# Evaluation of Environmental Radiation Trends through Long-Term Monitoring in the Emergency Planning Zone of Hanbit Nuclear Power Plant (2017-2024)

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***Keywords :** *Environmental radiation monitoring, Emergency Planning Zone, Hanbit NPP, Cesium-137, Tritium, Public dose assessment*

## 1. Introduction

In 2015, the amendment to the Act on Physical Protection and Radiological Emergency Preparedness for Nuclear Facilities expanded the Emergency Planning Zone (EPZ) for domestic nuclear power plants from a radius of 8-10 km to 30 km [1]. Consequently, the Yeonggwang, Muan, Hampyeong, and Jangseong regions near the Hanbit Nuclear Power Plant were newly included within the EPZ, leading to a significant increase in the need for long-term environmental radiation monitoring in these areas. Previous studies have been largely limited to short-term surveys or single-medium analyses, with few comprehensive, long-term time-series evaluations integrating multiple environmental media. This study represents the first comprehensive, long-term analysis in Korea to integrate multi-media monitoring—including rainwater, surface soil, seawater, and food—conducted over an eight-year period (2017-2024) across the entire EPZ, together with an assessment of public radiation dose. Through this approach, the variations and long-term trends in environmental radiation within the Hanbit NPP EPZ were scientifically characterized.

## 2. Methods and Results

### 2.1 Sample Collection

To ensure the accuracy and representativeness of environmental radiation analysis, sample collection was carried out in accordance with scientific criteria and standardized procedures. The target environmental media included rainwater, surface soil, seawater, and food, with sampling sites selected based on the physical and chemical properties of each medium and the purpose of collection. Specifically, sampling locations were determined by comprehensively considering factors such as major population centers, distance from the Hanbit Nuclear Power Plant, prevailing wind directions, geographical characteristics (e.g., coastline configuration, river inflow), and accessibility. These criteria were established in reference to the Regulation on Radiation Environmental Surveys and Radiation Environmental Impact Assessments around Nuclear Facilities (Notice of the Nuclear Safety and Security Commission) and the guidelines of the International Commission on Radiological Protection (ICRP).

Rainwater samples were collected monthly from nine sites within the EPZ as representative samples for monitoring airborne radioactive materials. Surface soil samples were collected semiannually from non-cultivated land at a depth of 0-5 cm. Seawater samples were collected quarterly from five coastal sites to monitor the dispersion of radioactive materials in the marine environment, with hydrochloric acid added to ensure sample stability. Food samples, consisting of locally consumed agricultural and marine products, were collected quarterly for analysis.

All samples were transported and stored immediately after collection to prevent degradation, and field information such as geographic coordinates and weather conditions was recorded. This systematic sampling approach contributed to enhancing the reliability of the analytical results.

Table 1. Sampling Sites and Environmental Media Characteristics

| Environmental Medium | No. of Sampling Sites | Sampling Frequency | Major Radionuclides Analyzed | Sample Pretreatment Method |
|---|---|---|---|---|
| Rain water | 9 | Monthly | $^{137}Cs$, $^{3}H$, Gross Beta | Filtration, Concentration |
| Surface Soil | 9 | Semi-annually | $^{137}Cs$, $^{60}Co$ | Drying, Homogenization |
| Seawater | 5 | Quarterly | $^{137}Cs$, $^{3}H$, Gross Beta | Coprecipitation, Concentration |
| Food stuffs | 5 | Quarterly | $^{131}I$, $^{134}Cs$, $^{137}Cs$ | Washing, Grinding |

### 2.2 Analytical Methods and Measurement Conditions

In this study, quantitative analyses of gamma-emitting radionuclides, tritium ($^{3}H$), and gross beta activity were conducted on rainwater, surface soil, seawater, and food samples collected within the Emergency Planning Zone (EPZ) of the Hanbit Nuclear Power Plant.

Depending on sample characteristics, appropriate pretreatment methods such as concentration, drying, or co-precipitation were applied. Gamma spectrometry was performed using a high-purity germanium (HPGe) detector, acquiring data over 8,192 channels within the 50 keV–3 MeV range. Rainwater samples (20 L) were concentrated to 2 L prior to analysis; soil samples were dried and homogenized; seawater samples were concentrated by co-precipitation with ammonium molybdophosphate (AMP) and manganese dioxide ($MnO_2$). Counting times were set between 80,000 and 100,000 seconds to meet the minimum detectable activity (MDA) requirements.

