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Radiological Risk Assessment Of 222 Radon Concentration And Annual Effective Dose Calculation In Groundwater From Zakho, Iraq

Idrees Majeed Kareem[1], Ahmed Mohammed Ahmed[2*], Rangeen Shihab Mohammed[3], Hasan Ramadhan Abdo[4], Waseem Youkhanna Shlaimoon[5], Nijyar Abdulaziz Karim[6]

[1]Department of Civil and Environmental Engineering, University of Zakho, KRG, Email: idrees.kareem@uoz.edu.krd
[2]Department of Civil and Environmental Engineering, University of Zakho, KRG, *Email: ahmedahmed1998@gmail.com*
[3]Civil Engineering Department, Nawroz University, Duhok, KRG, Iraq.Kurdistan Region-Iraq, Email: rangeen.mohammed@nawroz.edu.krd
[4]Department of Environment Laboratory, Duhok Environment Office, Duhok, KRG, Iraq, Email : Hassan_Abdo132@yahoo.com, waseemtkhoma@yahoo.com, nijyar_artoshy@yahoo.com

***Corresponding Author:** Ahmed Mohammed Ahmed*
Email: ahmedahmed1998@gmail.com

Abstract

Radon, the heaviest of noble gases in the periodic table, is a naturally occurring radioactive nuclide found in rocks, soil, and water. It has gained increasing attention in recent research due to its association with cancer. This study focused on assessing the potential radioactive risks associated with water usage in Zakho, Iraq, by analyzing 16 groundwater samples collected from the primary water source. Alpha spectrometry with RAD7 and RAD-H2O accessories from Durridge CO was employed for assay purposes. The measured ^{222}Rn concentrations ranged from 0.21 ± 0.1 to 19.75 ± 4.8 BqL^{-1}, with an average of 8.90 Bq. $^{-1}$. The recorded values indicate that 31% of the data surpasses the specified United States Environmental Protection Agency (USEPA) limit of 11.1 BqL^{-1}. Notably, the evaluation of the total annual effective dose revealed significant age-related variations. Specifically, 62% of infant samples and 68% of children samples exceeded the acceptable limit of 100 µSv/y, while 25% of adult samples surpassed the World Health Organization (WHO) recommended threshold. The obtained data align with similar studies conducted globally, emphasizing the need for continuous radon monitoring during water consumption. The findings advocate for proactive measures to ensure the safety of these water sources, addressing the pressing concern of radon-related health risks.

Keywords: Radon Concentration, Annual effective dose, RAD7, Radioactive risks, Cancer

