



# Radiation hazards in selected areas in the Adham Governorate, southwest of Saudi Arabia

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## Abstract

Buildings in Adham, Haqal, and Al Jaizah are constructed on/near granite rocks. They are also surrounded by high granite mountains, along which rainfall effects the livelihood of individual inhabitants. Uranium washed down from mountains has the potential to pollute agricultural activities, pastoral resources, and drinking water sources. Granite contains a high concentration of radioactive elements such as uranium, thorium, and potassium, which produce gamma rays that can cause environmental harm. Radon is produced from the decomposition of uranium and thorium and seeps into closed areas such as homes, offices, or nearby buildings. It also reaches groundwater via dissolved uranium in wells, which are used as a drinking water source and provide water for various agricultural activities. A car-borne gamma-ray spectrometer multichannel Canadian RS-700 device was used for the survey. The uranium, thorium, and potassium contents of these wells were determined, and the radiation dose rate was calculated and determined in units of mSv/year. The radiation dose rate in Haqal was 1.56 mSv/year, with an average value of approximately 0.7 mSv/year and standard deviation (*SD*) 0.18, while the radiation dose rate of Al Jaizah reached 1.17 mSv/year, with an average value of 0.4 mSv/year and *SD* 0.19, and in the Adham area, the dose rate reached 1.28 mSv/year, with an average value of 0.53 mSv/year and *SD* 0.14. Seventeen water samples were collected from different drinking water wells to measure their radon concentrations. DurrIDGE Co., USA, Rad-7 radon detector was used to record the results. The standard for radon contamination in drinking water is equal to 11.1 Bq L<sup>-1</sup> for public water supplies. The average value was approximately 6, 3.5, and 2.8 times the international limit in Haqal, Adham, and Al Jaizah, respectively.

**Keywords** Radiation dose rate · Granite · Adham · Leaching · Radon

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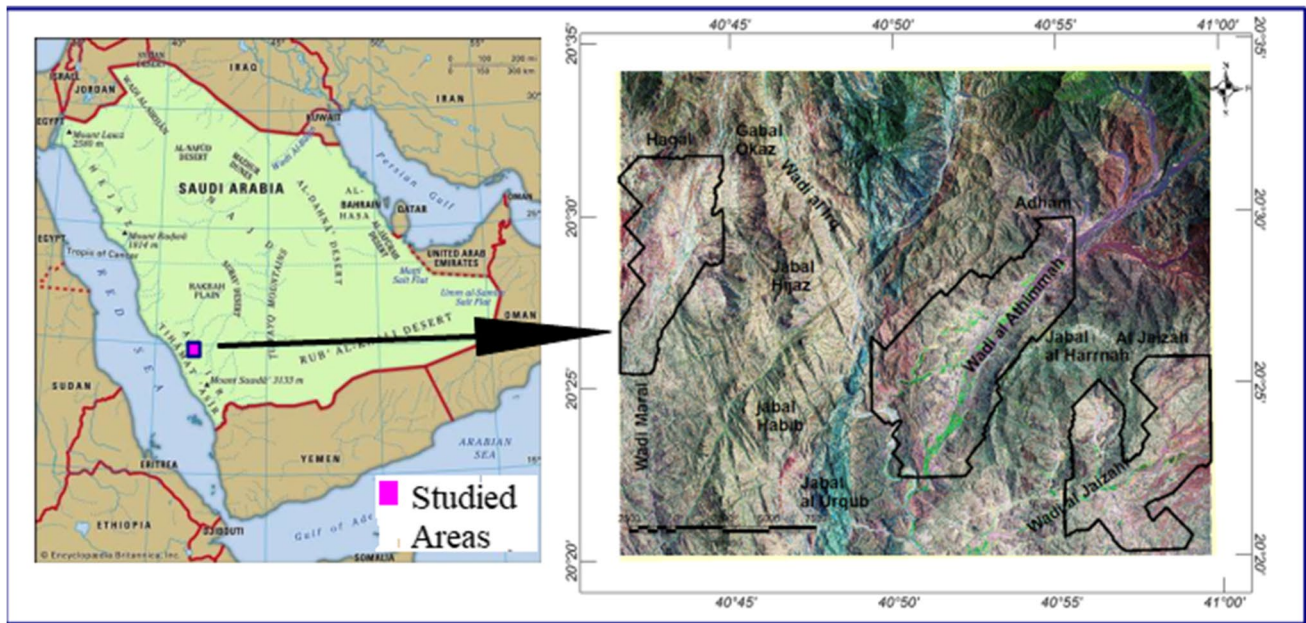
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## Introduction

The Adham Governorate is located southwest of the Makkah Al-Mukarramah region and borders the Emirate of Al-Baha region in the southeast, and it is bordered by the Maysan Governorate to the east. It is surrounded to the north, west, and south by the Al-Leith Governorate, and it shares a small part of its southern borders with the Al-Hajrah Governorate in the emirate of the Al-Baha Region. It belongs to the emirate of the Makkah Al-Mukarramah Region along the (41° – 41° 45′) longitude and (20° 15′ – 20° 30′) latitude ranges and is located approximately 150 km away from Makkah Al-Mukarramah (Fig. 1).

The Adham Governorate is included in the selected study area. The study area also includes residential areas, recreational areas, and government buildings. The expansion of these sectors is essential. Thus, the study of the environment



**Fig. 1** Location and land sat image maps showing the studied areas in Adham, Governorate, Southwest, Saudi Arabia

of this governorate is very important, especially because many homes and infrastructure units are built on basement rocks (especially granite or granitoid rocks). The expansion of cities always introduces the threat of the indiscriminate distribution of pollutants that come from agriculture or anthropogenic activities. In the study area, radiation pollution may come from the emission of gamma rays from surrounding mountains and subsurface rocks located under buildings. Many buildings in the Adham Governorate were constructed from or over granite rocks or their sediments. These rocks may be used to decorate kitchens, walls, and floors.

Gamma rays are emitted from granite units, buildings, and decoration materials (IAEA, 2000). Radon gas decomposes, and uranium and thorium are released from these rocks and accumulate in enclosed spaces, which may introduce cancer risks to humans after long-term exposure. Radon gas production can be reduced by constructing buildings where low radiation rocks are found, such as basic basement rocks.

Radioactive elements are among the most dangerous pollution sources that threaten life. In recent years, researchers have been interested in studying the distribution of these radioactive elements in the interior of the Earth in major cities (Cook et al., 1996; Pracilio et al. 2006; Dierke et al., 2011). Gamma-ray spectrometry has been used instead to study such a threat for environmental reasons (Drovnikov et al., 1997; Bollhöfer et al., 2008; Spadoni & Voltaggio, 2013).

The surveyed areas cover Adham city and the Al Jaizah and Haqal centers, as well as the hills that are distributed

within the region of focus. Radioactive sources such as uranium, thorium, and potassium were measured. The radiation dose was calculated considering the exposure rate by detecting gamma rays with a car-borne spectrometric system. This method used in this study is applied to the Adham Governorate area and its adjacent centers. Sanderson et al. (2004) surveyed Belgium by employing the airborne gamma-ray method and measuring the background radiation. Mohamed et al. (2016) reported that the annual effective doses are relatively lower in granitic building material samples in Madinah, Saudi Arabia. Hedley et al. (2016) determined the impact of radioactive elements on the environment by surveying dairy farms at Massey University, Auckland. Al-Kawazini et al. (2016) demonstrated that the background radiation varies between sites according to the building materials used, the type of building, the implemented ventilation used and the site in which it is located at German Jordanian University in Jordan. Osman et al. (2019) conducted a survey on campuses in Istanbul, Turkey, and calculated the average annual radiation dose. Aboud and Aboelnaga (2019) surveyed the King Abdulaziz University campus using a car-borne RS-700 system, and the results showed that the highest annual dose was 3.66 mSv/year, with an average value of 0.96 mSv/year in the university administration area and at newer buildings. They recommended that precautions should be taken to prevent the corresponding hazards.

