Radon Activity Concentration Measurements in the Water Collected from the Lower Zab River in the Kurdistan Region of Iraq

Jahfer M. Smail[1], Hiwa H. Azeez[2], Habeeb H. Mansor[2] and Saddon T. Ahmad[3]

[1]Department of Physics, Faculty of Science and Health, Koya University, Koya KOY45, Kurdistan Region – F.R. Iraq

[2]Department of Physics, College of Education, Salahaddin University – Erbil, Erbil, Kurdistan Region – F.R. Iraq

[3]Faculty of Medicine, Koya University, Koya KOY45, Kurdistan Region – F.R. Iraq

***Abstract*—This study aims to assess radon levels in the water of the Lower Zab River. Knowing the radon concentrations is crucial for understanding the potential risks to human health and implementing protective measures. A RAD7-H_2O detector has been used to measure the radon concentration in 28 water samples from the Lower Zab River in the Kurdistan Region of Iraq. Results show that the radon activity concentrations ranged from 0.5 to 4 Bq.L^{-1}, with an average of 0.61 Bq.L^{-1}, and the resulting annual effective dose (AED) varied from 0.137 to 60.06 Sv.y^{-1}, with an average of 12.08 Sv.y^{-1}. The average radon concentration and AED in the measured samples are below the reference levels recommended by the ICRP and the World Health Organization. Consequently, the LZR water is suitable for human consumption and use and does not present any health hazards related to radon exposure.**

***Index Terms*–Activity concentration, Annual effective dose, Lower zab river, RAD-H2O, Radon gas, Water**.

I. Introduction

Radon, a naturally occurring radioactive gas resulting from uranium and radium decay in rocks and soil, can contaminate groundwater. Physical properties of radon are a colorless, odorless, and tasteless gas at room temperature and pressure. Radon is denser than air and is about 9 times denser than the air we breathe (Ismail, 2008). Radon's melting point is around −71°C, and its boiling point is about −61.7°C. Radon is sparingly soluble in water, which means it can dissolve to some extent in water (Baskaran, 2016). Radon is highly radioactive. It is a decay product of uranium and thorium, which are naturally present in the Earth's crust. It decays into various radioactive isotopes known as radon decay products, some of which are also radioactive and can attach to airborne particles (Hussein, et al., 2018).

And chemical properties of radon are classified as a noble gas (Group 18 of the periodic table), making it chemically inert. It does not readily form chemical compounds with other elements. Due to its high ionization energy and electron configuration, radon does not readily react with other elements or compounds. It does not typically form stable compounds under normal conditions. While radon's chemical reactivity is low, some compounds containing radon have been synthesized under specialized laboratory conditions (Baskaran, 2016). These compounds are generally unstable and fleeting. The most significant aspect of radon's chemical behavior is its radioactive decay. Radon (^{222}Rn), a naturally occurring radioactive gas, possesses a half-life of 3.824 days. It arises immediately following the decay of radium (^{226}Ra). It undergoes alpha decay, emitting alpha particles (helium nuclei) and transforming into different elements in a decay chain. This decay chain eventually leads to stable lead isotopes (Aziz, et al., 2015). Radon activity concentrations in water vary due to geographic and geological conditions (UNSCEAR, 1988). Over 90% of the overall radiation dose from radon exposure is contributed by two of the ^{222}Rn daughters emitters, ^{214}Po and ^{218}Po (Gruber, Maringer and Landstetter, 2009). Radon is a by-product of the decay of ^{226}Ra, which comes from the natural decay series of ^{238}U. Radon daughters are generally solids that follow to the surface of airborne dust particles, unlike radon itself which is a gas. The risk of developing lung cancer rises if such contaminated dust is inhaled because the particles might follow to the lung's airways (Baykara, Karatepe and Doğru, 2011). When radon enters the human body through inhalation and ingestion, health risks associated with radon arise due to its short-lived progenies.

Most radon gas that enters the lungs is excreted and does not accumulate in the alveoli. Although only a small amount

ARO-The Scientific Journal of Koya University
Vol. XI, No. 1I (2023), Article ID: ARO.11192. 08 pages
Doi: 10.14500/aro.11192
Received: 09 May 2023; Accepted: 09 September 2023
Regular research paper: Published: 18 September 2023
Corresponding author's e-mail: jahfer.majeed@koyauniversity.org
Copyright © 2023 Jahfer M. Smail, Hiwa H. Azeez, Habeeb H. Mansor and Saddon T. Ahmad. This is an open access article distributed under the Creative Commons Attribution License.

of radon enters the lining of the lungs, it has the potential to cause DNA damage in vulnerable lung tissue and lead to cancer. Furthermore, when we inhale, we can take in radon decay products that are present in the air (Corrêa, et al., 2009). Because the half-life of radon decay products is brief, they mostly decay entirely inside the lungs (Hussein, 2018).

Radon can enter homes through two primary sources: Soil and water. Radon gas that emanates from soil is responsible for health issues associated with radon exposure (Najam, et al., 2018). Inhaling Radon from household water can cause lung cancer, while drinking water contaminated with radon can lead to stomach cancer (Al-Alawy, et al., 2018). A recent study found that the level of naturally occurring radioactive materials present in soil samples taken from the LZR was below the allowed limit (Smail, et al., 2021). The activity concentration of prompt radon gas in the Jale and Mersaid springs in Koya region has been measured using an HPGe spectrometer. These warm springs contain a considerable activity level arranged between 19.04 ± 0.55 $Bq.L^{-1}$ and 30.11 ± 0.67 $Bq.L^{-1}$ (Ahmad, Almuhsin and Hamad, 2021). The relationship between radon activity concentration and physicochemical parameters in groundwater of 24 different wells in Erbil city, Iraq, has been investigated using the RAD 7/H_2O detector (Qadir, et al., 2021). The main purpose of this research is to determine the activity concentration of radon in water samples collected from the LZR in the Kurdistan Region of Iraq using a RAD-H_2O semi-conductor radon detector, and its implications for human health. Furthermore, the relationship between radon concentration and physicochemical parameters was estimated for water samples collected from various locations. The most commonly used parameters by researchers are pH, Temperature, and EC.