1. Introduction

Natural radionuclides are inherent components found in the environment, comprising rocks, soil, and water[1, 2]. As humans are a product of this environment, they experience radiation exposure through various pathways, including inhaling outdoor and indoor air, consuming food and water, and direct exposure from the ground or through skin contact[3].
The primary source of human radiation exposure from natural sources is attributed to radon gas[4]. Radon, a highly radioactive noble gas devoid of odor, color, or taste, raises radiological concerns due to the immediate danger it presents through inhalation or ingestion, given its alpha-emitting radioactive daughters[5,6]. This gas is released during the decay of radium, a byproduct of the natural breakdown of uranium. Radon, with a half-life of 3.8 days, emanates from rocks and soil, with a tendency to accumulate in confined spaces like underground mines and indoor environments[7-10]. The radioactive daughters, ^{214}Po and ^{218}Po, resulting from the decay of ^{222}Rn, contribute to approximately 90% of the total radiation dose received by humans due to radon exposure, as they decay through alpha emissions[11]. Recognized as the primary cause of lung cancer among non-smokers, radon has been the focus of extensive research at regional, national, and international levels[12,13]. The heightened attention to radon stems from its radioactive nature, widespread occurrence in the natural environment, and the associated risks it poses to public health. Numerous studies have been conducted to better understand its activity and its implications for human well-being[14].
Water is essential for human life and pivotal in environmental, geological, and radiological inquiries[15]. Elevated levels of radionuclides in groundwater raise health concerns, especially when individuals are exposed through the consumption of water in regions with increased background radiation. Additionally, inhalation of air, which is mixed with radon evaporating from the environment, contributes to potential health risks [16,17]. This emphasizes the crucial need to comprehend and monitor radionuclide occurrences in water sources to safeguard public health and the environment[18].
The concentrations of radon dissolved in groundwater are influenced by several parameters, including the characteristics of the aquifer, the residence time of water within the aquifer, water rock interactions, and the mineral content of the bedrock[19-23]. These factors collectively contribute to the dynamic variations in radon levels found in groundwater. Understanding and analyzing these parameters are crucial for assessing the potential risks associated with radon exposure through water consumption and for implementing effective strategies to manage and mitigate such risks in areas with varying geological and hydrological conditions[24,25].
Researchers have studied radon in groundwater, aligning with hydro-geological, geological, and radiological health investigations. Their goal is to understand radon distribution, associated risks, and broader hydro-geological and radiological conditions. Some studies reveal strong links between radon concentration and local geological features. Elevated ^{222}Rn in water can increase individual effective doses, potentially raising lung and gastric cancer risks[26-28].
Iraq is facing its most severe water shortage, affecting 7 million people, as warned by the Ministry of Water Resources. Compounded by the fact that 90 percent of the country's rivers are polluted the situation is urgent[29]. To address this impending crisis, exploring alternative methods for a more sustainable water supply is imperative, especially considering the inadequacy of the current water resources[30, 31]. Notably, the untapped potential of numerous wells in every community across the country could play a crucial role in alleviating the imminent water scarcity, emphasizing the need for immediate attention and proactive measures.
This study aimed to measure ^{222}Rn concentrations in drinking water from various groundwater sources in the study area and determine annual effective radon doses for groundwater consumers. The results are expected to complement existing baseline data and serve as a database for future research and policy formulation regarding ^{222}Rn concentrations in groundwater for Iraq.

2. Materials and Method

2.1 Study Area

Zakho, located about 55 km northwest of Dohuk in northern Iraq, at coordinates 37°08′37.00″N 42°40′54.88″E., serves as a vital commercial hub. Situated just 8 km from the Turkish-Iraqi border, it plays a crucial role as a customs point. The city, with a population of approximately 260 thousand residents, is a significant center for economic activities in the region.
GIS techniques proficiently evaluate and map the spatial distribution of groundwater quality, depicting selected well locations in the specified area, as illustrated in Fig. 1.

