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# Analisis Konsentrasi Isotop Radioaktif di Berbagai Lokasi Pasca Bencana Nuklir: Studi Kasus I-131, Cs-134, dan Cs-137 di Republik Ceko

*Analysis of Radioactive Isotope Concentrations at Various Locations after a Nuclear Disaster: Case Study of I-131, Cs-134, and Cs-137 in the Czech Republic*

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**ABSTRAK**

Penyebaran radioaktif tetap menjadi perhatian utama setelah bencana nuklir. Penelitian ini menyelidiki konsistensi konsentrasi isotop radioaktif (I-131, Cs-134, dan Cs-137) di dua kota di Republik Ceko - Praha dan Usti - untuk menentukan apakah durasi pengambilan sampel dan variabilitas konsentrasi isotop mempengaruhi stabilitas kontaminasi. Penelitian ini menggunakan analisis statistik, termasuk ANOVA, uji Kruskal-Wallis, dan uji korelasi Pearson dan Spearman, untuk memeriksa hubungan isotop dan variasi spasial. Data dikumpulkan selama beberapa titik waktu untuk menilai perubahan pola kontaminasi. Temuan menunjukkan bahwa Praha menunjukkan konsentrasi isotop radioaktif yang lebih tinggi, tetapi variasi waktu pengambilan sampel tidak mempengaruhi stabilitas kontaminasi. Tidak ada perbedaan signifikan yang diamati antara kedua lokasi, dan korelasi yang kuat ditemukan di antara I-131, Cs-134, dan Cs-137, yang mengindikasikan bahwa peningkatan satu isotop secara konsisten disertai dengan peningkatan isotop lainnya. Durasi pengambilan sampel tidak memiliki dampak yang signifikan terhadap tingkat kontaminasi. Hasil ini menunjukkan bahwa kontaminasi isotop stabil di seluruh lokasi, terlepas dari durasi pengambilan sampel. Kesenjangan penelitian yang utama adalah terbatasnya penelitian tentang hubungan antara konsistensi konsentrasi isotop dan waktu pengambilan sampel di beberapa lokasi. Kesimpulan Penelitian ini menyoroti bahwa konsentrasi isotop radioaktif tetap relatif konsisten meskipun terdapat variabilitas yang besar dalam nilai yang diukur. Temuan ini menggarisbawahi perlunya strategi manajemen kontaminasi yang berfokus pada sumber-sumber yang signifikan secara global daripada variabilitas lokal. Korelasi yang kuat di antara isotop menawarkan nilai prediksi yang potensial untuk memantau kontaminasi radioaktif dalam situasi bencana.

**Kata Kunci**: Konsentrasi Isotop Radioaktif, Bencana Chernobyl, Pemantauan Lingkungan, Korelasi Isotop, Manajemen Kontaminasi Nuklir

**ABSTRACT**
*Radioactive dispersal remains a major concern after a nuclear disaster. This study investigated the consistency of radioactive isotope concentrations (I-131, Cs-134, and Cs-137) in two cities in the Czech Republic - Prague and Usti - to determine whether sampling duration and isotope concentration variability affect contamination stability. The study used statistical analyses, including ANOVA, Kruskal-Wallis test, and Pearson and Spearman correlation tests, to examine isotope relationships and spatial variation. Data were collected over multiple time points to assess changes in contamination patterns. Findings showed that Prague exhibited higher concentrations of radioactive isotopes, but variations in sampling time did not affect contamination stability. No significant differences were observed between the two locations, and a strong correlation was found among I-131, Cs-134, and Cs-137, indicating that an increase in one isotope was consistently accompanied by an increase in the other. The sampling duration had no significant impact on the contamination levels. These results suggest that isotope contamination is stable across sites, regardless of sampling duration. A major research gap is the limited research on the relationship between consistency of isotope concentrations and sampling time across multiple sites. The study highlighted that radioactive isotope concentrations remained relatively consistent despite the large variability in measured values. Findings underscore the need for contamination management strategies that focus on globally significant sources rather than local variability. Strong correlations among isotopes offer potential predictive value for monitoring radioactive contamination in disaster situations.*

***Keywords:*** *Radioactive Isotope Concentration, Chernobyl Disaster, Environmental Monitoring, Isotope Correlation, Nuclear Contamination Management*

## 1. INTRODUCTION

Nuclear energy has become one of the main sources of energy in the modern world, providing a solution to the ever-increasing need for energy (Kalmykov, 2022). However, the use of nuclear energy is not free from significant risks, especially in terms of safety (Muellner dkk., 2021). One of the most memorable events in the history of the use of nuclear energy is the Chernobyl disaster that occurred on April 26, 1986 (Insch & Loughran, 2022).

Nuclear disasters are tragic events in the history of nuclear energy, and leave long-term environmental impacts in many parts of the world (Friederich & Boudry, 2022). Understanding the long-term impacts of disasters is a key foundation for many studies that focus on the distribution and concentration of the resulting radioactive substances. Among the various radionuclides released, Iodine-131 (I-131), Caesium-134 (Cs-134), and Caesium-137 (Cs-137) are the most studied subjects due to their radioactive properties and impacts on human health and the environment (Nagataki & Takamura, 2014).

