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A Comprehensive Analysis of Radiological Parameters in Historical City Soil: The Case of Mardin, Turkiye

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Abstract: This study evaluates the levels of natural radioactivity in surface soil samples across all districts of Mardin Province, Turkiye, using data from the Turkish Environmental Radioactivity Atlas. The activity concentration levels of Ra-226, Th-232, K-40, and Cs-137 were re-mapped, and radiological parameters (Ra_{eq}, D_R, H_{ex}, AEDE, AGDE, and ELCR) were calculated for an environmental risk assessment. The average Ra-226 concentration (33.66 $Bq \cdot kg^{-1}$) exceeded the Turkiye average but remained near the UNSCEAR global median. The Th-232 concentration (29.37 $Bq \cdot kg^{-1}$) was lower than both reference values, while K-40 (385.63 $Bq \cdot kg^{-1}$) was below the Turkiye average but higher than the global median. The Cs-137 concentration (20.52 $Bq \cdot kg^{-1}$) surpassed the Turkiye average, with the highest value detected in Yeşilli district of Mardin (75.05 $Bq \cdot kg^{-1}$), suggesting an anthropogenic influence. The radiological parameters indicated that the Ra_{eq} and H_{ex} values remained within safe limits across all districts. However, the D_R and AEDE exceeded UNSCEAR global medians in Ömerli and Midyat, while the AGDE was elevated in six districts. The ELCR surpassed the global median only in Ömerli. The districts of Artuklu, Derik, Kızıltepe, Mazıdağı, Midyat, and Ömerli exhibited higher natural radioactivity, whereas Dargeçit, Nusaybin, Savur, and Yeşilli had lower risk levels. Nusaybin was identified as the least radiologically hazardous district. Given these findings, radiological parameters should be considered when selecting new residential areas. Further studies with an increased number of soil samples are recommended for a more precise environmental risk assessment.

Keywords: natural radioactivity; radiological risk assessment; surface soil; Mardin Province

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1. Introduction

Environmental radiation primarily originates from natural sources, including primordial radionuclides in the Earth's crust and cosmogenic radionuclides formed through cosmic ray interactions in the atmosphere. According to estimates, natural sources account for around 80% of radiation exposure worldwide. The world average annual effective dose from both natural and artificial radiation sources is about 2.8 mSv, with natural radiation contributing approximately 2.4 mSv and artificial sources accounting for around 0.4 mSv [1]. The annual effective doses from natural background radiation and their distribution percentages are summarized in Table 1, while the variations in natural radioactivity levels across different regions of the world are illustrated in Figure 1.

Table 1. Annual effective doses of natural background radiation millisieverts [2,3].

Sources	Dose Ranges	World Averages
Inhalation (Rn-222)	0.20–10.00	1.26
Cosmic Rays	0.30–1.00	0.39
Terrestrial Gamma Rays	0.30–1.00	0.48
Ingestion (K-40)	0.20–1.00	0.29
Total	1.00–13.00	2.40

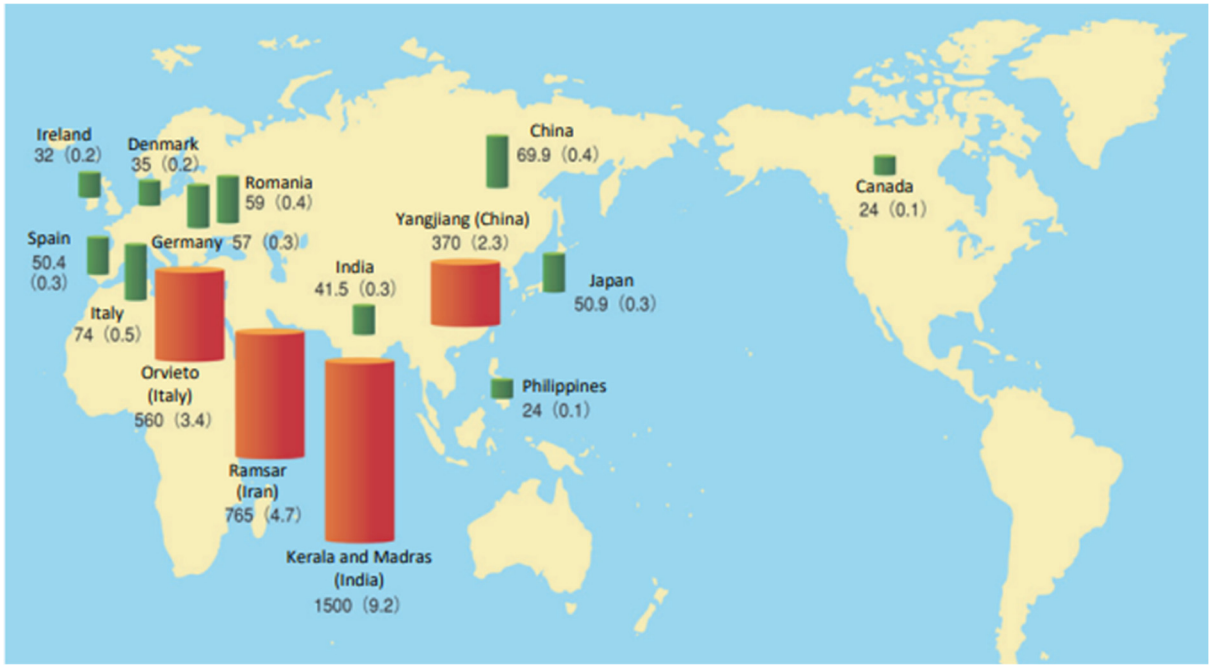


Figure 1. Natural background radiation levels in different regions of the world (annual average natural radiation, mSv) [3].

Natural background radiation levels vary significantly across different geographical regions due to variations in soil and rock composition. While these levels are relatively stable, human activities, such as nuclear accidents, industrial processes, and medical applications involving radiation, can lead to elevated background radiation levels, making continuous monitoring essential for assessing potential radiological risks. The majority of background radiation exposure comes from natural sources, with terrestrial radiation being a major contributor. Terrestrial radiation arises from radionuclides in the uranium (U-238) and thorium (Th-232) decay series, as well as potassium-40 (K-40), which is widely distributed in the Earth's crust [4–7]. Additionally, cosmic radiation contributes to background radiation levels, as high-energy particles from space interact with atmospheric atoms, producing secondary radiation that reaches the Earth's surface. Since terrestrial background radiation depends on the local geological structure, measuring soil radioactivity levels provides critical information about regional radiation hazards [8–11].

The levels of natural radioactivity and their potential health impacts can vary due to factors, such as the geographical location and geological structure of the region [12]. Natural radioisotopes present in soil and water can enter the food chain, transferring from soil to plants and subsequently to human and animal metabolism. Determining the radiation dose to which living organisms are exposed from both natural and artificial sources, along with the potential damage it may cause, is of critical importance.