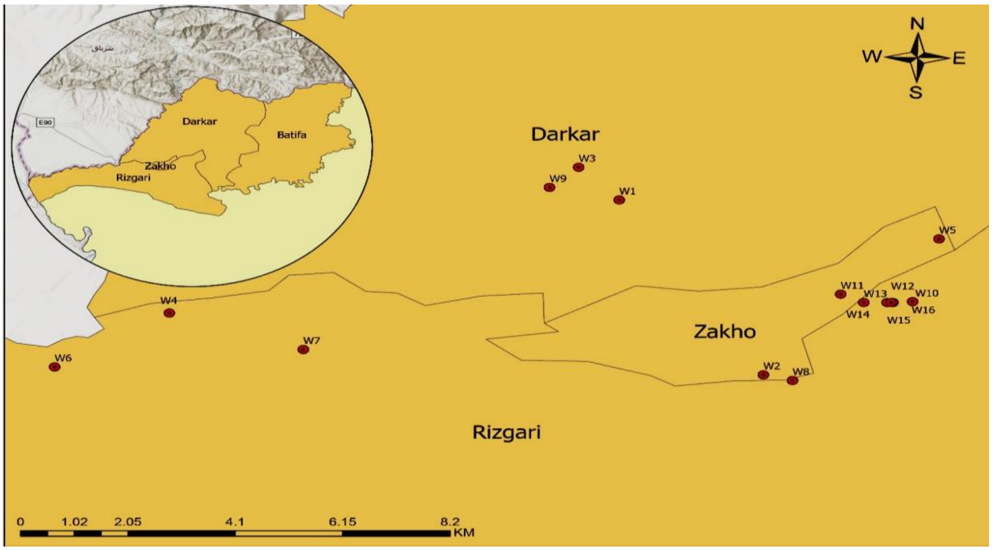

Fig.1 Map depicting the study area with sampling points

Due to ongoing population growth, Zakho faces a significant shortage of potable water, despite having a substantial river like Khabor as its primary water source. The river, however, runs along the city and is heavily polluted due to waste disposal. Consequently, the available water does not meet the required standards for consumption. Fortunately, the city has numerous wells that tap into groundwater, offering an alternative and potentially cleaner water source. The city's average daily water surface consumption is 110,000 cubic units in 2023, while the water consumption for the previous year was 37,000 cubic units. Fig.2 illustrates the distribution of surface water and groundwater utilization for water consumption in the area. The figure demonstrates an increase in the utilization of groundwater in the area compared to the surface over the years. This underscores the importance of conducting investigations into the safe consumption of groundwater.

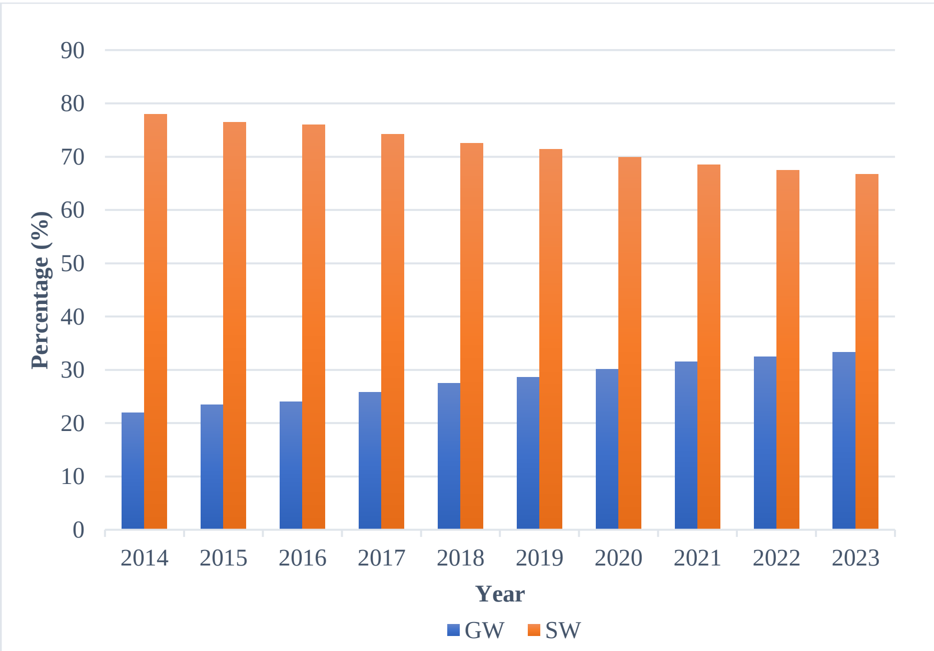

Fig. 2 Comparison between the utilization of surface water and groundwater in the study area.

'2.2 Sampling and Experimental Process

Sixteen wells have been strategically chosen at considerable intervals to provide a comprehensive assessment of the overall radon gas concentration in the area. The sampling process encompassed various groundwater sources. Notably, the selection of these wells took into account the potential for some wells to exhibit similar radon gas percentages due to their proximity and shared characteristics in terms of ground layers. This meticulous selection approach not only ensures a thorough representation of the diverse geological context within the area but also acknowledges the likelihood of certain wells displaying comparable radon gas

