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ASSESSMENT OF RADON (^{222}RA) CONCENTRATION AND ASSOCIATED ANNUAL EFFECTIVE DOSE IN GROUNDWATER OF DARKAR, ZAKHO, IRAQ

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ABSTRACT
This study investigates the concentration of radon (^{222}Ra) in groundwater sources in the Darkar subdistrict, located in the Zakho region of northern Iraq, an area heavily reliant on groundwater for both drinking and agricultural purposes. A total of eight groundwater samples were collected from various locations and analyzed for radon concentration and the corresponding Annual Effective Dose (AED) due to ingestion and inhalation for different age groups (infants, children, and adults). The results showed that radon concentrations ranged from 3.45 to 9.21 Bq/L, remaining well below the World Health Organization's recommended limit of 100 Bq/L. However, the calculated AED values revealed that infants and children in several locations exceeded the 100 µSv/y reference dose, with the highest exposures recorded in samples S1, S2, S7, and S8. These findings are particularly significant given the dependence of Darkar's rural population on untreated groundwater sources. The area's geological setting and lack of centralized water treatment may contribute to natural radon levels in drinking water. The study underscores the importance of continuous monitoring and risk assessment to protect public health and maintain the safety of groundwater used in daily life and agricultural irrigation. The results provide a valuable reference for local authorities and health planners to implement preventive measures and public awareness programs, especially in remote and agriculturally vital regions.
Keywords: radon; annual effective dose; groundwater quality; human health risk

1. INTRODUCTION

Radon (Rn) is a naturally occurring radioactive noble gas that poses significant health and environmental concerns due to its radioactivity and ability to migrate through soil and dissolve in groundwater [1]. It is a decay product of uranium-238, present ubiquitously in the Earth's crust. Among its isotopes, radon-222 is the most stable and most commonly encountered, with a half-life of 3.82 days. Though odorless, colorless, and tasteless, radon is a major source of natural radiation exposure to humans, especially through inhalation and ingestion [2]. Over the past few decades, increasing attention has been drawn to the presence of radon in drinking water supplies, particularly groundwater sources such as wells and springs, due to the potential health risks it poses [3].

Groundwater is a critical resource for drinking, irrigation, and industrial use across many regions of the world. However, in areas with uranium-rich geological formations, radon concentrations in groundwater can reach significantly elevated levels. As groundwater flows through rocks and soils that contain uranium, radon gas can leach into the water [4, 5]. When such water is used domestically, radon may be released into the air during household activities like showering, cooking, or laundering, resulting in a secondary exposure through inhalation. Moreover, direct ingestion of radon-contaminated water contributes to internal radiation exposure, affecting internal organs such as the stomach [6].

The health risks associated with radon exposure are well-documented, especially in relation to lung cancer. The World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) have identified radon as the second leading cause of lung cancer after smoking [7, 8]. While the inhalation route is considered the most dangerous, the ingestion of radon in drinking water has also raised concern due to its radiological dose to the stomach lining. The magnitude of the risk is influenced by various factors including the concentration of radon in water, water usage habit, building ventilation, and lifestyle practices [9].

The effective dose from radon exposure depends on the route of entry (inhalation or ingestion) and the amount of radon present in the environment or water source. According to WHO and UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), the average global effective dose from natural background radiation is about 2.4 mSv/year, of which radon contributes approximately 1.2 mSv/year [10].

For drinking water, USEPA has set an alternative maximum contaminant level (AMCL) for radon at 148 Bq/L (4,000 pCi/L) for states that implement a multimedia mitigation program, and 11 Bq/L (300 pCi/L) if no such program exists. These values are designed to keep the annual effective dose within recommended safety limits.

Despite these guidelines, radon levels in groundwater can vary widely depending on geology, depth of the water source, temperature, and other hydrogeological conditions [11]. In some regions, especially those with granitic or phosphate-rich rocks, radon concentrations may greatly exceed recommended limits, necessitating regular monitoring and mitigation [12]. The importance of assessing radon levels in groundwater is thus twofold: first, to understand the public health implications of chronic exposure, and second, to develop appropriate water treatment or ventilation strategies to reduce associated risks [13].

