Determination of Radon Concentrations and Annual Average Effective Doses in Some Well Waters Near the Akşehir-Simav Fault System

Ayla Gümüş

sandikci@aku.edu.tr

Afyon Kocatepe University

Research Article

Keywords: Radon, Well-water, Fault-radon, Annual average effective dose, AlphaGUARD, Afyonkarahisar

Posted Date: May 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1587693/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Radiation Protection Dosimetry on February 21st, 2023. See the published version at https://doi.org/10.1093/rpd/ncad031.

Abstract

Afyonkarahisar and its surroundings are located in the middle part of the Akşehir-Simav fault system (ASFS). This fault system is one of the most important tectonic elements of Southwest Turkey. In this study, radon concentrations were measured in four-well and spring water, which is used as drinking water, in the villages and districts of Afyonkarahisar province near ASFS for 24 month period, and the annual average effective dose amounts were calculated. In addition, the relationship between the average radon concentration results of potable water wells and the distance of the wells to the fault was examined for the first time in this region.

Radon concentrations were measured between 0.11 ± 0.22 BqL^{-1} and 17.89 ± 0.58 BqL^{-1}, and mean radon concentrations were measured between 1.87 ± 0.28 BqL^{-1} and 11.93 ± 0.48 BqL^{-1}. The annual effective dose values were calculated between 10.99 ± 1.65 μSvy^{-1} and 70.11 ±2.82 μSvy^{-1} for infants, 4.03 ± 0.60 μSvy^{-1} and 25.69 ± 1.03 μSvy^{-1} for children and 4.78 ± 0.72 μSvy^{-1} and 30.48 ± 1.23 μSvy^{-1} for adults. In addition, the effect of the distance of the wells from the fault on the mean radon concentrations was also investigated. The regression coefficient (R^2) was calculated as 0.85. The average radon concentration was observed higher in the water wells close to the fault. The highest mean radon concentration was measured in well 4, closest to the fault and 1.07 km away.

1. Introduction

Since the existence of the universe, humans have been under the influence of natural radioactivity originating from long, half-lived radioactive nuclei in the earth's crust. Radiation released during the decay process of long-lived radioactive elements constitutes an important part of natural radioactivity. Most of the natural radioactivity on Earth originates from ^{235}U, ^{238}U, ^{232}Th, and ^{40}K. The main sources of uranium and thorium radioactive elements are the rocks and soil that make up the earth's crust. ^{238}U and ^{232}Th radioactive elements and their decay products show the different distribution in soil, water, air, rocks, building materials obtained from soil, food, and beverages. The radioactive elements in the soil can dissolve in the waters in constant contact with the soil and form the radioactivity level in the waters. Groundwater is expected to contain higher levels of radioactive elements than surface water. Although it varies according to geographical regions, the average ^{238}U concentration in the earth's crust is estimated to be about 2 ppm (Durrani and Radomir 1997). Most of the radioactive elements found in nature occur in the decay chain of ^{238}U. Radon is formed from ^{226}Ra produced in the decay chain of ^{238}U. The long half-life of the element radium is a significant factor in the formation of radon. Radon is formed due to the alpha decay of the element radium. Radon, in group VIIIA of the periodic table, ranks 86th with a half-life of 3.82 days. It is an invisible, odorless, tasteless, colorless gas that leaks from the ground and diffuses into the air. Depending on the regional geology, radon can dissolve in groundwater and radon from waters enters the interior of houses when water is used. It is the only and heaviest radioactive element found in nature, which does not form any compounds and does not react.