II. Materials of Methods

A. Study Area

The Zab River gathers most of its water from the mountains in Iran (around 80%) and the rest from the mountains in the Kurdistan region of Iraq. The Dukan Lake generates 150 megawatts of electricity, irrigates 3,000 dunums of farmland, and supports the establishment of 400 fish farms (Smail, et al., 2023). It lies between 36° 11' 28.4" N and 35° 47' 23.3" N latitude and 45° 15' 43.6" E and 44° 10' 26.3" E longitude. Fig. 1 shows the geographic location of LZR in the Kurdistan region of Iraq, as well as the location of the sampling sites. The LZR is regarded as the primary source of potable water for a significant portion of the Raparin administration, as well as the cities of Sulaimaniyah, Kirkuk, Chamchamal, and Duzkhurmatu.

B. Sample Collection

The researchers gathered 28 water samples from various locations on the surface of the (LZR). These samples were collected in polyethylene containers with a capacity of 2 L, placed in a cool box, and then transported to the laboratory at Koya University. They were preserved at room temperature for radon exhalation. When collecting water samples, it is important to close the tubes so that the internal radon gas of the water does not evaporate to the outside, and to preserve the amount of real radon inside.

C. Sample Counting

The active-method RAD-H_2O solid-state detector was used to analyze the samples in a timely manner. The bottles were 250 mL filled with 200 mL of the water sample, and then the instrument was set up. The RAD-H_2O was programmed with the test Wat250 and has a 4-cycle of 5-min protocol, which uses this protocol with the use of a tube of 250 ml for the Rad device, and is usually used when there are samples of water in a large amount. The RAD - H_2O system consists of three primary units, which are depicted in Fig. 2.

The RAD7 radon monitor, a water vial with an aerator, and a small desiccant tube, which are all shown. Before taking measurements, the RAD7 was connected to the dry unit and purged for 30 min to eliminate any radioactive particles from the measurement chamber. Then, the RAD7 was connected to 250 mL water vials, and the test began by bubbling water for 5 min to extract radon from the sample. The RAD7 pump cycled air between the measurement chamber and the vials, at the end of the process, the RAD7 produced a summary of

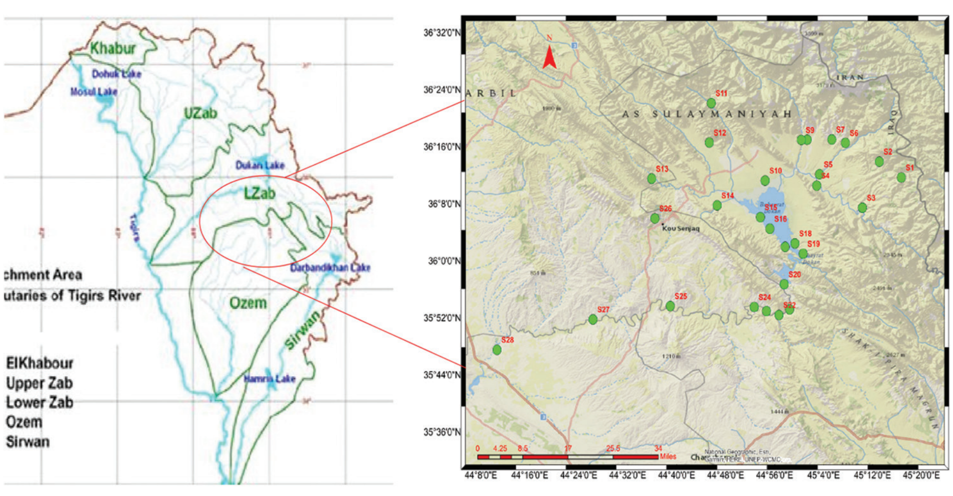

Fig. 1. The geographic location of LZR.

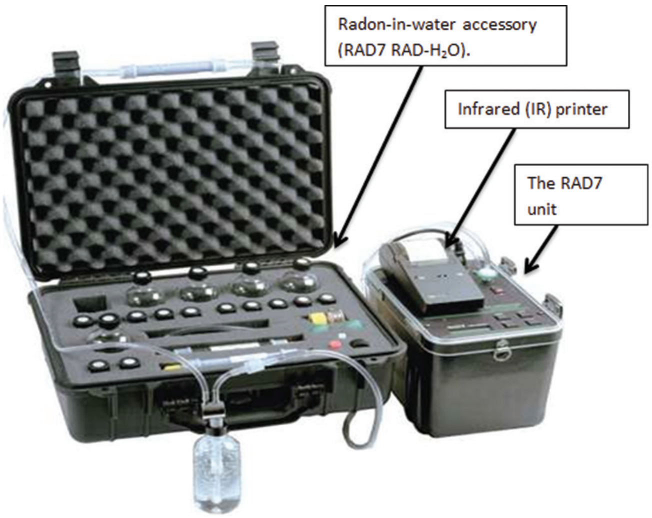

Fig. 2. RAD - H_2O instrument comprises three units: The RAD7 unit, the infrared printer, and the radon - in-water accessory.

the radon activity concentration in the water samples from the ^{218}Po source.

III. Calculation

A. Activity Concentration

The corrected radon concentration in the water during the sampling period was calculated using the equation provided below.

$$C_{(Rn)_0} = C_{Rn}\, e^{\lambda t} \quad (1)$$

Where $C_{(Rn)0}$ represent the actual radon concentration in the water, C_{Rn} is the radon concentration readied by the RAD7, λ is the decay constant of radon (λ = 0.181 day^{-1}), and t is the time interval between sampling and testing (Ezzulddin and Mansour, 2020).