Recently, background radioactivity levels have been increasing rapidly due to factors, such as nuclear accidents and medical procedures involving radiation. To assess the extent

of radioactive pollution in a given region, it is essential to establish baseline measurements of environmental radioactivity before contamination occurs. Regular monitoring of radioactivity levels allows for the tracking of changes over time and the detection of potential pollution. Therefore, conducting routine activity measurements in regions with high radioactive contamination is crucial for public health.

Establishing baseline radioactivity levels is essential for determining potential risks and tracking changes over time. Many studies have assessed background radiation levels in various regions, including cities, such as Artvin-Ardahan [13], Osmaniye [14], Rize [15], Kars [16], Gümüşhane [17], Kayseri [18], Kilis [19], and Edirne [20]. However, no comprehensive study has yet been conducted on Mardin province, a region of historical and cultural significance in southeastern Türkiye. Given the importance of natural radioactivity assessments in public health and environmental safety, it is crucial to fill this gap in research. While similar methodologies have been applied in other regions, no study has specifically focused on Mardin province. This research applies established radiological assessment methods to Mardin, providing updated spatial data and a reference point for future studies on naturally occurring radioactivity in the region

Mardin's geological characteristics make it an important location for evaluating natural radioactivity. The region's soil and rock formations contain varying concentrations of naturally occurring radionuclides, which can contribute to external and internal radiation exposure through inhalation, ingestion, and direct radiation. The determination of natural radioactivity levels in soil samples from this region will help in assessing the radiological risks associated with environmental exposure.

This study aims to systematically evaluate natural radioactivity levels in Mardin and assess the associated radiological risks. Key radiological hazard indices, including radium equivalent (Raeq), air-absorbed gamma dose rate (DR), annual effective dose equivalent (AEDE), annual gonadal dose equivalent (AGDE), excess lifetime cancer risk (ELCR), and external radiation hazard index (Hex), will be used to quantify potential health impacts. By comparing these findings with data from other regions in Türkiye and worldwide, this study will provide valuable insights into the radiation hazards in Mardin and contribute to future research on naturally occurring radioactivity.

The findings of this study are expected to serve as a reference for environmental and public health authorities in developing radiation protection strategies. Additionally, the results will contribute to the scientific literature by providing baseline data for future studies in the region. Given the increasing importance of monitoring environmental radiation, particularly in areas with high geological variability, such research is essential for ensuring long-term radiation safety and public health protection.

2. Materials and Methods

Mardin, situated in the Dicle (Tigris River) section of Turkiye' s the Southeastern Anatolia Region, borders Syria to the South and is surrounded by Şanlıurfa, Diyarbakır, Batman, Siirt, and Şırnak. Covering an area of 8779 km^2, the province had a population of 888,874 as of 2023 [21]. The location of the Mardin Province is given in Figure 2. Its economy is primarily based on agriculture, animal husbandry, and trade, with industry contributing only 5.5% to its income. Positioned on the Southern slopes of a highland at an elevation of 1052 m (3450 feet), Mardin overlooks vast limestone plateaus and has been a settlement since antiquity, known as Marida in Roman times. Incorporated into the Ottoman Empire in 1516, it features historical landmarks, such as the Seljuk-era Ulu Cami (Great Mosque) and Sultan İsa Medrese. Strategically located along east–west trade routes, Mardin serves as a key trading hub, connected by rail to the Istanbul–Baghdad route and by road to major cities like Gaziantep and Diyarbakır. With its rich history, cultural heritage,

and strategic location, Mardin holds significant cultural and economic importance in the region [22].

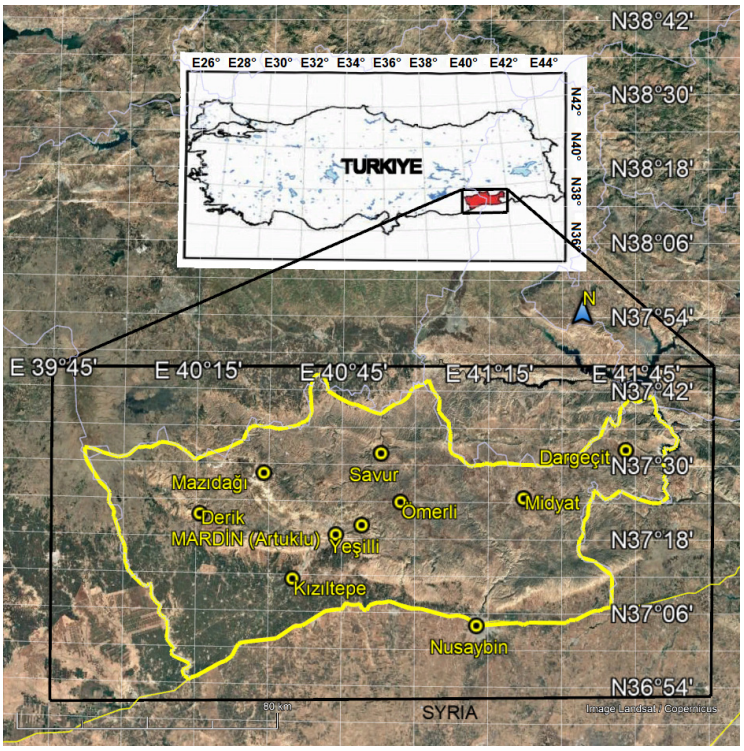


Figure 2. The location of the Mardin Province [23,24] (combined and modified).

2.1. Sample Preparation and Measurements of Gamma Spectrometry

The activity concentrations of radionuclides, such as radium-226, thorium-232, potassium-40, and cesium-137, used in this study were obtained from the Environmental Radiation Atlas of Türkiye, prepared by the Turkish Atomic Energy Authority (TAEK) [24]. This report provides a geographical mapping of the natural radioactivity levels in Mardin Province (including its districts) but does not include radiological parameter calculations. The use of TAEK data in this study is based on its reliability, standardized measurement methods, and national acceptance, ensuring consistency with previous research conducted in other regions of Türkiye. The primary reason for using the existing data provided by TAEK in our study is to analyze regional radiological risks based on a dataset consisting of long-term, reliable measurements. These data have been collected using standard methods and are recognized as reliable at the national level. In our study, we re-mapped the natural radioactivity levels using equal activity distribution curves for each radionuclide and performed radiological parameter calculations. Additionally, the spatial distributions of these calculated radiological parameters were presented to offer a more comprehensive assessment. According to the TAEK report [24], 23 surface soil samples were collected from Mardin Province. It was stated that the sampling locations were selected to best represent the region, prioritizing areas with good water permeability that were not affected by flooding or excessive rainfall, were free from vegetation or leaf cover, and were located in open, undisturbed, flat areas. The report further specifies that soil samples were collected from an area of approximately 1 m^2 at a depth of 0–5 cm, with at least three subsamples mixed to create a composite sample. Before analysis, the samples were cleaned of foreign materials, such as stones, plant roots, and other debris. The activity concentrations of the soil samples were analyzed using a High-Purity Germanium (HPGe) detector (Canberra Inc., Meriden, CT, USA) at TAEK's [24] research and training centers in Ankara (SANAEM)

and Istanbul (CNAEM). The minimum detectable activities (MDAs) of the detector in use were determined using Equation (1), as outlined in similar reports.

$$\mathrm{MDA} = \frac{2.71 + 4.65\sqrt{\mathrm{B}}}{(\varepsilon \times \mathrm{t} \times \gamma \times \mathrm{m})} \quad (1)$$

where B is the background counts, ε is counting efficiency, γ is the gamma emission probability for the gamma of interest, m is the sample mass, and t is the measurement time.

