



Assessment of Radionuclide Deposition on Korean Urban Residential Area

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ABSTRACT

Background: An important lesson learned from the Fukushima accident is that the transition to the mid- and long-term phases from the emergency-response phase requires less than a year, which is not very long. It is necessary to know how much radioactive material has been deposited in an urban area to establish mid- and long-term countermeasures after a radioactive accident. Therefore, an urban deposition model that can indicate the site-specific characteristics must be developed.

Materials and Methods: In this study, the generalized urban deposition velocity and the subsequent variation in radionuclide contamination were estimated based on the characteristics of the Korean urban environment. Furthermore, the application of the obtained generalized deposition velocity in a hypothetical scenario was investigated.

Results and Discussion: The generalized deposition velocities of ^{137}Cs , ^{106}Ru , and ^{131}I for each residence type were obtained using three-dimensional (3D) modeling. For all residence types, the deposition velocities of ^{131}I are greater than those of ^{106}Ru and ^{137}Cs . In addition, we calculated the generalized deposition velocities for each residential types. Iodine was the most deposited nuclide during initial deposition. However, the concentration of iodine in urban environment drastically decreases owing to its relatively shorter half-life than ^{106}Ru and ^{137}Cs . Furthermore, the amount of radioactive material deposited in nonresidential areas, especially in parks and schools, is more than that deposited in residential areas.

Conclusion: In this study, the generalized urban deposition velocities and the subsequent deposition changes were estimated for the Korean urban environment. The 3D modeling was performed for each type of urban residential area, and the average deposition velocity was obtained and applied to a hypothetical accident. Based on the estimated deposition velocities, the decision-making systems can be improved for responding to radioactive contamination in urban areas. Furthermore, this study can be useful to predict the radiological dose in case of large-scale urban contamination and can support decision-making for long-term measurement after nuclear accident.

Keywords: Radioactive Contamination, Radionuclide Deposition, Urban Environment

Introduction

According to the official announcement of Korean Ministry of Land, Infrastructure and Transport in 2016, 91.82% of 51.7 million people live in Korean urban areas [1]. If an unexpected major nuclear accident at a nuclear power plant happens, radioactive materials released into the environment would spread to large urban areas and affect many people. Especially, in Korea, there are several metropolitan cities such as Busan, Pohang, and Ulsan located within a radius of 30 km from a nuclear power plant. If a

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nuclear accident occurs, high population density may lead to high collective dose.

An important lesson learned from the Fukushima accident is that the transition to mid and long term phases from emergency response phase is not so long, within a year. Therefore, it is important to develop the site-specific mid- and long-term response technology. In order to establish the mid- and long-term countermeasures in urban area after a radioactive accident, it is necessary to know how much radioactive material is deposited onto the urban area. However, there are restrictions in the prediction of radionuclide deposition using existing models, due to each country's site-specific urban environmental characteristics. Therefore, it is necessary to develop an urban deposition model that can reflect the site-specific characteristics. One of the important site-specific characteristics of urban area is the compositional ratio of the urban surface.

In this study, the generalized urban deposition velocity and subsequent variation of radionuclide contamination were estimated by reflecting the characteristics of Korean urban environment. Furthermore, a study on the application of the obtained generalized deposition velocity to a hypothetical scenario was conducted.

Materials and Methods

1. Deposition Velocities on Urban Surfaces

The rate of deposition is an indicator of surface contamination. The amount of deposition per unit area per hour can be obtained by multiplying the air concentration by the deposition velocity. Deposition in an urban environment might be considered as an overall effect or as deposition to individual surface types [2]. However, due to the various types of surface and structures of the urban environment, it is difficult to apply the generalized urban deposition velocity. Therefore, an estimate of an integrated deposition velocity

for an urban area can be obtained by summing the surface types for a given type of location [2]. In order to generalize the urban deposition velocity reflecting the surface types, the average deposition velocity in each grid was obtained by the following equation.