Although more than three decades have passed since the Chernobyl disaster, its impact on the environment is still being felt today (Jargin, 2025). One of the main issues of concern is the spread of radioactive substances produced by the nuclear reactor explosion (Malizia dkk., 2021). Iodine-131, Caesium-134, and Caesium-137, the main products of the disaster, were widely dispersed through the atmosphere and contaminated large areas, not only around the disaster site, but also in many other countries.

Concentration data of radioactive substances at various sites show significant variability in concentration and geographical distribution. However, many uncertainties remain regarding the distribution patterns and factors that influence the concentrations of these substances in the environment (Alrammah dkk., 2022). Further research is needed to better understand how these radioactive substances spread, how long they stay in the environment, and what the long-term impacts are.

The Chernobyl disaster occurred at reactor No. 4 of the Chernobyl Nuclear Power Plant, near the town of Pripyat, then part of the Ukrainian Soviet Socialist Republic (Naoum & Spyropoulos, 2021). The explosion occurred during a reactor safety test causing the release of large amounts of radioactive particles into the atmosphere, which then spread across Europe.

This disaster was one of two nuclear disasters categorized at level 7 on the International Nuclear Event Scale, which is the highest severity level (Caldera & Wirasinghe, 2022; Ohba dkk., 2021). Another disaster was the Fukushima Daiichi disaster that occurred in 2011 in Japan (Tsuboi dkk., 2022). History records that the immediate impacts of the Chernobyl disaster included mass evacuations, a sharp increase in thyroid cancer cases in the affected region, and extensive environmental contamination (Ory dkk., 2021). Research conducted after the disaster showed that radioactive particles released by Chernobyl remained in the environment for years, and in some cases, to this day (Mousseau, 2021).

The research hypotheses focus on analyzing the distribution and variation of radionuclide concentrations in different cities of the Czech Republic. First, the study will test whether there is a significant distribution pattern in the geographical spread of the data. Through analysis of variance (ANOVA) and Kruskal-Wallis test, the research will determine if there are significant differences in the concentrations of I-131, Cs-134, and Cs-137 among the cities analyzed. The study also evaluates the effect of sampling duration on variations in radionuclide concentrations. Finally, the relationship between the concentrations of I-131, Cs-134, and Cs-137 will be analyzed using the Pearson and Spearman correlation methods to identify the interrelationships between radionuclides in the collected samples.

The study aims to analyze the concentration distribution of radioactive isotopes such as Iodine-131 (I-131), Caesium-134 (Cs-134), and Caesium-137 (Cs-137) at various locations after the Chernobyl disaster. The research was conducted with the aim of understanding how the isotopes are distributed and what factors influence the variability of their concentrations. The research identifies the relationship between the concentrations of I-131, Cs-134, and Cs-137, thus gaining a deeper understanding of the interrelationships between isotopes resulting from nuclear reactions.

The research will examine the effect of sampling duration on the detected isotope concentrations, to evaluate the reliability of the measurement method used. The research is expected to provide several significant benefits. One benefit is an improved scientific understanding of the distribution and dynamics of radioactive isotope concentrations in the atmosphere after a nuclear disaster, which can serve as a basis for further research in this area.

The research is expected to contribute valuable information for policy makers and authorities in developing mitigation and risk management strategies due to radioactive contamination, especially in nuclear disaster management. The research is expected to provide recommendations for improving the methodology of measuring radioactive isotope concentrations, so as to increase the accuracy and reliability of data in the future. The research provides a real practical impact in managing the risk of nuclear disasters in the future.

This study has several limitations that need to be considered. First, in terms of geographical coverage, the dataset used only includes radioactive isotope concentrations from certain identified locations. The study only focused on three isotope types, namely I-131, Cs-134, and Cs-137. Although these isotopes are the most significant in terms of health and environmental impacts, the study did not consider other isotopes that were also released during the Chernobyl disaster.

The duration of the observations was a limiting factor. The data analyzed were from a specific time period after the disaster, so the study did not cover long-term observations or variations in isotope concentrations that may occur at a later date. The quality of the data used in the study is affected by inaccuracies or inconsistencies caused by measurement methods, weather conditions, or other factors that cannot be controlled.

The research recognizes the limitations in terms of data quality, which may affect the results of the analysis. The study did not include an in-depth temporal analysis, so changes in isotope concentrations over time were not explored. In the past few decades, studies have been conducted on the concentration of radioactive isotopes at various sites following nuclear disasters, particularly in relation to the accident at the Fukushima-Daiichi Nuclear Power Plant (NPP) in 2011.

Previous studies have explored various aspects of radionuclide dispersion, monitoring methods, and impacts on the environment and human health. Research by (Ohnishi, 2012) used a combination of SPEEDI and direct monitoring methods to evaluate evacuation areas based on radioisotope distribution after the Chernobyl and Fukushima accidents. Another study by (Thakur dkk., 2012) highlighting the radioactive fallout in the United States due to the Fukushima accident, showing that the isotopes released have far-reaching effects across the globe.

Research conducted by (Bu dkk., 2018) underscores the role of mass spectrometry in assessing radioactive contamination around nuclear accident sites, while (Fujiwara dkk., 2012) exploring the vertical distribution of radionuclides in soil in affected areas. However, although various studies have focused on the distribution of radioisotopes in different locations after a nuclear disaster, there is still a gap in understanding the consistency of radioactive isotope concentrations in different locations after a disaster.

