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Original Article

Analysis of the influence of nuclear facilities on environmental radiation by monitoring the highest nuclear power plant density region

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ABSTRACT

Monitoring of environmental radioactivity is essential for ensuring the radiological safety of residents who live near nuclear power plants. Ulsan, South Korea, is surrounded by 16 nuclear power plants, the highest density in the country. In addition, the city contains facilities for conducting radiological nondestructive testing and using radioisotopes for medical purposes. It makes the confirmation of radiological safety particularly necessary. In this study, sampling points were selected based on regional characteristics, and surface water samples were pretreated and analyzed for gross beta and gamma radiation levels. In addition, the distribution of the city's gamma dose rate was determined using a mobile monitoring system and distribution visualization program. The results showed that there is no effect on the gross beta and gamma nuclides of artificial radionuclides, and the gamma dose rate of the entire region did not exceed the environmental radiation level in South Korea overall, confirming the radiological safety of the city.

1. Introduction

Most radiation exposure is caused by natural radionuclides under normal circumstances, but evaluations of environmental radiation should be managed in terms of radiological safety aspect [1–6]. As the nuclear industry develops, there is a growing interest in radiation exposure within the human environment, so systematic radiation environmental monitoring is required [7–11]. Such monitoring is particularly essential for ensuring the radiological safety of residents near nuclear facilities [12–18], such as those in Ulsan Metropolitan City in South Korea, which is surrounded by 16 nuclear power plants. The Ulsan region has the largest population in an emergency radiation planning area, including almost all areas within 30 km of nuclear power plants (NPPs).

In recent years, large and small earthquakes have occurred frequently in active faults located in southeastern South Korea's Gyeongju, including an earthquake of magnitude 5.8 in 2016. Given the many NPP facilities located near the active fault and the issues following the 2011 Fukushima nuclear accident in Japan, there is a growing need to review and implement the procedures and conditions necessary for the safe operation of NPPs in Ulsan.

Radiation can be produced from other sources in addition to NPPs, such as in industrial (nondestructive testing machines) and medical (X-ray filming of patients and radiation therapy for cancer patients) settings. As Ulsan contains many such facilities in addition to NPPs, it is essential to confirm the region's radiological safety by monitoring its overall environmental radioactivity.

In order to conduct such monitoring, precise analysis is required through pretreatment with appropriate methods [19–25], evaluating the effect of environmental radiation through gross beta radioactivity analysis [26–32]. In addition, it is necessary to confirm the effect of environmental radiation by confirming the spatial gamma dose rate in residential areas [33–39]. In this study, beta and gamma analyses were performed by selecting monitoring points with reference to NPP locations in Ulsan, and wide-scale monitoring was performed using a mobile gamma monitoring system and radiation dose distribution visualization program.

2. Methods

2.1. Selection of sampling points

The 12 operating NPPs located 30 km from the radiological

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emergency planning zone of Ulsan are Shin-Wolseong NPP 1–2, Wolseong NPP 1–4, Shin-Kori NPP 1–3, and Kori NPP 2–4. There are currently 24 operational NPPs, including Hanbit 1–6 and Hanul 1–6. Half of the NPPs are adjacent to Ulsan Metropolitan City. In addition, Ulsan Metropolitan City has the largest concentration of nuclear facilities in Korea, including the Gyeongju intermediate and low-level radioactive waste repository. A variety of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), representing uranium-thorium-types, alphas/betas, and long-half-life radionuclides, are produced by the aforementioned industries (Table 1). These can be a factor in the development of cancer through the inhalation of recently released substances like radon. Activities such as nondestructive testing and radiation therapy can produce artificial gamma radionuclides with a relatively short half-life that can acutely influence the human body during exposure. For example, in 2012, a nondestructive company in Ulsan experienced an accidental death due to radiation exposure and a high level of spatial gamma doses in the vicinity of a hospital. Such incidents make it essential to analyze the environmental radioactivity around related industries. Environmental radiation is affected not only by the surrounding facilities but also by geological factors. Therefore, comparisons were made through radioactivity analysis within the same geological area rather than between regions. To confirm the effect of nuclear facilities on the surrounding environment, radiological safety was verified by comparison between the area near the nuclear facility and the populated area far from the nuclear facility. In this study, major sampling points were selected based on characteristic information such as the proximity of NPPs and other sites utilizing radioactive material using four selection criteria:

1. Was the sampling point located within the radiation emergency planning area (within 30 km of an NPP)?
2. Was there at least one point within 10 km of the Kori/Wolseong NPP?
3. Did the sampling point include densely populated areas?
4. Was it possible to effectively provide information on environmental radiation levels through rapid analysis?

Representative water samples that were selected according to the above criteria and that can be pretreated by the same method were selected for environmental radiation/radioactivity analysis. In order to analyze these water samples quickly, pretreatment methods such as evaporative concentration and distillation were used for analyzing the gross beta radiation concentrations. Here, the gross beta can be used for rapid monitoring of radiation internal exposure. The sample types include surface water that can be contaminated by precipitation, water around the NPP, water from industrial facilities, and sewage in the area. In order to examine the effect of NPPs, Ganjeolgot Cape is set as a representative sampling point near the Kori NPP, and a Columnar Joint is set as a representative sampling point of the Wolseong NPPs. In order to confirm the influence of the effluent from the industrial facilities, Gaeun Bridge was defined as a sampling point. Gaeun Bridge is in the lower part of the Oehwang River immediately adjacent to Ulsan's petrochemical and industrial complex. Gaeun Bridge is the best place to check whether the effluent of an industrial facility flows into the surrounding rivers. Samples from Bangeojin were taken to confirm the effect of Ulsan University Hospital, which uses radioactive materials for medical purposes. Finally, Myeongchon and Old Samho Bridge were selected as sampling points for the densely populated areas. The population of the middle and southern districts in Ulsan Metropolitan City is about 48.9%. The samples from the Old Samho and Myeongchon Bridge, which are the sampling points along the boundary between the middle and southern districts, were used as representatives of the populated area [40]. Fig. 1 shows the location of the sampling points in this study.

Table 1
Occurrence and usage of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORMs) and artificial nuclides by industry.

Industry	TENORM or Artificial Nuclides
Coal combustion	Pb-210, Po-210
Oil and gas production	Ra-228, Ra-226, Ra-224
Mining	Ra-226
Phosphate and fertilizer production	Ra-226, Pb-210
Use and production of thorium compounds	Th-232, Ra-228, Rn-220
Tantalum and niobium production	Th-232, Pb-210, Po-210, U-238, Ra-226
Manufacturing of titanium dioxide pigment	Ra-228, Ra-226
Use and production of zirconium compounds	Pb-210, gross Po-210
Metal production and smelting	Pb-210, Po-210
Water treatment facilities	Industrial waste
Shaft material production and utilization	Ra-226, Th-232, K-40
Rare earth element extraction	Th-232, Ra-228, Rn-220
Nondestructive inspection	Ir-192, Co-60, Se-75
Radiation therapy machine (Hospital)	Co-60, Ir-192

Nuclear power plants are adjacent to the sea. Therefore, analysis of seawater samples is required to check the radiological safety of the area near the nuclear power plant. However, seawater contains many ions, which makes the measurement of the gross beta difficult. For this reason, seawater samples were used to analyze gamma nuclides including K-40, Be-7, Te-123 m, I-131, and Cs-137 and the gamma doses rate. Seawater was collected at the Columnar Joint, Bangeojin Port, and Ganjeolgot Cape sites due to their coastal locations, while river water was collected at the Old Samho Bridge, Myeongchon Bridge, and Gaeun Bridge sites for freshwater analysis (Fig. 2). Environmental data were recorded at each sampling point (Table 2), including temperature, pH, and total dissolved salts (TDS) which is an indicator of how the quantity of solid impurities dissolved in the water. This value was used to estimate how much of the solid sample would remain after the water sample was evaporated.