$$v_{ptot} = \frac{\sum_{i=1}^n v_{pi} \cdot A_i}{A_{site}} \quad (1)$$

where v_{ptot} is the average deposition velocity (m/s) of the residential area of interest, v_{pi} is the deposition velocity (m/s) at surface type i , A_i is the area of surface type i (m^2), and A_{site} is the site area of interest (m^2). In order to estimate the average deposition velocity for each residential area, the different deposition velocities for surface type such as roof, paved road, wall, soil and tree, which are major compositional surfaces in an urban area, were applied. Table 1 shows the deposition velocity used to determine the average deposition velocity for ^{137}Cs , ^{106}Ru , and ^{131}I . These values are from METRO-K (Model for Estimating the Transient Behavior of Radioactive Materials in Korean Urban Environment) [3].

Following its deposition, material is transferred by number of processes which modify the relative deposition to different surfaces [2]. The deposition of radioactive materials on the urban surface is reduced by the radioactive decay and weathering effect of the nuclides after deposition and the retention of contamination on surface is commonly described using a double exponential form as follows [2]:

Table 1. Deposition Velocity to Surface Types (unit: m/s)

	Cesium	Ruthenium	Iodine (particulate)
Roof	4.32×10^{-4}	2.68×10^{-4}	1.07×10^{-3}
Pavement	8.14×10^{-5}	2.82×10^{-4}	2.45×10^{-4}
Wall	1.80×10^{-5}	4.93×10^{-5}	1.28×10^{-4}
Grass/Soil	6.12×10^{-4}	1.27×10^{-3}	1.62×10^{-3}
Tree	1.21×10^{-3}	3.27×10^{-3}	1.99×10^{-3}

Table 2. Coefficients Used in Weathering Equation

	a			b			c		
	Cesium	Ruthenium	Iodine	Cesium	Ruthenium	Iodine	Cesium	Ruthenium	Iodine
Roof	0.50	0.29	0.75	340.0	29.2	17.0	2,420	2,409	2,420
Pavement	0.60	0.30	0.75	80.0	69.4	40.0	10,100	10,100	10,100
Wall	0.20	0.17	0.30	365.0	314.0	182.5	6,935	6,935	6,935
Grass/Soil	0.63	0.95	0.95	317.6	91.0	160.0	15,600	4,453	15,600
Tree	0.80	0.95	0.80	36.5	36.5	18.0	36,500	36,500	36,500

a, short-term constant; b, short-term weathering half-lives; c, long-term weathering half-lives.

$$C(t) = C(0)\exp\left(-\frac{\ln 2}{T_{1/2}}t\right)\left(a\exp\left(-\frac{\ln 2}{b}t\right) + (1-a)\exp\left(-\frac{\ln 2}{c}t\right)\right) \quad (2)$$

where $C(t)$ is the radionuclide concentration (Bq) at time t and $C(0)$ is the initial radionuclide concentration (Bq). $T_{1/2}$ is the half-life of the nuclide (day), a is the short-term weathering half-life constant, b is the short-term weathering half-life (day), and c is the long-term weathering half-life (day). The short- and long-term weathering half-lives for each surface are shown in Table 2. These values are also from METRO-K.

2. Modeling of Urban Residential Area

According to the results of census on population and housing, 99% of the population in Korea is living in three typical residential types; single houses, multi-family houses, and

apartments. Therefore, the types of residential areas are classified as a single house, a multi-family house, and an apartment. In order to model each type of residence, we have modelled each type of residence by referring to the Daejeon City Ordinance and Building Law. The surface area of each residence type was obtained by 3D modeling. In the case of a single house, the coverage ratio is 50% according to the Daejeon City Ordinance [4]. The building is one story, with grass and trees in the yard. The coverage ratio of multi-family house is 60% and the floor space ratio is 200% [4]. Because the floor space ratio is limited to 200%, the building consists of three floors. There is a parking lot in the yard of the building without green space. In the case of an apartment, the distance between the buildings should be at least 50% of the height of the building due to the Building Law of Daejeon City. The building consists of 18 stories. The coverage rate is 20% and the green land ratio in the complex is 30%.