In this TAEK report [24], the soil sample analysis method was described as follows: The samples of soils were first dried in the air at room temperature, then crushed, and after a homogenization process, they were sieved through a 30 mesh BS (0.5 mm mesh). A total of 1 kg of the sieved samples was further dried at 110 °C for 24 h for removal of moisture and then subsequently cooled in a dry ambient area. The prepared samples were kept in 250 cm^3 polystyrene bottles, which were hermetically sealed and left undisturbed for 4 weeks to achieve secular equilibrium. This equilibrium ensures that the decay rate of radon progeny becomes equal to that of the parent isotope, which is a critical stage to confine radon gas in the sample volume, and retain its progeny in the material [24].

2.2. Geology

In the Mardin region, Mesozoic units are represented by Cretaceous-aged formations. Cretaceous and Tertiary-aged units have transgressively overlain Paleozoic-aged formations, which dip southward at an angle of 20–40 degrees, creating an angular unconformity. A significant sedimentation gap exists between the Paleozoic and Cretaceous units. The Mesozoic-aged sequences, from bottom to top, consist of the Areban Formation, the Mardin Formation (Mardin Group), the Karaboğaz Formation, and the Germav Formation. The Areban Formation is typically observed around the villages of Bedinan and Areban. It transgressively overlies the Paleozoic series and consists of red and greenish sandstone, clay, and conglomerate. The thickness of the formation is 130 m [25]. In the region, the Mardin Group, which belongs to the Coniacian–Early Campanian-aged Southeast Anatolian Autochthon, and its associated Karababa Formation, the Campanian-aged Adıyaman Group and its associated Karaboğaz Formation, the Midyat Group consisting of the Eocene–Oligocene-aged Hoya Formation and Gaziantep Formation, the Early Miocene-aged Kapıkaya Formation, and the Middle–Late Miocene-aged Şelmo Formation are exposed. Over all these units, the Pliocene–Quaternary-aged Karacadağ Group, formed during the second phase of the Karacadağ Volcanics, includes the Kuşdoğan Basalt, Seyran Basalt, Ilırkapınar Basalt, İnanözü Basalt, Çelkanyayla Basalt, and Mergimir Pyroclastics. Additionally, the Late Pleistocene-aged Ovabağ Group, formed during the third phase of volcanism, comprises the Hama Basalt, Leblebitaşı Basalt, Görgü Basalt, and Kırmızıtepe Pyroclastics, along with older and newer alluvial deposits [25]. Among these geological formations, the Pliocene–Quaternary-aged Karacadağ Group, which formed during the second phase of volcanic activity, includes basaltic rocks. These basaltic rocks may contain radioactive isotopes, such as U-238 and U-235, as indicated in the studies by Dzaugis et al., [26] and Seow et al. [27] Therefore, the basalt layers in the region are considered a significant source of radioactivity. This suggests that the radioactivity levels measured in surface soil samples may also be associated with these basaltic formations. In addition, the older and newer alluvial deposits found in the region may also serve as a source of natural radioactivity, as they could contain naturally occurring radioactive isotopes leached from surrounding rocks [28]. Considering both the radioactivity levels of volcanic rocks and the potential contributions from alluvial deposits will provide a more comprehensive radiological risk assessment for the region. A geology map of Mardin province is given in Figure 3.

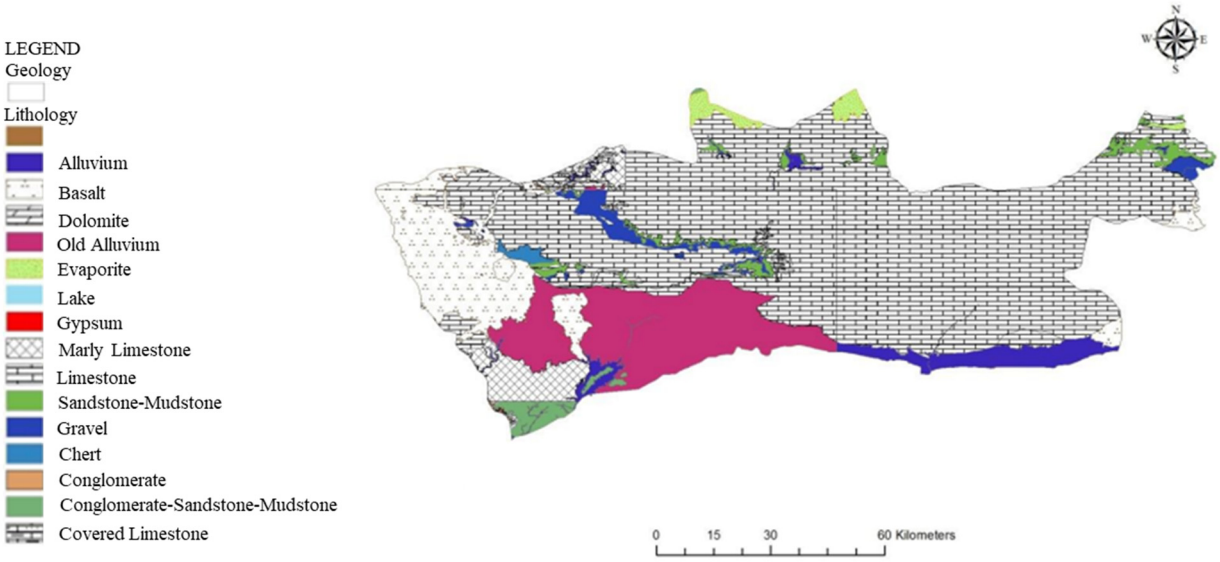


Figure 3. Geology Map of Mardin Province taken from [25] and modified.

2.3. Radiological Hazard Determination

This study scrutinized the potential radiological risks in the surface soil samples in Mardin province by analyzing the activity concentrations of radioactive isotopes: Ra-226, Th-232, K-40, and Cs-137. The six radiological hazard indices, including radium equivalent activity (Ra_{eq}), absorbed dose rate (D_R), annual effective dose equivalent (AEDE), external radiation hazard index (H_{ex}), annual gonadal dose equivalent (AGDE), and excess lifetime cancer risk (ELCR) were computed in this study. All radiological parameter equations arere presented in Table 2.

Table 2. Equations of radiological parameters.