Radon has three natural isotopes: ^{222}Rn (emanon), ^{220}Rn (toron), ^{219}Rn (actinon). These are the radioactive decay product of ^{238}U, ^{232}Th, and ^{235}U, respectively. The half-life of ^{222}Rn is 3.82 days, thoron (^{220}Rn) has a half-life of 54.5 seconds, and actinon (^{219}Rn) has a half-life of 3.92 seconds. Due to the low activity concentration of ^{235}U and the short half-life of the other two isotopes, ^{222}Rn is the most important, most abundant, and dangerous isotope in nature. Studies to determine natural radioactivity have revealed that approximately 55% of the radiation humans are exposed to be caused by radon (ICRP 1993; Gillmore et al. 2002). Two of the ^{222}Rn decay products, ^{214}Po and ^{218}Po, are alpha emitters, responsible for more than 90 percent of the total radiation received due to human exposure to radon (Marques et al. 2004). For all these reasons, radon gas is a crucial parameter that should be considered in human health. Radon gas, which undergoes radioactive decay, turns into particles captured by the lungs when inhaled. These particles, which enter the body by breathing the air, decompose until they become stable, and radiation is released at every stage. Radon and its isotopes form radioactive aerosols by clinging to dust and water droplets in the air and are taken to the lungs by respiration. Once radon gas enters the respiratory system, it emits α and β radiation, causing a very rapid decay mechanism, and this decay also includes ^{210}Po, a toxic radioisotope that leads to lung cancer (UNSCEAR 2008). Therefore, inhalation of radon and its degradation products poses a significant health risk. The energy released when these particles continue to decompose causes damage to the lung tissue, thus causing cancer over time (Field et al. 2000; Lázár et al. 2003; UNSCEAR 2008; WHO 2009; ICRP 2010). Humans and all living things need water to survive. It is a crucial issue that water is seriously related to many aspects of human health as it must be suitable and reliable. In addition to various solid substances dissolved in the water content, there may be radioactive substances depending on the environment passed through, or the location found. Especially underground waters are in contact with different geological formations. The chemical compounds in these underground formations mix with the groundwater more or less according to their solubility in water. In this respect, it is recommended that drinking water should not exceed the limits set by the international organizations in terms of metal and chemical substances and radioactive elements. Especially groundwater contains radioactive elements from ^{235}U and ^{232}Th groups at different concentrations (Duenas et al. 1993). The radon in water is absorbed by the organs, mainly into the walls of the intestine and stomach, resulting from the ingestion of the dissolved radon. The presence of nutrients in the stomach and absorption of most radiation creates the risk of stomach cancer (Krewski et al. 2006; Ouabi 2009; Binesh et al. 2010). In other words, radon exposure from breathing and ingestion of radon and its short-lived products can cause lung cancer (UNSCEAR 2008; WHO 2009; ICRP 2010). A person's cancer risk can be 89% with the inhalation of water-soluble and released radon. It is estimated that this rate maybe 11% due to the radon emission that people get from drinking water (USEPA 1991; USNRC 1999). Smoking is the biggest cause of lung cancer, which is the leading cause of death worldwide, and the World Health Organization (WHO) has reported radon gas as the second leading cause of this cancer (WHO 2009). In addition, the WHO predicts that the risk of lung cancer will increase by approximately 16% for every 100 Bq/m^3 increase in the long-term average radon concentration (WHO 2009). International organizations have suggested limiting values in drinking water for the safety of public health against radon risks. The United States Environmental Protection Agency (USEPA) recommends the limit value for radon concentration in waters as 11.1 Bq^{-1}, WHO 100 Bq^{-1}, and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 4–40 BqL^{-1} (USEPA 1991; UNSCEAR 2008; WHO 2011). It is very important to determine radon gas concentrations in drinking water as posing a health risk. Significant radon gas is likely to present in groundwater because radon comes from rock and soil. Studies emphasize that there may be higher radon concentrations in the fault line or near areas (Al-Tamimi and Abumurad 2001; Atallah et al. 2001; Ajayi and Adepelumi 2002; Xuan et al. 2020). In this respect, this study aimed to determine the radon gas concentrations and obtain the annual average effective dose amounts in four-well and a spring water sources located on or near the fault line and used as a drinking water source in the villages and districts of Afyonkarahisar province. The results were commented on whether it poses a health threat or not. It is vital to detect radon activity concentration in drinking water and compare the values with the recommended values reported by international organizations. Measuring radon concentrations in water wells near ASFS, where earthquakes that have devastating effects on the tectonic system at different times and cause loss of life and property are also important in terms of radon and fault relationship. In this study, different from previous years, water wells closer to the ASFS were determined, and the relationship between the average radon concentration results and the distance to the fault was examined for the first time in this region.

2. Materials And Methods

2.1. Study area

Afyonkarahisar province, one of the 81 provinces of Turkey, is located in the middle of the Anatolian peninsula close to the West and the inner part of the Aegean Region (Fig. 1). It is a province that spreads over three of Turkey's geographical regions (Aegean, Mediterranean, Central Anatolia). It is located at 37° 45'- 39° 17' north latitude, 29° 40' and 31° 43' east longitude.

Afyonkarahisar and its surroundings are located in the middle part of the Akşehir-Simav fault system (ASFS), and this fault system is one of the most important tectonic elements of Southwest Turkey extensional Neotectonic region (Koçyiğit and Deveci 2007). ASFS is an active tectonic line and therefore has produced a series of historical and current earthquakes, and there is a possibility of earthquakes up to 7 magnitudes in the region (Yıldız et al. 2012). Since 1921, 9 earthquakes ranging from 4.7 M to 7.2 M have occurred in ASFS. Afyonkarahisar and its surroundings are geologically divided into three main parts namely the Taurus Belt (Sultandağları part), the Inner Taurus Belt (North part of Afyon), and the Northern part of Sandıklı district by (Metin et al. 1987) and (Erkan et al. 1996). In the study area, rock assemblages formed in different geological periods from the Taurus and Inner Taurus Belts, from Paleozoic to Quaternary, are observed.

2.2. Sampling and experimental analysis

This study was carried out to determine the radon concentrations and annual effective dose rates in 5 different water samples along the fault line in the Çay-Sultandağı districts of Afyonkarahisar province.

Four different deep-water wells and spring water used as drinking water close to ASFS were determined by taking water samples from these wells (Fig. 2). Point 2, one of the 5 points selected in the study, is not well water but a source flowing spontaneously for more than 40 years, according to the information received from the authorities in the region. It is not known exactly where this water comes from. The other 4 points are deep water wells, and the depth information is seen in Table 1.

Samples were taken in monthly cycles over 24 months from January 24, 2014, to December 22, 2015. Before the water samples were taken, sources were let flow for about 5 minutes until clean water was obtained. The water samples were then filled into 250 ml glass bottles with leak-proof caps. These bottles are special bottles with an apparatus on the cap that prevents gas escape. Each bottle is filled to the brim, leaving no spaces inside to prevent bubbling and escape of radon gas; the bottles' caps are tightly closed under the flow of water. All samples were immediately taken to Afyon Kocatepe University Nuclear Physics Laboratory to determine their radon concentrations. The names of the water wells from which the samples taken are shown in Table 1 and their locations are shown in Fig. 2.