The aim of this study is to evaluate the concentration of radon gas in groundwater sources in Dakar village, Zakho, Iraq, in order to assess the potential radiological health risks to the local population. By measuring radon levels and estimating the effective dose from water ingestion, the study seeks to determine whether the groundwater used for drinking and domestic purposes complies with international safety standards. The findings will support efforts to ensure safe water quality, raise public awareness, and provide recommendations for risk mitigation and sustainable groundwater management in the region.

2. MATERIAL AND METHOD

2.1 Study Area

Darkar is one of the subdistricts of Zakho District, located in the Dohuk Governorate within the Kurdistan Region of Iraq. The town is situated approximately 15 kilometers northeast of Zakho city, near the border with Turkey. Darkar is characterized by its mountainous terrain and moderate climate, making it a region of strategic importance for agriculture and groundwater use.

The village plays a vital role in local food production, as agriculture forms the backbone of its economy. The fertile land, supported by natural water sources, enables the cultivation of various crops and sustains livestock farming. Due to the absence of a centralized water supply system in many rural parts of the Kurdistan Region, the residents of Darkar depend heavily on groundwater wells for their daily domestic and agricultural water needs.

Figure 1 illustrates the geographical location of Darkar village along with its surrounding agricultural areas. The map also highlights the locations of the eight main groundwater wells that were selected for radon concentration measurement in this study. These wells are commonly used by local households and farms, making them critical points for assessing potential exposure to naturally occurring radioactive substances.

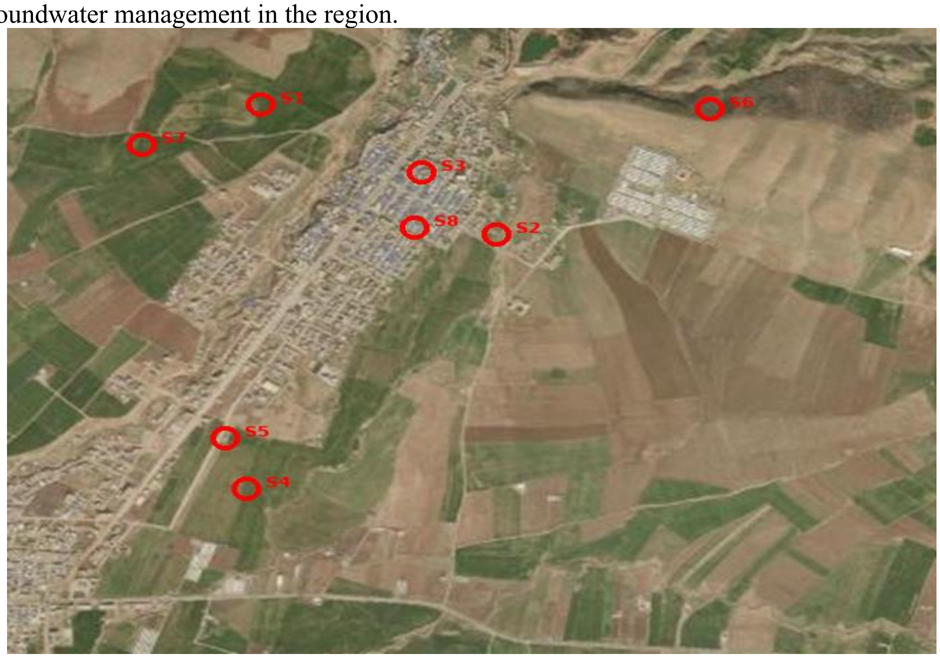

Figure 1. Locations of Groundwater Sampling Points in Darkar Village

2.2 Radon Analysis Method

The radon concentration in groundwater samples was measured using the RAD7 radon detector, a highly sensitive and widely used electronic device developed by Durridge Company. To enhance accuracy and reliability, the RAD7 was used in conjunction with the RAD H2O accessory, which is specifically designed for measuring radon in water samples as shown in Figure 2.

Figure 2 RAD7-Active used in this study

Before analysis, the RAD7 unit was calibrated according to the manufacturer's specifications to ensure consistent and precise readings. The RAD H2O system operates by degassing radon from the water into a closed air loop, allowing the RAD7 to detect and measure the released radon in its vapor phase. Each water sample was placed in a special vial and sealed tightly to prevent radon escape. The vial was then connected to the RAD H2O system, and the air loop was purged to remove any background radon or moisture that might affect the readings [14].