Abuelnaga et al. (2021) surveyed the Al Aziziah area and its vicinity, Al Madinah Al Monawarah, Saudi Arabia, using a car borne RS-700 system for radiation environmental studies. The results show that when encountering granite, the

average dose rate is approximately 2.4 mSv/year; thus, the study recommended that continuous radon measurements be taken in closed spaces and within the ventilation system of homes and offices built in these places. Radon-222 is an element on the periodic table and is part of the noble gas group (helium, neon, xenon, and others). It is an invisible gas that is tasteless and odorless. Several other radioactive elements are generated to end this decay series with elemental lead (Reid, 1986). It is a chemically inert gas with a mass number of 222 and an atomic number of 86 with a density of  $9.7 \text{ kg/m}^3$ ; its boiling point is  $-61.8 \text{ }^\circ\text{C}$ , its freezing point is  $-71 \text{ }^\circ\text{C}$  (Mazen Hamid Hussein, 2010), and it is seven times heavier than air. Approximately one and a half are found in all places and at all times (Yunus et al., 2010). Radon-222 gas is a source of natural nuclear radiation, which is mainly generated from the natural decomposition of uranium ( $^{238}\text{U}$ ), thorium ( $^{232}\text{Th}$ ), and uranium ( $^{235}\text{U}$ ), and it is the only mineral that exists in a gaseous state (Hanaa, 2002). Radon has three radioactive isotopes: radon ( $^{222}\text{Rn}$ ), thorn ( $^{220}\text{Rn}$ ), and actinone ( $^{219}\text{Rn}$ ). It is known in geological and environmental studies that the isotope  $^{222}\text{Rn}$  has a relatively long half-life (3.82 days) when compared with the other radon isotopes. The role of the other two isotopes, i.e.,  $^{220}\text{Rn}$  and  $^{219}\text{Rn}$ , can be neglected due to their short half-lives (5.66 and 3.92 s, respectively). Radon can induce health risks through two pathways: the inhalation of radon and its decomposition products after its release from water into the air of homes and the direct ingestion of radon gas into drinking water. The risk of lung cancer is introduced due to the inhalation of radon decay products. Radon is not associated with any other disease. Numerous studies have been conducted in various regions of the world to determine the levels of exposure to radon gas using RADH2O. In Pakistan, researcher (Khattak et al. 2011) studied the concentration of radon gas in drinking water at Peshawar University using RAD7, and in Australia, a study that measured the concentration of radon in groundwater using RAD7 was presented by Hofmann et al. (2011). In India, Mehra and Badhan (2010) conducted a study to measure the concentration of radon gas in groundwater for villages and cities in Punjab Province using RADH2O, similarly to the work of Baldik et al. (2011). In their study, 39-CR reagent is used to study the concentration of radium-226 and radon-222 in the soil and surface water under 20 buildings in Turkey.

## Geologic setting

The Arabian shield and Arabian shelf (sedimentary rocks) are the two main rock units found in the Kingdom of Saudi Arabia and are representative Precambrian basement rocks. The Arabian shield represents one-third of the country's total area and is distributed in most of the western part of

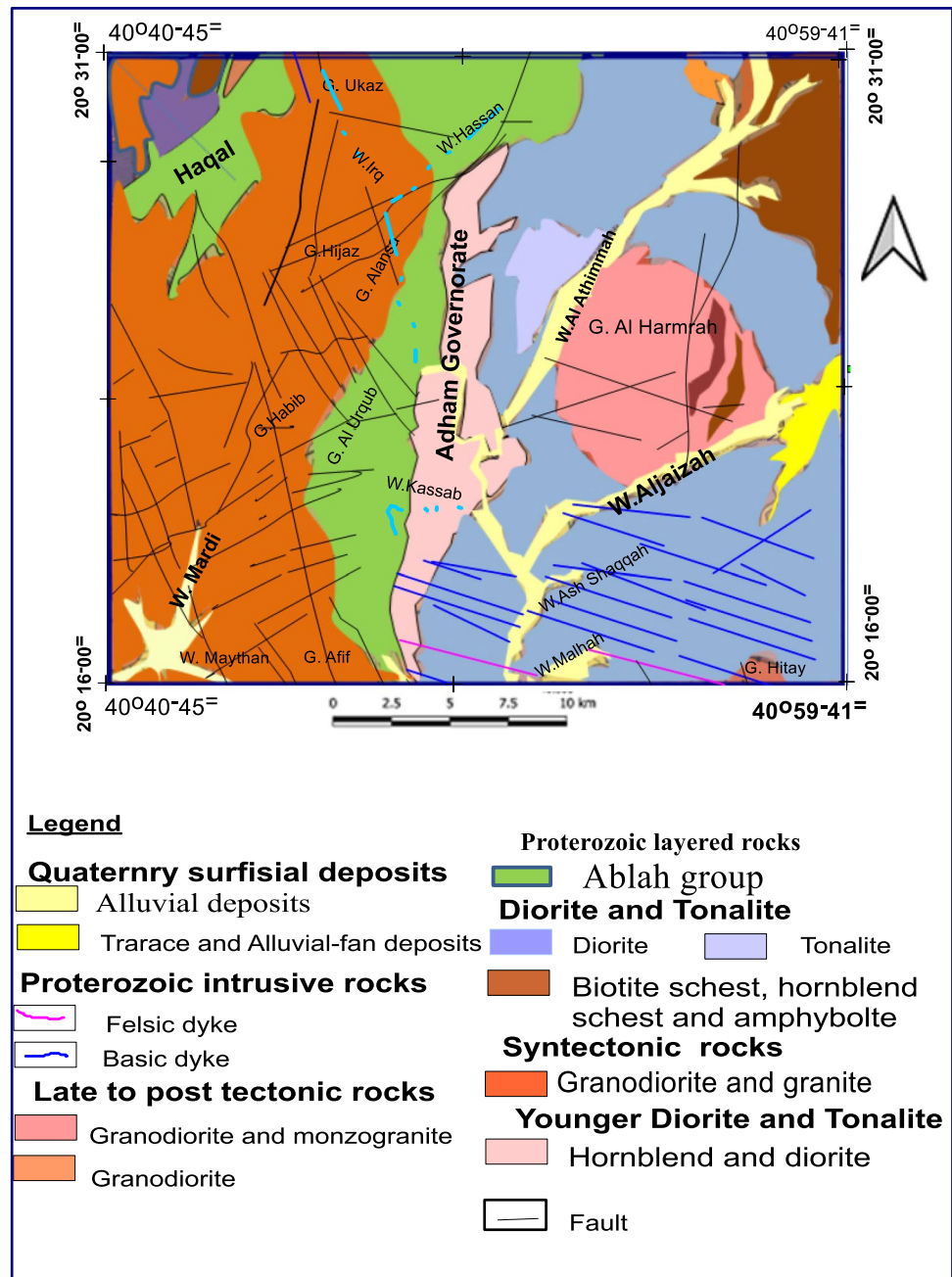
Saudi Arabia (Al-Shanti, 2009). The surveyed area of this study, i.e., the Adham area, is located in the southwestern part of Saudi Arabia. The rock units that are characteristic of the survey area and its surroundings are mostly basement derived excluding the Wadi sediments, which can be distinguished with a geologic map of scale 1:250,000 as a part of sheet No20 E, Gabal Ibrahim Quadrangle (1987) of the ministry of petroleum and mineral resources (Fig. 2) compiled by Fred W Cater and Peter R. Johnson (1987A.D-1407AH).

