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Assessment of Indoor and Water Radon Concentrations in Esenyurt and Beylikdüzü Districts of Istanbul, Marmara Region, Turkey

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ABSTRACT

The radon activity concentration measurements for indoor and tap water were studied in Esenyurt and Beylikdüzü districts of Istanbul Province, Turkey. The mean radon concentration value received from thirty-six passive radon detectors was obtained as 63.56 Bq/m³. The mean annual effective dose for indoor radon measurements is 1.60 mSv/y in this measurement period. The radon activity results of calculated tap water samples were under 0.8 Bq/L. The annual effective doses resulting from ingestion and inhalation were calculated to evaluate the health risk across various age groups. All radon measurement results, and the associated calculated data for ingestion and inhalation remained below the threshold values established by international organizations.

Keywords: Radon, Indoor, Tap Water, LSC, Dose.

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Introduction

In the nature, radon occurs naturally as a product of α-decay of uranium, and it is the heaviest radioactive gas. Radon (^{222}Rn) is a natural radioactive gas, and its half-life is 3.84 days. Radon, which is in the ^{238}U natural radioactive series, is formed as a result of α emission of ^{226}Ra. The known isotopes of radon, which is a colorless, odorless, and tasteless gas, ^{220}Rn and ^{219}Rn, have very short half-lives, 55 s and 3.9 s, respectively. Therefore, the radon element is dominated by ^{222}Rn. Formation of radon is based on the radioactive decay of natural uranium in soil, rocks and water. The main atoms of this degradation chain can be found in all natural materials. Therefore, radon is released into the environment from all surface rock and soil fragments and building materials. As a result of the potential hazard of radon gas on human health, a vast number of studies on radon monitoring and annual effective dose calculations have been introduced. Radon mixes with the air underground through cracks in soil and rocks and from water coming to the surface. Consequently, studies to assess radon concentration are primarily conducted in water and soil [1]. Büyükuslu et al. (2018) conducted indoor and tap water radon measurements at selected sampling areas of Giresun University. Thirty-eight CR-39 solid-state nuclear track detectors were placed. To measure radon concentrations, water samples were collected from six distinct departments. The average indoor radon concentration was determined to be 193.7 Bq/m³. Furthermore, the concentrations of radon in tap water samples were observed to vary between 0.98 Bq/L and 27.28 Bq/L [2]. In another study, radon and radium concentrations of well waters in Afyonkarahisar were determined. In this study, the measured maximum values were 28.82 Bq/L and 7.16 Bq/L, for the radon and radium concentrations, respectively. Similarly, the measured minimum concentrations were 0.42 Bq/L and 0.07 Bq/L for radon and radium, respectively [3]. Köksal et al. (1993) conducted measurements of the average indoor ^{222}Rn concentrations across over four hundred homes within the Istanbul province. The radon concentration averages ranged from 10 Bq/m³ to 260 Bq/m³, with a median concentration of 50 Bq/m³ [4]. Tufaner carried out indoor radon measurements in Edirne provincial center in the Marmara Region and reported that the radon concentration measurement results ranged between 2-125 Bq/m³. The mean radon concentration was determined to be 27.58 Bq/m³, and the annual effective dose was computed to be 0.728 mSv [5]. Günay et al., performed short term indoor radon measurements in Istanbul and their results varied between 19–53 Bq/m³. The annual radiation dose values varied between 0.150 mSv -0.402 mSv [6].

Esenyurt and Beylikdüzü, two districts located in the west of Istanbul, have experienced rapid growth and a significant increase in population in recent years. The geological structure of these districts differs from other regions of Istanbul. They are composed of alluviums formed during the Tertiary and Quaternary periods, which typically consist of sand, gravel, and clay. The relationship between radon and geological structure depends on several factors. Some factors such as uranium content of rocks, soil and rock porosity, groundwater, cracks and fault lines in the earth's crust, geological and topographic features, regional geological structure are critical in determining radon levels and exposure risks in a region. Hence, geological structures must be considered in the process of conducting radon risk assessments.

Depending on the water geology and geological structure of the place where the resources are located, very high concentration values can be detected. Radioactivity concentrations vary over a wide range depending on the geological and chemical composition of the environment [7].

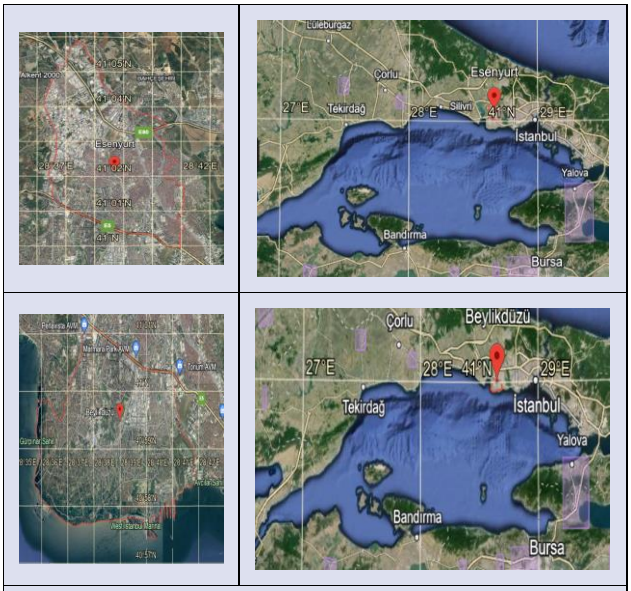

Figure 1. The satellite imagery of the Esenyurt and Beylikdüzü districts was acquired by Google Earth, version 10.49.0.0, on March 20, 2024.