Most of the existing studies have only focused on initial estimates of the distribution or impact on the environment, but have not comprehensively examined whether radionuclide distribution patterns are consistent or undergo significant changes over time. This research aims to fill this gap by conducting a consistency analysis of the concentration of radioactive isotopes I-131, Cs-134, and Cs-137 in various locations after a nuclear disaster.

The novelty in the study lies in analyzing the consistency of radioactive isotope concentrations (I-131, Cs-134, and Cs-137) at various locations after a nuclear disaster, which has not been widely explored in previous studies. While previous studies have focused more on the initial estimation of dispersion or environmental impact of radionuclide releases, the research provides a more systematic approach in evaluating radioisotope distribution patterns over time.

Using analytical methods based on data from various affected sites, the research will identify changes in radionuclide concentrations, and assess whether there are stable or fluctuating distribution patterns after a nuclear event. The research will provide a deeper understanding of the dynamics of radioisotope movement, which can be used as a basis for radiation risk mitigation strategies as well as environmental and public health policy planning post-nuclear disaster.

## 2. RESEARCH METHODS

### 2.1 Geographic Data Preparation and Analysis

The study began with the preparation of the working environment which included the installation of the software packages required in the analysis, namely `ggplot2`, `dplyr`, `readxl`, and `scales` (Nogueira, 2024). The first step is to verify whether the packages are already installed on the system. If the required package is not available, then the package and its dependencies are installed. After ensuring that all packages are installed, the next step is to load the packages into the working environment using the `library()` function (Giorgi dkk., 2022).

The data used in the analysis came from Excel files, which were read using the `read_excel()` function from the `readxl` package (Monkman, 2024). Next, the data cleaning and transformation process is carried out. The `X` and `Y` columns are converted to numeric type if they are not already numeric (De Jonge & Van Der Loo, 2013). Two new columns are created, `Ville_short`, which contains the first three letters of the city name (`Ville`), and `PAYS_short`, which contains the first three letters of the country name (`PAYS`).

### 2.2 Implementation and Optimization of Location Data Visualization

The algorithm for data visualization using R starts with setting up a suitable working environment. The first step is to ensure that the packages required for analysis and visualization are available. These packages include `leaflet`, `dplyr`, `readxl`, `leaflet.extras`, and `RColorBrewer`. If any packages are not installed, the system will automatically install them and their dependencies. Once all packages are installed, the next step is to load them into the R session using the `library()` function.

Once the package is loaded, data is imported from an Excel file located at a predefined path. This data is read using the `read_excel()` function of the `readxl` package and stored in the `CHERNAIR` variable. Next, the loaded data needs to be processed. This processing includes verifying that the latitude and longitude columns, identified by the names `X` and `Y`, have a numeric format. In addition, two new columns were added to the dataset. The `Ville_short` column contains the first three letters of the `Ville` column, while the `PAYS_short` column contains the first three letters of the `PAYS` column. The data is then filtered to only include entries where the value in the `PAYS_short` column is "CZ". The filtered data is stored in a new variable called `CHERNAIR_CZ`.

For visualization, a color palette was prepared using functions from the `RColorBrewer` package. This palette is based on the unique categories contained in the `Ville_short` column and was used to color the markers on the map. An interactive visualization was created using the `leaflet()` function. The map was supplemented with various elements: the tile provider used was `CartoDB.Positron` as the map background. Circular markers were added to locations within `CHERNAIR_CZ`, colored based on the value of `Ville_short`, borderless, with fill transparency, and of a certain size. Labels and popups are added to display detailed information of each location.

A legend is added at the bottom right corner of the map to explain the meaning of the marker colors based on the initials `Ville`. Layer controls are also provided to manage the overlays displayed on the map. A scale and mini-map are added to aid orientation, and a map reset button is provided to restore the map view to its original state.

### 2.3 Radiasi Statistical Analysis and Hypothesis Test on Radiation Data

#### 2.3.1 *ANOVA*

Data that is divided into (k) groups, with each group (i) having ( $n_i$ ) observations. The data of group (i) is expressed as ( $y_{ij}$ ), where (j) is the index of observations in group (i). The ANOVA model is written as:

$$y_{ij} = \mu + \tau_i + \epsilon_{ij} \quad (1)$$

where $(\mu)$ is the grand mean, $(\tau_i)$ is the effect of group (i) (factor effect), $(\epsilon_{ij})$ is the random error, which is assumed to be normally distributed with zero mean and variance $(\sigma^2)$. Null Hypothesis ($H_0$) is All groups have the same mean, $(\tau_1 = \tau_2 = \cdots = \tau_k = 0)$. There is no significant difference between groups. Alternative Hypothesis ($H_1$) There is at least one group whose average is different. Between-Groups Variance is the variance caused by the difference between group means. Within-Groups Variance is the variance caused by variation within each group. The total variance formula is:

$$\text{SST} = \sum_{i=1}^{k}\sum_{j=1}^{n_i}(y_{ij} - \bar{y}_{..})^2 \quad (2)$$

where $(\bar{y}_{..})$ is the grand mean. Intergroup Variance :

$$\text{SSB} = \sum_{i=1}^{k} n_i(\bar{y}_{i.} - \bar{y}_{..})^2 \quad (3)$$

where $(\bar{y}_{i.})$ is the group mean (i), and ( $n_i$ ) is the number of observations in group (i). Within-Group Variance:

$$\text{SSW} = \sum_{i=1}^{k}\sum_{j=1}^{n_i}(y_{ij} - \bar{y}_{i.})^2 \quad (4)$$