B. Annual Effect Dose (AED)

The AED resulting from radon in water can be classified into two categories: the dose that is received from ingesting radon and the dose that is received from inhaling radon. When radon and its offspring are present in drinking water, they can mainly cause a radiation dose in the stomach through ingestion. Nonetheless, radon gas that is present in water can escape into the indoor air during daily activities such as showering, washing dishes, and using water in homes, which can significantly increase the risk of lung cancer from the radon that is inhaled. The calculation for the AED resulting from radon ingestion can be determined using the equation below (Abdullah, et al., 2023):

$$AED_{ing} = C_{RnW} \times C_w \times DCF \quad (2)$$

C_{RnW} =Represents the radon concentration present in the water.

C_w =For infants, children, and adults, the annual water intake is respectively equivalent to (150, 350, and 500) litters per year.

DCF=The Dose Conversion Factor varies according to age and is equal to (23, 5.9, and 3.5) Nano Sieverts per Becquerel for infants, children, and adults, respectively. To calculate the dose resulting from the inhalation of radon, the following equation can be utilized.

$$AED_{iha} = C_{RnW} \times R \times F \times O \times DCF \quad (3)$$

R, which denotes the ratio of radon in the air to water and has a value of; F, which represents the equilibrium factor between radon and its progeny and has a value of 0.4; O, which refers to the average time that an individual spends indoors and has a value of 7000 h/year; and DCF, which is the factor used to convert radon exposure into health risks and has a value of 9 Nano Sieverts per (Becquerel hour per meter cubed).

IV. Results and Discussion

A. Activity Concentration

The RAD-H_2O electronic device is utilized for gauging the amount of radon gas concentration. In sniff mode, the device exclusively relies on alpha particles emitted by ^{218}Po to calculate the concentration of ^{222}Rn. Table I contain a measured summary of the average radon activity concentrations in the surface water samples collected from LZR. The concentrations ranged from (0.15 ± 0.01) Bq.L^{-1} to (4 ± 0.06) Bq.L^{-1}, with an average concentration of (0.61 ± 0.02) Bq.L^{-1}. The results indicate that the highest level of contamination was found in sample S12 (Sarwchawa), which was below the recommended limit of 11.1 Bq.L^{-1} set by the EPA. The lowest concentration of radon gas was observed in samples S17 and S18, located in the central part of the Dukan Lake construction, where the water is stagnant. Radon gas was released to the open air, leading to a lower concentration of radon gas. The variation in radon gas concentration in the water samples is due to the varying geological formations and radium content in different areas of the study region. Table II presents a comparison of the present study's results with the average values obtained from the previous studies on water samples, both locally and internationally.

B. AEDs of Radon

Equations (2) and (3) can be used to calculate the AED for ingestion through the stomach and inhalation through the lungs, respectively. Table III presents the average AED for ingestion, inhalation.

The AED for ingestion had a range of 4.17–114.46 μSv.y^{-1}, with an average of 17.62 μSv.y^{-1}. In the case of infants aged 1–2 years who consume an average of 150 L of water annually, the AED_{ing} values varied between 0.5 and 13.78 μSv.y^{-1}, with an average of 2.12 μSv.y^{-1}. The dose received by this age group was lower than the recommended limit of 100 μSv.y^{-1} set by UNSCEAR in 2000 and the World Health Organization (WHO) for the general public.

The ICRP age groups for children range from 7 to 12 years old and have an average annual water intake of 350 L. The corresponding AED_{ing} values ranged from 0.31 to 8.25 μSv.y^{-1}, with an average of 1.269 μSv.y^{-1}. The dose received by children in the 7–12 age groups was lower than

http://dx.doi.org/10.14500/aro.11192

the recommended limit of 100 μSv.y^{-1} by UNSCEAR in 2000 and the WHO for the general public. Adults in ICRP age groups above 17 years have an average annual water intake of 500 L and the corresponding AED_{ing} values ranged from 0.25 to 6.99 μSv.y^{-1}, with an average of 1.07 μSv.y^{-1}. The dose rates received by adults in the ICRP age group

TABLE I
The Measured Radon Activity Concentrations in the Surface Water Collected from LZR

Code of samples	Location	^{222}Rn Activity concentration (Bq.L^{-1})
S1	Halsho	0.33±0.02
S2	Shekh awdalan	1.17±0.03
S3	Kawya	0.40±0.02
S4	Sndolan	0.26±0.02
S5	Braym awa	1.32±0.12
S6	Grd ester	0.15±0.01
S7	Sharwet	0.26±0.02
S8	Kona Mase	0.22±0.01
S9	Dole shahedan	0.51±0.02
S10	Darband	0.29±0.02
S11	Daraban	0.40±0.02
S12	Sarwchawa	4.00±0.06
S13	Jaly	3.59±0.06
S14	Khdran	0.20±0.01
S15	Kalkan	0.73±0.03
S16	Aleqa	0.22±0.01
S17	Merza Rostam	0.19±0.01
S18	Tangzha	0.15±0.01
S19	Khoshaw	0.15±0.01
S20	Lower Dukan	0.68±0.03
S21	Sartk	0.33±0.02
S22	Dwawan	0.29±0.02
S23	Klesa	0.22±0.01
S24	Bogd	0.22±0.01
S25	Mokharas	0.22±0.01
S26	Hamamok	0.15±0.01
S27	Segrdkan	0.34±0.02
S28	Prde	0.26±0.02
Average		0.61±0.02

were lower than the recommended limit of 100 μSv.y^{-1} set by UNSCEAR in 2000 and the WHO for the general public. Children and adults have a similar level of susceptibility to radon exposure. These findings emphasize the significance of calculating the AED separately for infants, children, and adults. These results are consistent with the earlier findings (Wallner and Steininger, 2007).