Radon measurement studies aim public health protection, and, in this context, it involves identification of radon concentrations, acquiring knowledge about their impact on human health, and integration of radon mitigation measures in the design and construction of buildings. Radon measurement studies provide the basis for the development of effective strategies to reduce radon exposure and minimize its potential harms on human health. In our research, the primary motivations for performing radon measurements include "Health Effects" and "Environmental Monitoring and Risk Assessment." The results of the measurements were analyzed to provide a basis for public health policies and housing standards. The most serious health-related risk about radon exposure is lung cancer. In this regard, comprehending and minimizing radon exposure is crucial, especially for high-risk groups. Potential risk groups involve individuals such as smokers, miners, underground workers, and residential inhabitants. Radon protection measures include radon testing, ventilation, and engineering controls. In this regard, the present study aims to measure the tap water and indoor radon concentrations in Beylikdüzü and Esenyurt districts of Istanbul Province of Marmara Region. A total of 36 indoor (air) radon concentration measurements were performed for indoor radon measurements. Four (4) sampling locations were determined for tap water measurements to support the indoor radon measurements. The radon activity measurements for indoor and tap water samples were performed using CR-39 detector and LSC system. Passive radon detectors and liquid scintillation counting system are two different methods used to measure environmental radon gas concentration.

Twenty passive radon detectors were placed in the selected residences between two sampling dates (29.05.2019 - 24.09.2019). Sixteen passive radon detectors were placed in the selected residences between two sampling dates (18.02.2020–13.08.2020). Also, radon concentration values of tap water samples taken from four houses on 02.07.2019 were determined. The obtained radon concentration measurements were compared with the literature studies performed in Marmara Region and other regions of Turkey. The factors and parameters likely to be effective on the obtained results were also discussed.

Material and Method

Description of The Study Area

Beylikdüzü is one of the western districts of Istanbul. It is surrounded by the Marmara Sea in the south, Avcılar in the east, Büyükçekmece in the west and Esenyurt in the north. Esenyurt district is in the Trakya sub-region of the Marmara Region, within the boundaries of the Istanbul Metropolitan area. The radon concentration measurements for indoor and tap water radon concentration were performed in Esenyurt and Beylikdüzü districts (Figure 1). The distribution of the sampling locations was specified so as to represent the whole study area. All selected sampling locations for indoor and drinking water measurements are apartments located in the study area. All detectors were placed in rooms that were free of electronic systems or devices, at around 50 cm height from the floor. Passive radon detectors for indoor sampling points were placed in the locations identified in Figure 2 and Figure 3. The satellite view of the sampling points for drinking water samples is shown in Figure 4. The flow diagram for radon measurement is provided in Figure 5, in our study.

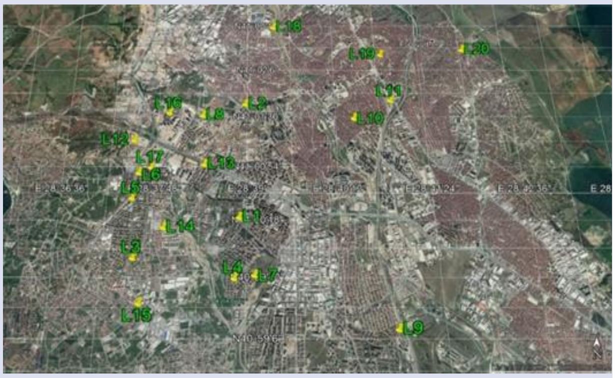

Figure 2. The satellite image of twenty indoor sampling points received by Google Earth Pro (March 14, 2020). Eye altitude 12.26 km. Maxar Technologies 2020 (Google Earth Pro V5 2020).

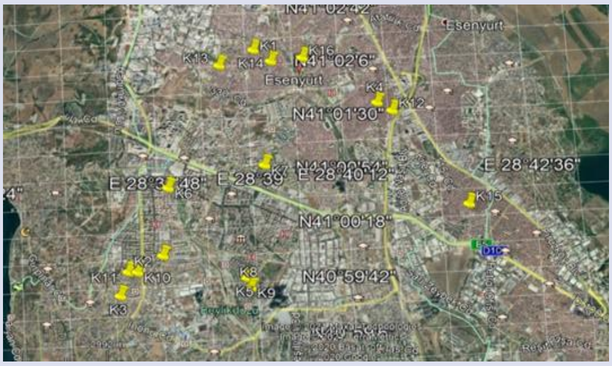

Figure 3. The satellite image of sixteen indoor sampling points received by Google Earth Pro (January 14, 2021). Eye altitude 12.26 km. Maxar Technologies 2020 (Google Earth Pro V5 2020).

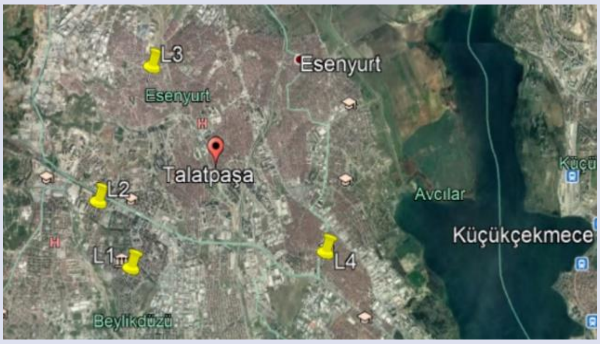

Figure 4. The satellite image of water sampling points received by Google Earth Pro V. (March 26, 2020). Eye altitude 22.39 km. Maxar Technologies 2020 (Google Earth Pro V5 2020).

Passive Radon Detectors (CR-39)

Semiconductor detectors based on CR-39 are often used in nuclear physics and radiation dosimetry. The high energy separation capabilities of semiconductor detectors, which began to be used in the 1960s, as well as their fast-timing characteristics and effective thickness, make them superior to other detectors. Rapid developments in micro-electronics in recent years have led to an increase in the quality of detector fabrication technology and ease in the production of complex structured detectors.