Table 1
Names and location information of the water samples

Sample No	Location name	Latitude	Longitude	Altitude (m)	Depth(m)
1	Ali İhsan Paşa district	38.7110°	30.6055°	1008	130
2	Maltepe	38.6070°	30.9098°	1005	-
3	Kadıköy Başel district	38.6458°	30.8342°	1001	120
4	Ali Kaleli district	38.5979°	30.9882°	988	120
5	Çayırpınar	38.5900°	31.0951°	996	100

Radon concentrations in water samples were measured with the professional AlphaGUARD PQ2000PRO radon detector (Saphymo GmbH 1998, 2001; Genitron Instruments 2008). This device is an ionizing chamber measuring with the alpha spectrometric technique and is designed to measure radon in air, water, and soil. To make measurements of radon concentrations in water, an additional device, Special AquaKIT equipment, was used with this detector. AlphaGUARD PQ2000PRO detector and AquaKIT equipment containing glass containers in the experimental setup were connected via an air pump, as shown in Fig. 3. The aguakit apparatus was set to "10 min-diffusion modes" for the detector to measure 10 min cycles. Also, the airflow was set to be measured at 0.5 L/min modes.

DataEXPERT software was used to transfer, view, and save the experimental data to the computer during the measurements made with the device. Each water sample was measured three times, and the results were averaged. All these measurements were made in monthly cycles over 24 months. With the data obtained from the detector result, the radon concentrations of each water sample were calculated using the following equation (Saphymo GmbH 1998; Genitron Instruments 2008).

$$C_w = \frac{C_{air} x \left(\frac{V_{system}-V_{sample}}{V_{sample}}+k\right)-C_0}{1000} \quad (1)$$

where C_w:^{222}Rn concentration in the water sample (BqL^{-1}), C_{air}: ^{222}Rn concentration in the measuring set-up after expelling the radon (Bqm^{-3}); C_0: ^{222}Rn concentration in the measuring set-up before sampling (Bqm^{-3}), V_{system}: The interior volume of the measurement set-up (1102 ml), V_{sample}: The volume of the water sample (100 ml); and k: Radon distribution coefficient, (k = 0,26).

2.3. Annual effective doses from ^{222}Rn ingested with water

The annual effective dose for infants, children, and adults was calculated by the following formula according to Eq. (2) (Somlai et al. 2007; Han et al. 2021):

$$E_i = C_i x I_F x W x T \quad (2)$$

where E_i is the annual effective dose due to ingestion of drinking water (Svy^{-1}); C_i is the measured ^{222}Rn activity in water (BqL^{-1}); I_F is the ingesting dose conversion factor of ^{222}Rn, this estimation was calculated by the (UNSCEAR 2000) at infants; 23, children; 5.9, and adults; 3.5 $nSvBq^{-1}$ for the individuals in the age groups from 1 year to 2 years (infants), from 7 years to 12 years (children), and over 17 years (adults); W is the water consumption (infants; 0.7; children; 1.0 and adults; 2.0 L day^{-1}); T is the water consumption period (UNSCEAR 2000).

3. Results And Discussion

The radon concentrations of the water samples were measured in monthly cycles, and the study was carried out over 24 months. Each water sample was measured three times and the average of these three measurements was calculated. Then, the average radon concentration values were calculated over the 24-month period. The obtained range and the average radon concentration values are given in Table 2. The lowest radon concentration value was obtained as 0.11 BqL^{-1} in spring water (point 2), and the highest radon concentration was obtained as 17.89 BqL^{-1} in well no. 4. The lowest average radon concentration value was also obtained for the spring water, 1.87 ± 0.28 BqL^{-1}, and the highest value was determined in well no. 4 as 11.93 ± 0.48 BqL^{-1}. The duration of the study for 24 months enabled the long-term radon concentrations of the wells to be observed. Monthly measurements of each well did not show a large and significant change during the study period.

Table 2
Average concentrations of ^{222}Rn and annual effective doses by ingestion for infants, children, and adults

Sample No	^{222}Rn concentration range (BqL^{-1})	Average ^{222}Rn concentration (BqL^{-1})	Annual effective dose due to ingestion (μSvy^{-1})		
			Infants	Children	Adults
1	0.16–13.49	5.13 ± 0.40	30.15 ± 2.35	11.05 ± 0.86	13.11 ± 1.02
2	0.11–4.18	1.87 ± 0.28	10.99 ± 1.65	4.03 ± 0.60	4.78 ± 0.72
3	0.94–12.92	8.93 ± 0.43	52.48 ± 2.53	19.23 ± 0.93	22.82 ± 1.10
4	6.36–17.89	11.93 ± 0.48	70.11 ± 2.82	25.69 ± 1.03	30.48 ± 1.23
5	5.52–11.30	8.50 ± 0.44	49.95 ± 2.59	18.30 ± 0.95	21.72 ± 1.12

The values of radioactive elements in drinking water are required to be below the limit values determined by international organizations. USEPA recommends the limit value of radon concentration in waters as 11.1 BqL^{-1}, WHO as 100 BqL^{-1}, and UNSCEAR as 4–40 BqL^{-1} (USEPA 1991; UNSCEAR 2008; WHO 2011). The average radon concentration values of these water samples, which are used as a drinking water source by the region's people, were compared with the limit values recommended by international institutions. Accordingly, only the average radon concentration in well no. 4 exceeded the USEPA limit value of 11 BqL^{-1}. But it is close to the limit value. The mean radon concentration values of all water samples did not exceed the limit values recommended by WHO and UNSCEAR, as seen in Fig. 4.