It is necessary to test the statistical significance of the relationship between populated areas and other sampling areas, such as industrial facilities, NPP, and medical facilities, respectively. To do this, T-test and F-test are used in this study. T-test is a statistical hypothesis test, which is applied when the sample size is small and standard deviation is unknown. It enables to compare the means of two populations. F-test is also a statistical test, which is conducted when it is unknown whether the two populations have the same variance. It allows to determine the equality of the variances of the two normal populations and compare two population variances. From the standpoint of statistical analysis, the number of sampling points was low in the case of sampling for the gross beta and gamma nuclides analysis, but the samples were collected 10 times at each sampling point before the radioactivity analysis was performed. In the case of the gamma dose rate, at least 1500 data were measured per sampling point.

2.2. Pretreatment and measurement methods

For pretreatment and measurement of gamma isotopes, 10 L water samples were placed in a beaker and evaporated to 1 L on a hot plate. The concentrated sample was then transferred to a 1 L Marinelli beaker and allowed to cool. The prepared sample was measured for 80,000 s per sample using an HPGe detector [41].

For pre-pretreatment and measurement of gross beta values, a 250 mL aliquot of sample was placed in an evaporator (if the TDS measurement result was >2000 ppm, a 10 mL sample volume was used). The evaporation dish was heated on a hot plate, and the sample evaporated to 10 mL. The TDS was transferred to a planchet and evaporated with an infrared drier, then it was transferred to a

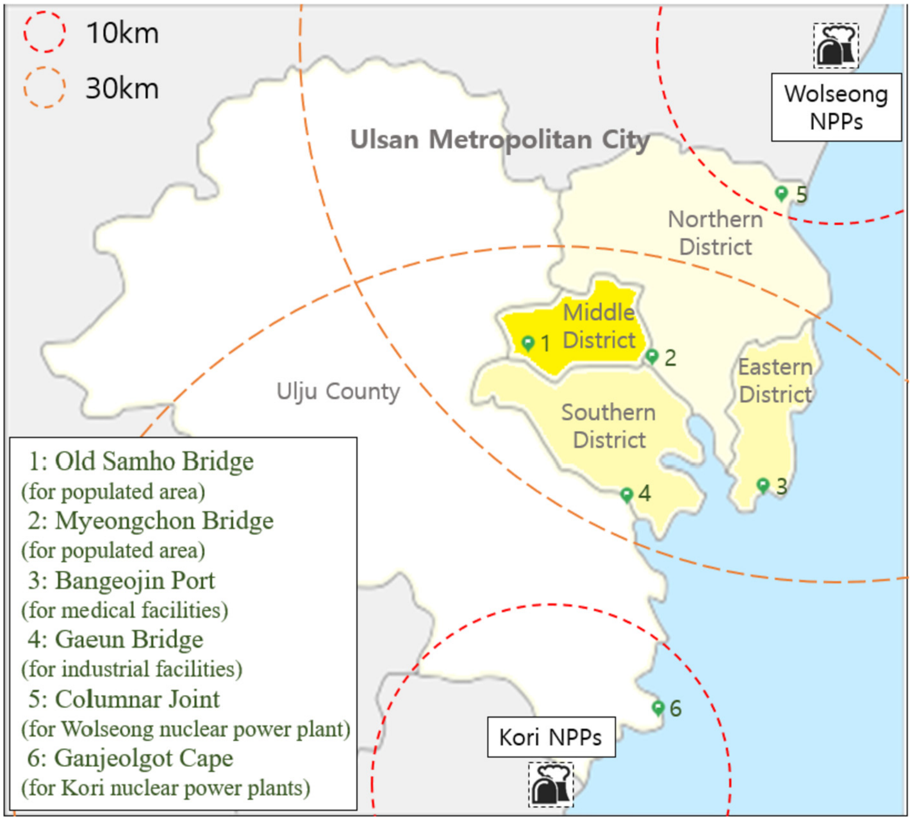

Fig. 1. Location for sampling points considering nuclear power plants (NPPs) near Ulsan Metropolitan City.