As per the guidelines set by the European Union (E.U. 1998) and the World Health Organization (WHO, 2004), drinking water is considered safe if the dose of radiation it contains is 100 μSv.y^{-1} or lower. In such cases, no further steps need to be taken. However, if the dose exceeds this limit, steps to lower the radiation levels are recommended.

The AED from inhaling radon released into the air through water varied between 3.97 and 108.92, with an average of 16.76 μSv.y^{-1}. The total AED for adults the whole body (including the stomach and lungs) ranged from 3.92 to 107.67, with an average of 16.57 μSv.y^{-1}. According to UNSCEAR's 2000 guidelines, the recommended mean dose for drinking and inhaling are 0.002 and 0.025 mSv.y^{-1}, respectively. Except for samples S12 and S13, all samples were within the recommended values for infants, children, and adults for both ingestion and inhalation.

Table IV provides information on the mean yearly effective dose for the entire body, ingestion, and inhalation.

The AED for ingestion of radon gas ranged from 4.17 to 114.46 μSv.y^{-1}, with an average of 17.62 μSv.y^{-1}. The AED for inhalation of radon released into the air varied from 3.97 to 108.92 μSv.y^{-1}, with an average of 16.76 μSv.y^{-1}. The total yearly effective dose for adults the entire body (stomach and lungs) ranged from 3.92 to 107.67 μSv.y^{-1}, with an average of 16.57 μSv.y^{-1}. All samples, except for S12 and S13, were within the UNSCEAR-recommended mean dose for drinking and breathing value which is 0.002 and 0.025 mSv.y^{-1}, respectively, for infants, children, and adults for both ingestion and inhalation (UNSCEAR, 2000). From Table IV, it is clear that infants are more affected by the dose of radon

TABLE II
Comparison of the Activity of RADON in the Present Study with that of Local and Foreign Countries

Country	^{222}Rn concentration Bq.L^{-1}	Source of water	References
Iraq – Erbil (Barserin village) Winter season	33.86±2.4	Drink water	Are and Mansour, 2022
Iraq - Kurdistan (Erbil)	0.06–13.06	Drink water	Ezzulddin and Mansour, 2020
Iraq Kurdistan (Darbandikhan Lake)	0.151–34.21	Drink water	Jafir, Ahmed and Saridan, 2016
Iraq (Kirkuk)	0.31–0.36	Drink water	Kareem, Ibrahim and Ibrahiem, 2020
Iraq (Baghdad province)	94.9±10.81	Drink water	Najam, et al., 2018
Iraq (Anbar)	2.1–6.4	Drink water	Farhan, et al., 2020
Iraq (Bagdad)	0.07–0.29	Drink water	Kadhim, 2015
Saudi Arabia	4.39–11.02	Drink water	Tayyeb, Kinsara and Farid, 1998
Pakistan	8.8	Drink water	Khattak, et al., 2011
Malaysia	0.041–3.97	Drink water	Nuhu, et al., 2020
Poland	0.42–10.52	Drink water	Bem, et al., 2014
Nigeria	4.3–42	Drink water	Avwiri, Tchokossa and Mokobia, 2007
Spain	0.22–52	Drink water	Dueñas, et al., 1999
Barzil	1.88–196	Drink water	Corrêa, et al., 2009
Iraq (Shatt-Al-Arab)	0.062	Surface water	Jebur and Subber, 2015
Turkey	0.091	Surface water	Canbazoğlu, et al., 2012
Iran (Mashhad City)	2.15	Surface water	Binesh, Mowlavi and Mohammadi, 2012
LZR	0.15–4.02	Surface water	Present study

TABLE III
The AEDs Resulting from the Ingestion of Radon in Water Samples in the LZR Area and the AED Caused by Inhaling Radon that Has Escaped into the Indoor Air of Homes For infants, Children, and Adults

Code of samples	Location	AED_{ing} (μSv.y^{-1})			AED_{inh} of radon gas by water in homes (μSv.y^{-1})
		Infant	Children	Adult	
S1	Halsho	1.13±0.06	0.68±0.04	0.57±0.03	8.26±0.46
S2	Shekh awdalan	4.03±0.12	2.41±0.07	2.04±0.06	29.42±0.86
S3	Kawya	1.39±0.07	0.83±0.04	0.71±0.04	10.16±0.50
S4	Sndolan	0.88±0.05	0.53±0.03	0.45±0.03	6.43±0.38
S5	Braym awa	4.55±0.41	2.73±0.24	2.31±0.21	33.26±2.99
S6	Grd ester	0.50±0.04	0.30±0.02	0.26±0.02	3.68±0.30
S7	Sharwet	0.88±0.06	0.53±0.03	0.45±0.03	6.46±0.40
S8	Kona Mase	0.76±0.05	0.45±0.03	0.38±0.03	5.54±0.37
S9	Dole shahedan	1.76±0.08	1.06±0.05	0.89±0.04	12.88±0.55
S10	Darband	1.01±0.06	0.60±0.04	0.51±0.03	7.36±0.43
S11	Daraban	1.39±0.07	0.83±0.04	0.7±0.04	10.12±0.50
S12	Sarwchawa	13.78±0.21	8.25±0.12	6.99±0.10	100.67±1.51
S13	Jaly	12.39±0.21	7.42±0.12	6.29±0.10	90.53±1.51
S14	Khdran	0.67±0.05	0.40±0.03	0.34±0.02	4.92±0.35
S15	Kalkan	2.52±0.09	1.51±0.06	1.28±0.05	18.41±0.68
S16	Aleqa	0.76±0.05	0.45±0.03	0.38±0.03	5.52±0.37
S17	Merza Rostam	0.67±0.05	0.40±0.03	0.34±0.02	4.91±0.35
S18	Tangzha	0.50±0.04	0.30±0.02	0.25±0.02	3.67±0.30
S19	Khoshaw	0.50±0.04	0.30±0.02	0.25±0.02	3.67±0.30
S20	Lower Dukan	2.35±0.09	1.41±0.05	1.19±0.05	17.15±0.66
S21	Sartk	1.13±0.06	0.68±0.04	0.57±0.03	8.27±0.46
S22	Dwawan	1.01±0.06	0.60±0.04	0.51±0.03	7.35±0.43
S23	Klesa	0.75±0.05	0.45±0.03	0.38±0.03	5.51±0.37
S24	Bogd	0.75±0.05	0.45±0.03	0.38±0.03	5.51±0.37
S25	Mokharas	0.75±0.05	0.45±0.03	0.38±0.03	5.51±0.37
S26	Hamamok	0.50±0.04	0.30±0.02	0.26±0.02	3.68±0.30
S27	Segrdkan	1.17±0.06	0.70±0.04	0.60±0.03	8.57±0.46
S28	Prde	0.88±0.06	0.53±0.03	0.45±0.03	6.43±0.40
Average		2.12±0.082	1.269±0.049	1.07±0.04	15.45±0.60