The area is surrounded by various basement rocks, with ages ranging from Proterozoic layered rocks to Cenozoic rocks. The Proterozoic rocks represented in this map by the Al Baha and Baish groups are undivided, and the older group of the two consists of biotite schist, hornblende schist, and amphibolite schist (designated as metamorphosed mafic to felsic volcanic, volcanic clastic, and epiclastic rocks, respectively). The second is represented by basalt and dacite (metamorphosed basaltic rocks, dacitic tuffs, and agglomerate rocks with subordinate mafic and felsic flow rocks and subordinate fine-grained epicyclic sedimentary rocks). The second group of Proterozoic layered rocks is represented by the Ablah unit (ANDIVIDID- amphibolite grade sedimentary rocks including amphibolite; quartzite locally containing kainite, calcitic quartz sericite phyllite; graphite-staurolite-hornblende; garnet-gneiss; locally kainite hornblende schist; and marble). The layered Proterozoic rocks in the surrounding selected area are represented by tonalite (hornblende-biotite tonalite and subordinate quartz diorite and granodiorite) and diorite (massive to foliate quartz diorite and gabbro). The Proterozoic intrusive rocks in this units are represented in the study area by two kinds of rocks, namely, hornblende diorite, secondary granodiorite and granite, which mostly cover the land and surround the selected study area, and are strongly foliated into gneissic hornblende-biotite granodiorite and monzogranite. The syn-tectonic granitic rocks are represented by diorite, granodiorite, and granite complexes, and they are strongly foliated to gneiss granodiorite and granite, lesser diorite and tonalite, minor gabbro, and abundant amphibole xenoliths. The mafic and felsic dikes cross-cut the previous rocks. The alluvial terraces are classified as recent deposits that were placed before the deposition of the Wadi deposits. The main wades are covered by Quaternary deposits, which are the weathering products of the adjacent rocks.

## Structure

The selected study area is surrounded by the Harmah pluton to the east, the Shaqqah pluton to the south and east, and the Afif pluton to the south and west. These plutons are dissected by many faults trending in many directions, and most of them drain towards the Adham study area. Many sets of felsic and acidic dikes and veins cross the study area and its

**Fig. 2** A brief geologic map of Adham study area, Southwest Saudi Arabia (compiled by Fred W. Cater and Peter R. Johnson (1987A.D–1407AH))

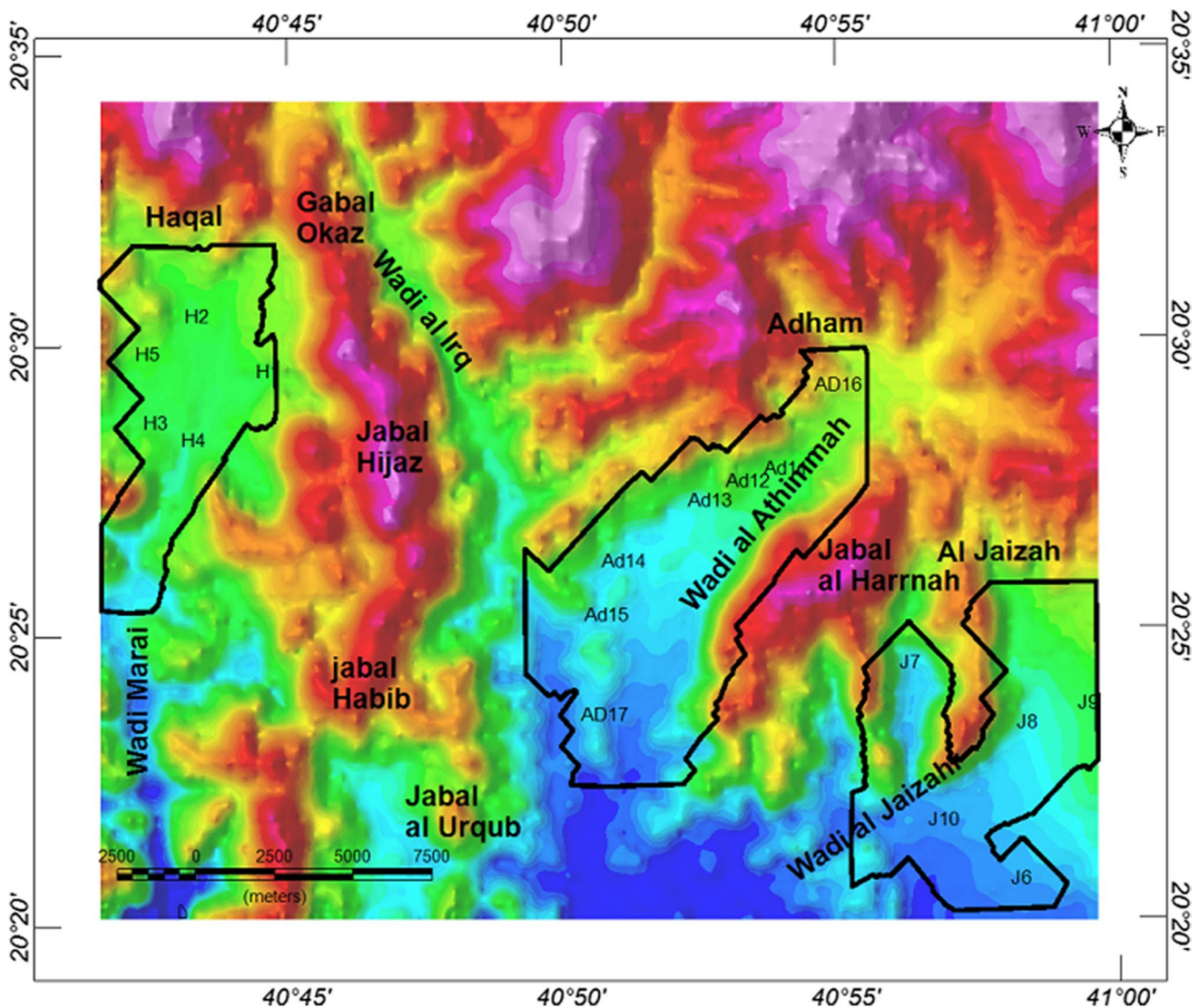


surroundings (structural sketch map of G. Ibrahim from the ministry of petroleum and mineral resources (1987)).

**Topography of the Adham Governorate**

The governorate of Adham, the centers of Giza and Haqal, are three basins of granite deposits (Fig. 3), which consist of the sediments of the surrounding mountains and contain residential areas within them. Therefore, it is important to know the direction of rain and flood flows, their impact on uranium leaching from the mountains, and the location of their deposits in the three basins. In general, the valley

land which hosts the city of Adham resembles a semiflat valley with a few simple hills, especially in the middle; there are many agricultural areas within Wadi Adham, which is surrounded by high mountains, especially from the east and west. The same topography in the Al Jaizah area, where the main area of in the middle of Wadi Al Jaizah resembles a flat valley, contains a few simple hills and agricultural areas; this area is surrounded by high mountains, especially from the north and northwest. The Haqal area contains many hills, with a widespread agricultural area. The eastern side appears to be flat. The elevation reaches 471 m above sea level in Adham and slopes



**Fig. 3** Topographic map showing the Adham Governorate, Aljaizah, and Haqal (ground water well numbers H in Hagal, A in Adham, and J in Aljaizah)

to the south until it reaches 360 m. The topographies of the three study areas are shown in Fig. (3).