Fig. 2. Sampling points of (a) Old Samho Bridge, (b) Columnar Joint, (c) Myeongchon Bridge, (d) Gaeun Bridge, (e) Bangeojin Port, and (f) Ganjeolgot Cape.

desiccator and cooled for three days to reach the secular equilibrium. The prepared samples were measured for 120 min with an automatic low background alpha/beta counting system which is series 5 XLB™ detector [42]. The schematic diagram for pretreatment is shown in Fig. 3.

2.3. Detection method for gamma radiation dose distribution

Gamma doses were measured using a mobile monitoring system based on a NaI (Tl) scintillation-based detector; the monitoring device was installed in a car, and continuous measurements were made during travel between the main sampling points (Fig. 4) [43]. Continuous measurements were performed with the portable gamma dose rate detector. If the measured value was greater than 2.00E-01 μSv/h, or if the measurement value suddenly increased, the process to conduct the analysis of the artificial radionuclide was stopped and a measurement was made for more than 100 s at one point. The measured spectrum was analyzed to identify each artificial nuclide by its energy. In this study, analysis for artificial radionuclides were not performed because the measured values corresponded to levels of environmental radioactivity. The measured latitude, longitude, and dose rate values determined the radiation dose rate distribution, which was mapped using 2D and 3D contour lines. MATLAB was used to generate radiation distributions as 2D and 3D contour lines. Functions such as plot and contour in MATLAB and the quadratic interpolation method were used.

3. Results and discussion

3.1. Gamma radionuclide analysis

At most sites, nuclides other than K-40 fell below the minimum

Table 2
Environmental conditions at the sampling points.

Sampling point	Sample type	GPS information	Measured objects	Temperature (°C)	pH	TDS (ppm)
Old Samho Bridge	River water	35.552510,129.277623	gross beta, K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.23E+01	7.45E+00	9.10E+00
Columnar Joint	Seawater	35.635224,129.443702	K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.33 E+01	8.25E+00	>2.00E+3
Bangeojin Port	Seawater	35.480318,129.432133	K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.34 E+01	8.23E+00	>2.00E+3
Myeongchon Bridge	River water	35.530888,129.375196	gross beta, K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.30 E+01	7.88E+00	>2.00E+3
Gaeun Bridge	River water	35.475110,129.339274	gross beta, K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.46 E+01	7.76E+00	>2.00E+3
Ganjeolgot Cape	Seawater	35.355234,129.357892	K-40, Be-7, Te-123 m, I-131, Cs-137, gamma dose rate	2.23 E+01	8.24E+00	>2.00E+3

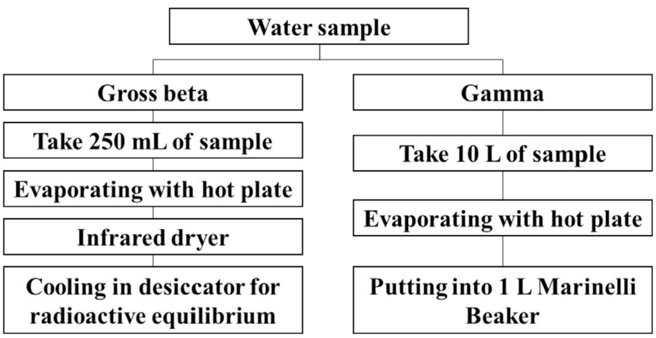

Fig. 3. The schematic diagram for pretreatment of gross beta and gamma analysis.