MDA values were calculated using the Currie equation (MDA = $(k \cdot \sqrt{B}) / (E \cdot t \cdot V)$), where k is the confidence factor (1.645 for 95% confidence level), B is the background count rate, E is detector efficiency, t is counting time, and V is sample volume or mass. The calculation followed ISO 11929 [6] and IAEA Safety Guide No. RS-G-1.8 [4]. As a result, MDAs were determined to be 0.001–0.006 Bq/L for rainwater and seawater samples, and 0.2–0.5 Bq/kg-dry for surface soil samples.

Gross beta activity was measured using a low-level alpha-beta counter (S5XLB, Canberra). Samples were evaporated to dryness, uniformly fixed onto planchets, and counted for 60 minutes per replicate, with 11 replicates per sample. Net count rates were corrected for background, providing an effective measure of total beta emission without isotope discrimination.

Tritium analysis was performed using a low-level liquid scintillation counter (Quantulus 1220, PerkinElmer). Pretreatment involved adding potassium permanganate ($KMnO_4$) and sodium peroxide ($Na_2O_2$) to remove organic matter and salts, followed by distillation to obtain pure water [2]. The purified samples were mixed with scintillation cocktail, stabilized for 24 hours in a dark and cool environment, and measured for 60 minutes per replicate, with 11 replicates per sample. As a low-energy beta emitter, $^{3}H$ is effectively analyzed by the LSC method, which offers high sensitivity and low detection limits for environmental samples.

Food samples were washed, cut, homogenized, and packed into 1 L Marinelli beakers for gamma spectrometric analysis using an HPGe detector (GC4020, Canberra). The results were evaluated against the radioactivity limits specified in the Korean Food Code (100 Bq/kg for iodine and cesium radionuclides).

The radionuclides analyzed included artificial nuclides ($^{60}Co$, $^{131}I$, $^{134}Cs$, $^{137}Cs$) and natural nuclides ($^{7}Be$, $^{40}K$), with additional analyses for $^{54}Mn$, $^{59}Fe$, $^{106}Ru$, and $^{144}Ce$ in soil and seawater samples. Analytical parameters, pretreatment procedures, and measurement equipment complied with the Regulation on Radiation Environmental Surveys and Radiation Environmental Impact Assessments around Nuclear Facilities (NSSC Notice) [3], and all analyses were performed in accordance with ISO 11929 and IAEA technical guidelines [4,5]. The resulting data were used to scientifically characterize the environmental radiation levels and temporal variation trends in the vicinity of the Hanbit NPP.

### 2.3 Quality Assurance

To ensure the reliability and accuracy of environmental radiation analysis, regular calibrations of key analytical instruments—including the HPGe detector, low-level alpha-beta counter, and liquid scintillation counter (LSC)—were performed using gamma mixed standard sources certified by the Korea Research Institute of Standards and Science (KRISS). For gamma-emitting radionuclide analysis, both energy and efficiency calibrations were conducted within the 50 keV–3 MeV range, and volume corrections were applied according to sample geometry, maintaining measurement errors within ±5%.

In addition, to verify analytical proficiency and maintain quality control, the laboratory participated annually in proficiency testing programs organized by the Korea Institute of Nuclear Safety (KINS). During the entire study period (2017–2024), all parameters consistently achieved an "A" grade (Accepted), indicating that the relative deviation of measured values was within ±20% of the reference values. These results demonstrate that the data generated in this study meet both domestic and international standards of reliability. This calibration and proficiency management system will be maintained and further strengthened in the future.

## 3. Results and Discussion

From 2017 to 2024, environmental radiation analyses conducted within the Emergency Planning Zone (EPZ) of the Hanbit Nuclear Power Plant and adjacent areas indicated that overall environmental radiation levels remained stable, with observed fluctuations falling within the normal variation range.

Gamma spectrometric analysis of rainwater samples revealed that, throughout the entire monitoring period (2017–2024), artificial radionuclides such as $^{60}Co$, $^{134}Cs$, $^{137}Cs$, and $^{131}I$ were not detected at any sampling site. The naturally occurring radionuclide $^{7}Be$ was intermittently detected during precipitation events; however, it was assessed to be within the normal range for atmospheric origin. Gross beta activity in rainwater ranged from 22.5 to 261 mBq/L on an annual average basis, which falls within the variation range of gross beta activity in domestic precipitation (60.2–654 mBq/L). Here, the "normal range" was defined as the 10-year mean ± standard deviation based on nationwide environmental radiation survey data collected by the Korea Institute of Nuclear Safety (KINS) from 2013 to 2022. This trend is also evident in Figure 1, which shows that the average gross beta activity across sampling sites remained relatively consistent over time.