In Table 3, the results of radon concentration measurements (minimum and maximum value ranges, average concentration values) in groundwaters made in different countries and regions are given to be compared with this study. As shown in Table 3, radon concentration measurements were carried out in well water in Afyonkarahisar in 2007, too. The water samples in the present study are especially those closest to the ASFS and can also be used as drinking water sources. In this study, different from previous years, water wells closer to the fault line were determined, and the relationship between the average radon concentration results and the distance to the fault was examined for the first time in this region. When both average radon concentrations and radon concentration range values are compared, the present study is compatible with the work done in the same area in previous years.

Table 3
Comparison of this study with radon concentration measurements in groundwater in some other countries in the World

Location and Country	Radon Concentration Range (BqL^{-1})	Average Radon Concentrations (BqL^{-1})	References
Saudi Arabia	0.89–35.44	8.80	(Alabdula'aly 1999)
Italy	5.9-65.79	-	(Borio et al. 2005)
Afyonkarahisar,Turkey	0.7–31.7	2.2–7.7	(Yalım et al. 2007a)
Afyonkarahisar,Turkey	0.42–28.82	12.33	(Yalım et al. 2007b)
Ashanti, Ghana	1-41.26	10.97	(Asare-Donkor et al. 2018)
Konya,Turkey	1.44–27.45	-	(Erdogan et al. 2013)
Sakarya, Turkey	1.98–20.80	9.05	(Yakut et al. 2013)
Saudi Arabia	0.06–40.9	5.34	(Alabdula'aly 2014)
Yemen	1.0-896	226.4	(Abdurabu et al. 2016)
Haryana, India	1.4–22.6	-	(Duggal et al. 2017)
Ekiti, Nigeria	0.9–472	34.7	(Ajiboye et al. 2018)
China	1.29–31.31	10.47	(Tan et al. 2019)
Rajasthan, India	12.5–862	113	(Duggal et al. 2020)
Gadau, Nigeria	4.92–82.89	38.3	(Shu'aibu et al. 2021)
Çorlu (Turkey)	22.04–63.92	43.25	(Manisa et al. 2021)
Afyonkarahisar,Turkey	0.11–17.89	7.27	Present work

Using the 24-month average radon concentration values of the four different wells and the spring water, the annual effective dose values of the water samples were calculated. The calculated annual effective dose due to ingestion values are in the range of 10.99 ± 1.65 and 70.11 ± 2.82 μSvy^{-1} for infants, between 4.03 ± 0.60 and 25.69 ± 1.03 μSvy^{-1} for children, and from 4.78 ± 0.72 to 30.48 ± 1.23 μSvy^{-1} for adults (Table 2). The WHO and UNSCEAR recommend 100 μSvy^{-1} as the safe limit for the annual effective dose from radon intake in drinking water (WHO 2004; UNSCEAR 2008). All results obtained in this study are below the allowable limit value of WHO and UNSCEAR, 100 μSvy^{-1}. For this reason, the waters of these wells, which are located very close to the ASFS in Afyonkarahisar and its surroundings and are also used as drinking water by the region's people, do not pose any health threat due to radon intake.

In this study, the effect of the distance of the wells from the fault on the radon concentrations was also investigated. For this purpose, only four well water sources were taken into account since deep well water better reflects the underground changes (IAEA 1993). The regression coefficient (R^2) was obtained from the graph of the vertical distances to the fault according to the average radon concentrations values of the wells for 24 month-period (Fig. 5).

The R^2 value was obtained as 0.85. This result, therefore, indicates that there is a good relationship between radon concentrations and proximity to the fault. In the ASFS, the closest well to the fault as well no. 4, and its distance from the fault is only 1.07 km. The highest mean radon concentration was also measured in well no. 4. This result is consistent with studies that interpret radon concentrations at or near fault lines (Al-Tamimi and Abumurad 2001; Atallah et al. 2001; Ajayi and Adepelumi 2002). To better understand this relationship, it is thought that it would be helpful to measure radon gas in many more wells in the region.

4. Conclusions

In this study, radon concentrations were measured in four-well and a spring water, which are used as drinking water, in the villages and districts of Afyonkarahisar province near ASFS for 24 month period and the annual average effective dose amounts were calculated. The present results can be concluded as follows:

1. Radon concentrations were measured in a spring water no. 2 with the lowest 0.11 BqL^{-1}, and the highest in well no. 4 with 17.89 BqL^{-1}.
2. The lowest value of average radon concentrations was determined with 1.87 ± 0.28 BqL^{-1} in a spring water no. 2, and the highest value was obtained in well no. 4 with 11.93 ± 0.48 BqL^{-1} value.
3. Well, no. 4 has slightly exceeded the USEPA's limit value of 11 BqL^{-1}. It can be concluded that the use of drinking water from this well is not very healthy.
4. During the 24-month study period, the monthly measurements of each well did not show a large and significant change.
5. The annual effective dose due to ingestion values for all age groups was determined in the lowest a spring water no. 2 and the highest in well no. 4.