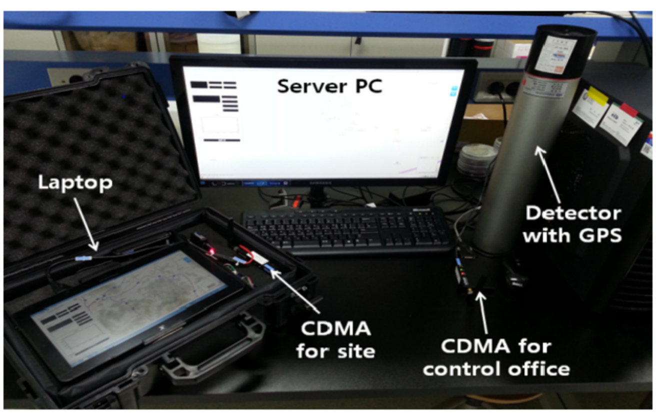

Fig. 4. The system components of the gamma dose rate distribution monitoring system.

detectible activity (MDA) values (Table 3). Concentrations of K-40 were higher at the Columnar Joint, Bangeojin Port, and Ganjeolgot Cape sites because these samples were seawater. Be-7 was detected at the Myeongchon Bridge and Gaeun Bridge sites but fell below MDA at the other sites. Therefore, the presence of artificial radionuclides was not observed.

3.2. Gross beta analysis

The gross beta radioactivity analysis was conducted only for the surface water, and the results are described in Table 4 [44]. The water samples of Old Samho and Myeongchon Bridge for populated areas and Gaeun Bridge for industrial facilities were analyzed with the gross beta values. The measured gross beta radioactivity concentration was compared with the water sample analysis around the NPP of Wolseong. The gross beta radioactivity value of Ulsan City was confirmed to be lower than the gross beta value of the water sample at the NPP. This is because of the rainfall when sampling, which dilutes the remaining dissolved substance, resulting in lower radioactivity.

A T-test was conducted to determine whether there is a significant difference in radiation levels between populated areas and industrial facilities. Table 5 shows the result of the F-test and T-test for statistical analysis. Prior to the T-test, the F-test revealed that the two groups have heteroscedasticity of the variance relation at the 95% confidence interval. Under the condition of heteroscedasticity of the variance, the result of the T-test at the 95% confidence interval was 8.41E-02. This result means that there is no statistical difference in the radiation levels between the two groups because the $P(T \leq t)$ two-tail value is larger than 0.05.

It can be verified that the difference between the average of the populated area and the industrial facilities is 1.19 Bq/L, and the variance of the populated area is 7.72. Therefore, a T-test was performed to statistically analyze each populated area sampling point and industrial facilities. Table 6 shows F-test and T-test results between the gross beta levels of the industrial facilities and each populated sample point. The F-test results under the 95% confidence interval showed that the P-value between the Gaeun and Myeongchon Bridge was 5.74E-01, and it was 4.41E-14 between the Gaeun and Old Samho Bridge. Therefore, a T-test was applied assuming homogeneity of the variance relation between Gaeun and Myeongchon Bridge and heteroscedasticity of the variance relation between the Gaeun and Old Samho Bridge. The results for the T-tests at the 95% confidence interval are 3.85E-05 and 2.16E-08, respectively. Each group is considered statistically different because both values are lower than 0.05.

However, the contamination cannot be defined as radiological contamination because of statistical differences between populated areas and industrial facilities. Gaeun and Myeonchon Bridge are located farther downstream compared to Old Samho Bridge. The water samples near Myeonchon Bridge contain more salinity, most of which is composed of NaCl, $MgCl_2$, Na_2SO_4, $CaCl_2$, and KCl salts. Therefore, such salinity increases the K-40 concentration due to the existence of KCl salt with natural isotopic abundance.

Table 3
Analysis results for major gamma radionuclides in environmental samples.