The measurement process typically took 30 to 60 minutes per sample, depending on the concentration of radon present. The RAD7 detector uses a solid-state alpha spectrometry sensor, which records alpha particles emitted by radon and its decay products. The resulting data is displayed digitally and stored for later analysis. All measurements were conducted under controlled laboratory conditions to minimize temperature fluctuations and environmental influences. Additionally, blank samples (distilled water) and standard reference samples were tested periodically to validate the accuracy and precision of the instrument. The final concentration of radon in water was reported in becquerels per liter (Bq/L).

2.3 Calculation of Annual Effective Dose (AED)

The Annual Effective Dose (AED) from ingestion and inhalation of radon (222 Rn) in drinking water was calculated based on guidelines provided by the UNSCEAR (2000) and WHO. The dose is assessed separately for different age groups: infants, children, and adults, considering both ingestion and inhalation pathways [15, 16].

Ingestion Dose Calculation:

The ingestion dose was estimated using the following formula:

(AEDing=CRn×IR×DCFing×365)

Where: C Rn C Rn = Concentration of radon in water (Bq/L) I R IR = Ingestion rate (L/day) D C F ing DCF ing = Dose conversion factor for ingestion (Sv/Bq) 365 = Days per year.

The ingestion rates and DCF values differ by age group, following standard recommendations.

Inhalation Dose Calculation: Radon released from water during household use contributes to inhalation exposure. The inhalation dose (A E D inh AED inh) is calculated as:

A E D inh = C Rn × F × O × D C F inh AED inh =C Rn ×F×O×DCF inh

Where: F F = Transfer coefficient of radon from water to air O O = Occupancy time indoors D C F inh DCF inh = Dose conversion factor for inhalation (Sv/Bq·m³) ◆ Total Dose: The total annual effective dose is the sum of ingestion and inhalation doses:

A E D total = A E D ing + A E D inh

These doses were computed for infants, children, and adults, and compared against the reference dose limits to evaluate radiological risk.

4. RESULTS AND DISCUSSION

4.1 Radon Concentration in Groundwater

The concentration of radon (^{222}Ra) in eight groundwater samples collected from different locations is presented in Figure 3 and summarized in Table 1. The measured values ranged from 3.45 ± 0.53 Bq/L (S6) to 9.21 ± 1.55 Bq/L (S8). The highest radon concentration was observed at S8, while the lowest was recorded at S6.

Most of the groundwater samples exhibited radon levels within the safe limits recommended by the World Health Organization (WHO, 2011), which sets a reference level of 100 Bq/L for radon in drinking water. This indicates that all samples fall well below the threshold of concern and are considered radiologically safe for human consumption in terms of radon content.

The variation in radon levels may be attributed to differences in the geological composition of the aquifer systems, particularly the presence of uranium-bearing minerals, as well as factors such as water-rock interaction, aquifer depth, and residence time. For example, locations such as S8 and S1 showed relatively higher radon concentrations, which may suggest greater contact with uranium-rich formations or extended stagnation of water allowing radon buildup. Figure 3 illustrates the spatial variation of ^{222}Ra concentrations across the sampled locations, highlighting that although some fluctuations exist, none of the sites pose a radiological risk based on current international standards

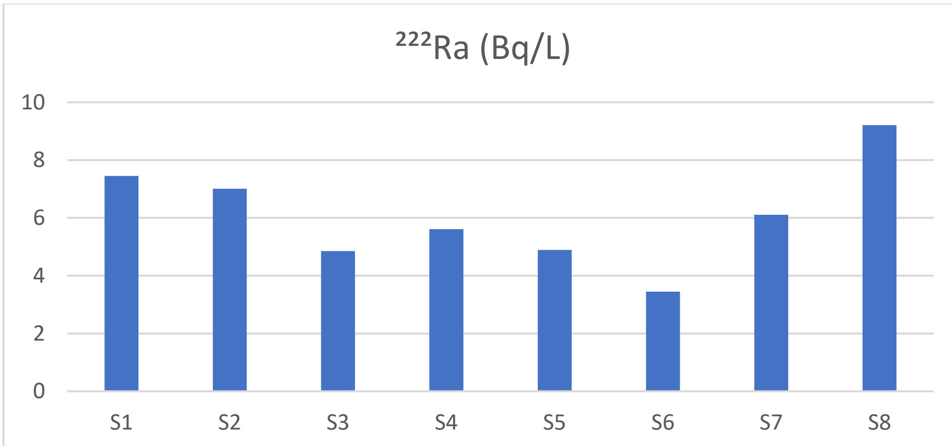

Figure 3. Radon concentration (^{222}Ra in Bq/L) in groundwater samples collected