Intergroup Degree of Freedom is (k - 1). Within-Group Degree of Freedom is (N - k), where (N) is the total number of observations. Total Degree of Freedom is (N - 1) (Kennedy & Wang, 2025). The ANOVA test statistic is the ratio of the between-group variance to the within-group variance (Rizk, 2023). This test statistic follows the F distribution with degrees of freedom and the formula is (Shi dkk., 2022):

$$F = \frac{\text{MSB}}{\text{MSW}} \quad (5)$$

where $(\text{MSB} = \text{SSB/dfB})$ is Mean Square Between, and $(\text{MSW} = \text{SSW/dfW})$ is Mean Square Within. Comparing the calculated F value with the critical value of the F distribution at the desired significance level $(\alpha)$ (Khatun, 2021). If the calculated F value is greater than the critical F value, then we reject the null hypothesis and conclude that there is a significant difference between the group means (Berner & Amrhein, 2022). If the test results show that there is a significant difference, the next step is to perform a post-hoc test (such as Tukey's test) to determine which groups are different from each other (Agbangba dkk., 2024).

### 2.3.2 *Kruskal-Wallis Test*

The Kruskal-Wallis test is a non-parametric statistical test used to determine whether there is a significant difference between the medians of three or more groups (Okoye & Hosseini, 2024). It is an alternative to one-way ANOVA when the assumptions of normality and homogeneity of variance cannot be met. Suppose that there are (k) groups and each group has ( $n_i$ ) observation, where $(i = 1, 2, \ldots, k)$. The purpose of the Kruskal-Wallis test is to determine if there is a significant difference in the distribution of medians between the groups (Lee, 2022). Combine all data from all groups. Sort the data as a whole from smallest to largest. On the sorted data. If there is data with the same values, give the average rank for the same values. Suppose the merged data is $(x_1, x_2, \ldots, x_N)$, where:

$$N = \sum_{i=1}^{k} n_i \quad (6)$$

The rankings are $(R_1, R_2, \ldots, R_N)$, ( $R_j$ ) is the rank for the j-th data. For each group (i), calculate the average rank as:

$$\bar{R}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} R_{ij} \quad (7)$$

where ( $R_{ij}$ ) is the rank of the jth data in group (i). Calculate the Kruskal-Wallis statistic (H) using the formula:

$$H = \frac{12}{N(N+1)}\sum_{i=1}^{k}\frac{T_i^2}{n_i} - 3(N+1) \quad (8)$$

where $(T_i)$ is the number of ranks for group (i). (N) is the total number of observations. To calculate $(T_i)$, use:

$$T_i = \sum_{j=1}^{n_i} R_{ij} \quad (9)$$

The test statistic (H) follows the chi-square distribution with (k-1) degrees of freedom (Lugo-Armenta dkk., 2021). Compare the calculated (H) value with the critical value of the chi-square distribution for (k-1) degrees of freedom and the desired significance level (e.g., 0.05).

If the calculated (H) value is greater than the chi-square critical value, then we reject the null hypothesis, which states that all group medians are equal. Conversely, if (H) is not greater than the critical value, then there is insufficient evidence to conclude that there is a significant difference between the group medians.

After performing ANOVA and Kruskal-Wallis tests for each isotope, it is important to compare the results of both tests. ANOVA is used because it assumes the data is normally distributed and has homogeneity of variance, meaning the variability of the data is similar across all groups. If these assumptions are met, ANOVA can give accurate results about the mean differences between groups. On the other hand, the Kruskal-Wallis test does not require the assumptions of normality or homogeneity of variance, so it can be used as an alternative when the data does not meet these conditions. This test is more robust to assumption violations, and as such, is particularly useful in cases where data may not be normally distributed.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Results

#### 3.1.1 *Data Distribution with Graphic Visualization and Mapping*

It can be seen in Figure 1, which displays two different visualizations. Figure 1 is a clear graphical representation of the location of points based on longitude (X) and latitude (Y). The dots in the figure are given different colors according to the city abbreviation category and different shapes based on the country abbreviation. The color palette of each city is represented by a unique color, and the shape of the dot is the respective country to identify the distribution pattern of the data across different cities and countries, as well as see if there are any other significant clusters or patterns in the data.