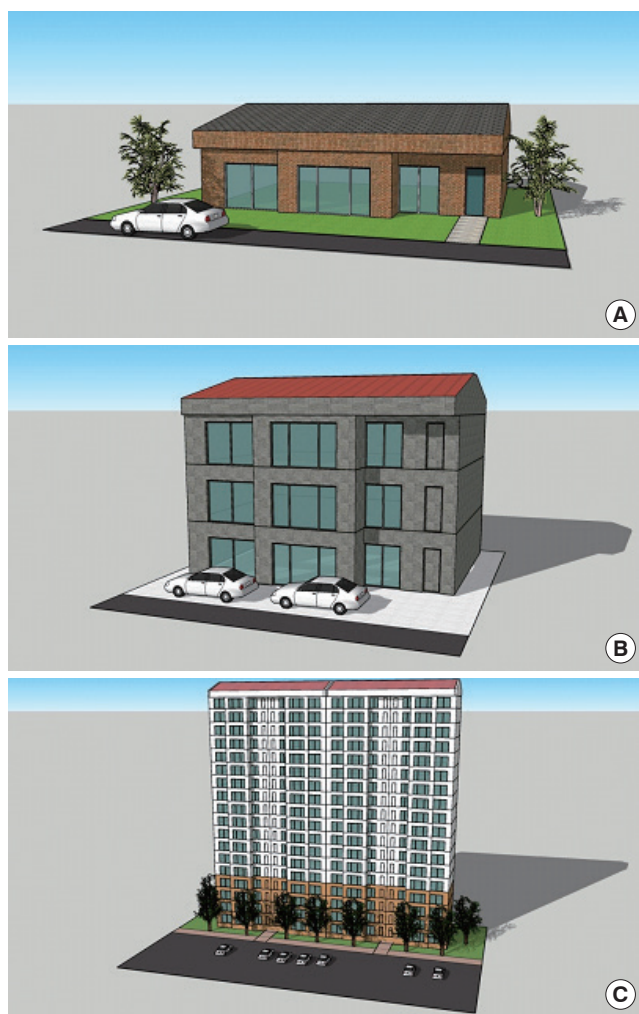


Fig. 1. The 3D modeling for each type of residences: (A) single house, (B) multi-family house, and (C) apartment.

Results and Discussion

1. Generalized Urban Deposition Velocity and Weathering Effect

Fig. 1 shows the 3D modelling results for each type of residence. Ratio of contaminated surface area per unit area of each residence type was derived from the 3D modelling results. Table 3 shows the ratio of each contaminated surface per unit floor for each residence type. The information obtained through modeling the urban residence type was applied to Equation (1) for obtaining the average deposition velocity. The radionuclides used in this study are ^{137}Cs , ^{106}Ru , and ^{131}I . The reason for choosing the nuclides is since ^{131}I and ^{137}Cs were the dominantly emitted substances in Chernobyl [5]. ^{137}Cs has a half-life of 30 years, whereas ^{131}I has a relatively short half-life of 8 days. In order to examine the time-dependent behavior of the nuclide with half-life between cesium and iodine, ^{106}Ru which has a half-life of 1 year and emitted

Table 3. Surface Ratio by Residence Types

	Surface ratio (%)		
	Single house	Multi-family house	Apartment
Roof	26	27	6
Pavement	33	49	70
Wall	18	23	17
Grass/Soil	24	0	7
Total area	100	100	100
Site area	67	41	30

Table 4. Average Deposition Velocity by Residence Types (unit: m/s)