concentrations. By adopting this nuanced methodology, the study aims to enhance its capacity to capture and analyze variations in radon concentration effectively, providing a more accurate and comprehensive understanding of the prevailing conditions in the study area.
Before experiments, the device undergoes a 20 to 30-minute purging process to remove residual air and reduce humidity to less than 6%. After every three experiments, an Active Carbon cleaning cycle eliminates particles from the inner walls.
Water samples were gathered using the 40 ml vial provided with the Durridge RAD-H20 system. Subsequently, these collected samples were transported to the laboratory for analysis, utilizing a radon detector RAD7 that had been factory-calibrated and coupled with RAD-H20 accessories[32].
Figure 2 illustrates the configuration of the RAD7 detector with RAD-H2O accessories employed for the measurements. The setup comprises four components: (1) the electronic RAD7 detector, (2) a 40 mL vial containing the water sample, (3) the desiccant tube supported by a resort stand, and (4) an infrared-enabled printer. In the RAD7 setup, a closed-loop aeration system is employed, ensuring that the volumes of air and water remain constant and independent of the flow rate as shown in Fig.3 [33]. The device expels radon from the water sample using a bubbling kit. The released radon enters a hemisphere chamber, producing polonium nuclei through decay. These nuclei are collected on a silicon solid-state detector in a high electric field. Their count estimates the radon concentration in the water sample through built-in software.

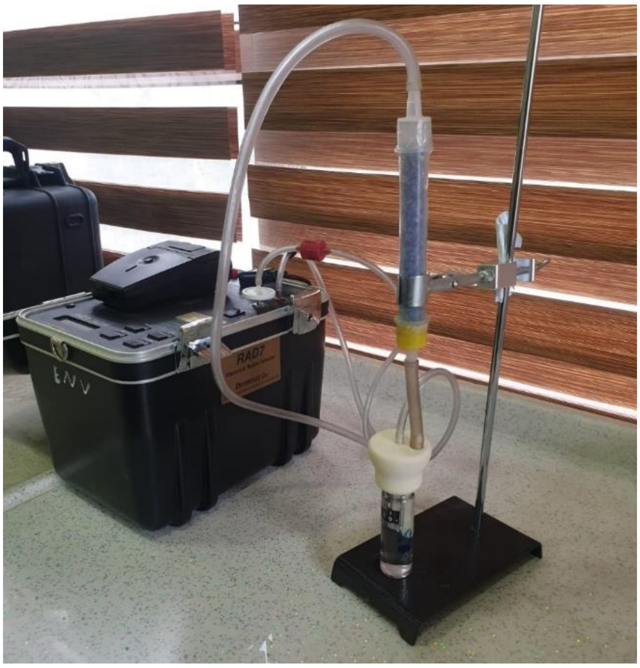

Fig.3 RAD7 Detector Setup with RAD-H2O Accessories used in this study

For method reliability and quality control, each water sample underwent automatic analysis in four 5-minute cycles. Before this, water aeration for 5 minutes using the kit released approximately 95% of radon. The RAD7 then automatically measured radon concentration. After a 30-minute interval, the printer generated a summary of results, presenting the average radon reading from the four cycles. This process includes calibration, sample vial volume, analysis time, and the closed air loop's total volume. The detector's sensitivity ranges from 10 pCi L^{-1} to 400,000 pCi L^{-1}. All measurements adhered to the ISO 13,164 protocol of the test method, utilizing two-phase liquid scintillation counting for ^{222}Ra in water[34, 35].

2.3 Calculating the Annual Effective Dose

Human exposure to radon in water involves two main pathways: ingestion and inhalation. Ingestion occurs when individuals consume water with a specific radon concentration, while inhalation involves the release of radon from water into indoor air, leading to inhalation. Though ingesting radon through water is generally considered lower risk than inhaling indoor air, it remains significant. This study quantifies the average annual effective dose from both pathways, using expressions denoted as Eq.1 and Eq.2 for ingestion and inhalation, respectively. The evaluation extends to the combined effect of both pathways.[35, 36].
Within the scope of this study, an integral facet involves scrutinizing the efficacy of radon concentration in water by evaluating the effective dose incurred during consumption, with a focus on infants, children, and

adults. The elucidation of these assessments encompasses the formulation of distinct equations, denoted as Eq.3, Eq.4, and Eq.5, each tailored to calculate the annual effective dose (AED_{ing}) pertinent to a specific age category[36-38]. The Annual Effective Dose (total), a key metric in assessing the overall impact, is determined through the application of Eq 6.