We detected tritium ($^{3}H$) only rarely during the monitoring period, and even in those cases, the annual mean concentrations remained low, at ≤ 1.86 Bq/L. These levels are considered to reflect natural background conditions attributable to residual effects from past atmospheric nuclear weapons testing [6].

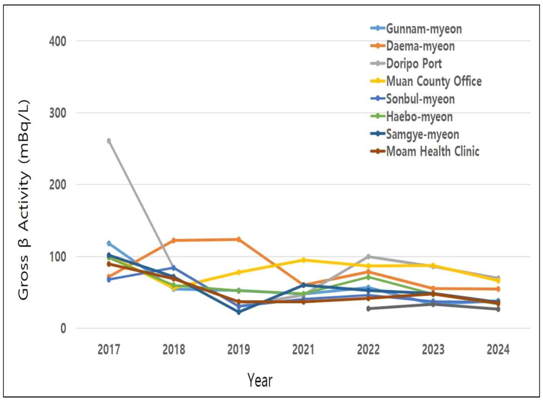


Figure 1. Annual Gross Beta Concentration in Rainwater (2017 - 2024)

In surface soil samples, $^{137}Cs$ was identified as the primary artificial gamma-emitting radionuclide and was detected at all sampling sites. At the beginning of the survey in 2017, the annual mean concentrations of $^{137}Cs$ in Yeonggwang, Muan, Hampyeong, and Jangseong ranged from 0.134 to 4.89 Bq/kg-dry. These levels are considered to have originated from long-range atmospheric deposition associated with past atmospheric nuclear weapons tests and the Chernobyl accident.

Subsequent annual trends showed that, from the 2020s onward, $^{137}Cs$ concentrations generally declined, with the mean concentration at major sites falling to 0.405 Bq/kg-dry by 2024. The temporal variation patterns of $^{137}Cs$ concentrations are presented in Figure 2, which indicates that average concentrations at most sites decreased markedly compared to 2017. This trend is interpreted as the result of the natural radioactive decay of legacy atmospheric fallout radionuclides, along with migration and dilution processes in soil. Similar patterns have been reported in monitoring studies conducted around other nuclear power plant sites in Korea [7].

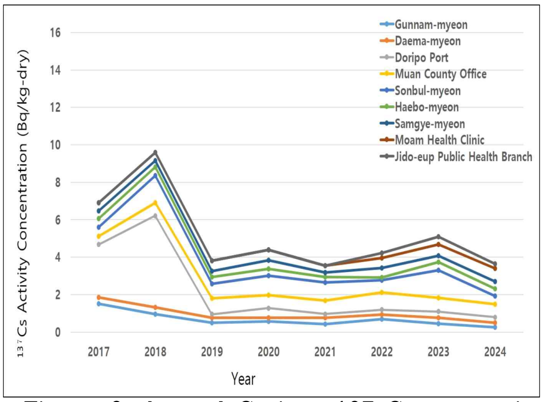


Figure 2. Annual Cesium-137 Concentration in Surface Soil (2017-2024)

Analysis of seawater samples showed that, due to the nature of the marine environment, the naturally occurring radionuclide $^{40}K$ was consistently detected at all sampling sites. The artificial radionuclide $^{137}Cs$ was detected at trace levels at all seawater sites, with annual mean concentrations ranging from 0.00076 to 0.00242 Bq/L. Although minor interannual fluctuations were observed, the overall annual mean concentration remained around 0.00136 Bq/L, which is comparable to or below the global marine background level. The temporal variations in $^{137}Cs$ concentrations are illustrated in Figure 3, confirming that levels in seawater remained within a stable range throughout the monitoring period.

Gross beta activity in seawater ranged from 6.85 to 14.3 Bq/L during the survey period, showing a stable trend without significant changes. Tritium ($^{3}H$) was mostly undetected; when present, the maximum annual mean concentration was only 5.35 Bq/L, and no statistically significant upward trend was observed over time.