6. The calculated annual effective dose due to ingestion calculated for different age groups did not exceed the 100 μSvy^{-1} limit recommended by WHO and UNSCEAR for ingestion dose exposure due to ^{222}Rn in drinking water (UNSCEAR 2008; Manisa et al. 2021).
7. The correlation coefficient (R^2) between the mean radon concentrations of the wells and their vertical distance from the ASFS was derived as 0.85. The highest mean radon concentration was measured in the water well closest to the fault (1.07 km and well no. 4). It is believed that it will be helpful to follow these wells (especially well no. 4) in future studies on this fault line.

Declarations

Acknowledgments

The author thanks Prof. Hüseyin Ali Yalım for his valuable comments and suggestions on the study.

Funding information This work is supported by Afyon Kocatepe University Science Research Projects Coordination Unit with the grant number 15.HIZ.DES.37.

Funding and/or Conflicts of interests/Competing interests

- The author declare that there are no conficts of interest.
- **Funding information** This work is supported by Afyon Kocatepe University Science Research Projects Coordination Unit with the grant number 15.HIZ.DES.37.
- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

References

1. Abdurabu WA, Ramli AT, Saleh MA, Heryansyah A (2016) The activity concentrations of 222Rn and corresponding health risk in groundwater samples from basement and sandstone aquifer; the correlation to physicochemical parameters. Radiation Physics and Chemistry 127:34–41. https://doi.org/10.1016/j.radphyschem.2016.06.001
2. Ajayi TR, Adepelumi AA (2002) Reconnaissance soil-gas radon survey over the faulted crystalline area of ile-ife, Nigeria. Environmental Geology 41:608–613. https://doi.org/10.1007/s002540100428
3. Ajiboye Y, Isinkaye MO, Khanderkar MU (2018) Spatial distribution mapping and radiological hazard assessment of groundwater and soil gas radon in Ekiti State, Southwest Nigeria. Environmental Earth Sciences 77:. https://doi.org/10.1007/s12665-018-7727-5
4. Alabdula'aly AI (1999) Occurrence of radon in the central region groundwater of Saudi Arabia. Journal of Environmental Radioactivity 44:85–95

5. Alabdula'aly AI (2014) Occurrence of radon in groundwater of Saudi Arabia. Journal of Environmental Radioactivity 138:186–191. https://doi.org/10.1016/j.jenvrad.2014.07.028
6. Al-Tamimi MH,, Abumurad KM (2001) Radon anomalies along faults in North of Jordan. Radiation Measurements 34:397–400
7. Asare-Donkor NK, Poku PA, Addison ECDK, et al (2018) Measurement of radon concentration in groundwater in the Ashanti region of Ghana. Journal of Radioanalytical and Nuclear Chemistry 317:675–683. https://doi.org/10.1007/s10967-018-5930-1
8. Atallah MY, Al-Bataina BA, Mustafa H (2001) Radon emanation along the Dead Sea transform (rift) in Jordan. Environmental Geology 40:1440–1446. https://doi.org/10.1007/s002540100337
9. Binesh A, Mohammadi S, Mowlavi AA, Parvaresh P (2010) Evaluation of the radiation dose from radon ingestion and inhalation in drinking water. International Journal of Water Resources and Environmental Engineering 2:201–205
10. Borio R, Rongoni A, Saetta DMS, et al (2005) Radon and tritium measurements in drinking water in a region of central Italy (Umbria). Journal of Radioanalytical and Nuclear Chemistry 266:397–403
11. Duenas C, Fernández MC, González JA, et al (1993) Ra-226 and Ra-224 in waters in Spain. Toxicological & Environmental Chemistry 39:. https://doi.org/10.1080/02772249109357903
12. Duggal V, Sharma S, Mehra R (2017) Radon levels in drinking water of Fatehabad district of Haryana, India. Applied Radiation and Isotopes 123:36–40. https://doi.org/10.1016/j.apradiso.2017.02.028
13. Duggal V, Sharma S, Mehra R (2020) Risk assessment of radon in drinking water in Khetri Copper Belt of Rajasthan, India. Chemosphere 239:. https://doi.org/10.1016/j.chemosphere.2019.124782
14. Durrani SA, Radomir I (1997) Radon measurements by etched track detectors: Applications in radiation protection, earth sciences, and the environment
15. Erdogan M, Eren N, Demirel S, Zedef V (2013) Determination of radon concentration levels in wellwater in Konya, Turkey. Radiation Protection Dosimetry 156:489–494. https://doi.org/10.1093/rpd/nct099
16. Erkan Y, Bayhan H, Tolluoğlu AÜ, Aydar E (1996) Afyon yöresi metamorfik ve volkanik kayaçlarının petrografik ve jeokimyasal incelenmesi. Ankara
17. Field RW, Steck DJ, Smith BJ, et al (2000) Residential radon gas exposure and lung cancer the Iowa radon lung cancer study. 151:
18. Genitron Instruments (2008) AquaKIT user manual, Heerstrasse 149 D-60488
19. Gillmore GK, Phillips PS, Denman AR, Gilbertson DD (2002) Radon in the Creswell Crags Permian limestone caves. Journal of Environmental Radioactivity 62:165–179
20. Han C-H, Hong JW, Im H-J (2021) A study of 222Rn concentration of salty underground water and spring water in Jeju, Korea. Journal of Radioanalytical and Nuclear Chemistry 330:563–569. https://doi.org/10.1007/s10967-021-07909-3
21. IAEA (1993) International Atomic Energy Agency, Isotopic and geochemical precursors of earthquakes and volcanic eruptions. Vienna, Austria