AED_{ing}= CRn × WCR × DCF_{ing} (1)

AED_{inh} = CRnw × Rnw × F × O × DCF_{inh} (2)

AED_{ing} infants= CRn × 0.6× 365× 7× 10^{-8}× 10^{6} (3)

AED_{ing} children= CRn × 0.8× 365× 7× 10^{-8}× 10^{6} (4)

AED_{ing} adult= CRn × 1.3× 365× 1× 10^{-8}× 10^{6} (5)

AED_{total} = AED_{ing} + AED_{inh} (6)

In this context, $AED_{ingestion}$ and $AED_{inhalation}$ represent annual effective doses resulting from the ingestion and inhalation of radon in water (µSv/year). Key parameters include CRn for radon concentration in water (Bq/L), WCR for water consumption rate (730 L/year), DCFing for the dose conversion factor for ingestion (3.5 µSv Bq^{-1}), Raw for the radon release ratio to air (10^{-4}), EF for the equilibrium factor between radon and progeny (0.4), OT for the average indoor occupancy time (7000 h/year), and DCFinh for the dose conversion factor for inhalation (9 µSv/h Bq/L).

3. Results and Discussion

3.1 Radon concentration

Table 1 displays the recorded concentrations of ^{222}Rn in groundwater samples gathered from both within and the surrounding residential areas of Zakho, Iraq.

Table.1 Activity concentration ^{222}Rn in groundwater from wells

Location	Sample code	Location coordinate	Radon concentration (Bq.L^{-1})
Distilled and Deionized water	W0	-	0
Jamshko Zakho Well Camp No. 3	W1	37.174444°N, 42.670000°E	2.98 ± 0.4
Fashkhabour project, old well	W2	37.135833°N, 42.694722°E	0.21 ± 0.1
Jamshko Zakho Well Camp No. 6	W3	37.181667°N, 42.663056°E	6.52 ± 0.9
Hizawa well candle	W4	37.186194°N, 42.468350°E	7.61 ± 1.4
Zakho Telkbar Well No. 7	W5	37.165852°N, 42.724847°E	8.68 ± 2.7
Ibrahim Al-Khalil Complex,	W6	37.137580°N, 42.573181°E	8.41 ± 1.6
Jam Korek Complex	W7	37.141431°N, 42.615817°E	1.89 ± 0.2
Khabur Zakho River	W8	37.134583°N, 42.699722°E	7.04 ± 3.7
Jammashkwi camp, well No. 1	W9	37.177222°N, 42.658056°E	0.81 ± 0.3
Telkabri Well 1 locality	W10	37.152000°N, 42.720322°E	11.01 ± 2.8
Karez district, well 9,	W11	37.153637°N, 42.707997°E	16.45 ± 4.3
Kariz Beer locality 106	W12	37.151806°N, 42.716958°E	18.15 ± 5.4
Al-Firqa locality, well 6	W13	37.151806°N, 42.711950°E	12.81 ± 2.1
Karez district, well 8,	W14	37.151806°N, 42.716958°E	19.75 ± 3.2
Hazel well 2	W15	37.151806°N, 42.715958°E	19.75 ± 4.8
Hazel locality, Silo stream	W16	37.151806°N, 42.716650°E	0.36 ± 0.1
Average			8.90 ± 2.12

Initially, the radon device underwent a check to ensure its accurate functioning and determine if calibration by the company was necessary. Radon-free distilled and deionized water were placed on the device test the radon percentage. Fortunately, the results showed a radon percentage of zero, validating the accuracy and reliability of the radon device readings, as evidenced by W0 sample.