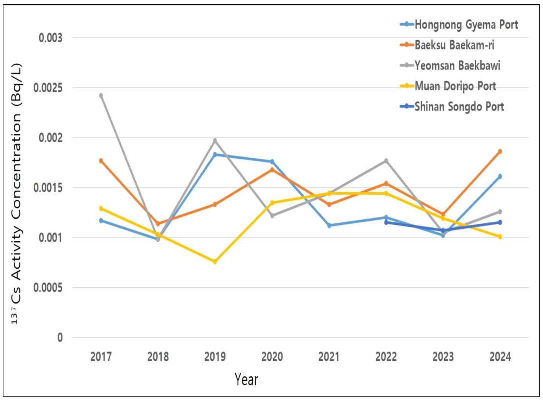


Figure 3. Annual Cesium-137 Concentration in Seawater (2017-2024)

Analysis of food samples collected between 2017 and 2024 showed that all artificial radionuclides in the tested agricultural and marine products were below the minimum detectable activity (MDA) of the analytical instruments and thus not detected. In particular, targeted analyses were conducted on staple food items produced in Yeonggwang, Muan, Hampyeong, Jangseong, and Shinan—such as rice, apples, onions, octopus, and mullet—yet no instances were found that exceeded the radioactivity limits stipulated in the Korean Food Code. These findings demonstrate that local food products consistently remained free from radioactive contamination throughout the survey period.

Overall, the results of the long-term environmental radiation monitoring from 2017 to 2024 indicate that radiation levels in the vicinity of the Hanbit Nuclear Power Plant remained stable, with no clear evidence of contamination from artificial radionuclides. Concentrations of major radionuclides fluctuated within the normal variation range, and $^{137}$Cs exhibited a gradual long-term decline. In addition, $^{3}$H concentrations in both rainwater and seawater were mostly within natural background levels, and gross beta activity remained stable across the years without any significant upward trend.

These results provide scientific confirmation that the region has maintained a safe environment with respect to radiological impact. Continued systematic environmental radiation monitoring and quality assurance practices are expected to further support public confidence and ensure safety in the future. Furthermore, the present findings are consistent with the results of environmental radiation impact assessments conducted by the plant operator. The annual mean concentrations of all radionuclides analyzed in each environmental medium are summarized in Table 2, and all values were confirmed to be well below both domestic and international safety standards.

Table 2. Annual Mean Radionuclide Concentrations in Environmental Media (2017-2024)

| Environmental Medium | Detected Radionuclides | Annual Average Concentration | Typical Range |
|---|---|---|---|
| Rainwater | Gross Beta | 64.6 mBq/L | 22.5-261 mBq/L |
| | Tritium ($^{3}$H) | 1.26 Bq/L | 0.822-1.86 Bq/L |
| Surface Soil | $^{137}$Cs | 0.405 Bq/kg-dry | 0.136-4.89 Bq/kg-dry |
| Seawater | Gross Beta | 10.2 Bq/L | 6.85-14.3 Bq/L |
| | Tritium ($^{3}$H) | 2.13 Bq/L | 1.02-5.35 Bq/L |
| | $^{137}$Cs | 0.00136 Bq/L | 0.00076-0.00242 Bq/L |
| Food | $^{131}$I, $^{134}$Cs+$^{137}$Cs | Not detected | Not detected |

In this study, the annual effective doses to the general public were quantitatively estimated for major artificial radionuclides detected in environmental media within and adjacent to the Emergency Planning Zone (EPZ) of the Hanbit Nuclear Power Plant. For the key radionuclides $^{3}$H and $^{137}$Cs, ingestion and external exposure scenarios were established based on rainwater, seawater, and surface soil pathways, and internationally recognized dose coefficients (ICRP Publication 119 and IAEA TECDOC standards) were applied [8].

Assumptions regarding intake rates and exposure durations were based on data from the Korea National Health and Nutrition Examination Survey (Korea Disease Control and Prevention Agency, 2023) and the Korea Institute of Environmental Radiological Safety's Environmental Living Condition Survey Report (2022). For example, daily drinking water intake for adults was set at 2 L/day, annual seafood consumption at 20 kg/year, and annual outdoor exposure to soil at 1,000 hours/year.

The evaluation was conducted for a representative adult and applied conservative assumptions to reflect potential exposure under typical living conditions. Effective doses were calculated separately for each pathway, and the estimated values were found to be significantly lower than the public dose limit of 1 mSv/year recommended by international radiological protection standards.