$Ra_{eq} = A_{Ra} + 0.077\ A_K + 1.43\ A_{Th}$	(2)
$D_R = 0.462\ A_{Ra} + 0.604\ A_{Th} + 0.0417\ A_K + 0.03A_{Cs}$	(3)
$AEDE\ (\mu Sv{\cdot}year^{-1}) = DR\ (nGyh^{-1}) \times 8760\ (h{\cdot}year^{-1}) \times 0.7\ (SvGy^{-1}) \times 0.2 \times 10^{-3}$	(4)
$H_{ex} = \frac{A_{Ra}}{370\ Bq{\cdot}kg^{-1}} + \frac{A_{Th}}{259\ Bq{\cdot}kg^{-1}} + \frac{A_K}{4810\ Bq{\cdot}kg^{-1}}$	(5)
$AGDE\ (\mu Sv{\cdot}year^{-1}) = 3.09A_{Ra} + 4.18A_{Th} + 0.3147A_K$	(6)
$ELCR = AEDE \times DL \times RF$	(7)

A_{Ra}, A_K, and A_{Th} are the specific activities of Ra-226, K-40, and Th-232
D_R is the absorbed dose rate in the air (nGy h^{-1})
DL is expectancy of life (estimated as 70 years), and RF is the risk factor provided as 0.05 Sv^{-1} (fatal cancer risk per Sievert)

Radium equivalent activity (Ra_{eq}) serves as a key parameter in assessing radiation safety for human populations [28,29]. This metric, estimated using Equation (2), is derived from radionuclides Ra-226, Th-232, and K-40, for instance, in the surface soil samples. The equation adopts that 259 Bq·kg^{-1} of Th-232, 4810 Bq·kg^{-1} of K-40, and 370 Bq·kg^{-1} of Ra-226 contribute to a similar gamma dose rate [30]. The absorbed dose rate (D_R) in air, a crucial factor in radiation exposure assessment, was calculated using Equation (3). This estimation was based on activity concentrations to calculate gamma radiation from soil sources. The dose rate (D_R) was calculated using activity concentrations in this study, providing an estimation of the dose in the air 1 m above the ground [31]. To estimate the Annual Effective Dose Equivalent (AEDE), Equation (4) was applied. This calculation incorporated a conversion coefficient of 0.7 Sv/Gy and an outdoor occupancy factor of 0.2,

reflecting the dose absorbed in the air and its impact on adult exposure [32]. The external hazard index (H_{ex}) is another important parameter for evaluating radiation exposure, particularly for individuals working outdoors. Equation (5) was utilized to determine this index [33]. Exposure to radiation beyond critical levels can have serious biological consequences, including cellular mutations and death [34]. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, [1]) has reported that radiation particularly affects the bone marrow, bone surface cells, thyroid, lungs, and gonads [1]. Given the significance of radiation effects on reproductive organs, the annual gonadal dose equivalent (AGDE) was computed based on Equation (6). Prolonged exposure to naturally occurring radiation in soil, particularly in residential areas, poses a risk of severe health conditions, such as cancer. Regulatory agencies rely on quantitative risk indices to determine the Excess Lifetime Cancer Risk (ELCR). This parameter was determined through Equation (7), and integrates intake levels, exposure durations, and dose-response data to estimate lifetime cancer risk [35,36].

3. Results and Discussion

According to the TAEK [25] report, the average activity concentrations of Ra-226, Th-232, K-40, and Cs-137 in the districts of the Southeastern Anatolia region of Turkiye are provided in Table 3. Among these, Mardin has the highest Ra-226 value at 33.66 Bq·kg^{-1}, which is higher than the Turkiye mean but lower than the global median. The Ra-226 activity concentration in Mardin is the highest among all provinces in the Southeastern Anatolia region.

Table 3. Comparison of average activity concentrations of districts in the Southeastern Anatolia region of Turkiye (taken from TAEK, [24]).

Province	Num. of Samples	Ra-226 (Bq·kg^{-1})	Th-232 (Bq·kg^{-1})	K-40 (Bq·kg^{-1})	Cs-137 (Bq·kg^{-1})	Ref.
Mardin	23	33.66	29.37	385.63	20.52	[24]
Adıyaman	32	23.98	29.09	402.20	6.58	
Batman	12	30.17	30.58	471.17	14.05	
Diyarbakır	27	23.45	19.76	368.70	16.02	
Gaziantep	23	26.29	24.78	225.22	6.29	
Kilis	19	18.80	17.60	222.09	11.11	
Siirt	19	28.50	30.16	497.41	10.22	
Şanlıurfa	24	27.58	29.82	330.13	11.12	
Şırnak	24	32.45	26.46	339.33	18.57	
Turkiye (mean)	1913	27.56	32.65	439.93	12.03	[24]
World (median)	N/A	35.00	30.00	400.00	N/A	[1]

N/A: Not available.

The average activity concentrations of Th-232 in the Southeastern Anatolia region are all lower than the Turkiye mean. In Mardin, the Th-232 concentration is 29.37 Bq·kg^{-1}, which is also lower than the global mean. The K-40 activity concentration in Mardin is 385.63 Bq·kg^{-1}, ranking in the mid-range compared to other provinces in the region. However, this value is lower than both the Turkiye mean and the global median. Lastly, the Cs-137 activity concentration in Mardin is 20.52 Bq·kg^{-1}, making it the highest among the provinces in the region. This concentration is also higher than the Turkiye mean.

Table 4 presents the coordinates of the districts of Mardin province along with the mean activity concentrations of Ra-226, Th-232, K-40, and Cs-137 radionuclides obtained

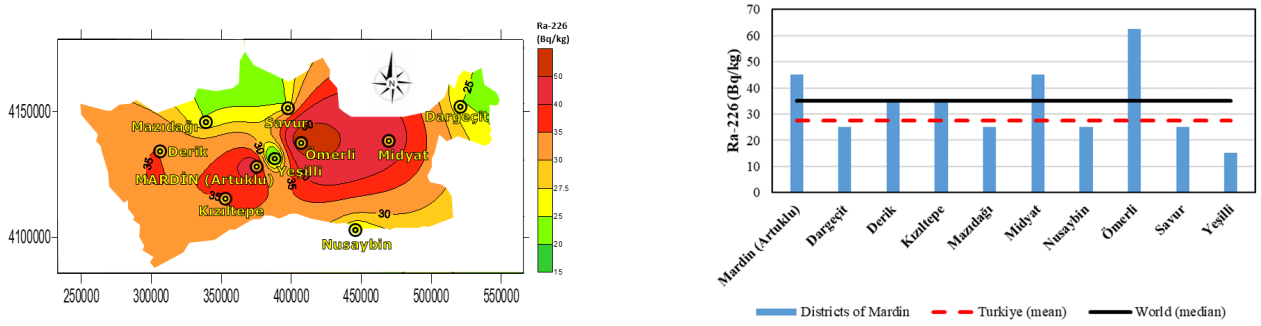
from the TAEK [24] report. Based on Table 4, the spatial distribution of Ra-226 activity concentrations in Mardin' s districts are illustrated in Figure 4a, while comparisons among the districts are shown in Figure 4b. The Ra-226 activity concentrations range between 15.05 Bq·kg^{-1} and 62.55 Bq·kg^{-1}, with an average of 33.66 Bq·kg^{-1}, which is higher than the Turkish average of 27.56 Bq·kg^{-1}. The maximum Ra-226 activity concentration was found in the Ömerli district, with a value of 62.55 Bq·kg^{-1}, and five out of ten districts exceeded the UNSCEAR world median of 35.00 Bq·kg^{-1}; the lowest value was observed in Yeşilli district at 15.05 Bq·kg^{-1}.