22. ICRP (1993) The International Commission on Radiological Protection, Protection against radon-222 at home and at work
23. ICRP (2010) The International Commission on Radiological Protection, Lung cancer risk from radon and progeny and statement on radon
24. Koçyiğit A, Deveci Ş (2007) A N-S-trending active extensional structure, the Şuhut (Afyon) graben: Commencement age of the extensional neotectonic period in the Isparta Angle, SW Turkey. Turkish Journal of Earth Sciences 16:391–416
25. Krewski D, Lubin JH, Zielinski JM, et al (2006) A combined analysis of north American case-control studies of residential radon and lung cancer. Journal of Toxicology and Environmental Health - Part A 69:. https://doi.org/10.1080/15287390500260945
26. Lázár I, Tóth E, Marx G, et al (2003) Effects of residential radon on cancer incidence. Journal of Radioanalytical and Nuclear Chemistry 258:. https://doi.org/10.1023/B:JRNC.0000011745.88739.53
27. Manisa K, Erdogan M, Usluer A, et al (2021) Assessment of natural radioactivity level of soil and water in the region of Çorlu (Turkey). Journal of Radioanalytical and Nuclear Chemistry 329:1213–1221. https://doi.org/10.1007/s10967-021-07906-6
28. Marques AL, dos Santos W, Geraldo LP (2004) Direct measurements of radon activity in water from various natural sources using nuclear track detectors. Applied Radiation and Isotopes 60:801–804. https://doi.org/10.1016/j.apradiso.2004.01.015
29. Metin S, Genç Ş, Bulut V (1987) Afyon ve dolayının jeolojisi. Ankara
30. Ouabi H (2009) Modeling of radon and its short-lived decay products emanating from tap water used inside a house: Dose to adult members of the public. Applied Radiation and Isotopes 67:115–121. https://doi.org/10.1016/j.apradiso.2008.07.010
31. Saphymo GmbH (1998) AlphaGUARD User Manual Portable Radon Monitor, Heerstrasse 149 D-60488
32. Saphymo GmbH (2001) AlphaPUMP Technical Description, Heerstrasse 149 D-60488
33. Shu'aibu HK, Khandaker MU, Baballe A, et al (2021) Determination of radon concentration in groundwater of Gadau, Bauchi State, Nigeria and estimation of effective dose. Radiation Physics and Chemistry 178:. https://doi.org/10.1016/j.radphyschem.2020.108934
34. Somlai K, Tokonami S, Ishikawa T, et al (2007) 222Rn concentrations of water in the Balaton Highland and in the southern part of Hungary, and the assessment of the resulting dose. Radiation Measurements 42:491–495. https://doi.org/10.1016/j.radmeas.2006.11.005
35. Tan W, Li Y, Tan K, et al (2019) Distribution of radon and risk assessment of its radiation dose in groundwater drinking for village people nearby the W-polymetallic metallogenic district at Dongpo in southern Hunan province, China. Applied Radiation and Isotopes 151:39–45. https://doi.org/10.1016/j.apradiso.2019.05.008
36. UNSCEAR (2008) Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, General Assembly Official Records Sixty-third Session Supplement No. 46. New York

37. UNSCEAR (2000) Sources and Effects of Ionizing Radiation, Report to the General Assembly, with Scientific Annexes Volume I: Sources United Nations
38. USEPA (1991) The United States Environmental Protection Agency, National primary drinking water regulations for radionuclides. EPA/570/9–91/700. Washington: US, Governmental Printing Office
39. USNRC (1999) United States Nuclear Regulatory Commission, Risk assessment of radon in drinking water. National Academies Press
40. WHO (2009) The World Health Organization, Handbook on Indoor Radon: a Public Health Perspective. World Health Organization
41. WHO (2011) The World Health Organization, Guidelines for drinking-water, quality, Fourth edition. World Health Organization
42. WHO (2004) The World Health Organization, Guidelines for drinking-water quality, Volume 1: Recommendations. World Health Organization
43. Xuan PT, Duong NA, Chinh V van, et al (2020) Soil Gas Radon Measurement for identifying active faults in Thua Thien Hue (Vietnam). Journal of Geoscience and Environment Protection 08:44–64. https://doi.org/10.4236/gep.2020.87003
44. Yakut H, Tabar E, Zenginerler Z, et al (2013) Measurement of 222Rn concentration in drinking water in Sakarya, Turkey. Radiation Protection Dosimetry 157:. https://doi.org/10.1093/rpd/nct157
45. Yalım HA, Sandıkcıoglu A, Ünal R, Orhun Ö (2007a) Measurements of radon concentrations in well waters near the Akşehir fault zone in Afyonkarahisar, Turkey. Radiation Measurements 42:505–508. https://doi.org/10.1016/j.radmeas.2006.12.013
46. Yalım HA, Akkurt I, Özdemir FB, et al (2007b) The measurement of radon and radium concentrations in well water in the Afyonkarahisar area of Turkey. Indoor and Built Environment 16:77–81. https://doi.org/10.1177/1420326X06074731
47. Yıldız A, Dumlupunar İ, Bağcı M, et al (2012) Afyonkarahisar ve Çevresinin Depremselliği. Afyon Kocatepe University Journal of Sciences 12:1–7