### Aim of the research

The current research aims to determine the environmental radiation risk of the study areas. Total count radiation and radiation dose rate maps will be developed from carborne spectrometric system measurements. In addition, the concentration of radioactive radon gas in the groundwater wells used for drinking, agriculture, and animal husbandry in different areas of the Adham Governorate and the Al Jaizah and Haqal centers was measured, due to the absence of previous studies in the study area and

according to what was reported on the spread of cancerous diseases in this governorate in the Al-Arabiya channel in 2011. Radon is important because it can endanger human health due to its widespread distribution in building materials and soil and groundwater sources where people live in various parts of the governorate in valleys and on mountains that mostly consist of granite. Rainfall dissolves uranium from these rocks, which then descends into valleys, infiltrating into the regions soil and groundwater, where radon gas related to uranium and thorium is concentrated. Radon reaches the population in their homes via agricultural, drinking water, and grazing sources, and this gas can be found in the water of desalination networks in certain areas.

## Data source and availability

Based on the above information, gamma radiation was measured in the Adham area. The Geohazards Research Center conducted a radiation survey using a RS-700 device Canadian company (Radiation Solution Company). The spectrometric device was calibrated before the field survey by communicating with the manufacturer, and knowing the constants, it is installed above a car in December 2020 (Fig. 4), and the recording was monitored continuously while in motion. This system comprises a carbon/mobile spectrometer used for radiation control applications. It has advanced features, such as a gamma detector system, a digital signal spectrometer, a global positioning system, and a specially designed carbon fiber detector range. The RS-700 system consists of two 4-l NaIs with thallium detectors, Trimble detectors, power sources, and trailer vehicles, with an RS-700 multichannel analyzer and a computer for data collection. The NaI detectors consist of rectangular saws that are 73.1 cm long, 16.2 cm wide and 17.2 cm tall. The software version 5.7.1.0 is updated in Aprile 2017.

The collected data will be available on reasonable request for the scientific communities.

## Gamma-ray spectrometry interpretations

### Total count radiometric distribution in CPS

Total count (TC) radiometric contour maps of the three studied areas, i.e., Haqal, Adham, and Al Jaizah, south-west of Saudi Arabia (Fig. 5), show that the southern and middle portions of the Haqal study area reflect a high total count radiation reaching 2443 cps, while low TC radiation readings in the northern part and the midsection areas of N-S Wadi are recorded. In the Adham area, high amounts of TC radiation are recorded over most of the mid-area of studied region, excluding the main NE-SW-trending Wadi



Fig. 4 Carbone gamma-ray spectrometer system RS-700

location. These high readings reflect the presence of granite or granitic deposits, and boulders in these places, where the maximum reading reaches 1635 cps (pink color). In the Al Jaizah area, the TC radiation map shows high readings in the western part, especially the mid-reach reading of 2304 cps, which reflects the presence of granitoid rocks. The total count radiation decreased towards the east of the study area and reached its lowest value in the southern portion (Fig. 5). The statistical treatments of radioactive elements in the three studied areas are shown in Tables 1, 2 and 3.

## Methods for estimating radiation dose rate

Specialists used two methods to assess the potential external exposure to natural radionuclides. The first method is described as follows:

By subtracting the dose rate resulting from cosmic rays from the direct measurement of the external gamma dose rate, the dose rate is given in nGy/h.

Dose rate in nGy/h = the direct measured external gamma dose rate – cosmic rays.

The dose rate in nGy/h can be calculated considering the results of the concentrations of K%, eU, and eTh according to (IAEA 1989, IAEA 1991) as shown in Eq. (1).

$$Doserate(nGy/h) = 13.078K(\%) + 5.675eU(ppm) + 2.494eTh(ppm) \quad (1)$$

In this study, we use the second method. The radiation dose rate reported in mSv/year can also be calculated from the concentrations of the three radioactive elements of K%, eU, and eTh. The exposure rate was calculated in  $\mu$ R/h according to the equation provided by the IAEA (1991) as shown in Eq. (2).

Exposure rate ( $\mu$ R/h) = 1.505 K (%) + 0.653 eU (ppm) + 0.287 eTh (ppm)

$$Exposurerate(\mu R/h) = 1.505K(\%) + 0.653eU(ppm) + 0.287eTh(ppm) \quad (2)$$

The equivalent radiation dose can be estimated from the radiation exposure rate by using a conversion factor (IAEA, 1979) as shown in Eq. (3).

$$Doserate(mSv/year) = 0.0833 \times exposurerate(\mu R/h) \quad (3)$$

## Results and discussion of the radiation dose rate

### RDR contour maps in mSv/year

The calculated effect of (radiation dose rate) RDR within the three studied areas exceeded 1 mSv/year, which is

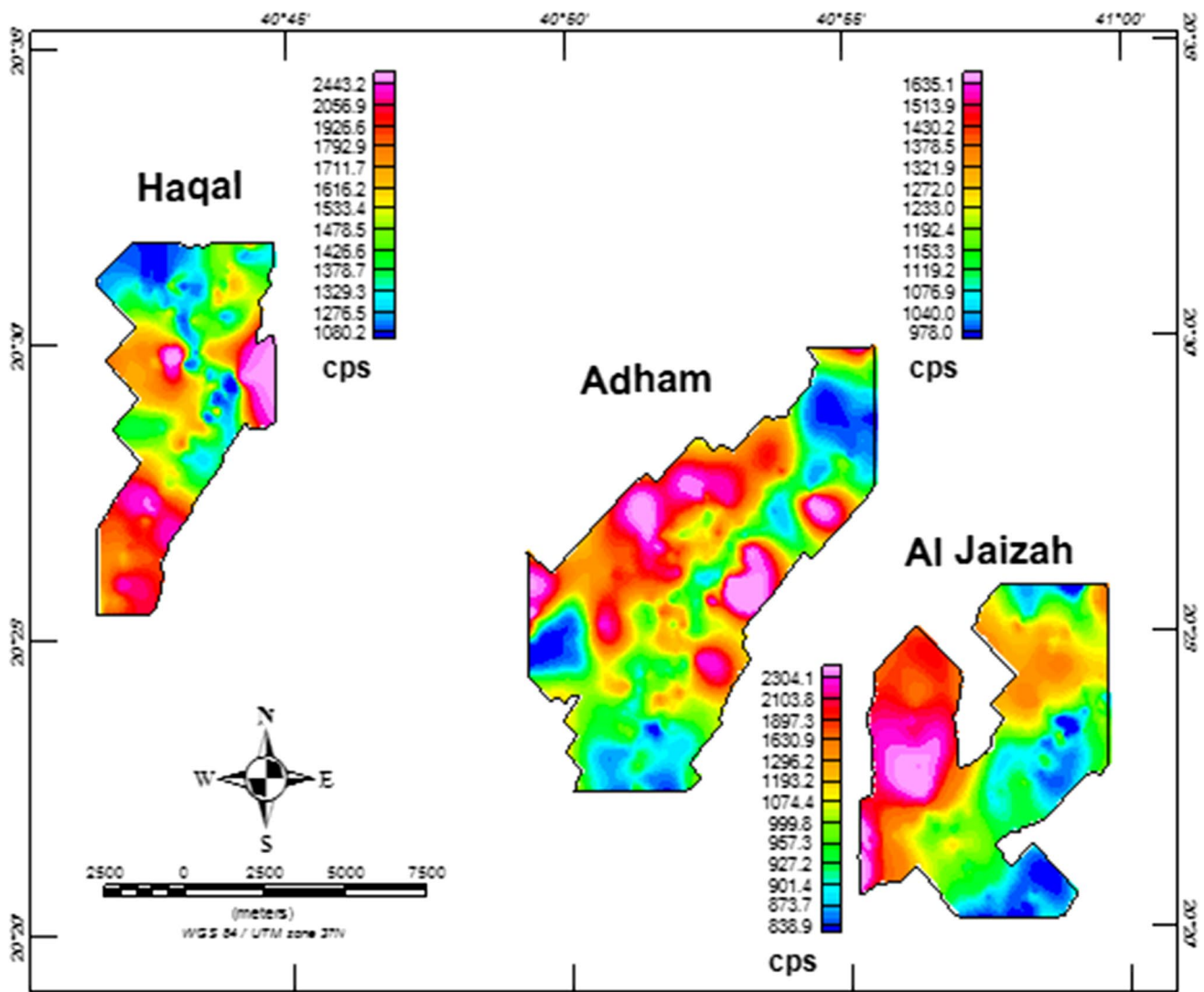


Fig. 5 Total Count (TC) radiation image contour map in cps, in the three studied areas Haqal, Adham, and Aljaizah, southwest of Saudi Arabia