Sampling Points	K-40 (Bq/L)	Be-7 (Bq/L)	Te-123 m (Bq/L)	I-131 (Bq/L)	Cs-137 (Bq/L)
Ganjeolgot Cape	1.11E+01 ± 1.77E-01	<1.97E-01 (MDA)	<1.43E-02 (MDA)	<2.27E+00 (MDA)	<1.29E-02 (MDA)
Gaeun Bridge	5.97E+00 ± 1.41E-01	<2.20E-01 (MDA)	<1.47E-02 (MDA)	<8.20E+00 (MDA)	<1.19E-02 (MDA)
Myeongchon Bridge	1.01E+01 ± 1.68E-01	<2.39E-01 (MDA)	<1.57E-02 (MDA)	<9.87E+00 (MDA)	<1.31E-02 (MDA)
Bangeojin Port	1.14E+01 ± 1.81E-01	<2.26 E−01 (MDA)	<1.64E-02 (MDA)	<1.78E+01 (MDA)	<1.30E-02 (MDA)
Columnar Joint	1.15E+01 ± 1.82E-01	<2.93 E−01 (MDA)	<1.71E-02 (MDA)	<3.41E+01 (MDA)	<1.28E-02 (MDA)
Old Samho Bridge	1.48E-01 ± 4.00E-02	<1.52 E−01 (MDA)	<1.23E-02 (MDA)	<1.35E+00 (MDA)	<9.77E-03 (MDA)

Table 4
Comparison of gross beta radioactivity analysis results between samples from Ulsan and a nearby nuclear power plant (NPP).

Sampling Points (Ulsan)	Radioactivity of Gross Beta (Bq/L)	Sampling Points (Near the Wolseong NPP)	Radioactivity of Gross Beta (Bq/L)
Old Samho Bridge	2.07E-01 ± 1.29E-02	Intake # 1	1.14E+01 ± 7.59E-01
Gaeun Bridge	4.08E+00 ± 6.75E-01	Intake #2	1.26E+01 ± 7.78 E−01
Myeongchon Bridge	5.57E+00 ± 5.56E-01	Bonggil-ri	1.14 E+01 ± 7.67 E−01

Table 5
F-test and T-test results between the gross beta levels of industrial facilities and populated areas.

	Industrial facilities (Bq/L)	Populated area (Bq/L)
Mean	4.08E+00	2.89E+00
Variance	4.55E-01	7.72E+00
P(F ≤ f) one-tail	7.41E-05	
P(T ≤ t) two-tail	8.41E-02	

The radioactivity concentration of K-40 can be excluded by utilizing an analysis with HPGe, making it possible to deduce the gross beta contribution of the natural radionuclide. The gross beta radioactivity concentration after K-40 correction of the sample is shown in Table 7. In the case of Gaeun Bridge, water samples show high values of gross beta radioactivity concentrations because the U-238 and Th-232 radionuclides are generated from sedimentary soils and rocks have high solubility concentrations due to the slow flow rate. In the case of Myeongchon Bridge, the samples located downstream at the point adjacent to the seawater are analyzed to show concentration trends similar to those of the U-238 and Th-232 series nuclides in seawater. It was confirmed that there was no gross beta contamination in populated areas due to industrial facilities.

3.3. Gamma dose rate distribution

Table 8 shows the gamma dose rates at six sampling points. The minimum, maximum, and average gamma dose rate values at each point are shown. For the gamma dose rate, a portable NaI detector was used and measurements were taken at each sampling point for more than 5 min. As a result of the measurement of the gamma dose rate, the minimum value and the maximum value of all the data were 6.00E-02 and 7.50E-02 μSv/h, respectively. The biggest difference between the maximum and minimum values was 9.00E-03 μSv/h at Columnar Joint and Gaeun Bridge. This confirmed that the variation of the data was not large in the measurement of the gamma dose rate. The highest measured point is the Columnar Joint, and its value is 0.075 $\mu Sv/h$. The point with the lowest average value is the Gaeun Bridge, whose value is 0.0653$\mu Sv/h$. The highest mean value is 0.0721$\mu Sv/h$ at the Columnar Joint. The difference between the measured maximum value and the minimum value is 0.0068 $\mu Sv/h$, which shows a very small difference. There was no significant difference in the measured gamma dose rates in the area adjacent to the NPPs, populated areas, industrial facilities, and medical facilities. The distribution of the gamma dose rate in the measured Ulsan area is shown in Fig. 5. It was confirmed that similar radiation dose rates were obtained without any significant difference by region.