Figures

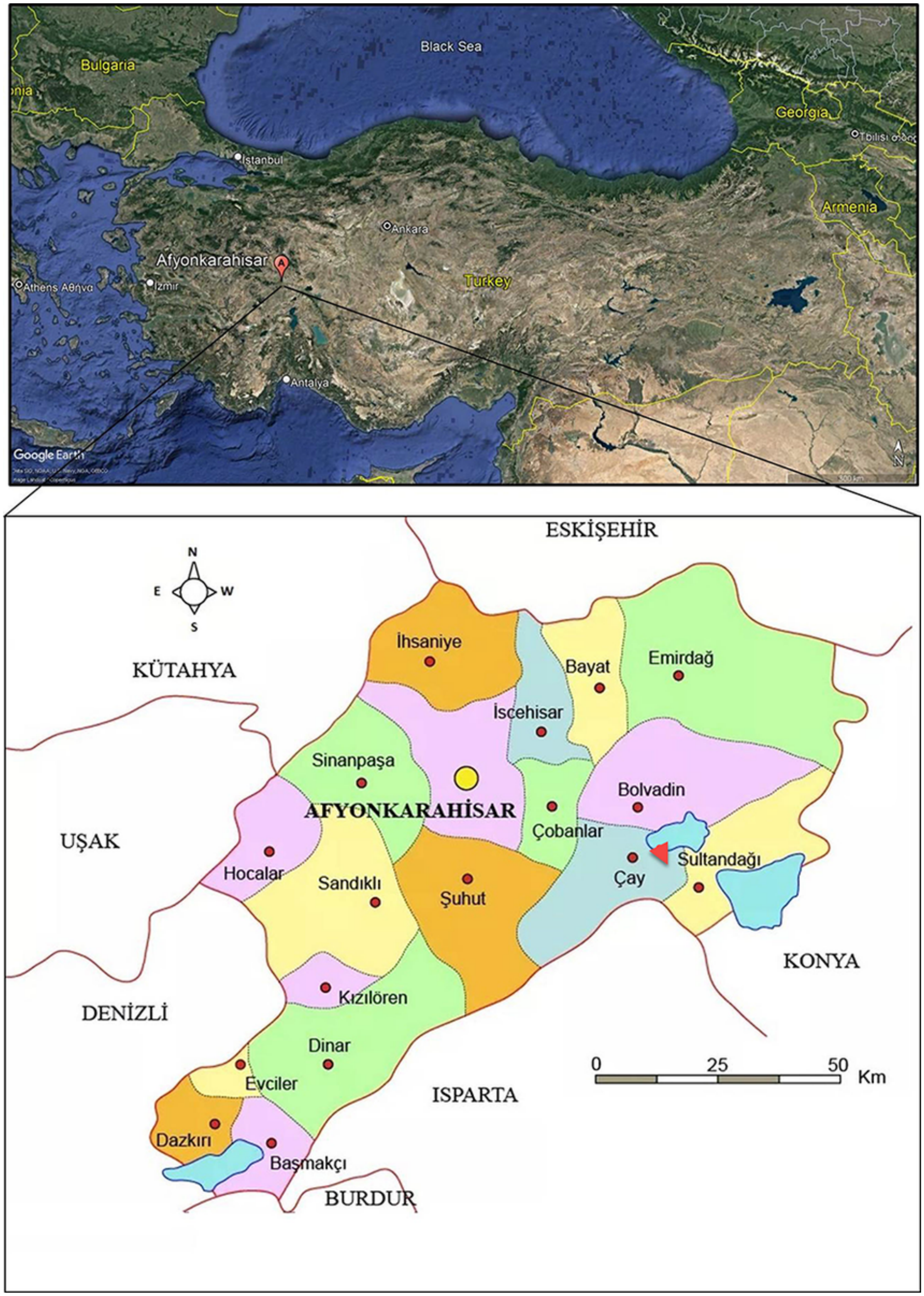

Figure 1

Afyonkarahisar city and districts, including the study area

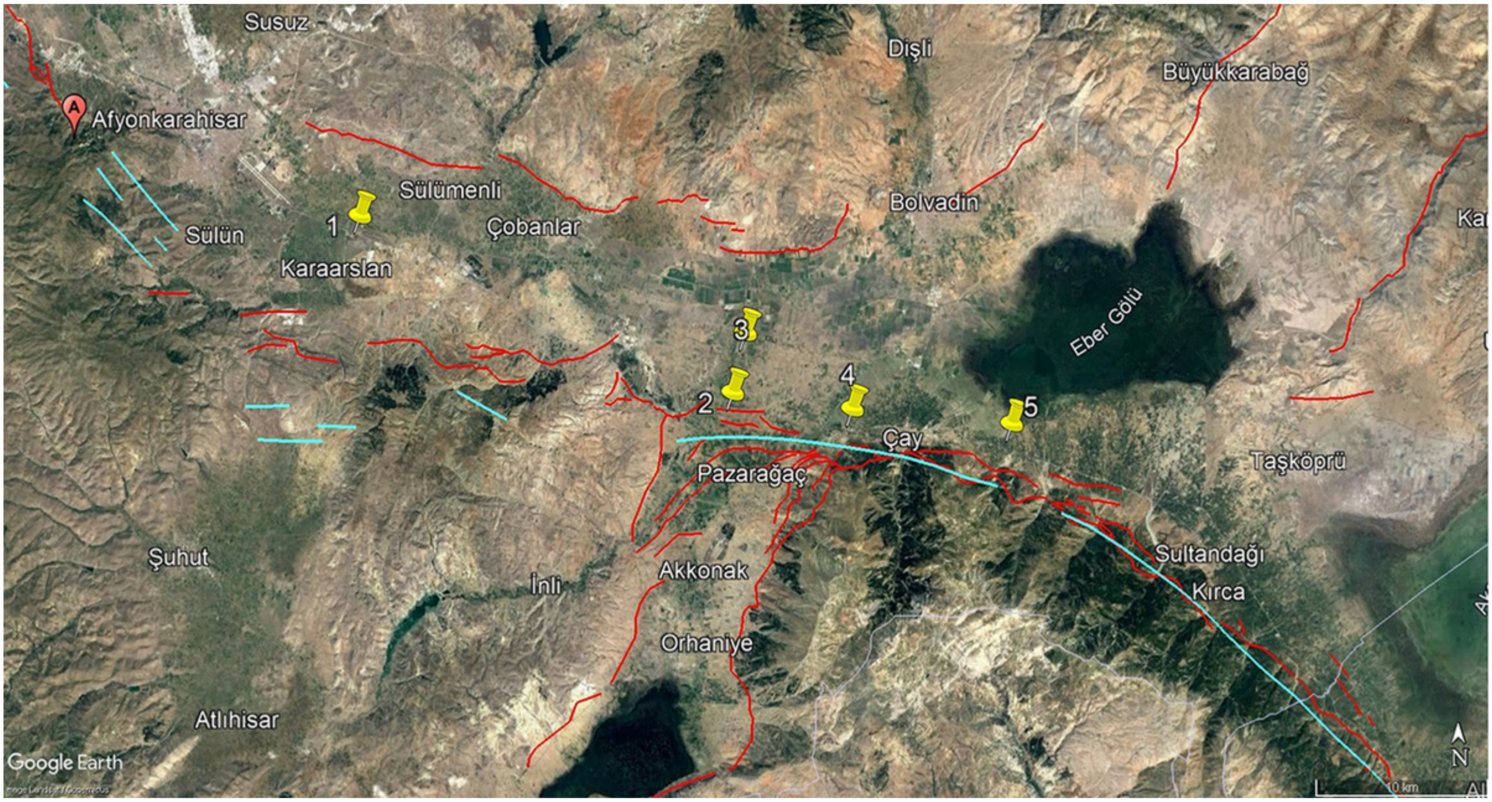

Figure 2