Table 1 The statistical treatments of radioactive elements in Haqal, Saudi Arabia

Statistical treatments	Total Count	Exposure rate	Dose rate mSv/h	K%	eU	eTh	eU/eTh
No	5410	5410	5410	5410	5410	5410	5410
Min	1080	6.6	0.55	0.2	0.02	0.2	0.001
Max	2443	18.7	1.56	10.2	28.5	48.9	12
X	1616	8.4	0.7	2.97	3.8	8.7	1.5
SD	464	1.7	0.14	1.6	3.28	6.7	6.5
CV	0.38	0.20	0.20	0.54	0.87	0.77	3.2

No. number of readings, Min minimum, Max maximum  
 X mean, S standard deviation, CV coefficient of variability

considered a safe limit (ICRP, 2000) in some localities, especially in Haqal and Al Jaizah (Fig. 6). The safe limit published by the ICRP has changed over many years according to the results of new studies (Fig. 7). However, more

radon gas concentration research is necessary within the closed space of the three study areas. The population needs to be educated about radiation culture and the nature of the place in which they live, especially considering the risks

**Table 2** The statistical treatments of radioactive elements in Aljaizah Saudi Arabia

Statistical treatments	Total count	Exposure rate	Dose rate mSv/h	K%	eU	eTh	eU/eTh
No	5112	5112	5112	5112	5112	5112	5112
Min	838	0.22	0.02	0.14	0.2	0.02	0.04
Max	2504	14.0	1.17	8.5	12.2	25.5	1.52
X	1993	4.9	0.4	2.3	2.00	4.6	0.53
SD	303	2.3	0.19	1.2	1.5	3.5	0.16
CV	0.35	0.46	0.46	0.53	0.75	0.75	0.29

No. number of readings, *Min* minimum, *Max* maximum

X mean, S standard deviation, CV coefficient of variability

**Table 3** The statistical treatments of radioactive elements in Adham Saudi Arabia

Statistical treatments	Total count	Exposure rate	Dose rate mSv/h	K%	eU	eTh	eU/eTh
No	20,268	20,268	20,268	20,268	20,268	20,268	20,268
Min	898	1.01	0.08	0.18	0.02	0.02	0.04
Max	1720	15.3	1.28	6.8	14.7	29.1	1.5
X	1270	6.4	0.53	2.4	2.3	5.3	0.5
SD	188	2.2	0.18	0.78	1.7	3.6	0.12
CV	0.17	0.34	0.34	0.33	0.72	0.68	0.25

No. number of readings, *Min* minimum, *Max* maximum

X mean, S standard deviation, CV coefficient of variability

associated with granitic areas, and know how radon accumulates in closed places and poses a threat to health.

The average annual exposure to natural radiation sources worldwide is in the range of 1–10 mSv/year, with an average central value of 2.4 mSv/year (UNSCEAR 1993, 2000). Radon and its decay products represent approximately one-half (1.2 mSv/year) of this value. In the USA, the mean annual background exposure rate is higher (3.0 mSv/year) due to the higher average radon concentration levels. In the UK, radon provides an annual average dose of 2.6 mSv/year. This is followed by cosmic rays, which supply the next highest percentage of natural ionizing radiation exposure, which is further followed by terrestrial sources and “internal” emissions (National Academy of Sciences, 2006). Most of the three studied areas lie in the range lower than the world’s central average value, as shown in the presented image contour maps (Fig. 6).

Figure 8 shows the bar diagrams of the maximum and average radiation dose rates in mSv/year in the Haqal, Al Jaizah, and Adham study areas. These diagrams show that the average radiation dose rate in mSv/year in Haqal is higher than that in Adham, and a lower dose is recorded in the Al Jaizah study area (safe limit is 1 mSv/year (ICRP, 2000)).

In the study areas, and in many cases, residents prefer to live in stable places in the mountains to avoid heavy torrents and eruptions, and they cut and remove granite

sections to build on or over, as shown in Fig. 12b, c. In addition, the risk of radon gas leakage from granite rocks into homes and into kitchens or bathrooms can be reduced if there is good ventilation. As we know, the half-life of radon is 3.8 days. Therefore, radon accumulation in closed rooms and offices affects the population, which increases the risk of cancer. Smoking along with the inhalation of radon gas leads to higher risks of lung cancer.

### Radon measurements

Durrige Co., USA, manufactured the RAD7 device in 2012, which acts as a supplement to RADH2O, and is designed to measure accurate radon gas in water. The water sample must never have contact with air to be a good representative of the water being tested. Wells or taps connected to wells outside homes were chosen before the radon gas was allowed to escape and prior to any treatment process. A plastic tube was connected to a tap, the flask was filled, and water was allowed to flow while the flask was kept full and covered with fresh water. The tip of the tube was pulled out, and the flask was immediately covered. The cap was tightened, and we ensured that there were no air bubbles in the flask so that it was ready to be measured immediately or after a few hours with radon decay time correction.