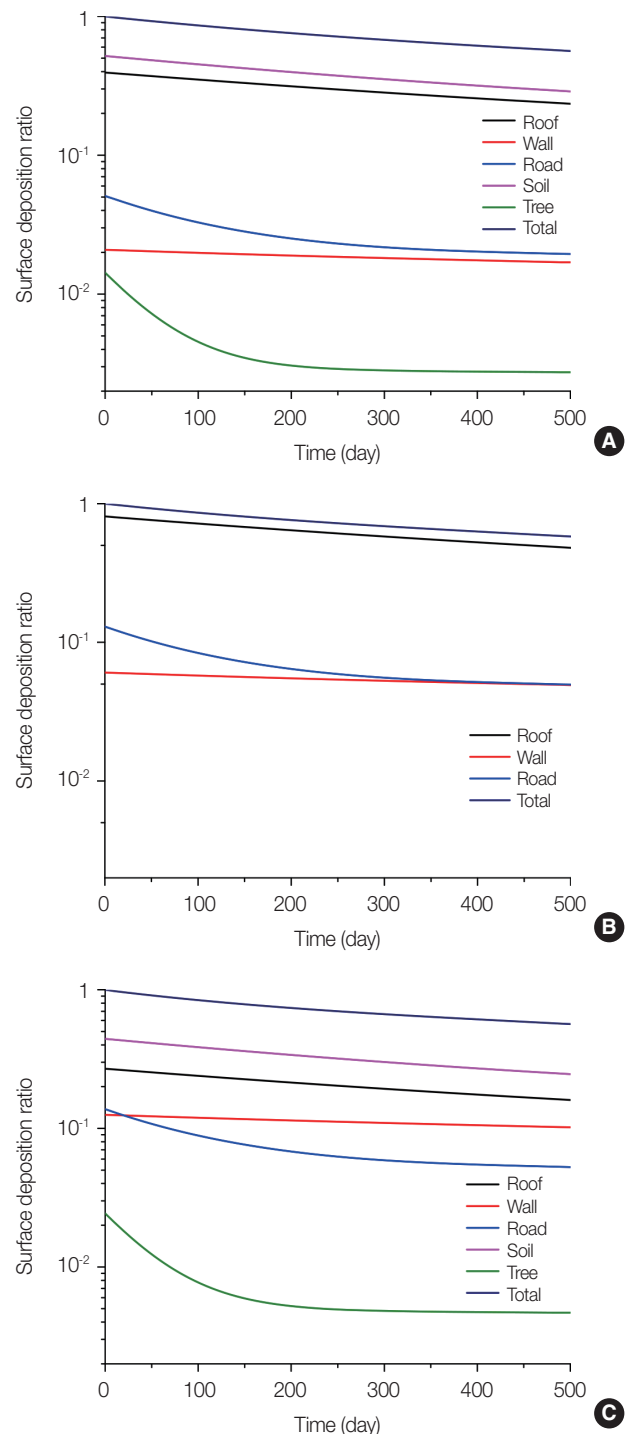
	Cesium	Ruthenium	Iodine
Single house	4.24×10^{-4}	6.76×10^{-4}	1.14×10^{-3}
Multi-family house	3.57×10^{-4}	3.99×10^{-4}	1.01×10^{-3}
Apartment	3.31×10^{-4}	6.54×10^{-4}	1.06×10^{-3}

in the accident at the Chernobyl Nuclear Power Plant was applied to the assessment. In the environment, iodine comes in three forms: particulate, organic, and elemental iodine. In this study, it is assumed that iodine is released in the particulate form, as applied to cesium and ruthenium, since the main purpose of this study is to compare the deposition and its post-deposition behavior of these nuclides on the urban environment surfaces. Table 4 represents the generalized deposition velocity of the radionuclides ^{137}Cs , ^{106}Ru , and ^{131}I for each residence type. For all residence types, deposition velocities of ^{131}I (particulate) are higher than those of ^{106}Ru and ^{137}Cs .

The results are also applied to Equation (2) for evaluating the radionuclide concentration change on the contaminated surface due to weathering effect. The results are represented in Figs. 2–4. The unit radioactive concentration of the whole region of interest area was assumed, and Fig. 2 shows the relative concentration ratio on each surface. Using these results, it is possible to determine the priority of decontamination for each surface in the mid- and long-term responses after a nuclear accident. For example, since the most radionuclides are deposited on the roofs of the buildings after the accident, decontamination of these surfaces as an accident response act can be set as the highest priority. On the other hand, because the half-life of ^{131}I is very short as 8 days, the concentration decreases rapidly than that of ^{137}Cs and ^{106}Ru . Therefore, it is much more effective to prevent ^{131}I exposure in the initial contamination measures than the mid- and long-term response to these radionuclides.