Table 4. Activity concentrations of districts of Mardin province (taken from TAEK [24]).

Districts	Coordinates	Ra-226 (Bq·kg^{-1})	Th-232 (Bq·kg^{-1})	K-40 (Bq·kg^{-1})	Cs-137 (Bq·kg^{-1})
Mardin (Artuklu)	37.31290° N, 40.73411° E	45.05	25.05	450.05	15.05
Dargeçit	37.54618° N, 41.72038° E	25.05	25.05	350.05	35.05
Derik	37.36466° N, 40.26794° E	35.05	25.05	350.05	5.00
Kızıltepe	37.19138° N, 40.58595° E	35.05	35.05	450.05	5.00
Mazıdağı	37.47737° N, 40.48674° E	25.05	45.05	450.05	25.05
Midyat	37.41515° N, 41.37343° E	45.05	35.05	450.05	15.05
Nusaybin	37.06964° N, 41.21400° E	25.05	25.05	250.05	5.00
Ömerli	37.40311° N, 40.95482° E	62.55	35.05	450.05	15.05
Savur	37.53393° N, 40.88709° E	25.05	25.05	350.05	25.05
Yeşilli	37.33961° N, 40.82302° E	15.05	25.05	350.05	75.05
Max	-	62.55	45.05	450.05	75.05
Min	-	15.05	25.05	250.05	5.00
Mean	-	33.66	29.37	385.63	20.52
Turkiye (mean) *	-	27.56	32.65	439.93	12.03
UNSCEAR **	-	35.00	30.00	400.00	N/A

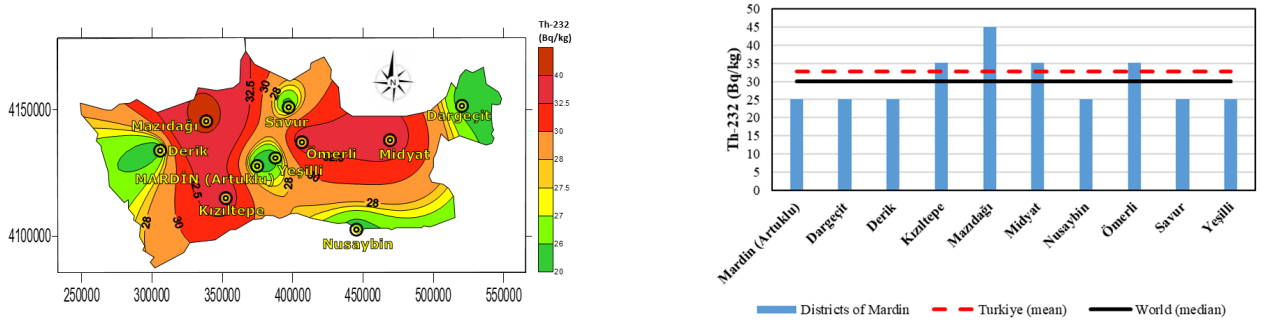
* TAEK, [24]. ** UNSCEAR, 2000 [1]—World (median). N/A: Not available.

The spatial distribution of Th-232 activity concentrations is depicted in Figure 5a, and comparisons among the districts are provided in Figure 5b. The Th-232 activity concentrations vary between 25.05 Bq·kg^{-1} and 45.05 Bq·kg^{-1}, with an average of 29.37 Bq·kg^{-1}, which is lower than the Turkish average of 32.65 Bq·kg^{-1}. The highest Th-232 activity concentration was detected in the Mazıdağı district, with a value of 45.05 Bq·kg^{-1}, and four out of ten districts exceeded the UNSCEAR world median of 30.00 Bq·kg^{-1}. The lowest values, 25.05 Bq·kg^{-1}, were recorded in the Artuklu, Dargeçit, Derik, Nusaybin, Savur, and Yeşilli districts.



(**a**) (**b**)

Figure 4. (**a**) Spatial distribution of Ra-226 activity concentrations (taken from [24]). (**b**) Comparison of Ra-226 activity concentrations (taken from [24]). The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.

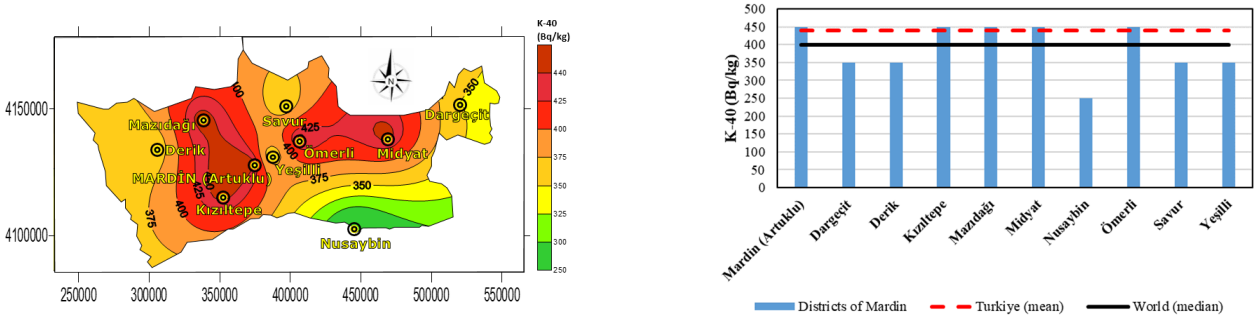


(**a**) (**b**)

Figure 5. (**a**) Spatial distribution of Th-232 activity concentrations (taken from [24]). (**b**) Comparison of Th-232 activity concentrations (taken from [24]). The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.