The concentrations of ^{222}Rn in the samples displayed a range from 0.21 ± 0.1 to 19.75 ± 4.8, averaging 8.90 BqL^{-1}. Approximately 31% of the recorded values exceeded the USEPA-specified limit of 11.1 Bq.L^{-1}, yet fell within the recommended range set by the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) and the European Union Commission (EU) at 4 – 40 Bq.L^{-1} and 100 Bq.L^{-1}, respectively[39].

The data presented in Table 1 reveals a significant disparity in the activity concentration of ^{222}Rn among the well results. This variation can be attributed to various factors, including the characteristics and composition of the aquifer, the presence of radionuclides in the bedrock, the duration of water residence within the aquifer, and the storage facilities, among other potential influences[40, 41]. Water on the surface usually has less radon, which comes from sources like springs underground. But when this water travels, the radon levels drop because it has a short half-life of 3.8 days and evaporates easily. On the other hand, groundwater often has more radon because it passes through or stays in places with uranium. The uranium changes and produces radon. The study looks into how radon breaks down in water, focusing on understanding how much time it takes for half of it to disappear.

Table 2 presents a comparison between the findings of our study and radon measurements from various locations globally. Upon examining the table, it becomes evident that the range of values recorded for groundwater sources in our study aligns with the ranges reported in existing literature, with one notable exception. Boreholes in India, displayed higher ranges compared to the values documented in other locations. This discrepancy invites further exploration and analysis to understand the specific factors contributing to the elevated radon concentrations observed in the Indian boreholes, distinguishing them from the patterns observed elsewhere in the world.

Table 2 Comparison of the activity concentrations of ^{222}Rn obtained in our study with results from various locations within and outside Iraq

Location	Water type	Radon Concentration (BqL^{-1})	References
Saudi Arabia	Groundwater	2.47	El-Araby *et al* (2019)[42]
India	Hand pump wells	12.5- 862	Duggal *et al* (2020)[43]
Ado-Ekiti, Nigeria	Wells/borehole	13.59	Oni *et al* (2014)[44]
Czech Republic	Hot spring	5.04	Girault *et al* (2018)[45]
Iran	Tap/wells/surface	16–23	Binesh *et al* (2010)[46]
Vietmann	Wells	1.4	Le *et al* (2015)[47]
Jamaica	Wells	18	Smith and Voutchkov (2017)[48]
Strzelin, Poland	Shallow wells	0.5–119.4	Przylibski *et al* (2020)[26]
Turkey	Tap	0.98–27.28	Buyukuslu *et al* (2018)[49]
Baghdad, Iraq	Drinking water	94.9±10.81	Najam *et al* (2018)[50]
Erbil, Iraq	Drinking water	0.06–13.06	Ezzulddin and Mansour (2020)[51]
Zakho, Iraq	Wells	0.21-19.75	Present Study

2.2 Calculated annual effective dose

Table 3 offers a detailed breakdown of the annually calculated effective doses, encompassing both ingestion and inhalation pathways, for individuals across different age groups, including infants, children, and adults within the specific study area. The comprehensive data in the table sheds light on the varying levels of exposure and risk assessment tailored to distinct age categories, providing a nuanced understanding of the potential impact of the studied factors on different segments of the population within the specified geographical region.