2. Hypothetical Nuclear Facility Accident Scenario

The obtained generalized deposition velocity for residential types was applied to a hypothetical radioactive facility accident scenario and the initial deposition and the change in deposition amount of radioactive material in urban residential areas was evaluated. The accident was assumed to occur in a research reactor located at the Korea Atomic Energy Research Institute in Daejeon, Korea. The closest city residence area for research reactor is located in Gwanpyeong-dong, also called Daedeok Techno Valley. There are about 23,000 populations in this area. This district is a residential

**Fig. 2.** Change of radionuclide concentration ratio on the surfaces (cesium): (A) single house, (B) multi-family house, and (C) apartment.

complex consisting of residential areas such as apartments and apartment complexes and non-residential areas such as schools and commercial facilities built in the end of the 2000s.

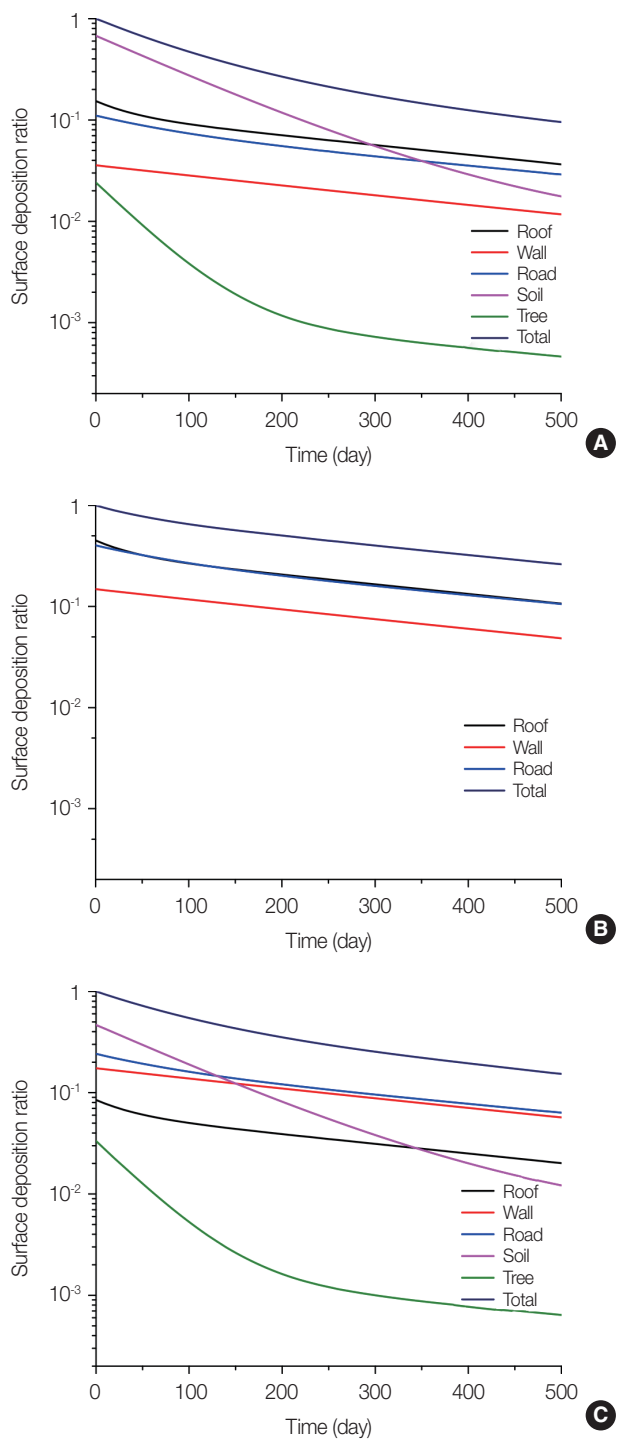


Fig. 3. Change of radionuclide concentration ratio on the surfaces (ruthenium): (A) single house, (B) multi-family house, and (C) apartment.