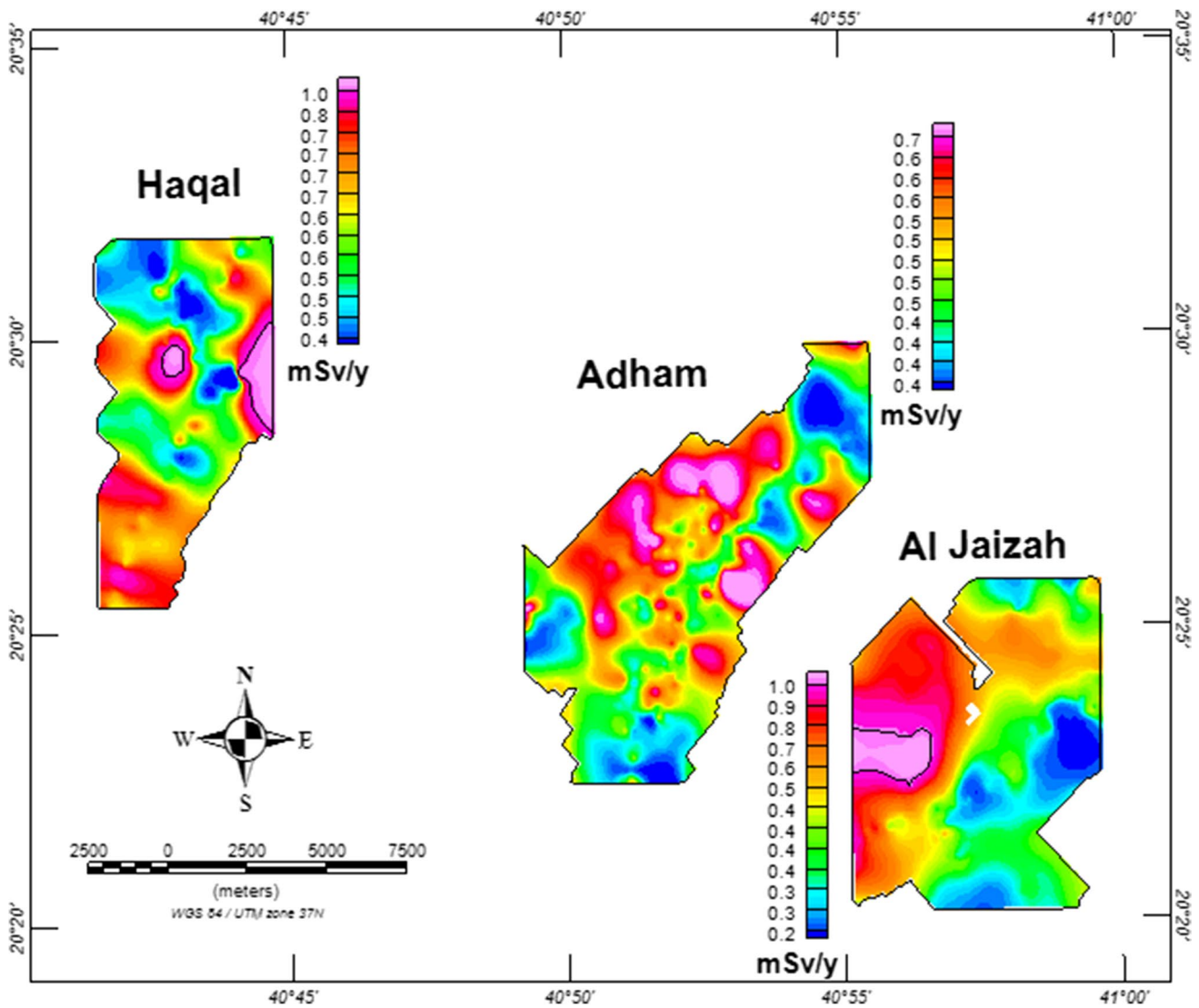


Fig. 6 Radiation dose rate image contour map in mSv/year, in the three. Studied areas Haqal, Adham, and Aljaizah, Southwest of Saudi Arabia

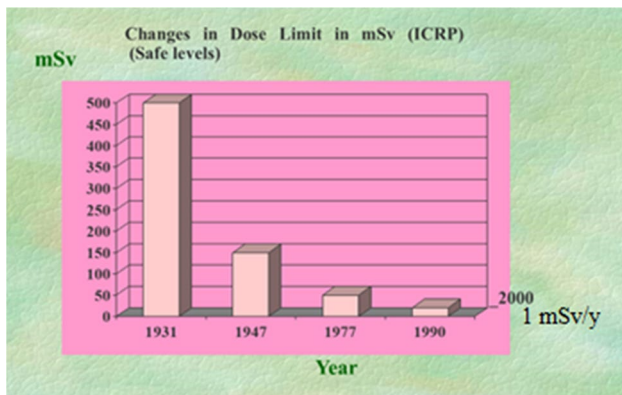
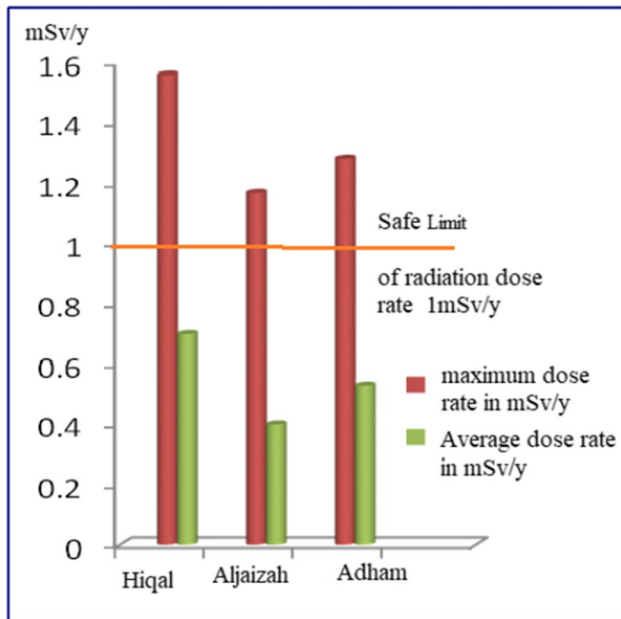


Fig. 7 Changes in Dose Limit in mSv/year (safe level 1 mSv/year (ICRP-2000b))

The RAD7 detector must be purged with fresh air for ten minutes by connecting a drying unit to the system so the air outside is allowed to pass through the desiccant and then return to the inside. If the humidity is less than 6%, this test will restart when the pump is operational for five minutes, removing the radon from the sample and delivering it to the measuring component of the RAD7 detector. The RAD7 system stops and waits for more than five minutes to reach an equilibrium state, and the processes is then repeated for five cycles for five minutes per cycle; thus, the test duration is 30 min. At the end of each run, the RAD7 computer will print the results, including the average radon concentration, standard deviation, humidity, and temperature reading inside the device, date and time of the test, operation number, and number of cycles. Then, the system outputs a graph of four

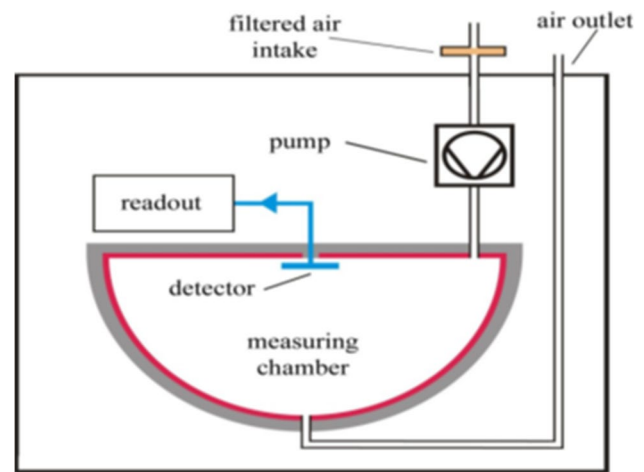


**Fig. 8** Bar diagrams showing the maximum and average radiation dose rate in mSv/year in Haqal, Aljaizah, and Adham study areas (safe limit is 1 mSv/year (ICRP-2000))

cycles and the accumulated spectrum, where the extraction efficiency or the radon removal percentage from the water in the air loop is high in a 250 mL sample at 94% (RADH2O, 2011). Figures 9 and 10 show the schematic diagram of RADH2O.



**Fig. 9** Measurement apparatus RAD



**Fig. 10** Measurement chamber of the RAD7

## Annual effective dose

The effective dose to humans per year can be calculated and evaluated through the use of groundwater or tap water using the relationship reported by the EPA (US Environmental Protection Agency, 1991) as shown in Eq. (4).

$$AED_w = C_w C_{RW} D_{CW} \quad (4)$$

where  $AED_w$  is the annual effective dose in  $\text{mSv/year}^{-1}$  as a result of radionuclide ingestion derived through the evaluation of water;  $C_w$  is radon concentration in the groundwater ( $\text{Bq.l}^{-1}$ );  $C_{Rw}$  is the annual intake of drinking water ( $730 \text{ ly}^{-1}$ ), as humans need at least 2 l/day of drinking water (in Saudi Arabia); and  $D_{cw}$  is the ingested dose conversion factor for  $^{222}\text{Rn}$  ( $4 \text{ Sv. Bq}^{-1}$ ) (EPA, 1991; Somashekar and Ravikumar, 2010).

## Results and discussion of the measured radon concentrations

The resulting radon concentrations in well water samples collected from the Adham Governorate and the Al Jaizah and Haqal centers (Fig. 4) are measured in  $\text{pCi.l}^{-1}$ , converted to  $\text{Bq.l}^{-1}$  and reported in Table 4. The average concentration represents the (mean); (high) represents the highest value, and the lowest value is represented by (low) in the table. The annual effective dose for each sample was calculated (Table 4).