4.2 Annual Effective Dose from Radon Exposure

The Annual Effective Dose (AED) from ingestion and inhalation of radon in groundwater was calculated for three age groups: infants, children, and adults. The results are shown in Table 1 and illustrated in Table 1. The ingestion dose (AED_ing) for infants ranged from 52.27 µSv/y (Sample 6) to 141.76 µSv/y (Sample 8), while for children it ranged from 68.15 to 183.34 µSv/y, and for adults from 15.89 to 44.27 µSv/y. As expected, infants and children received higher ingestion doses due to their greater water intake per unit body mass compared to adults.

The inhalation dose (AED_inh), resulting from the release of radon during household activities such as cooking, bathing, and dishwashing, varied between 8.35 µSv/y (Sample 6) and 22.96 µSv/y (Sample 8). The total dose (ingestion + inhalation) ranged from 60.62 to 164.72 µSv/y for infants, 76.50 to 206.30 µSv/y for children, and 24.24 to 67.23 µSv/y for adults.

All AED values for adults remained below the WHO reference level of 100 µSv/y for drinking water ingestion. However, it is noteworthy that the total annual dose for infants and children exceeded this level in several samples, particularly in Samples 1, 2, 7, and 8. These findings highlight the potential vulnerability of younger populations and emphasize the need for continued monitoring and protective measures, especially in areas where groundwater is the primary source of drinking water.

Table 1. Annual Effective Dose (AED, µSv/y) from ingestion and inhalation of radon

Sample	AED_ing Infants	AED_ing Children	AED_ing Adults	AED_inh	AED_total Infants	AED_total Children	AED_total Adults
1	114.82	152.61	37.11	18.95	133.77	171.56	56.06
2	107.34	144.25	34.02	17.62	124.96	161.87	51.64
3	73.81	98.02	23.14	12.02	85.83	110.04	35.16
4	86.92	115.34	26.79	14.32	101.24	129.66	41.11
5	74.63	97.82	22.75	12.08	86.71	109.9	34.83
6	52.27	68.15	15.89	8.35	60.62	76.5	24.24
7	93.24	125.45	30.32	15.55	108.79	141	45.87
8	141.76	183.34	44.27	22.96	164.72	206.3	67.23

The results of this study reveal that radon (^{222}Ra) concentrations in groundwater samples collected from the Darkar area of Zakho are generally within the safe limits recommended by international standards such as those of the World Health Organization (WHO). However, the calculated Annual Effective Dose (AED) indicates that while adults remain below the reference level of 100 µSv/y, the total dose for infants and children exceeded this limit in several samples, particularly in samples S1, S2, S7, and S8. This is of concern because the population in Darkar depends almost entirely on groundwater for drinking and household uses, often consuming water directly from wells and springs without treatment. The area's geology, characterized by sedimentary and fractured formations, may contribute to the natural presence of radon in water. Given the rural nature of Darkar and the absence of centralized water treatment infrastructure, residents—especially vulnerable groups like infants, children, and pregnant women—may be at risk of chronic exposure to low doses of radiation through ingestion and inhalation. These findings emphasize the need for continued monitoring of groundwater quality in the region and the implementation of awareness programs or simple mitigation methods such as aeration. Overall, the study highlights the importance of safeguarding public health in regions like Darkar, where groundwater is the primary and sometimes sole source of water supply.

5. CONCLUSION

The study revealed that radon concentrations in groundwater from the Darkar area of Zakho are below the WHO recommended limit of 100 Bq/L, indicating generally safe water quality regarding radon content. However, the calculated Annual Effective Dose for infants and children exceeded the 100 µSv/y reference level in several samples, highlighting potential health risks for vulnerable populations. Given the heavy reliance on groundwater for drinking and agricultural use in this rural region, continuous monitoring of radon levels and public awareness are essential to minimize long-term radiation exposure. Implementing simple mitigation measures and improving water treatment infrastructure will be crucial to protect both human health and agricultural productivity in Darkar. This study provides a foundational baseline for future environmental health assessments in the region.

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