Generally, the responsiveness of CR-39 nuclear track detectors to radon radiation is influenced by a variety of factors, including the configuration of the detector, conditions of exposure, duration of exposure, the methodology employed in the etching process, and the calibration procedure [8]. Detectors play a pivotal role in measuring diverse physical phenomena within the domain of particle physics. The most critical functions include: the identification and detection of particles, the determination of their positions (trajectories), the measurement of time intervals, the assessment of momentum, the evaluation of energy [9].

The passive radon detectors were provided by Turkey Energy, Nuclear and Mining Research Institute (TENMAK). Detection of indoor radon gas is based on the counting of the traces in the film detector (CR-39) in the diffusion container created by alpha particles released as a result of radioactive decay. CR-39 detectors used in both research and public health applications are a popular tool for detecting radioactive gases and they are commonly employed for measuring radon in air, water, and soil. Additionally, because they are easy to use and portable, they are suitable for measuring radon levels in homes and workplaces. CR-39 detectors are typically used in indoor spaces, especially in areas such as basements and ground floors where there is a high probability of radon accumulation. The advantages of CR-39 detectors include high sensitivity, wide measurement range, long-term exposure measurement, low cost, and ease of use. On the other hand, long analysis periods, the need for technical expertise, being single-use, environmental effects, and the inability to perform instant readings lead to limited use of CR-39 detectors. Despite such limitations, CR-39 remains as one of the most widely employed methods for radon measurement across residential, commercial, and industrial domains due to its reliability and effectiveness.

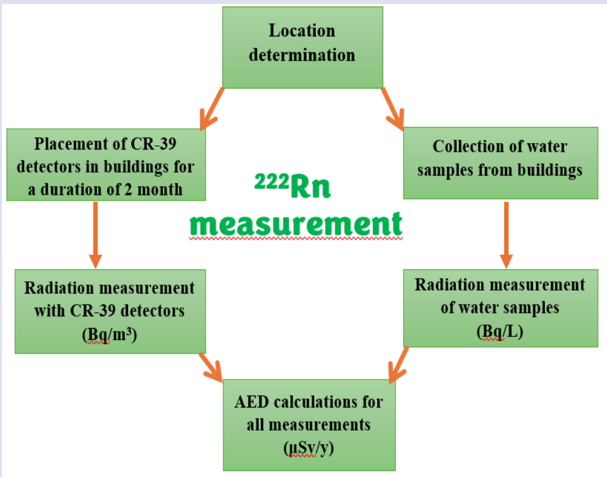

Figure 5. Flow diagram of radon measurement.

Sample Collection for CR-39

CR-39 detectors in cylindrical geometry were placed in aluminum containers and sent to Sarayköy Nuclear Research and Training Center (SANAEM) for analysis. Radon gas concentration values per unit volume of the indoor environment were obtained in Bq/m^3 as given in Figure 6. Thirty-six passive radon detectors were left in the sampling locations for periods ranging between 98-175 days. In the measurements of radon concentration in the air, the CR-39 detector was placed 1 meter above the ground. During this period, they were not relocated, and they were checked at various time intervals.

Liquid Scintillation Counting (LSC)

Scintillation detectors' working principle is based on the emission of visible light in proportion to the amount of radiation they absorb. The intensity of this light is quantified using photomultiplier tubes, enabling the determination of the radiation level. The Liquid Scintillation Counting (LSC) method exhibits high sensitivity in the detection of low-level radioactivity. The Liquid Scintillation Counting (LSC) method is characterized by its broad applicability, facilitating the analysis of liquid, solid, and gaseous samples. As an active measurement technique, LSC systems offer the advantage of immediate measurement, thereby providing instant access to measurement values. Additionally, waste management emerges as a pertinent issue encountered within Liquid Scintillation Counting (LSC) systems. Another concern pertains to the risk of chemical contamination. Chemical interactions between the scintillation fluid and the sample can induce background noise, potentially affecting the measurements. The preparation and processing of samples in the LSC method constitute another area requiring precision. Particularly, the proper mixing of the scintillation fluid with the samples is of significance.

Sample Collection and Preparation

The drinking water samples collected from four sampling locations were put into 250 ml glass bottles. The glass bottles were closed with a cork stopper and a cap to avoid air inlet. This consideration was taken into account for all water samples. Liquid scintillation counting was applied as per ASTM D5072 standard.

Liquid scintillation counting technique is one of the most preferred techniques for radioactivity measurements in water samples. This detection method was used for the analysis of all water samples. Radon gas concentrations in water were obtained in Bq/L. In the ASTM D5072 standard, an aliquot of unaerated water is injected beneath the liquid scintillation mixture of 10 mL. The vials are then capped, shaken, and left to remain 3 hours before the counting process. In the current work, water samples were counted using 1220 Quantulus Ultra Low Level Liquid Scintillation Counter and the scintillation cocktail used is Mineral Oil. 10 ml of water samples were mixed with 10 ml of the scintillation cocktail (Mineral Oil). The counting efficiency was estimated by mixing the Ra-226 standard solution with 10 ml of the scintillation cocktail and leaving it for 30 days. Distilled water was used to prepare the background sample. Both the samples and the solution were prepared using glass vials with 20 ml.