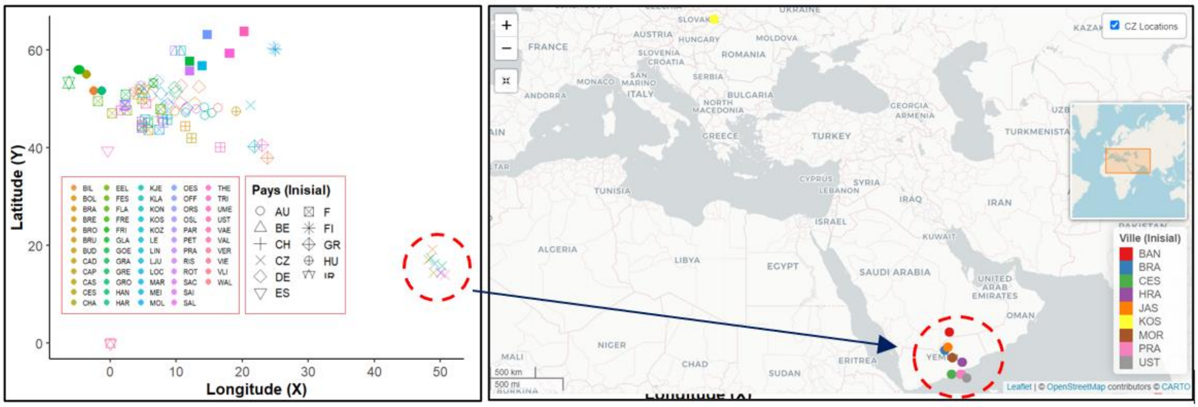


**Figure 1**. Data Collection in Two Main Locations in The Czech Republic

**Table 1**. Summary of ANOVA Test Results on Radioactive Isotope Concentrations

| Issue | Concentration | F value | P-value |
|---|---|---|---|
| **I-131** | $Bq/m^3$ | 0,108 | 0,955 |
| **Cs-134** | $Bq/m^3$ | 0,081 | 0,97 |
| **Cs-137** | $Bq/m^3$ | 0,304 | 0,822 |

Analysis of radioactive I-131, Cs-134 and Cs-137 concentrations across the different cities in the dataset showed statistically insignificant variations as seen in table 2. The Kruskal-Wallis test conducted for I-131 concentrations yielded a chi-square value of 1.9465 with 3 degrees of freedom and a p-value of 0.5836, which exceeds the significance threshold of 0.05. These results indicate that the differences in I-131 concentrations between cities are not statistically significant, indicating a relatively uniform distribution across the sites analyzed. Similarly, the Kruskal-Wallis test results for Cs-134 concentrations showed a chi-square value of 1.8303 with 3 degrees of freedom and a p-value of 0.6084, confirming no significant difference in Cs-134 distribution among the cities. Comparable results were also obtained in the analysis of Cs-137 concentrations, with a chi-square value of 3.4558 and a p-value of 0.3265, further reinforcing the conclusion that Cs-137 levels do not vary significantly across cities.

In the Kruskal-Wallis test results table for the three radioactive isotopes, the p-value is greater than the typical significance level (0.05), indicating no significant difference in the concentrations of these isotopes among the cities analyzed. Any differences in concentrations were influenced by other factors beyond the differences between cities. It shown in . Table 2.

**Table 2.** Summary of Kruskal-Wallis Test Results on Radioactive Isotope Concentrations

| Isotopes | Chi-Squared | Degrees of Freedom (df) | P-Value |
|---|---|---|---|
| **I-131** | 19.465 | 3 | 0.5836 |
| **Cs-134** | 18.303 | 3 | 0.6084 |
| **Cs-137** | 34.558 | 3 | 0.3265 |

**Figure 2** represents three box plots representing the distribution of radioactive concentrations of I-131, Cs-134, and Cs-137 across cities. Each box plot represents the range of concentration distribution in each city, where the median line indicates the middle value, and the box itself indicates the interquartile range (IQR), which includes values between the first quartile (Q1) and the third quartile (Q3). The overall distribution of radioactive concentrations appears relatively uniform across the city, as indicated by the similar shape and position of the boxes for each isotope. Outliers, represented by red dots, represent extreme concentration values in certain cities. However, the deviations do not substantially affect the overall trend, as the concentration distribution remains consistent. For I-131, the variation in concentration between cities is very small, with a few outliers that are not statistically significant. Similarly, the distributions of Cs-134 and Cs-137 show no notable differences between cities, indicating a relatively homogeneous pattern of radioactive concentrations. The addition of jitter to the boxplot further corroborates the observation, showing that the majority of the concentration data is clustered around the median value, with little variation between cities. The use of consistent colors for each city reinforces the uniformity in the distribution pattern, as the isotope concentrations do not show significant differences among the analyzed location

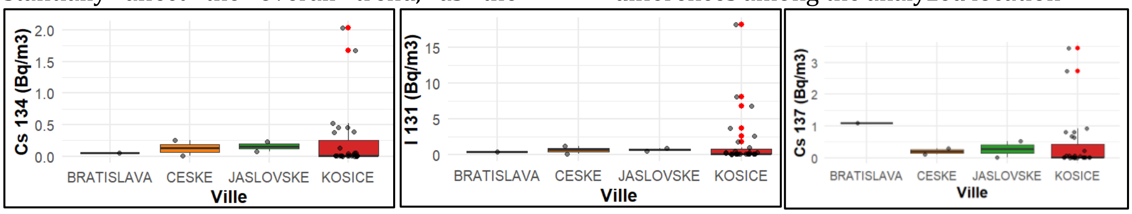


**Figure 2.** Distribution of Radioactive Concentrations of I-131, Cs-134, and Cs-137 in Some of The Cities Analyzed

### 3.1.2 *Analysis of Distribution and Variability of Radioactive I-131, Cs-134, and Cs-137 Concentrations Based on Sampling Duration*