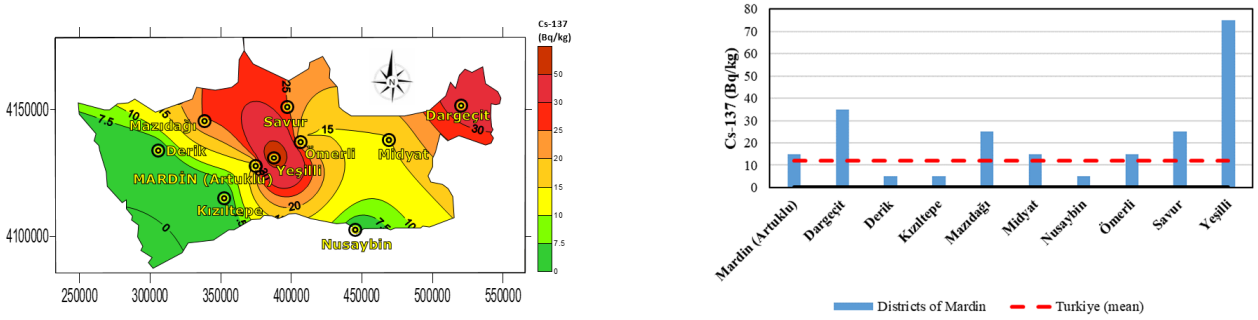
The spatial distribution of the K-40 activity concentrations is shown in Figure 6a, with district-wise comparisons illustrated in Figure 6b. The K-40 activity concentrations range from 250.05 Bq·kg^{-1} to 450.05 Bq·kg^{-1}, with an average of 385.63 Bq·kg^{-1}, which is lower than the Turkish average of 439.93 Bq·kg^{-1}. The highest K-40 activity concentration was observed in the Artuklu, Kızıltepe, Mazıdağı, Midyat, and Ömerli districts, with a value of 450.05 Bq·kg^{-1}, and five out of ten districts exceeded the UNSCEAR world median of 400.00 Bq·kg^{-1}. The lowest concentration, 250.05 Bq·kg^{-1}, was measured in the Nusaybin district.

The spatial distribution of the Cs-137 activity concentrations is illustrated in Figure 7a, while comparisons among the districts are presented in Figure 7b. Cs-137 activity concentrations range from 5.00 Bq·kg^{-1} to 75.05 Bq·kg^{-1}, with an average of 20.52 Bq·kg^{-1}, which is higher than the Turkish average of 12.03 Bq·kg^{-1}. The highest Cs-137 activity concentration was found in the Yeşilli district, with a value of 75.05 Bq·kg^{-1}, and seven out of ten districts exceeded the Turkish average. The lowest values, 5.00 Bq·kg^{-1}, were recorded in the Derik, Kızıltepe, and Nusaybin districts.



(**a**) (**b**)

Figure 6. (**a**) Spatial distribution of K-40 activity concentrations (taken from [24]). (**b**) Comparison of K-40 activity concentrations (taken from [24]). The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.



(**a**) (**b**)

Figure 7. (**a**) Spatial distribution of Cs-137 activity concentrations (taken from [24]). (**b**) Comparison of Cs-137 activity concentrations (taken from [24]). The color range used in the (**a**) represents varying levels of radioactivity. The yellow color indicates values that exceed the Turkiye average in the TAEK report [24], and the red color for only comparison.

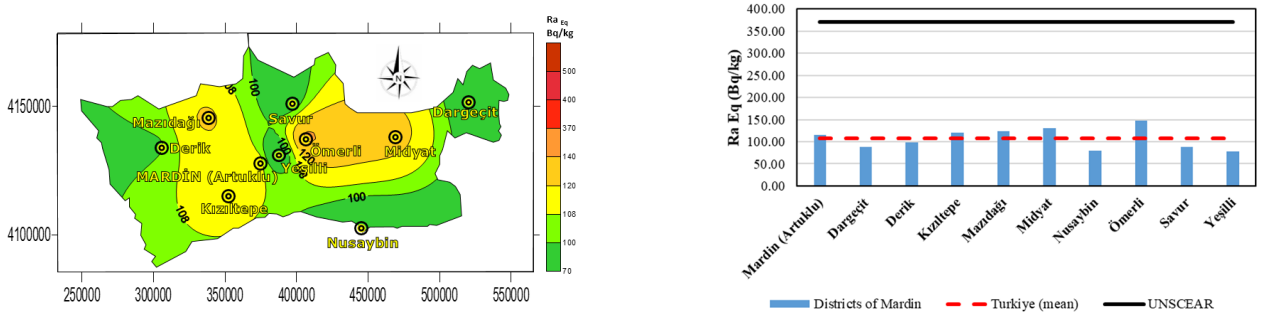
Cs-137 contamination can originate from various sources, including nuclear weapons testing, nuclear accidents, and industrial activities. Identifying the specific sources of Cs-137 in Mardin requires further sampling and detailed environmental analyses, which are not within the scope of this study. Future research should incorporate additional field measurements and isotopic analysis to determine potential contamination pathways. To mitigate potential risks, strategies, such as soil stabilization, regular environmental monitoring, and controlled agricultural practices, could be considered.

Table 5 presents the radioactivity parameters Ra_{eq}, D_R, H_{ex}, AEDE, AGDE, and ELCR calculated from the activity concentration values in Table 4 for the districts of Mardin. The calculated parameter results are also presented spatially and comparatively in Figures 8–13, respectively. As seen in Figure 8, none of the districts in Mardin exceed the UNSCEAR median value of 370 Bq·kg^{-1} for Ra_{eq}. The highest value was recorded in Ömerli at 147.32 Bq·kg^{-1}, and the districts of Artuklu, Kızıltepe, Mazıdağı, and Midyat also exceeded the Turkish average of 108.12 Bq·kg^{-1}. The minimum value was identified in Yeşilli at 77.82 Bq·kg^{-1}.

Table 5. Radioactivity parameters of districts of Mardin province (partially taken from [24]).

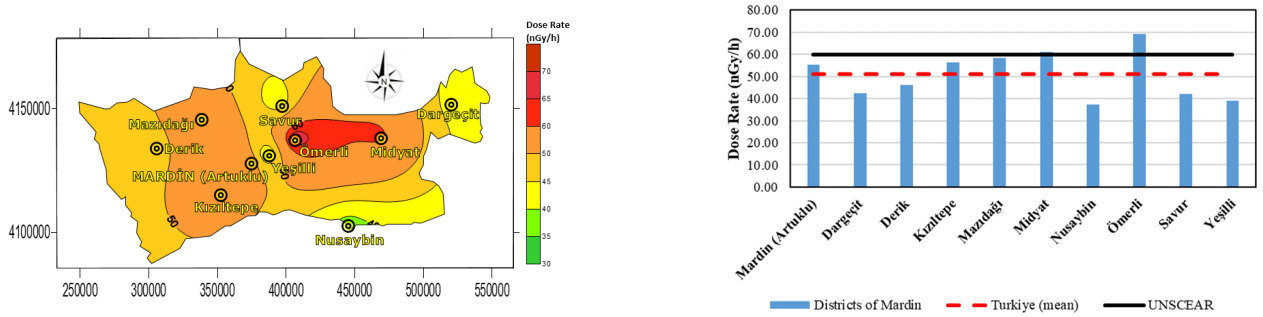
Districts	Ra_{eq} ($Bq \cdot kg^{-1}$)	D_R (nGy/h)	H_{ex}	AEDE (microSv/Year)	AGDE (microSv/Year)	ELCR
Mardin (Artuklu)	115.52	55.16	0.31	67.65	385.22	0.00023
Dargeçit	87.82	42.35	0.23	51.94	292.02	0.00018
Derik	97.82	46.07	0.26	56.50	322.92	0.00019
Kızıltepe	119.82	56.28	0.32	69.02	396.12	0.00024
Mazıdağı	124.12	58.30	0.33	71.50	407.02	0.00025
Midyat	129.82	61.20	0.35	75.05	427.02	0.00026
Nusaybin	80.12	37.28	0.21	45.72	260.62	0.00016
Ömerli	147.32	69.28	0.39	84.97	481.10	0.00029
Savur	87.82	42.05	0.23	51.57	292.02	0.00018
Yeşilli	77.82	38.93	0.21	47.74	261.12	0.00016
Max	147.32	69.28	0.39	84.97	481.1	0.00029
Min	77.82	37.28	0.21	45.72	260.62	0.00016
Mean	105.35	49.98	0.28	61.3	347.86	0.00021
Turkiye (mean) *	108.12	51.15	0.29	62.74	359.77	0.00021
UNSCEAR **	370	60	<1	70	300	0.00029