3. Radioactive Source and Geographic Information

The atmospheric diffusion model was not applied to clearly confirm the amount of surface deposition. Therefore, radioactive materials were assumed to be equally distributed

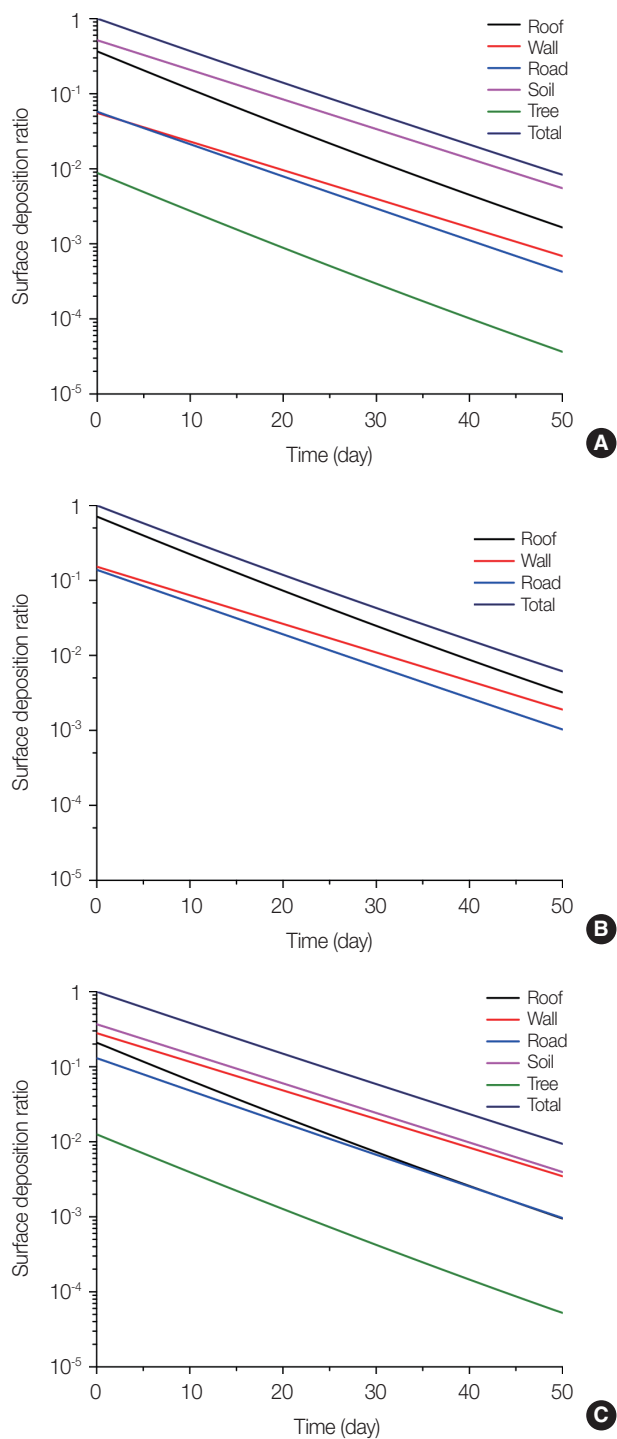


Fig. 4. Change of radionuclide concentration ratio on the surfaces (iodine): (A) single house, (B) multi-family house, and (C) apartment.

in all regions. The radionuclide concentration was assumed to be 1,000 Bq/m³ for all three nuclides and remain in atmosphere for 2 hours after the accident. This area was categorized into six types as shown in Fig. 5. There is no single house



Fig. 5. Interest area classified into six types.

in this area. Also, commercial facilities, schools, parks and roads in residential areas were roughly modeled with the same methodology applied for the residential area. The assessment results are shown with contamination maps of resolution $100 \times 100 \text{ m}^2$ in Figs. 6 and 7. Fig. 6 shows the initial contamination for cesium, ruthenium, and iodine. Fig. 7 shows their change over time. In the case of initial deposition, iodine is found to be the most deposited nuclide. On the other hand, since iodine has a relatively short half-life, its concentration on urban surfaces is sharply decreased. Furthermore, as a result of the assessment, it was found that more radioactive material is deposited in non-residential areas, especially in parks and schools, than in residential areas. This is because soil and trees are widely distributed in parks and schools.