Based on the statistical analysis performed, the data distribution for each isotope shows significant differences. As for the isotope I-131, the minimum value detected was 0 Bq/m$^3$, while the maximum value reached more than 17 million Bq/m$^3$. However, most of the I-131 measurements showed zero values, as seen in the median value which was also zero. At many sites, I-131 concentrations were not detected or were at very low levels. For the isotopes Cs-134 and Cs-137, the distribution of values also shows that many measurements have zero values, with some measurements showing very high concentrations. Maximum values for Cs-134 reached more than 4 million Bq/m$^3$, while Cs-137 reached more than 6 million Bq/m$^3$. However, as with I-131, the median value for both isotopes is zero, indicating very low concentrations at most sites. The Cs-134 and Cs-137 data had a more significant number of not available (NA) values, with 250 NA values for Cs-134 and 545 NA values for Cs-137. The sampling duration varies from about 0.2 hours to more than 711 hours. This duration distribution is an important aspect, as longer sampling durations can result in more accurate concentration measurements.

In **Figure 3**, the relationship between sampling duration (in hours) and contamination levels of three radioactive isotopes, namely I-131, Cs-134, and Cs-137, measured in Bq/m$^3$. Each isotope is represented by a different colored dot, including I-131 in blue, Cs-134 in red, and Cs-137 in green. The horizontal axis shows the sampling duration, while the vertical axis shows the contamination level on a logarithmic scale. The use of a logarithmic scale on the vertical axis aims to capture a wide range of contamination values, given the large variation in measurement results. For each isotope, a linear trend line has been added that reflects the general trend in the data. For the isotope I-131, the blue linear trend line shows a relatively flat pattern, indicating that there is no significant relationship between the sampling duration and the contamination level of the isotope. The same is observed for Cs-134 and Cs-137, where the red and green linear trend lines respectively also tend to be flat, indicating that the sampling duration does not significantly affect the contamination level of these two isotopes. The random distribution pattern of data points along the duration axis further reinforces the observation that there is no clear correlation between sampling duration and contamination levels for all three isotopes. In other words, an increase or decrease in sampling duration does not result in a consistent change in the measured contamination levels.

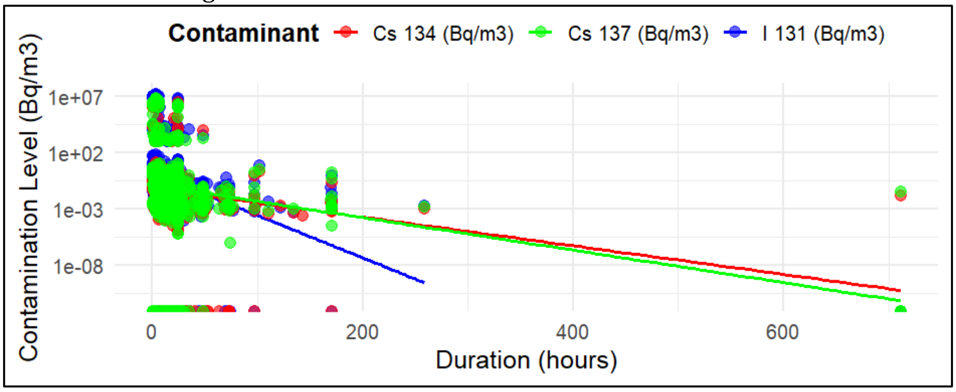


**Figure 3**. Relationship Between Sampling Duration (in Hours) and Contamination Levels of Three Radioactive Isotopes

### 3.1.3 *Pearson and Spearman Correlation Analysis Results between Radioactive Isotope Concentrations*

Based on the research conducted using Pearson correlation analysis, which measures the strength and direction of linear relationships between variables, a very strong correlation between the three isotopes was found. The correlation between I-131 and Cs-134 of 0.797 shows a strong positive relationship. As the concentration of I-131 increases in a region, the concentration of Cs-134 also tends to increase, although this relationship is not entirely linear. The relationship between I-131 and Cs-137 is stronger with a correlation value of 0.839, implying an almost linear positive relationship between the two isotopes. Meanwhile, the correlation between Cs-134 and Cs-137 is the strongest with a value of 0.872, reflecting a very strong linear relationship, where an increase in one isotope is very likely followed by an increase in the other. Based on Spearman's correlation analysis, which not only measures the strength of the relationship but also considers the regularity of the monotonic relationship between the variables, was used to ensure the observed relationship was not only limited to linearity, but also to the rank or order of the data. The results of the Spearman analysis supported the findings from Pearson, namely that the strong relationship between the three isotopes was not only linear but also monotonic. In other words, despite small differences in the pattern of the relationship, the order of the concentration values of one isotope remained consistent against the other isotopes.

This **Table 3** is the results of the correlation between the concentrations of radioactive isotopes I-131, Cs-134, and Cs-137 in Bq/m$^3$ using two methods: Pearson and Spearman. The Pearson correlation shows a strong linear relationship between the three isotopes.