present in water than children and adults in all regions under study. Due to some reasons, infants have a higher respiratory rate than older children and adults. This means they inhale a larger volume of air relative to their body weight, which can result in a higher intake of radon gas if it is present in the indoor air. An infant's respiratory system is still developing and may be less efficient at filtering and clearing harmful substances from the air compared to older children and adults. This can lead to a greater accumulation of radon and its decay products in their lungs. Rapid cell division and growth are characteristic of infancy. This increased cellular activity can make developing tissues more vulnerable to the damaging effects of ionizing radiation, such as that emitted by radon and its decay products. They have less developed DNA repair mechanisms compared to adults. Ionizing radiation from radon can cause damage to DNA, and a less efficient DNA repair system in infants may lead to a higher likelihood of genetic mutations (Berglund, et al., 1992; Tong et al., 2012).

Infants tend to consume a higher proportion of liquids relative to their body weight compared to older children and adults. Radon can dissolve in water, and this can result in increased ingestion of radon-contaminated water in infants, potentially contributing to their overall exposure. They spend more time indoors, especially in their homes, compared to older children who might spend more time outside. If a home has elevated radon levels, infants may experience prolonged exposure during critical developmental stages. Infants have a relatively larger body surface area compared to their body volume, which could lead to a higher proportion of radon absorption through their skin (Kumar et al., 2021). Furthermore, all water in the study is suitable for use by populations.

C. Correlation between Water Quality Parameter and Radon Activity Concentration

Table V summarizes the outcomes of measuring several physicochemical parameters such as temperature, electrical conductivity, and pH for all samples to determine their impact on radon concentrations.

The electrical conductivity of surface water ranged from 247 to 716 μS.cm^{-1}, with an average of 352.43 μS.cm^{-1}. The World Health Organization (WHO) has set a limit of 600 μS cm^{-1} for the permissible electrical conductivity level in water.

A weak correlation was observed between electrical conductivity and radon concentration in surface water, with a correlation coefficient of (R^2 = 0.29), except for samples S11 and S13. These samples are unsuitable for drinking due to their high sulfide content, which results in high electrical conductivity. The evaluated radon with an increase

TABLE IV
THE COMBINED YEARLY EFFECTIVE DOSE RESULTING FROM CONSUMING AND INHALING RADON IN WATER SAMPLES OVER AN EXTENDED PERIOD AT LZR IS REFERRED TO AS AED_{Total}

Code of samples	Location	AED_{Total} (μSv.y^{-1})		
		Infant	Childern	Adult
S1	Halsho	9.39±0.52	8.94±0.49	8.83±0.49
S2	Shekh awdalan	33.45±0.98	31.83±0.93	31.46±0.92
S3	Kawya	11.55±0.57	10.99±0.55	10.86±0.54
S4	Sndolan	7.31±0.43	6.96±0.41	6.88±0.40
S5	Braym awa	37.82±3.40	35.99±3.23	35.57±3.2
S6	Grd estr	4.18±0.34	3.98±0.33	3.93±0.32
S7	Sharwet	7.35±0.46	6.99±0.44	6.91±0.43
S8	Kona mase	6.3±0.42	5.99±0.4	5.92±0.40
S9	Dole shahedan	14.65±0.63	13.94±0.6	13.78±0.59
S10	Darband	8.37±0.49	7.96±0.47	7.87±0.46
S11	Daraban	11.5±0.57	10.95±0.55	10.82±0.54
S12	Sarwchawa	114.46±1.72	108.92±1.63	107.67±1.61
S13	Jaly	102.93±1.72	97.95±1.63	96.82±1.62
S14	Khdran	5.60±0.40	5.33±0.38	5.26±0.38
S15	Kalkan	20.93±0.77	19.92±0.74	19.69±0.73
S16	Aleqa	6.27±0.42	5.97±0.40	5.9±0.40
S17	Merza Rostam	5.58±0.40	5.31±0.38	5.25±0.38
S18	Tangzha	4.17±0.35	3.97±0.33	3.93±0.33
S19	Khoshaw	4.17±0.35	3.97±0.33	3.92±0.33
S20	Lower Dukan	19.5±0.75	18.56±0.71	18.34±0.7
S21	Sartk	9.4±0.52	8.94±0.49	8.84±0.49
S22	Dwawan	8.35±0.49	7.95±0.47	7.86±0.46
S23	Klesa	6.27±0.42	5.96±0.40	5.9±0.40
S24	Bogd	6.27±0.42	5.96±0.40	5.9±0.40
S25	Mokharas	6.26±0.42	5.96±0.40	5.89±0.40
S26	Hamamok	4.18±0.35	3.98±0.33	3.93±0.33
S27	Segrdkan	9.74±0.53	9.27±0.50	9.16±0.50
S28	Prde	7.31±0.46	6.96±0.44	6.88±0.43
Average		17.62±0.69	17.62±0.69	16.76±0.66

in electrical conductivity has been reported by (Tabar and Yakut, 2014). Fig. 3 illustrates the correlation between radon concentration in water and electrical conductivity.