Conclusion

In this study, the generalized urban deposition velocity and subsequent deposition change was calculated reflecting the urban environment in Korea. In order to estimate the generalized urban deposition velocity, 3D modeling was performed for each type of urban residential area, and the average deposition velocity was obtained by summing each surface. Furthermore, using the calculated deposition velocity, we set up a hypothetical radioactive facility accident scenario and calculated the initial deposition and the change in deposition amount of radioactive material in urban residential areas and drawn a contamination map. This study is a preliminary step in the development of decision-making systems for responding to radioactive contamination in urban areas. This study would contribute to the prediction of radiological dose in large-scale urban contamination and decision-making support.

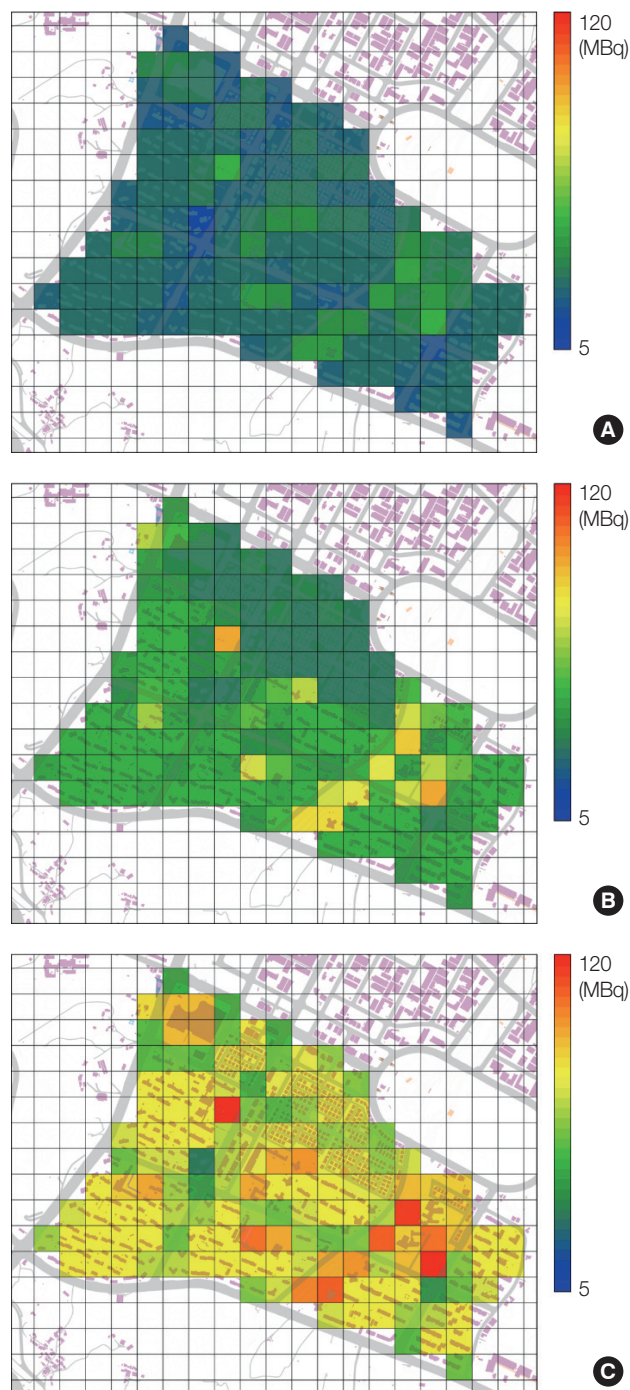


Fig. 6. Initial contamination maps of $100 \times 100 \text{ m}^2$ per grid resolution: (A) cesium, (B) ruthenium, and (C) iodine.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