**Table 3**. Correlation Between Radioactive Isotope Concentrations

| Correlation | I 131 (Bq/m$^3$) | Cs 134 (Bq/m$^3$) | Cs 137 (Bq/m$^3$) |
|---|---|---|---|
| | | **Pearson** | |
| **I 131 (Bq/m$^3$)** | 10.000.000 | 0.7972787 | 0.8388374 |
| **Cs 134 (Bq/m$^3$)** | 0.7972787 | 10.000.000 | 0.8723073 |
| **Cs 137 (Bq/m$^3$)** | 0.8388374 | 0.8723073 | 10.000.000 |

| Correlation | I 131 (Bq/m³) | Cs 134 (Bq/m³) | Cs 137 (Bq/m³) |
|---|---|---|---|
| | | **Spearman** | |
| **I 131 (Bq/m³)** | 10.000.000 | 0.4039837 | 0.7397608 |
| **Cs 134 (Bq/m³)** | 0.4039837 | 10.000.000 | 0.5269413 |
| **Cs 137 (Bq/m³)** | 0.7397608 | 0.5269413 | 10.000.000 |

### 3.2 Discussion

For radioactive isotope analysis in the Czech Republic, the research used a map-based visualization approach that displayed the geographical coordinates of each sampling point. The data is categorized by city with different colors used to distinguish locations, while the different shapes of the data points represent the country of origin of the samples. The two main locations of focus were Prague (50.08°N, 14.42°E) and Usti (50.68°N, 14.00°E), which were chosen for their significance in interpreting the distribution of radioactive deposition in the Czech Republic.

Measurements were made in the period from April to May 1986, which was a critical phase in monitoring the distribution of radioactive isotopes after the Chernobyl incident (Izrael, 2007). The mapping approach is in line with atmospheric diffusion theory, which states that the spread of radioactive pollutants in an area is influenced by meteorological factors such as wind direction and speed, rainfall, and other atmospheric conditions (Kozhevnikova & Levenets, 2023).

As with the visualization of data distribution in the form of maps, the distribution pattern can be further analyzed to identify any clustering patterns or homogeneity of distribution in the study area. This is in accordance with previous research by (Konoplev, 2022), which showed that the distribution of radionuclides from Chernobyl depends not only on the geographical distance from the emission source, but also on the weather patterns at the time of the event.

The time variation in sampling during the April-May 1986 period also allowed the study to observe changes in radionuclide concentrations over time. According to the study (Hosseini dkk., 2022; Pathak, 2023), isotopes such as I-131 have a relatively short half-life (about 8 days), so changes in the levels of these isotopes in air samples can interpret rapid deposition dynamics.

Therefore, by considering the temporal aspect in the distribution analysis, the study was able to evaluate how the time factor contributes to the variation of radionuclide concentrations in two major cities in the Czech Republic. The visualization results conducted in the study strengthen the hypothesis that the distribution of radioactivity in a region is not only determined by geographical proximity to emission sources, but also by atmospheric and temporal conditions that affect the movement and deposition of isotopes (Ulimoen & Klein, 2023).

Based on the research conducted, ANOVA and Kruskal-Wallis analysis of the concentrations of radioactive isotopes I-131, Cs-134, and Cs-137 showed that there is no significant difference in the distribution of isotopes in different cities in the Czech Republic. With p values well above the significance threshold ($\alpha = 0.05$) of 0.955 for I-131, 0.97 for Cs-134, and 0.822 for Cs-137, these results indicate that the variation in concentrations between cities is not large enough to be considered statistically significant.

The same was confirmed by the Kruskal-Wallis test, where all isotopes had p-values above 0.05, indicating that the distribution of radioactive isotopes did not differ significantly between the cities analyzed. This finding supports the initial hypothesis that the distribution of radioactive isotopes in the region is not directly influenced by differences in geographical location (Kinoshita dkk., 2011).

Based on the theory of atmospheric dispersion and radionuclide deposition after a nuclear accident, the distribution of radioactive particles in the atmosphere is influenced by meteorological factors such as wind direction and speed, rainfall, and atmospheric conditions at the time of release of radioactive substances (Bilgiç, 2022; Mavall, 2003). In this case, the uniformity of isotope concentrations in different cities in the Czech Republic can be explained by the relatively even atmospheric dispersion pattern in the region following the Chernobyl accident in 1986.

The findings are in line with previous studies showing that after a radioactive release into the atmosphere, isotopes can be dispersed in a broad pattern and do not always show significant differences between neighboring locations (Stohl dkk., 2012). Studies on the post-Chernobyl distribution of Cs-137 in various European countries have also shown that its distribution pattern is influenced more by atmospheric dynamics than by the local characteristics of each city (Piguet dkk., 2019).

In this case, it is likely that differences in concentrations between cities are influenced more by temporal variations in radionuclide deposition than by geographic differences between sampling sites. The distribution and variability of radioactive isotope concentrations in an area is a crucial aspect in understanding post-nuclear event environmental contamination patterns.

Based on the analysis of the isotopes I-131, Cs-134, and Cs-137, it was found that although the concentration range shows a very large variation, the distribution of the data tends to be uneven. The isotope I-131 has a very wide concentration range, ranging from 0 to more than 17 million $Bq/m^3$. However, most of the measurements show zero values, indicating that in many locations, this isotope is either not detected or is at very low levels.

Similarly, the Cs-134 and Cs-137 isotopes have maximum concentrations exceeding 4 million $Bq/m^3$ and 6 million $Bq/m^3$, respectively, but the median value remains zero. This phenomenon means that despite the presence of points with high concentrations, the majority of the analyzed area has very low or even undetectable levels of contamination. One of the factors tested in the study was the sampling duration, which ranged from 0.2 to more than 711 hours.