* TAEK, [24]. ** UNSCEAR, 2000 [1]—World (median).



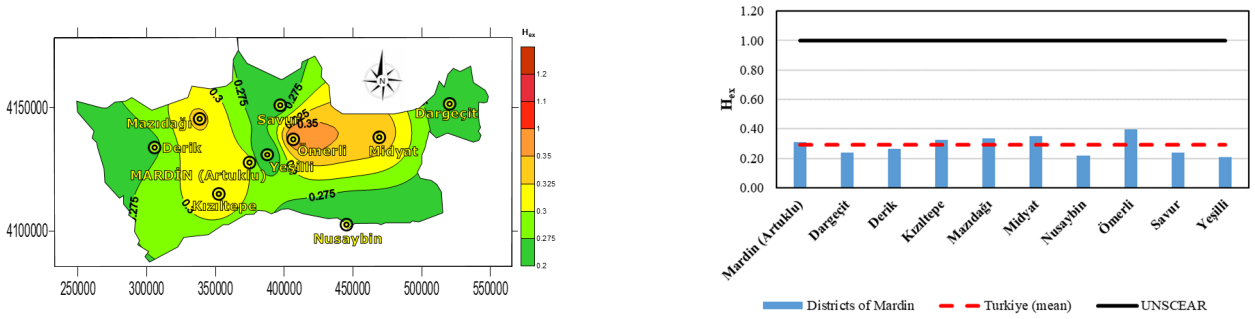
(**a**) (**b**)

Figure 8. (**a**). Spatial distribution of Ra_{eq}. (**b**) Comparison of Ra_{eq}. The color range used in the (**a**) represents varying levels of radiological parameter. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.



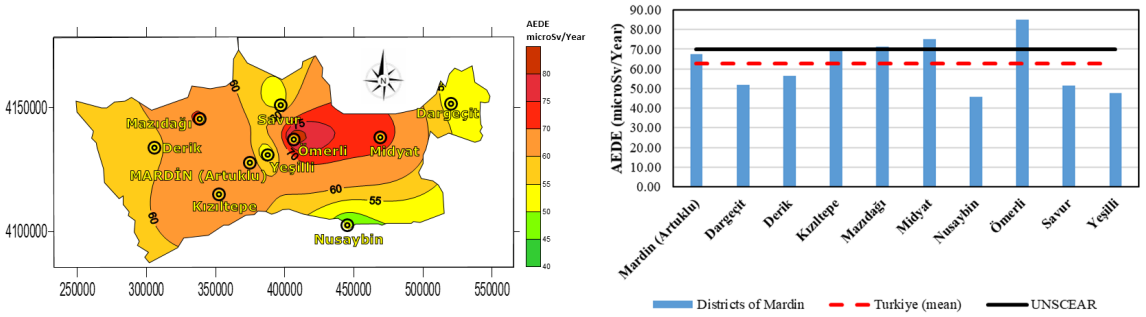
(**a**) (**b**)

Figure 9. (**a**) Spatial distribution of D_R. (**b**) Comparison of D_R. The color range used in the (**a**) represents varying levels of radiological parameter. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.



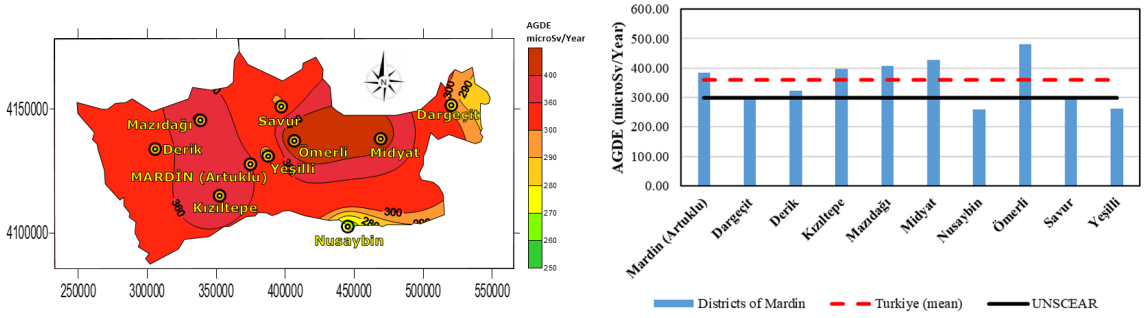
(**a**) (**b**)

Figure 10. (**a**) Spatial distribution of H_{ex}. (**b**) Comparison of H_{ex}. The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.



(**a**) (**b**)

Figure 11. (**a**). Spatial distribution of AEDE. (**b**) Comparison of AEDE. The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.



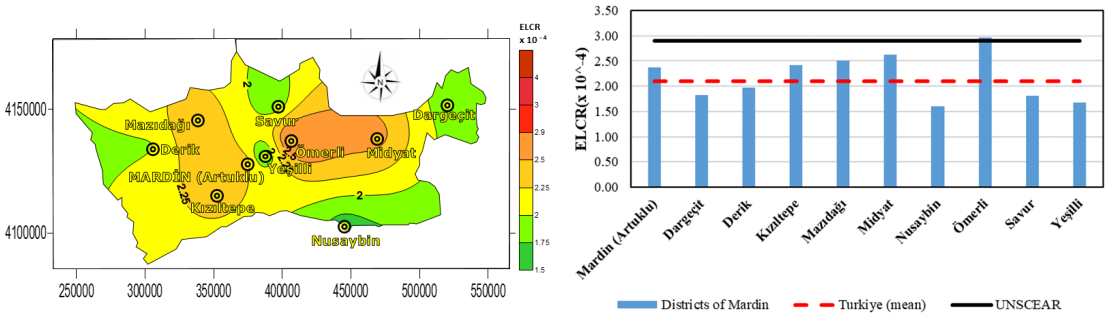
(**a**) (**b**)

Figure 12. (**a**) Spatial distribution of AGDE. (**b**) Comparison of AGDE. The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.