The minimum concentration was found at the Al Jaizah center in well 8 at  $25.86 \text{ Bq.l}^{-1}$ , while the maximum concentration was found in the samples taken from Haqal at  $89.5 \text{ Bq.l}^{-1}$ , with an average concentration of

**Table 4** The results obtained in this study for radon concentration, all of which are measured in (pCi/L) unit and converted to (Bq/l<sup>-1</sup>) unit (Bqreal/l) and the radiation dose rate calculated in the three studied locations Haqal, Aljaizah centers and Adham Governorate. High (Bq/l<sup>-1</sup>)

Site	Sample well no	Mean (pCi/L)	Mean (Bq.l <sup>-1</sup> )	High (Bq.l <sup>-1</sup> )	low (Bq.l <sup>-1</sup> )	Standard deviation (SD Bq/l <sup>-1</sup> )	Effective dose (mSv/year)	Sample well location (GPS)
Haqal wells	1	2210	81.77	83.62	78.07	2.12	238.8	20° 29' 26.14" N 40° 44' 35.96" E
	2	2100	77.7	83.62	73.63	4.14	226.9	20° 30' 24.26" N 40° 43' 18.22" E
	3	1460	54.02	65.86	24.9	16.95	157.7	20° 28' 33.60" N 40° 42' 31.85" E
	4-B	1730	50.69	63.64	23.09	16.43	186.9	20° 28' 15.72" N 40° 43' 13.22" E
	4-A	1370	64.01	68.82	57.72	4.33	148	20° 28' 15.72" N 40° 43' 13.22" E
	5	2300	85.1	89.54	76.22	5.29	248.5	20° 29' 45.65" N 40° 42' 2 4.58" E
Aljaizah wells	6	755	27.94	30.45	22.98	3.09	81.6	20° 20' 35.12" N 40° 58' 13.13" E
	7	798	29.53	32.01	26.94	2.35	86.3	20° 24' 19.65" N 40° 56' 14.28" E
	8	699	25.86	29.64	17.06	5.07	75.5	20° 21' 36.89" N 40° 56' 49.47" E
	9	871	32.227	38.85	24.12	5.51	94.1	20° 23' 16.69" N 40° 58' 21.64" E
	10	1090	40.33	44.4	36.63	3.28	117.8	20° 23' 35.32" N 40° 59' 28.36" E
Adham wells	11	1210	44.77	47.73	40.33	2.79	130.7	20° 26' 27.94" N 40° 52' 40.01" E
	12	1230	45.51	48.1	43.66	1.59	132.9	20° 27' 40.62" N 40° 54' 00.78" E
	Drinking	1180	43.66	45.14	41.44	1.41	127.5	Hotel
	13	884	32.71	37	0.03012	2.7	95.5	20° 27' 28.52" N 40° 53' 18.37" E
	14	928	34.34	39.59	0.02679	4.736	100.3	20° 27' 9.17" N 40° 52' 36.45" E
	15	1030	38.11	41.44	0.03415	1.96	111.3	20° 26' 6.41" N 40° 51' 1.40" E
	16	947	35.04	37.74	0.0289	3.57	102.3	20° 26' 6.41" N 40° 51' 1.40" E
	17	1080	39.96	42.18	0.03774	1.75	116.7	

Sample 4A after desalination, 4 B before desalination, Drinking a sample of drinking water in a hotel in Adham comes from well water

$46.5 \pm 18.2 \text{ Bq.l}^{-1}$  for all study areas. The average annual effective dose from using water wells was found to be  $201.1 \pm 43 \text{ mSv.year}^{-1}$  in Haqal,  $91.0 \pm 22.1 \text{ mSv.year}^{-1}$  in Al Jaizah, and  $114.6 \pm 25.1 \text{ mSv.year}^{-1}$  in Adham, as shown in Table 5. The differences in the characteristics of the geological formation in each study area and the corresponding soil type can explain these differences. We believe that the different rock units surrounding the wells are the main source of these variations. The resulting dose rates show that the three studied locations have high concentrations,

**Table 5** Statistics of the  $^{222}\text{R}$  concentration and dose rate effect in the three study locations Haqal, Aljaizah, and Adham

Statistical elements	Haqal 5 well samples	Aljaizah 5 well samples	Adham 7 well samples
Average of radon concentration ( $\text{Bq.l}^{-1}$ )			
Minimum	50.69	25.86	32.71
Maximum	89.1	40.33	45.51
Mean	68.88	31.18	39.26
Standard deviation	14.7	5.62	5.01
Effective dose rate ( $\text{mSv.year}^{-1}$ )			
Minimum	148	75.5	95.5
Maximum	248.5	117.8	132.9
Mean	201.1	91	114.6
Standard deviation	43	16.4	14.6

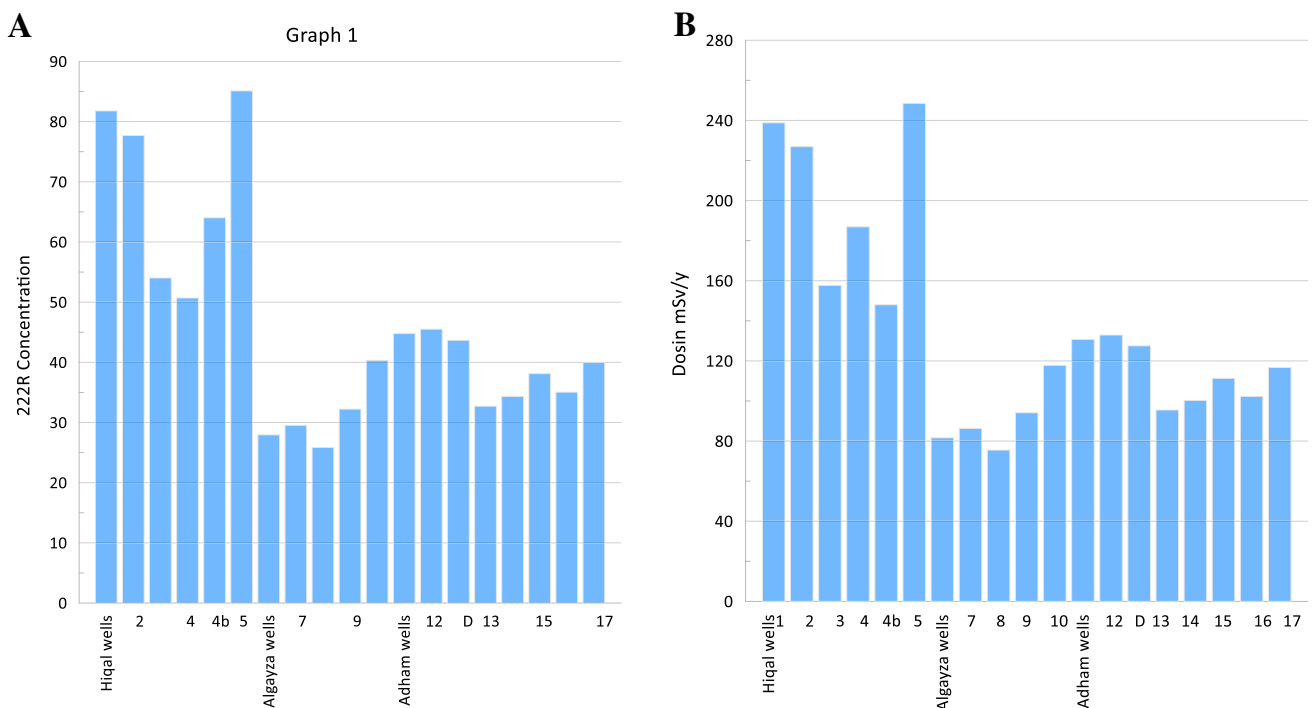
as revealed by their readings, and according to Fig. (7), the dose limit, expressed in  $\text{mSv/year}$ , changes.