Discussion

In this research, the indoor radon activity concentrations in Esenyurt and Beylikdüzü region were analyzed by CR-39 detector. As indicated in Figure 6, between 29.05.2019 and 24.09.2019, indoor radon concentration values were calculated as 34 Bq/m^3–99 Bq/m^3. The average radon concentration value was also obtained as 60.85 Bq/m^3. Average annual effective doses of indoor radon measurements in these dates ranged from 0.86 to 2.49 mSv/y as shown in Figure 9. Between 18.02.2020 and 13.08.2020, indoor radon concentration values were calculated as 57 Bq/m^3–83 Bq/m^3. The average radon concentration value was also obtained as 66.94 Bq/m^3. According to the Radiation Safety Regulation, the permitted value for radon in dwellings is 400 Bq/m^3 and it cannot exceed 1000 Bq/m^3 in workplaces. This value is not exceeded in the measured areas in this study.

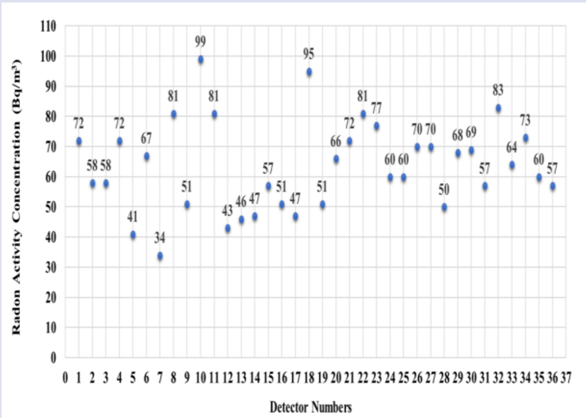

Figure 6. Indoor radon activity concentrations (expressed in becquerels per cubic meter) were quantified using passive detectors over the interval from May 29, 2019, to August 13, 2020.

Radon gas concentrations in Becquerels per m^3 (C_{Rn}) were calculated using Equation 1.

$$C_{Rn} = (CF)(D_{Rn})\left(\frac{1000}{24T}\right) \quad (1)$$

where T is the exposure period in days, CF is the calibration factor, and D_{Rn} is the track density for radon gas [10].

The annual effective dose attributed to indoor radon exposure can be determined through the application of Equation 2 [11]:

$$D = C_{Rn}F\,(O)(DCF) \quad (2)$$

where F represents the equilibrium factor (0.4), C_{Rn} denotes the concentration of radon (Bq/m^3), DCF signifies the dose conversion factor 9 $nSvh^{-1}$ $(Bqm^{-3})^{-1}$, and O is the occupancy (7000h), utilized in converting the radon concentration to effective dose.

The radon concentration measurement results in Beylikdüzü area were lower than those in Esenyurt area. The highest radon concentration value is in Esenyurt district as 99 Bq/m^3 and the lowest is in Beylikdüzü district as 34 Bq/m^3. The average radon concentration value was obtained as 63.56 Bq/m^3, standard deviation is 14.64 Bq/m^3 and median is 62 Bq/m^3.

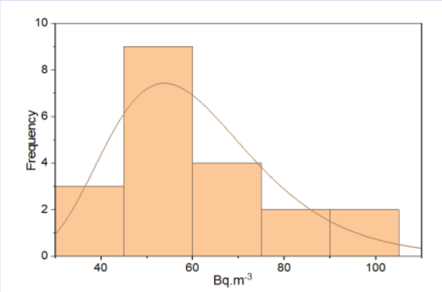

Figure 7. The histogram representing indoor radon measurements.

The histogram of the radon concentration was given in Figure 7. The distribution is consistent with the lognormal distribution. Radon concentration follows approximately lognormal distribution as expected from literature [12-14].

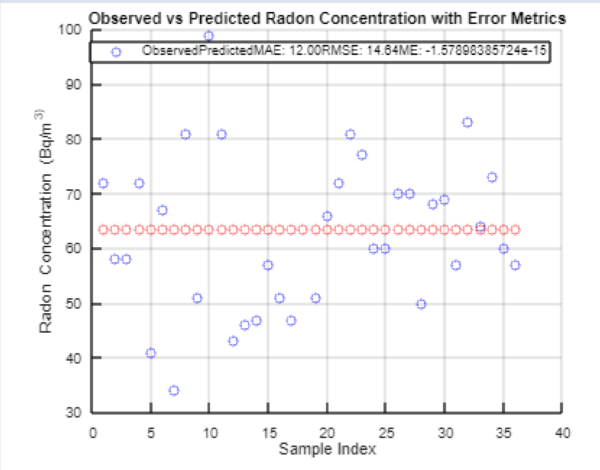

Figure 8. Cross-validation diagrams for indoor radon activity concentrations (measured in becquerels per cubic meter).

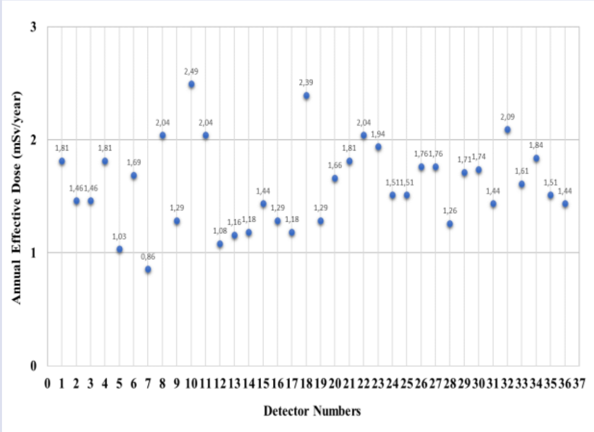

Figure 9. The annual effective dose (measured in millisieverts per year) was computed for indoor measurements spanning the period from May 29, 2019, to August 13, 2020.

Beylikdüzü is a district of Istanbul with a border to Marmara Sea. Esenyurt has no connection with the sea. There are thermal water resources in Esenyurt. This situation explains that the radon concentration level in Esenyurt region is higher than Beylikdüzü region as the thermal water coming from the underground has a high dissolved radon content. The results of annual effective dose calculations ranged from 0.86 to 2.49 mSv/year as given in Figure 9. The mean value of annual effective dose is 1.60 mSv/year.