An F-test and T-test were performed at 95% confidence intervals to determine the effect of the NPPs, industrial facilities, and medical facilities on the measured environmental gamma dose rate. Statistical analysis was conducted in the areas adjacent to the NPPs, industrial facilities, and medical facilities based on the populated areas, assuming that the populated areas are not radiologically affected by the surrounding facilities. Table 9 shows F-test and T-test results for the gamma dose rate between populated areas and other monitoring points. It was confirmed that the P-values of

Table 6
F-test and T-test results between the gross beta levels of industrial facilities and each populated sample point.

	Gaeun Bridge	Myeongchon Bridge	Gaeun Bridge	Old Samho Bridge
Mean	4.08E+00	5.57E+00	4.08E+00	2.07E-01
Variance	4.55E-01	3.10E-01	4.55E-01	1.66E-04
P(F ≤ f) two-tail	5.74E-01		4.41E-14	
P(T ≤ t) two-tail	3.85E-05		2.16E-08	

Table 7
Gross beta radioactivity concentrations after K-40 correction of the sample.

Sampling points	Including K-40 radioactivity concentrations (Bq/L)	Excluding K-40 radioactivity concentrations (Bq/L)
Old Samho Bridge	2.07E-01 ± 1.29E-02	6.00E-02 ± 4.20E-02
Gaeun Bridge	4.08E+00 ± 6.75E-01	2.63E+00 ± 6.78E-01
Myeongchon Bridge	5.57E+00 ± 5.56E-01	9.60E-01 ± 5.66E-01

Table 8
Gamma dose rate for each monitoring point.

Monitoring Point	Minimum ($\mu Sv/h$)	Maximum ($\mu Sv/h$)	Average ($\mu Sv/h$)
Old Samho Bridge	6.90E-02	7.00E-02	6.95E-02 ± 1.53E-03
Columnar Joint	6.60E-02	7.50E-02	7.21E-02 ± 4.27E-03
Bangeojin Port	6.30E-02	7.00E-02	6.78E-02 ± 2.39E-03
Myeongchon Bridge	6.20E-02	6.90E-02	6.68E-02 ± 3.81E-03
Gaeun Bridge	6.00E-02	6.90E-02	6.53E-02 ± 6.71E-03
Ganjeolgot Cape	6.20E-02	6.90E-02	6.67E-02 ± 4.59E-03