Table 3 Calculation of Total Annual Effective Dose

Location	AEDing infants (µSv/y)	AEDing children (µSv/y)	AEDing adult (µSv/y)	AEDinh (µSv/y)	AEDtotal (infants) (µSv/y)	AEDtotal (children)	AEDtotal (Adult)
Fashkhabour project, old well	45.72	60.96	14.15	7.52	53.23	68.47	21.67
Jamshko Zakho Well Camp No. 3	3.15	4.20	0.98	0.52	3.67	4.72	1.49
Jamshko Zakho Well Camp No. 6	100.02	133.36	30.96	16.44	116.46	149.80	47.40
Hizawa well candle	116.61	155.48	36.09	19.17	135.78	174.65	55.26
Zakho Telkbar Well No. 7	133.11	177.48	41.20	21.88	154.99	199.36	63.08
Ibrahim Al-Khalil Complex,	128.88	171.84	39.89	21.19	150.07	193.03	61.08
Jam Korek Complex	29.00	38.66	8.97	4.77	33.76	43.43	13.74
Khabur Zakho River	107.87	143.82	33.39	17.73	125.60	161.55	51.12
Jammashkwi camp, well No. 1	12.43	16.57	3.85	2.04	14.47	18.61	5.89
Telkabri Well 1 locality	168.86	225.14	52.27	27.76	196.62	252.90	80.02
Karez district, well 9,	252.19	336.25	78.06	41.46	293.64	377.71	119.51
Kariz Beer locality 106	278.17	370.89	86.10	45.73	323.89	416.61	131.82
Al-Firqa locality, well 6	196.35	261.80	60.78	32.28	228.63	294.08	93.05
Karez district, well 8,	302.72	403.63	93.70	49.76	352.48	453.39	143.46
Hazel well 2	302.72	403.63	93.70	49.76	352.48	453.39	143.46
Hazel locality, Silo stream	5.51	7.34	1.70	0.91	6.41	8.25	2.61

The effective doses of AEDing (ingestion) and AEDinh (inhalation) have been previously evaluated, leading to the calculation of the comprehensive annual effective dose for all samples. The total annual effective dose varies across different age groups, with a range of 3.67 to 352.48 µSv/y for infants, 4.72 to 453.39 µSv/y for children, and 1.49 to 143.46 µSv/y for adults.

The evaluation of the calculated total annual effective dose across various age categories reveals notable disparities. Specifically, the results indicate that for infants, (62%) of samples exceed the maximum acceptable

limit of 100 μSv/y, while for children, this number increases to (68%) of samples. In the case of adults, (25%) of samples surpass the recommended threshold according to WHO guidelines (2004)[52].
These findings draw attention to a concerning scenario, particularly for children, where the recorded maximum annual effective dose reaches 453.39 μSv/y. This result, notably exceeding the acceptable limit, suggests a significant radiation hazard in this category. Specifically, sources such as W15 and W16 exhibit levels of exposure that pose potential health risks, emphasizing the urgent need for targeted interventions and mitigation strategies in these areas.
This situation underscores the critical importance of age-specific considerations when assessing the overall impact on individuals within the studied population. The findings underscore the urgency of comprehensive understanding and management of the impact of ^{222}Rn in groundwater within the specified study area. These insights contribute significantly to a nuanced assessment of health-related concerns linked to radon exposure, providing valuable information for future interventions and regulatory measures tailored to the specific parameters and geographical region under investigation.

4. Conclusion

The study provides groundbreaking insights into the previously unexplored domain of radon gas concentration and its consequential effective absorbed dose in Zakho, Iraq a city increasingly reliant on groundwater due to the rapid growth and urban development observed in recent years. Addressing a significant gap in existing research, our investigation diverges from the conventional focus on water quantity and quality through chemical analyses by shedding light on the critical aspect of radon concentration and associated risks. The analysis of sixteen groundwater sources uncovered a diverse range in ^{222}Rn concentration, with values spanning from 0.21 ± 0.1 to 19.75 ± 4.8 Bq/L. Notably, 31% of recorded values surpassed the USEPA-specified limit of 11.1 Bq.L^{-1}. Evaluation of the calculated total annual effective dose across different age categories exposes marked disparities, particularly with 62% of infant samples and 68% of children's samples exceeding the maximum acceptable limit of 100 μSv/y. In the case of adults, 25% of the samples surpassed the recommended threshold according to WHO guidelines. Our findings underscore the pressing need for continuous radon monitoring in the area's drinking water, advocating for proactive measures to ensure the safety of these water sources. This study establishes a crucial baseline for future research and empowers regulatory authorities to formulate guidelines addressing radon concentration in the region.

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Declaration of Competing Interest

The authors state that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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