The performance of the interpolation estimates was evaluated using mean absolute error (MAE), root mean square error (RMSE), and mean error (ME) as performance metrics, as reported by Damla et al. (2022). Cross-validation figures pertaining to indoor radon activity concentrations are depicted in Figure 8.

Spatial interpolation distribution maps are derived from a methodology employed to infer values amidst points within a designated geographic location to utilize point data, such as radon concentrations gathered from diverse sites within an urban environment. Spatial interpolation method applies mathematical models to interpolate or extrapolate the values in interstitial spaces between discrete measurement locations. This methodology facilitates the estimation of anticipated values at arbitrary locations. This approach can be utilized to illustrate the spatial heterogeneity of environmental variables, including but not limited to air quality, aquatic contamination, pedological characteristics, or the dispersion of radon. A spatial interpolation distribution map of the Annual Effective Dose (AED) resulting from ingestion and inhalation across various age demographics, including adults, children, and infants, has been computed as described [15]. The distribution fit of interpolated Annual Effective Dose (AED) values is also shown in Figures 10-15.

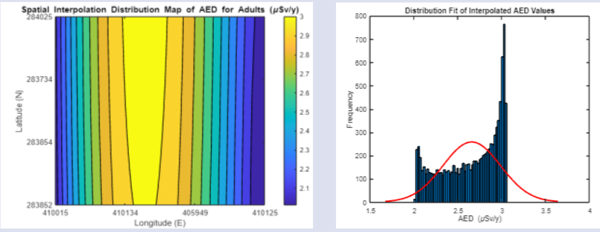

Figure 10. Spatial interpolation distribution map depicting the AED from ingestion for adults.

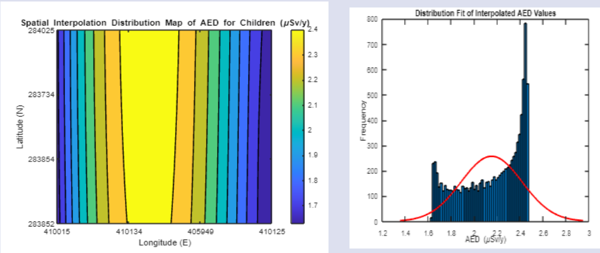

Figure 11. Spatial interpolation distribution map depicting the AED from ingestion for children.

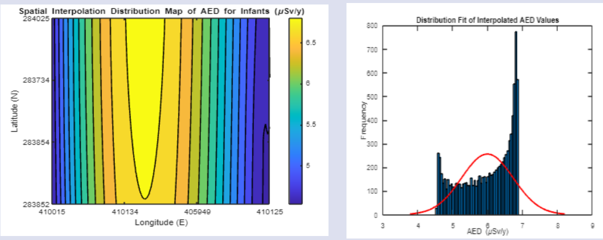

Figure 12. Spatial interpolation distribution map depicting the AED from ingestion for infants.

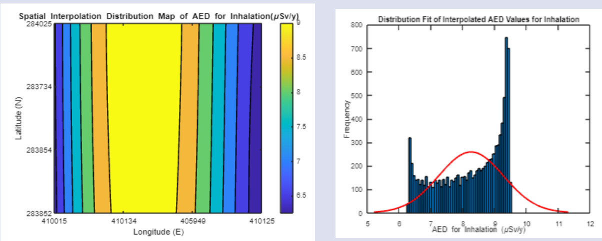

Figure 13. The histogram representing indoor radon measurements.

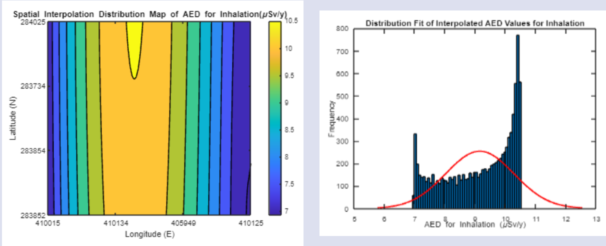

Figure 14. Spatial interpolation distribution map depicting the AED from inhalation for adults.

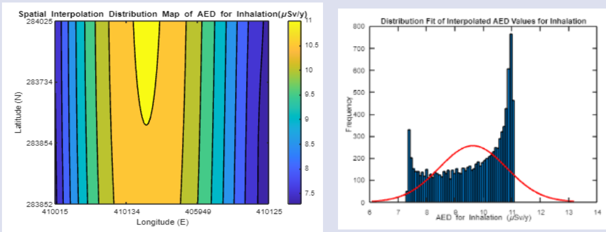

Figure 15. Spatial interpolation distribution map depicting the AED from inhalation for infants.

The colors on the maps indicate the estimated annual effective dose (AED) levels at various latitude and longitude points. It can be observed in Figures 10-15 that colors vary horizontally (longitude) and remain relatively constant vertically (latitude). Contour lines on the map represent equivalent AED levels. The opposite ends of color scale represent the lowest and highest AED values in the interpolation results. The histogram plot shows the frequency distribution of the interpolation results and a distribution fit curve (possibly a normal distribution) superimposed on it. This diagram demonstrates the variation of AED (Annual Effective Dose) values and outlines the general configuration of their distribution, emphasizing the central tendency. It is observed that the interpolation results span in a broad frequency spectrum, suggesting variability within a specific range throughout the interpolation process. The red fit curve exemplifies the anticipated frequencies under the assumption that the data adheres to a normal distribution. Nevertheless, the visualization reveals the presence of an extended tail, particularly on the right flank of the data distribution.

