increase, a more detailed estimation of exposure doses becomes necessary. This implies that while 95% of the population might be considered safe under the probabilistic dose, the most extreme 5% might need to consider specific radiation protection interventions.

3.2. On-site measurement results

This study conducted on-site measurements at four locations in Kashiwa City: Juvenile Guidance Center, Minami-Masuo Bird Forest, Kashiwa Citizen's Cultural Hall, and Ohorigawa Recreation Park. Compared with the theoretical values (calculated following the procedures in Fig. 1), the on-site measurement results showed an overestimation ranging from 4 to 280 times. However, after accounting for potential factors—such as measuring at the margin instead of the center right on top of decontaminated soil, and the distribution of decontaminated soil at 20 or more locations in the park—the overestimation for both the dwelling scenario and the park and schoolyard scenario can be corrected to a factor of 10^0, while the overestimation for asphalt coverage is decreased to a factor of 10^2 (due to radiocesium being washed away by rainwater with little vertical penetration into the ground). Considering the degree of uncertainty and the efficiency of dose assessment, the new dose assessment method proposed by this study could serve as a complementary and cost-effective precursor to the previous approach.

3.3. Results of (TE)NORM regulations

Following a review of international (IAEA and ICRP) and regional (Australia, Canada, EU, Japan, US, and Taiwan) regulations for (TE)NORM, this study recommends applying the concepts of optimization, justification, and reference levels not only to (TE)NORM but also to decontaminated soil (7,8). Additionally, the control measures for (TE)NORM, such as workplace categorization and dose values by work categories, could be effectively applied to the management of decontaminated soil as well.



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

Fig. 4. Probabilistic and deterministic doses for Kashiwa citizens

4. Conclusion and future scope

As outlined in the introduction, this study addressed three key objectives. For objective (a), the investigation revealed that decontaminated soil in Kashiwa City is buried 30-40 cm underground and remains in a stable condition. For objective (b), a dose assessment method was developed using Kashiwa City as a case study (as shown in Fig. 1). This method can be generalized and applied to other radiation-contaminated environments. For objective (c), a user input spreadsheet was created, enabling residents to determine their dose by entering their address, habits, house dimensions, and dates. Additionally, the deterministic and probabilistic doses for Kashiwa citizens were calculated. 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.

5. References

[1] Japan Atomic Energy Agency (JAEA). Ibaraki, Japan: JAEA. 2014. Airborne Monitoring in the Distribution Survey of Radioactive Substances. **[2]** Ben-Ezra M, Shigemura J, Palgi Y, Hamama-Raz Y, Lavenda O, Suzuki M, et al. From Hiroshima to Fukushima: PTSD symptoms and radiation stigma across regions in Japan. J Psychiatr Res. 2015 Jan;60:185–6. **[3]** United States Environmental Protection Agency. Evaluation of EPA's Guidelines for Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM): Report to Congress. EPA 402-R-00-001. June 2000. 2000 Jun. **[4]** Yoshimura K. Air dose rates and cesium-137 in urban areas—deposition, migration, and time dependencies after nuclear power plant accidents. J Nucl Sci Technol. 2022 Jan 2;59(1):25–33. **[5]** Sato R, Yoshimura K, Sanada Y, Mikami S, Yamada T, Nakasone T, et al. Assessment of individual external exposure doses based on environmental radiation in areas affected by the Fukushima Daiichi Nuclear Power Station accident. Environ Int. 2024 Dec;194:109148. **[6]** ICRP. Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public. ICRP Publication 101a. Ann ICRP. 2006;36(3). **[7]** International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann ICRP. 2007;37(2–4). **[8]** International Atomic Energy Agency (IAEA). Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (GSR Part 3). Vienna; 2014.