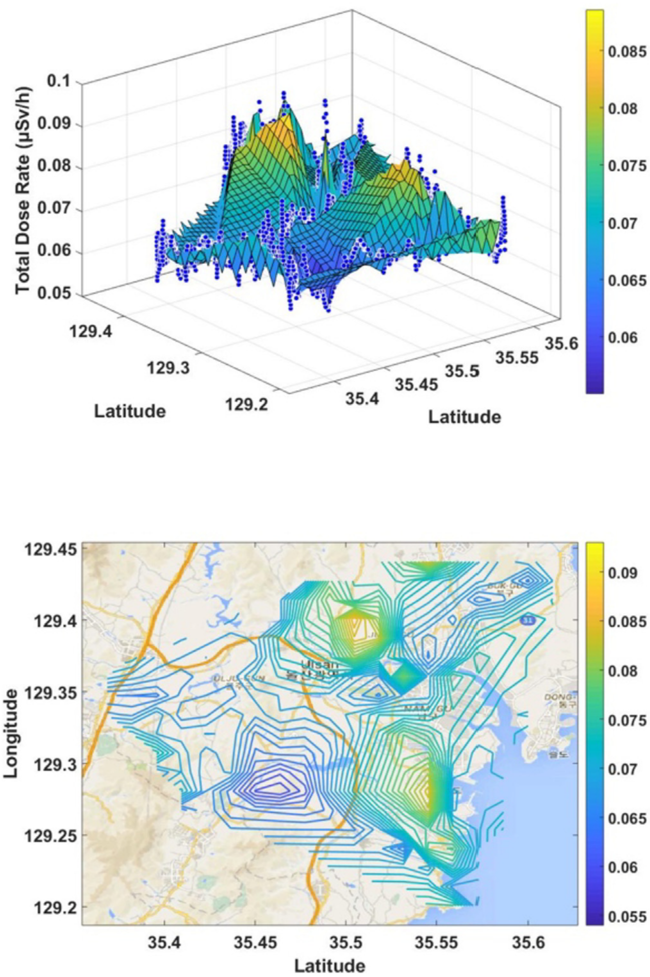

Fig. 5. Gamma dose rate distribution map for the entirety of Ulsan City.

Table 9
F-test and T-test results for gamma dose rates between populated areas and other monitoring points.

	Industrial facilities	Area adjacent to NPP	Medical facilities	Populated area
Average ($\mu Sv/h$)	6.53E-02	7.00E-02	6.78E-02	6.69E-02
Variance ($\mu Sv/h$)	5.02E-06	7.83E-06	1.04E-06	2.17E-06
Number of data	3.70E+02	8.39E+02	3.00E+02	4.15E+02
$P(F \leq f)$ two-tailed	2.10E-16	7.80E-43	2.76E-11	
$P(T \leq t)$ two-tailed	1.41E-30	6.59E-117	1.69E-19	

*NPP: Nuclear power plant.

2.10E-16, 7.80E-43, and 2.76E-11 were obtained from the F-test results between the populated area and the industrial facilities, NPP, and medical facilities, respectively. Since this value is less than 0.05, it is confirmed that each group has heteroscedasticity of the variance relation. A T-test of the heteroscedasticity of the variance condition was performed between the populated area and each sample point within the 95% confidence interval. T-test results confirmed that P-values were 1.41E-30, 6.59E-117, and 1.69E-19, respectively. This means that there is a statistically significant difference among the groups because the P-value is smaller than 0.05. However, the difference in the average between populated areas is 0.16E-02 for industrial facilities, 0.31E-02 for areas adjacent to the NPP, and 0.09E-02 for medical facilities. As the gamma dose rate measurement progressed more than 300 times at each point, a lot of small variance was formed, and the difference in the small averages between each monitoring point was also statistically analyzed as a different value.

Although there is a difference between each measurement point, gamma dose rate levels were included in the general South Korean environmental radiation level. The radiation dose rate of the environmental radiation monitoring fluctuates within the normal range between ~0.05 and 0.30 $\mu Sv/h$, according to the installation point in South Korea [45]. In Ulsan City, the gamma dose rate is not high, and there is no impact from NPPs or nuclear facilities.

4. Conclusion

Environmental radiation monitoring was carried out for the Ulsan area, which has a high density of NPPs. Sampling points were selected to confirm the influence of nuclear facilities, considering not only NPPs around Ulsan but also nondestructive testing facilities or hospitals using radioactive isotopes. Water at a selected sampling point was sampled and analyzed for gross beta and gamma isotope values. As a result of the analysis, it was confirmed that there was no influence from artificial radionuclides. The distribution of the gamma dose rate in the entire Ulsan area was performed using a mobile gamma monitoring system and a radiation distribution visualization program. As a result of the monitoring, it was confirmed that the gamma dose rate did not exceed the level of environmental radiation in Korea. It was confirmed that the radiation level of Ulsan, which has the highest density of NPPs, does not appear to be higher than that of other areas that are not adjacent to NPPs.

Declarations of interest

None.

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