Table 1. The radon activity results for tap water samples

Tap Water	Date: 02.07.2019 Experimental measurement results (Bq/l)	Minimum measured value (Bq/l)
Sample 1	< 0.8 Bq/l	0.8 Bq/l
Sample 2	< 0.8 Bq/l	0.8 Bq/l
Sample 3	< 0.8 Bq/l	0.8 Bq/l
Sample 4	< 0.8 Bq/l	0.8 Bq/l

Table 2. AED due to ingesting and inhalation ^{222}Rn from tap water for adults, children and infants

Tap Water	Ingestion (µSv/y)			Inhalation (µSv/y)		
	Adults	Children	Infants	Adults	Children	Infants
Sample 1	< 2.04	< 1.652	< 4.6	< 6.34	< 7.03	< 7.39
Sample 2	< 2.04	< 1.652	< 4.6	< 6.34	< 7.03	< 7.39
Sample 3	< 2.04	< 1.652	< 4.6	< 6.34	< 7.03	< 7.39
Sample 4	< 2.04	< 1.652	< 4.6	< 6.34	< 7.03	< 7.39

The radon concentration levels in the water samples for Esenyurt and Beylikdüzü regions were analyzed by liquid scintillation counting system as shown in Table 1. During the water radon activity measurements, domestic water samples used by the residents in their daily lives were used. All values were found to remain under the minimum detectable amount (MDA). In a large metropolis such as Istanbul, distribution of water from the source to households can be made through complicated networks and the water is stored by Istanbul Water and Sewage Administration for periods which exceed the half-life of Rn-222 (3.7 days), resulting in significantly low radon concentration levels. Our finding is also under the level of 0.8 Bq/L (Table 1) which is lower than the recommended limit value specified by USEPA as 11 Bq/L [16].

Mamun and Alazmi (2022) conducted a study on the investigation of radon in groundwater utilizing the RAD7 electronic portable radon detector. The radon concentrations in groundwater within the examined area ranged from 0.03 to 3.20 Bq/L, averaging at 1.16 Bq/L. These estimated measurements significantly fall below the safety limits established by international organizations. The calculated total annual effective dose from radon exposure for infants, children, and adults varied between 0.05 and 16.24 µSv/y, with an average dose of 5.89 µSv/y, as reported by [17]. Duong et al. (2023) studied the seasonal 222Rn activity in spring water. The AED for residents who consume the spring water resources were reported to rage within acceptable limits, with average values calculated at 37.9 µSv/year for adults, 29.3 µSv/year for children, and 79.6 µSv/year for infants, respectively [18]. In relation to these values, within the context of our study, the AED_{ing} (ingestion) values for infants, children and adults are < 4.6 µSv/y, < 1.652 µSv/y, and < 2.04 µSv/y, respectively (Table 2). The findings calculated for AED_{ing} and AED_{inh} are summarized in the Table 2. The AED_{inh} (inhalation) values for infants, children and adults are < 7.39 µSv/y, < 7.03 µSv/y, and < 6.34 µSv/y, respectively (Table 2). The estimated AED values for ingestion and inhalation are significantly lower than the recommended threshold of 100 µSv/year, as reported by the World Health Organization (WHO) [19]. These values are also far below the limit values of World Health Organization [19]. These measured and calculated results remain under the specified limit values and pose no risk for human health, however periodical radon monitoring is necessary since various dynamic parameters (such as seismic, geographic, etc.) may be effective on radon levels in water.

Ingestion is calculated as given in Equation 3. The annual effective dose (AED) attributable to the ingestion of 222Rn from water by an individual was determined through the application of the following [11]:

$$AED_{ing}=C_w \text{ X } W_L \text{ X } DCF \quad (3)$$

where AED_{ing} denotes the annual effective dose received by an individual due to the ingestion of radon, C_w is the ^{222}Rn concentration in water ($Bq.L^{-1}$), W_L represents the annual consumption of water by adults, children, and infants, measured in liters. The values are assumed to be 730 L for adults, 350 L for children, and 250 L for infants, respectively [20-21] and DCF represents the dose conversion factor applicable to radon ingestion. The values are specified as 3.5, 5.9, and 23 nSv/Bq^{-1} for adults, children, and infants, respectively [22-23].

Inhalation is calculated as given in Equation 4. The annual effective dose (AED) attributable to water samples can be determined using the equation provided below [11]:

$$AED_{inh} = C_w \times R_{w/a} \times EF \times ET \times DCF \quad (4)$$

where AED_{inh} denotes the annual effective dose attributable to inhalation, C_w represents the concentration of ^{222}Rn in water, and $R_{w/a}$ indicates the coefficient for radon transfer from water to air (10^{-4}), EF signifies the equilibrium factor between radon and its progeny, possessing a value of 0.4, ET represents the mean exposure time, expressed in hours. ET is assumed to be 7000 hours annually, based on the premise that individuals spend 80% of the year in indoor environments and DCF denotes the dose conversion factor for inhalation of radon. It is 28.3, 31.4 and 33.0 $nSv(Bq.h.m^{-3})^{-1}$ for adults, children and infants, respectively [22, 23, 24].

ELCR is the excess life-time cancer risk and is calculated as given in Equation 5.

$$ELCR = E_W.DL.RF\ (Excess\ life - time\ cancer\ risk) \quad (5)$$

where E_W is the mean effective dose due to radon exposure, DL is the average lifetime (estimated as 70 years), and RF is the fatal cancer risk, and its value is 5.5 x 10^{-2} Sv^{-1} determined by [25]. Radon-induced lung cancer risk was calculated to define the conversion ion factor which is 18 x 10^{-6} $mSv^{-1}\cdot y$ [26, 27].