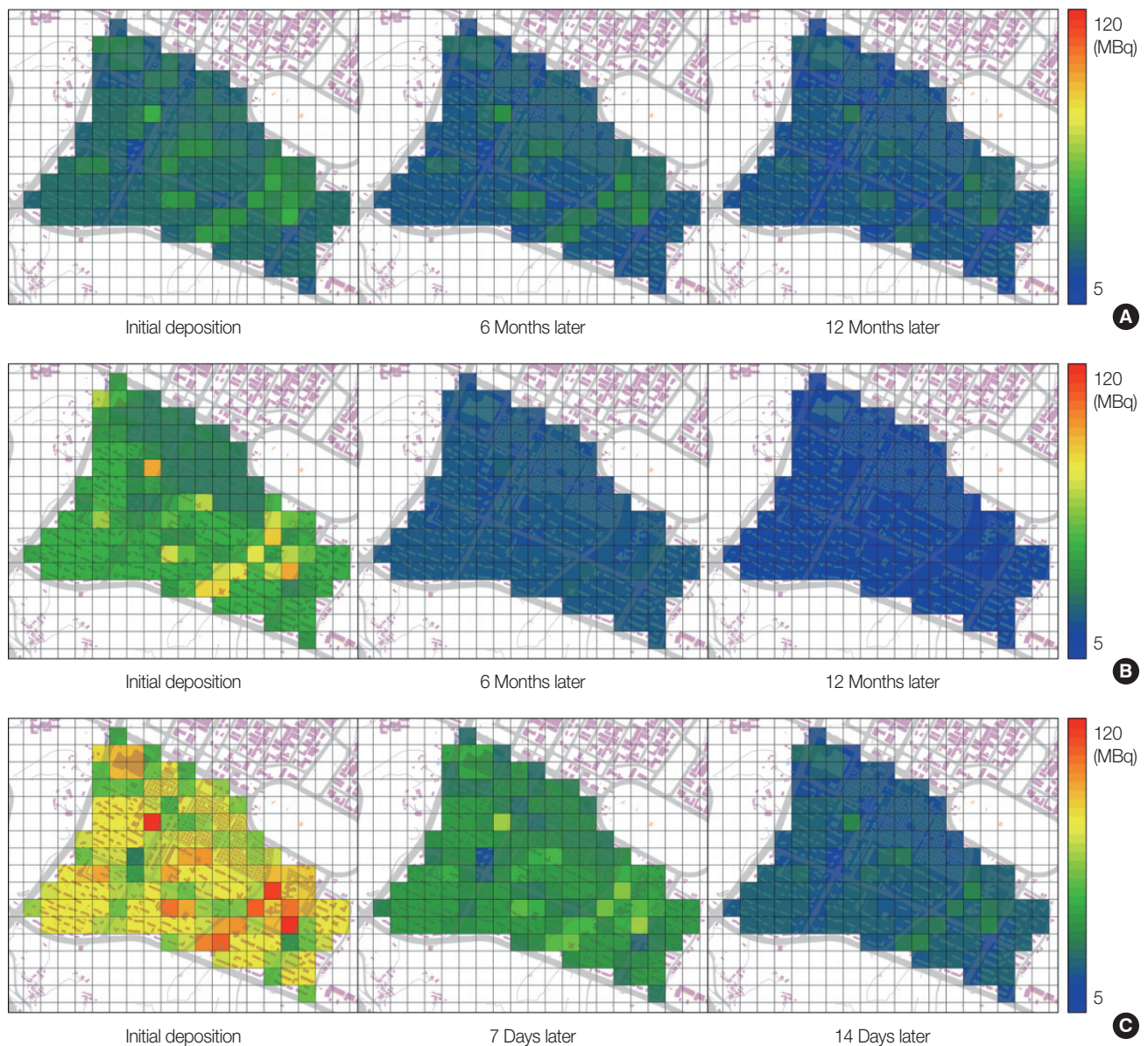


Fig. 7. Change of radionuclide concentration of 100 × 100 m² per grid resolution: (A) cesium, (B) ruthenium, and (C) iodine.

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