In theory, the longer the sampling duration, the greater the chance of detecting the presence of radioactive isotopes, as radioactive particles dispersed in the air can accumulate in the measurement device over time (Denham, 2019). However, the analysis showed no significant relationship between sampling duration and contamination level for the three isotopes analyzed.

The trend of the data obtained shows a random distribution pattern, with no tendency for concentrations to increase or decrease with the duration of sampling. This can be explained by considering other factors that have more influence on the distribution of radioactivity, such as atmospheric conditions, particle dispersal patterns, and environmental dynamics that were not controlled in this study.

This result is in line with several previous studies that have also found no significant relationship between sampling duration and contamination levels in wide-scale radioactive dispersal scenarios. Study by (Neroda dkk., 2014) showed that in the case of the Fukushima nuclear accident, the distribution of radioactive isotopes was more influenced by meteorological conditions than the sampling duration itself.

Similarly, research by (Persson dkk., 1987) found that the dispersion of radioactive isotopes after the Chernobyl accident was influenced more by geographical factors and weather patterns than by technical factors such as sampling duration. This finding also supports the initial hypothesis in the study, which states that the distribution of radioactive isotopes is more influenced by external factors than technical sampling parameters (Pommé, 2022).

In other words, while the sampling duration could theoretically affect the number of isotopes detected, in practice, this variable does not have a significant enough impact on the final measurement results. As an implication, the study emphasizes the importance of considering environmental factors in the interpretation of radioactivity data, rather than focusing solely on the technical aspects of sampling duration.

Based on Pearson and Spearman correlation analysis between the concentrations of radioactive isotopes I-131, Cs-134, and Cs-137, the relationship between isotopes in the distribution of radionuclides at the study site can be more clearly seen. Pearson analysis shows a strong positive relationship between I-131 and Cs-134 with a correlation value of 0.797, while the relationship between I-131 and Cs-137 is stronger with a correlation value of 0.839, indicating an almost linear relationship pattern.

The relationship between Cs-134 and Cs-137 shows the highest correlation, which is 0.872, indicating that the two isotopes have a very close and linear distribution pattern. The results are reinforced by Spearman's analysis, which shows that the relationship between isotopes is not only linear, but also monotonous, meaning that despite variations in the data, the order or rank of concentrations between isotopes remains consistent.

In other words, an increase in the concentration of one isotope tends to be followed by an increase in the other isotopes, confirming a close relationship in the distribution pattern of radioactivity in the study area. Theoretically, the strong relationship between isotopes can be explained through radioactive decay processes and atmospheric dynamics that affect the dispersion of radionuclides after they are released into the environment (Salbu, 2024).

I-131, Cs-134, and Cs-137 are the main products of nuclear fission and usually co-occur in radioactive release events resulting from nuclear accidents or nuclear tests (Dai dkk., 2023). I-131 has a shorter half-life compared to Cs-134 and Cs-137, which means that even if it is initially present in large quantities, it will decay faster. However, its initially high concentration may contribute to the strong association with Cs-134 and Cs-137.

These results are also in line with previous studies showing that radioactive isotopes from the same source tend to have high correlations because they are distributed through similar mechanisms, such as wind and rainfall patterns. Study conducted by (Takahashi dkk., 2021) on the distribution of radioactivity after the Fukushima incident showed that the isotopes experienced similar dispersal patterns and had a high correlation in their concentrations at various measurement sites.

## 4. CONCLUSIONS

The study showed that the distribution of radionuclides at the two main sites, Prague and Usti, was relatively consistent geographically, with variations in concentrations influenced more by environmental factors than sampling location. Statistical analysis confirmed that there were no significant differences in I-131, Cs-134 and Cs-137 concentrations between the cities, indicating that geographical factors are not the main determinant in isotope distribution.

The data showed high variability in concentrations, with most samples having low or zero values, while some extreme points showed very high levels, suggesting diverse environmental factors. Sampling duration had no significant effect on the measured concentrations, confirming that other factors, such as measurement methods and environmental conditions, were more dominant.

Furthermore, the relationship between radioactive isotopes shows a very strong correlation, where an increase in one isotope tends to be followed by an increase in another. This indicates that the three isotopes most likely came from the same contamination source and experienced similar dispersion patterns in the environment. Radioactivity monitoring should not focus solely on geographical differences, but rather consider environmental factors such as wind patterns, rainfall and soil properties that affect isotope distribution.

Sampling duration does not necessarily improve accuracy, so the frequency and method of measurement should be emphasized. The strong correlation between I-131, Cs-134 and Cs-137 suggests that the analytical approach should focus on the combined contamination pattern, not just one isotope in isolation. Given the high fluctuation of concentrations, radiation risk mitigation needs to be carried out with a multidimensional approach that considers aspects of time, environmental conditions, and isotope distribution patterns.

Given the high variability observed in radionuclide concentrations, future research should focus on identifying specific environmental and biological factors that influence radionuclide transport in tropical ecosystems. Further research could integrate advanced geospatial and remote sensing analysis to better understand spatial distribution patterns.

More controlled experiments on soil properties, plant physiology and radionuclide bioavailability will improve the accuracy of current predictive models. Addressing these aspects will contribute to the development of more effective environmental management strategies and remediation efforts in areas affected by radioactive contamination.

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