Table 3. ELCR calculation results

Tap Water	Excess life-time cancer risk ELCR (%)	Radon-induced lung cancer risk (per million persons)
Max C_{Rn}	0.96	44.82
Min C_{Rn}	0.33	15.48
Mean C_{Rn}	0.62	28.82

The calculated excess life-time cancer risk (ELCR) and radon-induced lung cancer risk values for minimum, maximum, and mean radon concentrations are shown in Table 3. The values of excess lifetime cancer risk range from 0.33 % to 0.96 %. The excess lifetime cancer risk values in the present study are lower than the EPA standard for the estimated risk as 1.3% corresponding with radon exposure of 148 Bq/m^3 for the entire population [28, 29].

The results of the published works related to water and indoor radon activity measurements in the Marmara Region and the corresponding calculated annual effective doses in various water sources are presented in Table 4 [30-36]. Tarım et al. (2012) measured Rn-222 concentrations in well and tap water samples from several geological formations in Bursa Province and reported that all measured concentrations were below the limit radon activity concentration value of 100 Bq/L specified by European Union. As reported by the authors, the radon activity concentration of tap water samples was lower than well water samples. They also reported a possible correlation between the activity concentrations and the geological structure of the subject area [30]. Akar (2010) carried out a work on radon activity levels in the thermal waters of Çekirge region in Bursa [31]. The author emphasized the necessity for determination of radioactivity around Bursa province due to the variation in the findings some of which exceeded the recommended value of 11 Bq/L determined by [16] and related this variation to the tectonic activities of North Anatolian Fault Zone and Eskişehir Fault Zone. Alakuş (2013) reported that the values exceeded the limit value of 11 Bq/L in several studied regions [32], which is consistent with the findings of [31] in the same region. Kılıç (2011) reported the radon activity concentration levels in Kükürtlü thermal waters from Bursa province and calculated the corresponding annual effective dose values. They attributed the significantly low concentration levels to the means of storage and escape of radon gas during sampling. The average indoor radon values were reported to range between 7.57 ± 4.35 Bq/m^3 and 179.09 ± 46.50 Bq/m^3 [33]. In a recent work of [34], radon activity concentration measurements were carried out with RAD7 radon detector Geyve, Doğançay and Örencik localities of Sakarya Province which are rich in granite soil in common. Drinking water radon concentrations were measured as 1.66 Bq/L in Geyve, 0.93 Bq/L in Örencik and 1.15 Bq/L in Doğançay [34]. Karahan et al. (1999) reported the activity concentrations of Rn-222 and Ra-226 in lake and tap waters (Bq/L). The concentrations were reported to be between 0.019 Bq/L and 0.048 Bq/L for Rn-222 [35]. In another recent work, Uludağ (2018) evaluated the radon gas levels in the spring water samples from Şile-Kandıra-İzmit in the Marmara Region. The radon measurement levels in the measured spring waters ranged from 0.334 Bq/L to 7.810 Bq/L and average value was 2.110 Bq/L. In the subject area, the results from spring waters did not indicate any health risk as they did not exceed the recommended values. The effective dose in Şile-Kandıra-İzmit regions is in the range of 0.12-1.64 mSvy^{-1} and it has an average value of 0.47 mSvy^{-1} [36].

Domestic use of groundwaters, which are in direct contact with geological formations rich in uranium and its decay products, leads to exposure to natural radiation via ingestion and inhalation of radon gas. Therefore, monitoring of radon activity concentration in waters has become an important task for protection of human health. In Marmara region, many of the drinking water supplies are directly connected to groundwater sources as shown in Table 4, thus monitoring of radon levels in these areas are of great importance. In the present research, on the other hand, the distribution of drinking water for the subject area (Esenyurt and Beylikdüzü districts of Istanbul) is provided indirectly via large water supply networks and after long storage periods which results in reduction in the radon levels due to the short half-life of radon gas until the drinking water reaches the end-users. Thus, the results of the present research in addition to those of the reported study in Table 4 carried out in Istanbul. Ref [35] indicate that, radon activity concentrations in Istanbul are lower than most of the other provinces of Marmara Region, such that, in the present research the measurement results remain under the minimum detectable level. The measurements of indoor radon concentration levels are based on the several factors. Acquisition of diverse measurement results from different study areas increase the importance of radon monitoring studies as well as establishment of a radon database. Aeration of indoor environments, elevation of detectors from the ground level, the subject building's structural material properties, its insulation, ground structure of the study area as well as the geological and seismic activities during the measurement period all contribute to the variance in indoor measurement results. Indoor radon concentration measurements were made in many areas of Turkey. In Table 5, the maximum average concentration values were measured as 793.6 Bq/m^3 in winter in Örencik [34].

Table 4. Radon activity concentrations and calculated annual effective dose values of water samples (min.-max. values, otherwise average values)

Location	Sampling source	Applied radon measurement method/detector	Radon activity concentration range (min.- max. Bq/L)	Annual effective dose	Ref.
Bursa	Well water Tap water	AlphaGUARD PQ 2000PRO	(1.46- 53.64) (0.91-12.58)	(0.02 -1.11 µSv/y)	[30]
Çekirge-Bursa	Thermal water	AlphaGUARD PQ 2000PRO	(2.513 ± 0.286) – (94.347 ± 4.361)	N/A	[31]
Bursa	Spring water	AlphaGUARD PQ 2000PRO	(0.62 - 50.96)	N/A	[32]
Kükürtlü-Bursa	Thermal water	AlphaGUARD PQ 2000PRO	(2.09 ± 0.145)	(0.0065 ± 0.0004 mSv/y)	[33]
	Pool water		(0.599 ± 0.115)	(0.0019 ± 0.0003 mSv/y)	
Geyve, Örencik and Doğançay - Sakarya	Drinking water	RAD7	(0.93 - 1.66)	N/A	[34]
Istanbul	Various sources	Lucas Radon detector	(0.019-0.048)	N/A	[35]
Şile-Kandıra-İzmit	Spring water	RAD7	(0.334 - 7.810)	(0.12-1.64 mSv/y)	[36]
Esenyurt and Beylikdüzü/Istanbul	Tap water	Liquid scintillation counting system	< 0.8	(Ingestion: 2.04 + Inhalation: 2.02 µSv/y)	Present study
Esenyurt and Beylikdüzü/Istanbul	Tap water	Liquid scintillation counting system	< 0.8	(Ingestion: 2.04 + Inhalation: 2.02 µSv/y)	Present study