The correlation between water temperature and radon concentration for surface water is presented in Fig. 4. From the samples analyzed for the effect of water temperature on the radon concentration, the results are presented in Table V. It was shown that there is no correlation between water temperature and the radon concentration for surface water with a correlation coefficient of (R^2 = 0.057).

The measured pH values for all water samples are presented in Table V. The average pH value of surface water was found to be 8.30, with a range of 7.5–9.4. The water tends to be more alkaline when it passes through the carbonate (Nilsson and Sandberg, 2017), and this may tend to decrease the radon concentration due to the capturing of radon by carbonate. It was observed that there is no correlation between radon concentration and pH with a correlation coefficient of (R^2 = 0.078) for surface water. The variation in pH water for drinking water is due to contact with the carbonate rocks such as limestone and dolomite (Alharbi, Abbady and El-Taher, 2015). All the measured values are within the acceptable ranges (6.5–8.5) declared by the WHO for drinking water, except for the samples

TABLE V
THE MEASURED RADON ACTIVITY CONCENTRATION AND PHYSICOCHEMICAL WATER QUALITY PARAMETERS

Code of Samples	Location	^{222}Rn concentration (Bq.L^{-1})	Water quality parameter		
			E.C. µs.cm^{-1}	Temp °C	pH
S1	Halsho	0.33±0.02	338	20	9
S2	Shekh awdalan	1.17±0.03	355	20	8.8
S3	Kawya	0.4±0.02	266	19	8.9
S4	Sndolan	0.26±0.02	273	16	9
S5	Braym awa	1.32±0.12	295	20	7.5
S6	Grd estr	0.15±0.01	247	22	9.1
S7	Sharwet	0.26±0.02	369	20	7.5
S8	Kona mase	0.22±0.01	290	20	7.8
S9	Dole shahedan	0.51±0.02	398	22	7.6
S10	Darband	0.29±0.02	255	16	8.3
S11	Daraban	0.4±0.02	716	12	9.4
S12	Sarwchawa	4±0.06	558	14	8.7
S13	Jaly	3.59±0.06	615	15	9.2
S14	Khdran	0.2±0.01	367	20	7.8
S15	Kalkan	0.73±0.03	257	18	8.5
S16	Aleqa	0.22±0.01	292	19	8.3
S17	Merza Rostam	0.19±0.01	247	17	8.5
S18	Tangzha	0.15±0.01	257	21	8.5
S19	Khoshaw	0.15±0.01	247	15	8.5
S20	Lower Dukan	0.68±0.03	330	15	7.7
S21	Sartk	0.33±0.02	324	18	7.9
S22	Dwawan	0.29±0.02	335	19	7.7
S23	Klesa	0.22±0.01	332	20	7.9
S24	Bogd	0.22±0.01	336	18	7.8
S25	Mokharas	0.22±0.01	337	12	7.9
S26	Hamamok	0.15±0.01	532	22	8.1
S27	Segrdkan	0.34±0.02	347	15	8
S28	Prde	0.26±0.02	353	10	8.4
Average		0.61±0.02	352.43	17.67	8.30

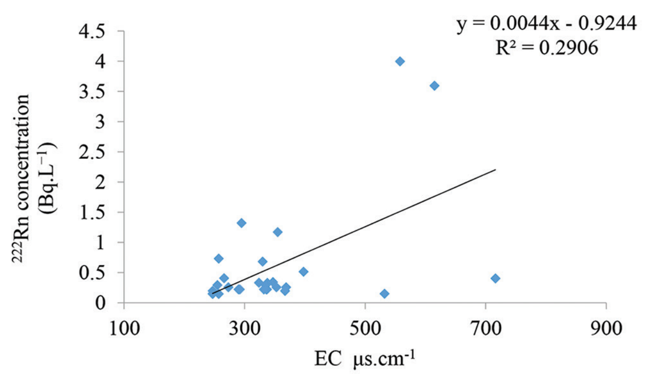

Fig. 3. The correlation between electrical conductivity and radon activity concentration for surface water.

(S1, S2, S3, S4, S11, S12, and S13) which are not suitable for drinking due to weak contact with the carbonate rocks such as limestone and dolomite.

Several studies have reported a similar negative correlation among dissolved radon, and some studies revealed a positive correlation between ^{222}Rn and pH. On the other hand, some studies show no correlation between pH and ^{222}Rn concentration. This is mainly because that radon is an inert gas. The correlation between water pH and radon concentration for surface water is presented in Fig. 5.

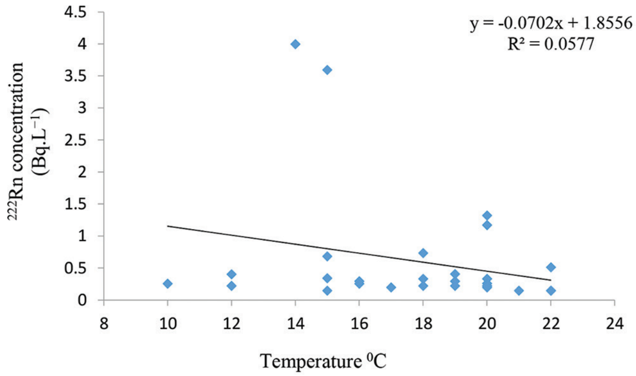

Fig. 4. The correlation between temperature and radon activity concentration for surface water.