Table 3. Annual Effective Dose by Exposure Pathway

| Environmental Medium | Radionuclide | Exposure Pathway | Average Concentration | Assessment Condition | Dose Coefficient (Sv/Bq) | Annual Effective Dose (µSv/year) |
|---|---|---|---|---|---|---|
| Rainwater | $^{3}$H | Ingestion | 1.26 Bq/L | 730 L/year (2 L/day) | $1.8 \times 10^{-11}$ | 16.6 |
| Surface Soil | $^{137}$Cs | External Exposure | 0.405 Bq/kg | 1,000 h/year | $6.7 \times 10^{-7}$ | 0.27 |
| Seawater | $^{137}$Cs | Ingestion (seafood) | 0.1 Bq/kg | 20 kg/year (fish consumption) | $1.3 \times 10^{-8}$ | 0.026 |

※ A biological concentration factor of 100 was applied to estimate radionuclide concentrations in seafood.

※ Dose coefficients were applied in accordance with ICRP Publication 119 and IAEA standards

In summary, the total annual effective dose summed across all exposure pathways was approximately 16.9 μSv/year, corresponding to less than 1.7% of the public dose limit of 1 mSv/year (1,000 μSv/year). Dose estimates for each pathway—ingestion, external exposure, and dietary intake—were aggregated under the assumption that these exposure routes are independent. In cases where potential overlap within the same pathway could occur, a conservative adjustment was applied to account for possible cumulative effects. This approach is consistent with the multi-pathway dose assessment principles outlined in ICRP Publication 101, and the actual dose to the public is likely to be lower than the calculated value.

## 4. Conclusion

This study presents the results of an eight-year (2017-2024) comprehensive evaluation of variations in the concentrations of major radionuclides in rainwater, surface soil, seawater, and food samples collected within and adjacent to the Emergency Planning Zone (EPZ) of the Hanbit Nuclear Power Plant. The findings indicate that, throughout the entire monitoring period, detections of artificial radionuclides were extremely limited, and concentrations in all environmental media remained within both domestic and international safety standards as well as within the natural variation range.

In particular, tritium ($^{3}H$) concentrations in rainwater and seawater were either undetected or very low (rainwater: 0.822-1.86 Bq/L; seawater: 1.02-5.35 Bq/L), corresponding to natural background levels with no evidence of anthropogenic contributions. Gross beta activity in both media remained stable, with year-to-year variations but no significant upward trends or abnormal indications. In surface soil, $^{137}Cs$—capable of long-term accumulation—was detected at some sites at concentrations ranging from 0.136 to 4.89 Bq/kg-dry, which were comparable to or lower than national averages, and showed a gradual decline over time. In seawater, $^{137}Cs$ was detected only at trace levels (0.00076-0.00242 Bq/L), confirming that the radiological status of the local marine environment has been maintained in a stable condition.

Food sample analyses revealed no detections of artificial radionuclides in agricultural or marine products throughout the study period, and no cases exceeding the radioactivity limits set in the Korean Food Code. This provides strong evidence that the risk of internal exposure to local residents through food consumption is extremely low.

Overall, from 2017 to 2024, environmental radiation levels in the vicinity of the Hanbit NPP remained stable and safe, with variations in artificial radionuclide concentrations occurring within the normal range attributable to natural factors. No scientifically measurable radiological impacts from plant operation were identified. This study demonstrates, through long-term and multi-media integrated monitoring, the radiological safety of the EPZ area, and establishes a framework that can serve as a fundamental reference for future radiation environmental management.

This study is the first in Korea to comprehensively demonstrate the radiological safety of the entire Emergency Planning Zone (EPZ) surrounding the Hanbit Nuclear Power Plant through long-term (eight-year), multi-media integrated monitoring combined with public dose assessment. This monitoring framework can serve as a fundamental reference for future radiation environmental management. Moving forward, it will be necessary to optimize monitoring frequency (e.g., increasing measurements during periods of high variability), incorporate additional environmental media (e.g., airborne particulate matter, river water, benthic organisms), and conduct expanded monitoring that integrates seasonal and meteorological analyses. Such measures will enable the early detection of long-term environmental changes and the establishment of a predictive, science-based radiation environmental management system. This approach will contribute not only to maintaining public trust but also to enhancing international standards in radiological safety management.

## Acknowledgements

This study was conducted as part of the Nuclear Safety Research Project supported by Jeollanam-do Province and Yeonggwang County.

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