The D_R parameter exceeds the UNSCEAR median value of 60 nGy/h in Ömerli, with a maximum value of 69.28 nGy/h, while Midyat also surpasses the UNSCEAR world median. The lowest value, 37.28 nGy/h, was recorded in Nusaybin.

All districts in Mardin have H_{ex} parameter values below the threshold of 1. Ömerli has the highest value at 0.39, while Nusaybin has the lowest value at 0.21.

The AEDE parameter exceeds the UNSCEAR world median of 70 microSv/year in Ömerli, reaching a maximum of 84.97 microSv/year, as well as in Mazıdağı and Midyat. The minimum value, 45.72 microSv/year, was recorded in Nusaybin.



(**a**) (**b**)

Figure 13. (**a**) Spatial distribution of ELCR. (**b**) Comparison of ELCR. The color range used in the (**a**) represents varying levels of radioactivity. The red color indicates values that exceed the UNSCEAR average, which are considered higher than typical background levels.

The AGDE parameter surpasses the UNSCEAR world median of 300 microSv/year in Ömerli, reaching a maximum of 481.10 microSv/year, as well as in the districts of Artuklu, Derik, Kızıltepe, Mazıdağı, and Midyat. The minimum value, 260.62 microSv/year, was recorded in Nusaybin.

For the ELCR parameter, only Ömerli reaches the UNSCEAR world median of 0.00029, while all other districts have lower values. The lowest values, 0.00016, are observed in Nusaybin and Yeşilli.

4. Conclusions

In this study, the average activity concentrations of Ra-226, Th-232, K-40, and Cs-137 radionuclides measured in 23 surface soil samples collected from all districts of Mardin province were obtained from the TAEK [24], Turkish Environmental Radioactivity Atlas, using an HPGe detector. The spatial distributions of these activity concentrations were mapped for each district. Subsequently, radiological parameters, including Ra_{eq}, D_R, Hex, AEDE, AGDE, and ELCR, were calculated to assess risk analysis. The activity concentrations and radiological parameters were compared with the Turkish average values and the UNSCEAR global median values to conduct an environmental risk assessment.

According to the obtained data, the average activity concentration of Ra-226 in Mardin province is 33.66 Bq·kg^{-1}, which is higher than both the Turkish average of 27.56 Bq·kg^{-1} and the UNSCEAR global median of 35.00 Bq·kg^{-1}. The highest Ra-226 concentration was found in Ömerli district, and five out of ten districts exceeded the UNSCEAR global median. The average Th-232 concentration is 29.37 Bq·kg^{-1}, which is lower than both the Turkish average of 32.65 Bq·kg^{-1} and the UNSCEAR global median of 30.00 Bq·kg^{-1}. The highest Th-232 concentration was observed in Mazıdağı district at 45.05 Bq·kg^{-1}, with four out of ten districts exceeding the UNSCEAR global median. The average K-40 concentration is 385.63 Bq·kg^{-1}, which is lower than the Turkish average of 439.93 Bq·kg^{-1} but higher than the UNSCEAR global median. The highest K-40 concentration of 450.05 Bq·kg^{-1} was detected in the Artuklu, Kızıltepe, Mazıdağı, Midyat, and Ömerli districts, with five out of ten districts exceeding the UNSCEAR global median of 400.00 Bq·kg^{-1}. The average Cs-137 concentration is 20.52 Bq·kg^{-1}, which is higher than the Turkish average of 12.03 Bq·kg^{-1}. The maximum Cs-137 concentration of 75.05 Bq·kg^{-1} was found in Yeşilli district, and seven out of ten districts exceeded the Turkish average. The relatively high Cs-137 activity concentration, which is largely anthropogenic, suggests the need for further investigation to prevent potential environmental impacts in residential areas.

Regarding the radiological parameters calculated from the activity concentrations, the Ra_{eq} value did not exceed the UNSCEAR global median of 370 Bq·kg^{-1} in any district, with the highest value being 147.32 Bq·kg^{-1} in Ömerli. Additionally, the Artuklu,

Kızıltepe, Mazıdağı, and Midyat districts exceeded the Turkish average of 108.12 $Bq \cdot kg^{-1}$. The D_R parameter exceeded the UNSCEAR global median of 60 nGy/h in Ömerli district (69.28 nGy/h) and in Midyat district. The H_{ex} parameter remained below the threshold limit of 1 in all districts, with Ömerli having the highest value at 0.39 and Nusaybin the lowest at 0.21. The AEDE parameter exceeded the UNSCEAR global median of 70 microSv/year in Ömerli (84.97 microSv/year), as well as in the Mazıdağı and Midyat districts. The AGDE parameter exceeded the UNSCEAR global median of 300 microSv/year in Ömerli (481.10 microSv/year) and in the Artuklu, Derik, Kızıltepe, Mazıdağı, and Midyat districts. The ELCR parameter reached the UNSCEAR global median of 0.00029 only in Ömerli, while the other districts had lower values.

Based on a general assessment of the Ra-226, Th-232, and K-40 activity concentrations relative to the UNSCEAR global medians, the Artuklu, Derik, Kızıltepe, Mazıdağı, Midyat, and Ömerli districts are at a higher natural radioactivity risk, while Dargeçit, Nusaybin, Savur, and Yeşilli have lower risk levels. When comparing anthropogenic Cs-137 concentrations with the Turkish average, higher values were found not only in naturally high-radioactivity districts, such as Artuklu, Mazıdağı, Midyat, and Ömerli, but also in Dargeçit, Savur, and Yeşilli, where natural radioactivity levels are lower. Nusaybin was found to be the least risky district in terms of both natural radionuclide and Cs-137 concentrations. The comparison of radiological parameters with UNSCEAR global medians indicated that all districts in Mardin had safe Ra_{eq} and H_{ex} values. Similarly, all districts except Ömerli had ELCR values below the UNSCEAR global median. The D_R parameter exceeded the UNSCEAR global median only in Ömerli and Nusaybin, while the remaining eight districts were within safe limits. For the AEDE parameter, seven districts had values below the UNSCEAR global median, except for Ömerli, Midyat, and Mazıdağı. The AGDE parameter was the most frequently exceeded parameter, with six districts (Artuklu, Derik, Kızıltepe, Mazıdağı, Midyat, and Ömerli) surpassing the UNSCEAR global median, while Dargeçit, Nusaybin, Savur, and Yeşilli had lower values. None of these four districts exceeded the UNSCEAR global medians for Ra_{eq}, D_R, H_{ex}, AEDE, AGDE, or ELCR parameters.

Considering both natural radionuclide activity concentrations and radiological parameters, Nusaybin district was found to have the lowest surface soil radiation risk, as it remained below the UNSCEAR global medians and had a Cs-137 concentration lower than the Turkish average. When selecting new residential areas, the radiological parameters examined in this study should be taken into account alongside local geological conditions. Further detailed radiological measurements should be conducted with a higher number of soil samples to ensure more accurate assessments of the selected regions.

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