According to new studies (ICRP, 2000) (safe levels), the dose rate readings in the three study locations fell within the safe limit before 150 years, but now, the safe limit is  $1 \text{ mSv/year}$  (ICRP, 2000).

The results show that the well samples taken from the Al Jaizah center have the smallest dose radiation and radon concentrations, while the Haqal center well samples have the highest dose rate among the studied areas (Fig. 11 and Table 5).

Compared with the results of previous studies in different countries around the world, as shown in Table 6, the three locations evaluated in this study have average concentrations in the range of 25.6 to  $83.6 \text{ Bq L}^{-1}$ ; this means that there are many countries or cities with radon concentration ranges exceeding that of the present three study locations, including Jordan, Tassili, Southeast Algeria, the outer Himalayas, Northern Venezuela, Bavaria, and Greece.

The highest permissible radon concentration within the recommended drinking water range of the EPA (1988a, 1988b) was  $18 \text{ Bq. L}^{-1}$ , under which that there is no risk to humans. The EPA (1991) reported the value of the maximum contaminant level (MCL) as a standard for radon contamination in drinking water is  $11.1 \text{ Bq L}^{-1}$  for public water supplies.



**Fig. 11** Bar diagrams for ground water well samples, in Haqal, Aljaizah, and Adham study areas showing **A** the radon concentration in  $\text{Bq.l}^{-1}$  and **B** radiation dose rate in  $\text{mSv/year}$

**Table 6** Concentration ranges of dissolved radon from different studies that included ground water and springs

Site	Range Bq l <sup>-1</sup>	References
Jordan (many locations)	2.8–116	Al-Kazwini and Hasan (2003)
Tassili, Southeast Algeria	0.67–21.25	Amrani et al. (2000)
Eastern Doon Valley, outer Himalaya	20–95	Choubey et al. (2003)
Northern Venezuela	0.1–576	Horvath et al. (2000)
Sudety Mountains, South-Western Poland	0.1–5 (ground water) 0.2–2 (tap water)	Kozłowska et al. (2001)
Cyprus (many locations)	0.1–5 (ground water) 0.2–2 (tap water)	Sarrou and Pashalidis (2003)
Bavaria, Germany (median)	Median 3–50 Max: 16–1220	Trautmannsheimer et al. (2002)
Midgonia Basin, Greece (below)	Below DL-161	Zouridakis et al. (2002)
Present study	25.6–83.6 ground water	Adham Governorate

The radon concentration in this study was high in the majority of wells, where all samples exceeded the standard national regulatory limit (11.1 Bq l<sup>-1</sup>). The average value in Haqal, Adham, and Al Jaizah was approximately 6, 3.5, and 2.8 times higher than this limit, respectively. UNSCEAR (2000) determined that the average concentration of radon in groundwater was 10 kBq m<sup>-3</sup>, whereas the values found worldwide are in the range of 1–100 kBq m<sup>-3</sup>. Although the radon concentration ranges in this study are in good agreement with the worldwide range, the average concentrations in Haqal, Adham, and Al Jaizah are greater than the worldwide average value (Table 6).

The obtained results make it possible to suggest that the study area is a generally radon-prone area, which is related to the occurrence of high radon concentrations in the groundwater.

The well depths in the three study areas ranged from 25 to 150 m, and no relationship was recorded between the depth of the well and the radon concentration in the groundwater of the wells. The amount of radon in water when used depends mainly on two factors: local geological specifications (place

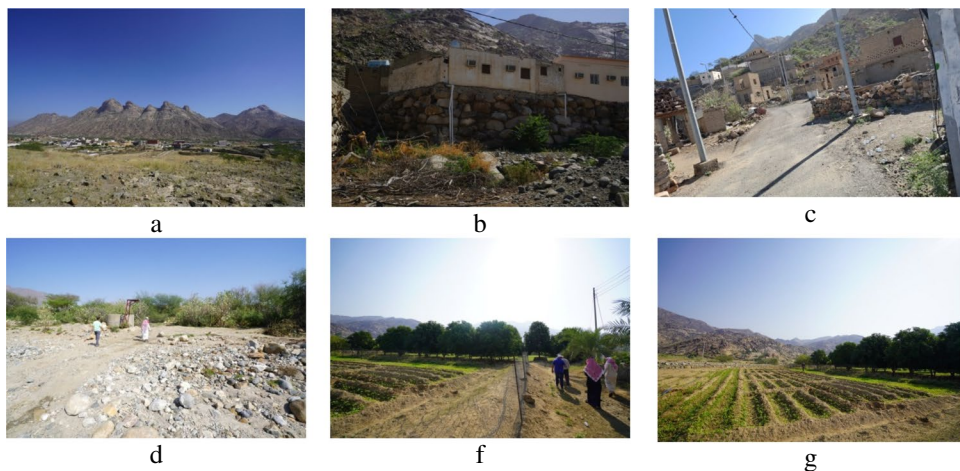
of water extraction) and the amount of radon emitted from soil grains, which depends mainly on the type and characteristics of the existing rocks (Fig. 12a).

The type of water used is a very important factor, and it was found that the radon produced from the water poses a risk to homes that use well water directly, while it is not a problem in homes that depend on the public water network as the water of the public network is usually safe after treatment, when it is then stored and distributed. The time, at which radon and its products degrade before reaching homes is vital, as in case sample no 4A from well 4 and 4B from the well before treatment.

### Conclusion and recommendations

The dose rate radiation in Haqal reached 1.56 mSv/year with a mean value of approximately 0.7 mSv/year, while in Al Jaizah, it reached 1.17 mSv/year with an average of 0.4 mSv/year, and in the Adham area, it reached 1.28 mSv/year with an average value of 0.53 mSv/year. Such high readings are restricted to certain granitic rocks that exceed

**Fig. 12** Photos express the cause of the high radon in water wells, homes, and the surrounding environment: **a** Adham Governorate buildings in the valley below the granite mountains. **b** and **c** People build their homes from local rocks, which are mostly granite on top of granite rocks. **d** A well in the middle of the valley in the stream of rain that falls on granite. **f** and **g** Well waters are used for drinking, agriculture, and animal husbandry



the worldwide recommended safe limit (1 mSv/year), while other parts in the three studied areas had average readings below the safe limit. The measured radon concentration was high in most wells, where all samples exceeded the standard national regulatory limit ( $11.1 \text{ Bq l}^{-1}$ ) for radon in drinking water. The average value was approximately 6, 3.5, and 2.8 times greater than this limit in Haqal, Adham, and Al Jaizah, respectively. UNSCEAR (2000) determined the average concentration of radon in groundwater was  $10 \text{ kBq m}^{-3}$ , with worldwide values ranging from 1 to  $100 \text{ kBq m}^{-3}$ . Although the radon concentration ranges in this study are in good agreement with the worldwide range, the average concentrations in Haqal, Adham, and Al Jaizah are greater than the worldwide average value. We recommend continuously ventilating homes and offices in these places and measuring radon continuously in closed spaces. In particular when considering buildings located in granite-dominated areas, we suggest avoiding taking drinking water directly from the wells, except after desalination or raising to semi opened tanks, especially the wells lie in valleys with granite sediments to give radon a chance to escape and decreased. We additionally advise against eating vegetables that are irrigated from these wells or those grown in granitic valleys, which contain high radioactive element content. The results of this research are important and useful to alert people to the dangers of radioactive contamination and its effects on humans and exposed plants and animals. This information can act as a reference for comparison with any activity or radioactive pollution source that is discovered in this area in the future.

**Data availability** Applicable.

## Declarations

**Competing interests** The authors declare no competing interests.

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