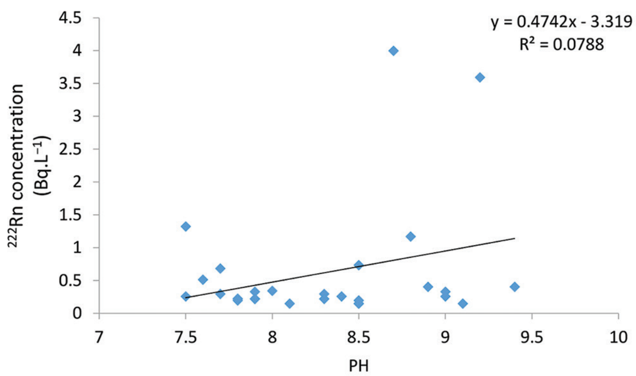

Fig. 5. The correlation between pH and radon activity concentration for surface water.

V. Conclusion

This study is to determined radon levels in surface water along the LZR. It is evident from the results that the radon levels in all examined surface water samples remain comfortably below the EPA's recommended limit of 11.1 $Bq.L^{-1}$, as stipulated in the guidelines from LZR. Furthermore, the investigation into the AEDs of radon for various age groups underscores the heightened vulnerability of infants compared to children and adults. However, reassuringly, the calculated AEDs to internal organs such as the stomach and lungs, arising from radon in surface water, remain well below the thresholds recommended by UNSCEAR for both ingestion and inhalation pathways. Interestingly, the lack of correlation between radon concentrations and key water quality parameters such as electrical conductivity and pH for surface water highlights the complex and multifaceted nature of radon distribution and behavior in aquatic environments. These findings hold significant implications, especially for governmental agencies entrusted with the responsibility of managing drinking water resources and ensuring their long-term sustainability. The insights gained from this study can serve as a foundational basis for informed decision-making, contributing to more effective strategies for the utilization and preservation of water resources. As such, this work stands to make a meaningful contribution to the broader goals of ensuring safe and sustainable drinking water sources for the well-being of communities and the environment.

Acknowledgments

The authors are appreciative to the Koya University and Salahaddin University-Erbil Research Centre teams for assisting with the completion of this work.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

References

Abdullah, G.M., Azeez, H.H., Mustafa, H.T., and Ismaeel, A.O., 2023. A study of radon concentration and physicochemical parameters in spring water of Erbil City, Iraqi Kurdistan Region. *Journal of Radioanalytical and Nuclear Chemistry*, 332(3), pp.775-784.

Ahmad, S.T., Almuhsin, I.A., and Hamad, W.M., 2021. Radon activity concentrations in Jale and Mersaid warm water springs in Koya District, Kurdistan Region-Iraq. *Journal of Radioanalytical and Nuclear Chemistry*, 328, pp.753-768.

Al-Alawy, I.T., Mohammed, R.S., Fadhil, H.R., and Hasan, A.A., 2018. Determination of radioactivity levels, hazard, cancer risk and radon concentrations of water and sediment samples in Al-Husseiniya River (Karbala, Iraq). *Journal of Physics Conference Series*, 1032(1), p.012012.

Alharbi, W.R., Abbady, A.G.E., and El-Taher, A., 2015. Radon concentrations measurement for groundwater using active detecting method. *American Scientific Research Journal for Engineering Technology and Sciences (ASRJETS)*, 14, pp.1-11.

Ameen, A.I.M., and Mansour, H.H., 2022. ^{222}Rn activity concentration measurement and its radiological risks in the environment of Barserin village, Erbil-Iraq. *Zanco Journal of Pure and Applied Sciences*, 34(2), pp.6-21.

Avwiri, G.O., Tchokossa, P., and Mokobia, C.E., 2007. Natural radionuclides in borehole water in Port Harcourt, rivers state, Nigeria. *Radiation Protection Dosimetry*, 123(4), pp.509-514.

Aziz, H.H., Samil, J.M., Ismail A.H., and Karim, H.H., 2015. Asses of indoor Radon dose and its risks on children's health using track detectors: Case study in Koya Kindergartens. *Journal of Kerbala University*, 11(2), pp.106-113.

Baskaran, M., 2016. *Radon: A Tracer for Geological, Geophysical and Geochemical Studies*. Springer, Berlin.

Baykara, O., Karatepe, Ş., and Doğru, M., 2011. Assessments of natural radioactivity and radiological hazards in construction materials used in Elazig, Turkey. *Radiation Measurements*, 46(1), pp.153-158.

Bem, H., Plota, U., Staniszewska, M., Bem, E.M., and Mazurek, D., 2014. Radon (^{222}Rn) in underground drinking water supplies of the Southern Greater Poland Region. *Journal of Radioanalytical and Nuclear Chemistry*, 299(3), p.1307-1312.

Berglund, B., Bert, B., Helmut, K., Thomas, L., Molhave, M.M.L., and Skov, P., 1992. Report no. 10 effect of indoor air pollution on human health. *Indoor Air*, 25, pp.2-25.

Binesh, A., Mowlavi, A.A., and Mohammadi, S., 2012. Estimation of the effective dose from Radon ingestion and inhalation in drinking water sources of Mashhad, Iran. *Iranian Journal of Radiation Research*, 10(1), pp.37-41.

Canbazoğlu, C., Doğru, M., Çelebi, N., and Kopuz, G., 2012. Assessment of natural radioactivity in Elaziğ Region, eastern Turkey. *Journal of Radioanalytical and Nuclear Chemistry*, 292(1), pp.375-380.

Corrêa, J.N., Paschuk, S.A., Schelin, H.R., Barbosa, L., Sadula, T., and Matsuzaki, C.A., 2009. Measurements of Radon Concentration Levels in Drinking Water at Urban Area of Curitiba (Brazil). In: *2009 International Nuclear Atlantic Conference-INAC 2009*.

Dueñas, C., Fernández, M.C., Carretero, J., Liger, E., and Cañete, S., 1999. ^{226}Ra and ^{222}Rn concentrations and doses in bottled waters in Spain. *Journal of Environmental Radioactivity*, 45(3), pp.283-290.