Table 5. Radon activity concentrations and calculated values for annual effective dose of indoor samples (min.-max. values, otherwise average values)

Location	Sampling source	Applied radon measurement method/detector	Average indoor Rn-222 concentrations (Bq/m3) (min.- max. Bq/L)	The mean annual effective dose	Ref.
Edirne	Indoor (apartment buildings and houses)	CR-39 nuclear track detectors	49.2 Bq/m3	1.24 mSv/y	(37]
Sakarya	Indoor (classrooms, laboratories and offices)	LR-115 type-II solid state nuclear track detectors	40 ± 5 Bq/m3	1.00 mSv/y	[38]
Kilis, Osmaniye, Antakya	Indoor (houses)	Passive nuclear track detectors	50 Bq/m3 (Kilis) 51 Bq/m3(Osmaniye) 40 Bq/m3 (Antakya)	1.26 mSv/y(Kilis) 1.29 mSv/y(Osmaniye) 1.01 mSv/y(Antakya)	[39]
Erzurum	Indoor (dwellings)	Nuclear track detector LR-115	* 11 ± 6 Bq/m3 - 380 ± 91 Bq/m3 in winter season * 8± 3 Bq/m3 - 356 ± 64 Bq/m3 in summer season	* from 0.278 to 9.59 mSv/y in winter * from 0.202 to 8.98 mSv/y in summer	[40]
Geyve, Örencik, Doğançay	Indoor (dwellings)	LR-115 detectors	in Geyve for winter 221.63 Bq/m3 and for summer 138.37 Bq/m3, in Örencik for winter 793.67 Bq/m3 and for summer 194.00 Bq/m3, in Doğançay for winter 273.67 Bq/m3 and for summer 150.56 Bq/m3	-	[34]
Esenyurt and Beylikdüzü/Istanbul	Indoor (houses)	CR-39 detectors	63.56 Bq/m3	1.60 mSv/y	Present study

The minimum average concentration value was measured as 8 Bq/m^3 in Erzurum during the summer months [40]. As compared to these results, the findings of the present work shown in Table 5 are also lower than several average indoor concentrations values reported in the literature for the other locations in the Marmara Region. Measured radon activity concentration and calculated annual effective dose values of indoor sample was 63.56 Bq/m^3, this value is higher than Edirne indoor study with 49.2 Bq/m^3 [37], Sakarya indoor study with 40 ± 5 Bq/m^3 [38] and Kilis, Osmaniye, Antakya indoor study with 50 Bq/m^3 (Kilis), 51 Bq/m^3 (Osmaniye), 40 Bq/m^3 (Antakya) [39]. As reported in literature studies on indoor radon measurements, indoor radon levels significantly vary depending on the seasonal changes as hot weather conditions require aeration of indoor measurements which results in reduced radon concentration levels. This is also supported by the findings of the present research. In addition to the aeration of indoor environments, the variation in indoor radon measurement results may have also arisen from geological activities of the study area.

Conclusion

In this study, radon concentrations within indoor environments and water samples, collected from the Esenyurt and Beylikdüzü districts of Istanbul Province during the period from May 29, 2019, to August 13, 2020, were analyzed utilizing passive radon detectors and a liquid scintillation counting system.

- A total of 36 measurements of indoor (air) radon concentrations were conducted. The average value of radon concentration was determined to be 63.56 Bq/m³. The average annual effective dose derived from indoor radon measurements amounted to 1.60 mSv/year, which also fell below the recommended threshold values for indoor radon concentrations.

- The outcomes of radon activity measurements for all tap water samples were below 0.8 Bq/L. The AEDing values for infants, children, and adults are less than 4.6 µSv/y, less than 1.652 µSv/y, and less than 2.04 µSv/y, respectively. Similarly, the AEDinh values for infants, children, and adults are less than 7.39 µSv/y, less than 7.03 µSv/y, and less than 6.34 µSv/y, respectively. The estimated AED values for ingestion and inhalation are significantly lower than the recommended threshold of 100 µSv/year, by the World Health Organization (WHO).

- Spatial radiological maps, categorized by ages, were visually constructed within the locations under investigation.

- The majority of radon concentration assessments, including the one presented in this research, are predicated on considerations of human health. Consequently, it is customary for these measurements to be conducted in regions characterized by significant human density. Therefore, two districts have been selected, and radon measurements have been conducted.

- This research was aimed to gather the existing body of radon mapping data for the Marmara Region of Turkey documented in the literature, while also furnishing readers with insights into the water and indoor radon activity levels within the Marmara region.

- Preparation of publicly accessible radon maps for the purpose of regularly monitoring radon levels on regional and national scales, implementing radon reduction measures during the design and construction of new buildings, conducting radon mitigation training among the public, and enhancing awareness of radon's potential health risks, are practical suggestions that can be implemented within public health policies. Furthermore, research should be conducted to better understand the relationship between radon exposure and health outcomes, such as lung cancer.

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Conflicts of Interest

The authors declare no conflict of interest.

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