Ezzulddin, S.K., and Mansour, H.H., 2020. Radon and radium activity concentration measurement in drinking water resources in Kurdistan Region-iraq. *Journal of Radioanalytical and Nuclear Chemistry*, 324(3), pp.963-976.

Farhan, A.O., Ahmed, A.M., Awadh, S.M., and Al-Sultani, A.H., 2020. Radon gas and effective dose in groundwater in Abu-jir village in Anbar, Western iraq. *Iraqi Geological Journal*, 53(2C), pp.26-33.

Gruber, V., Maringer, F.J., and Landstetter, C., 2009. Radon and other natural radionuclides in drinking water in Austria: Measurement and assessment. *Applied Radiation and Isotopes*, 67(5), pp.913-917.

Hussein, A.M., 2018. Natural radioactivity and Radon exhalation in the sediment river used in Sulaymaniyah governorate, Iraq, dwellings. *ARO-The Scientific Journal of Koya University*, 6(2), pp.7-12.

Hussein, Z.A., Ismail, A.H., Battawy, A.A., Karim, H.H., and Smail, J.M., 2018. Indoor Radon levels in apartments of Erbil city by using long and short term techniques. *Tikrit Journal of Pure science*, 21(3), pp.150-154.

Ismail, A.H., 2008. Analysis of Radon concentrations in drinking water in Erbil governorate (Iraqi Kurdistan) and its health effects. *Tikrit Journal of Pure Science*, 13(3), p.9.

Jafir, A.O., Ahmed, A.A., and Saridan, W.M., 2016. Seasonal Measurements of Natural Radionuclides in the Water Resources and Sediments of Darbandikhan Lake in Kurdistan Region, Northeastern Iraq. In: *AIP Conference Proceeding*s. Vol. 1718.

Jebur, J.H., and Subber, A.R.H., 2015. Level of radionuclide contents in surface water from Shutt-al-arab river in Basrah governorate, Iraq. *International Journal of Advanced Research in Physical Science (IJARPS)*, 2(5), pp.1-6.

Kadhim, I.H., 2015. Analysis of radon concentration in drinking water in some locations at Baghdad City/Iraq. *Journal of University of Babylon for Pure and Applied Sciences*, 23(4), pp.1686-1692.

Kareem, D.O., Ibrahim, A.A., and Ibrahiem, O.S., 2020. Heavy metal and radon gas concentration levels in Khasa River in Kirkuk City (NE Iraq) and the associated health effects. *Arabian Journal of Geosciences*, 13(19), p.1023.

Khattak, N.U., Khan, M.A., Shah, M.T., and Javed, M.W., 2011. Radon concentration in drinking water sources of the main campus of the University of Peshawar and surrounding areas, Khyber Pakhtunkhwa, Pakistan. *Journal of Radioanalytical and Nuclear Chemistry*, 290(2), pp.493-505.

Kumar, A., Arora, T., Singh, P., Singh, K., Singh, D., Pathak, P.P., and Ramola, R C., 2021. Quantification of radiological dose and chemical toxicity due to Radon and uranium in drinking water in Bageshwar Region of Indian Himalaya. *Groundwater for Sustainable Development*, 12, p.100491.

Najam, L.A., Ebrahiem, S.A., Abbas, S.A., and Mahdi, H.A., 2018. Assessment of Radon gas concentrations levels and radiation hazards in the dwellings of Baghdad province, Iraq. *Rasayan Journal of Chemistry*, 11(1), pp.37-40.

Nilsson, A.C., & Sandberg, B. (2017). *Elevated pH Values in Groundwater Observations from SKB investigations*. Skb. Available from: https://www.skb.com/publication/2485482/R-16-04.pdf [Last accessed on 2023 Apr 06].

Nuhu, H., Hashim, S., Sanusi, M.S.M., and Saleh, M.A., 2020. Radon activity concentration measurements in water sources from Perak State Malaysia. *Journal of Radiation Research and Applied Sciences*, 13(1), pp.665-671.

Qadir, R.W., Asaad, N., Qadir, K.W., Ahmad, S.T., and Abdullah, HY., 2021. Relationship between radon concentration and physicochemical parameters in groundwater of Erbil City, Iraq. *Journal of Radiation Research and Applied Sciences*, 14(1), pp.61-69.

Smail, J.M., Ahmad, S.T., and Mansour, H.H., 2021. Estimation of the natural radioactivity levels in the soil along the little Zab River, Kurdistan Region in Iraq. *Journal of Radioanalytical and Nuclear Chemistry*, 331, pp.1-10.

Smail, J.M., Mansour, H.H., and Ahmad, S.T., 2023. Evaluation of radiological hazards in lower zab river sediments. In: *Radiation Effects and Defects in Solids*. Taylor & Francis, United Kingdom.

Tabar, E., and Yakut, H., 2014. Determination of 226Ra concentration in bottled mineral water and assessment of effective doses, a survey in Turkey. *Internatuinal Journal of Radiation Research*, 12, pp.193-202.

Tayyeb, Z.A., Kinsara, A.R., and Farid, S.M., 1998. A study on the radon concentrations in water in Jeddah (Saudi Arabia) and the associated health effects. *Journal of Environmental Radioactivity*, 38(1), pp.97-104.

Tong, J., Qin, L., Cao, Y., Li, J., Zhang, J., Nie, J., and An, Y., 2012. Environmental Radon exposure and childhood leukemia. *Journal of Toxicology and Environmental Health Part B Critical Reviews*, 15(5), pp.332-347.

UNSCEAR, 1988. *1988 Report to the General Assembly*. 647. Available from: https://www.unscear.org/docs/publications/1988/unscear_1988_report.pdf [Last accessed on 2023 Apr 10].

Wallner, G., and Steininger, G., 2007. Radium isotopes and ^{222}Rn in Austrian drinking waters. *Journal of Radioanalytical and Nuclear Chemistry*, 274(3), pp.511-516.