Locations of the wells, the ASFS, and other faults

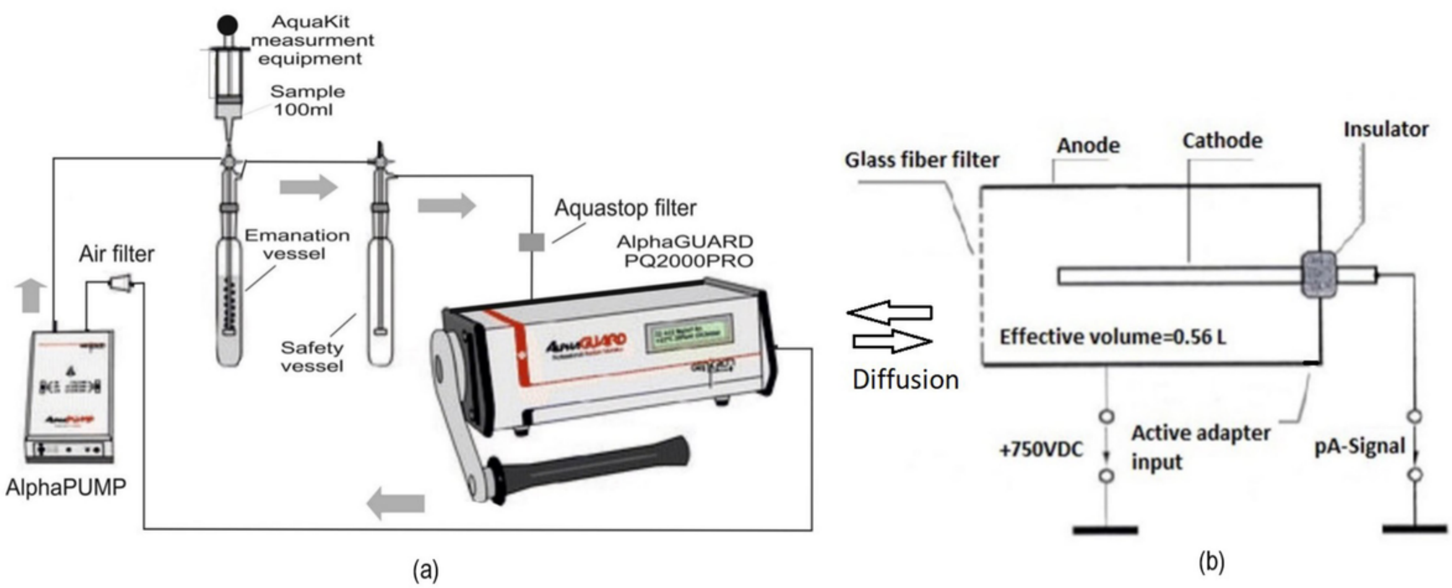

Figure 3

(a) Schematic of the experimental set-up (b) Schematic drawing of the ionization chamber of the AlphaGUARD detector

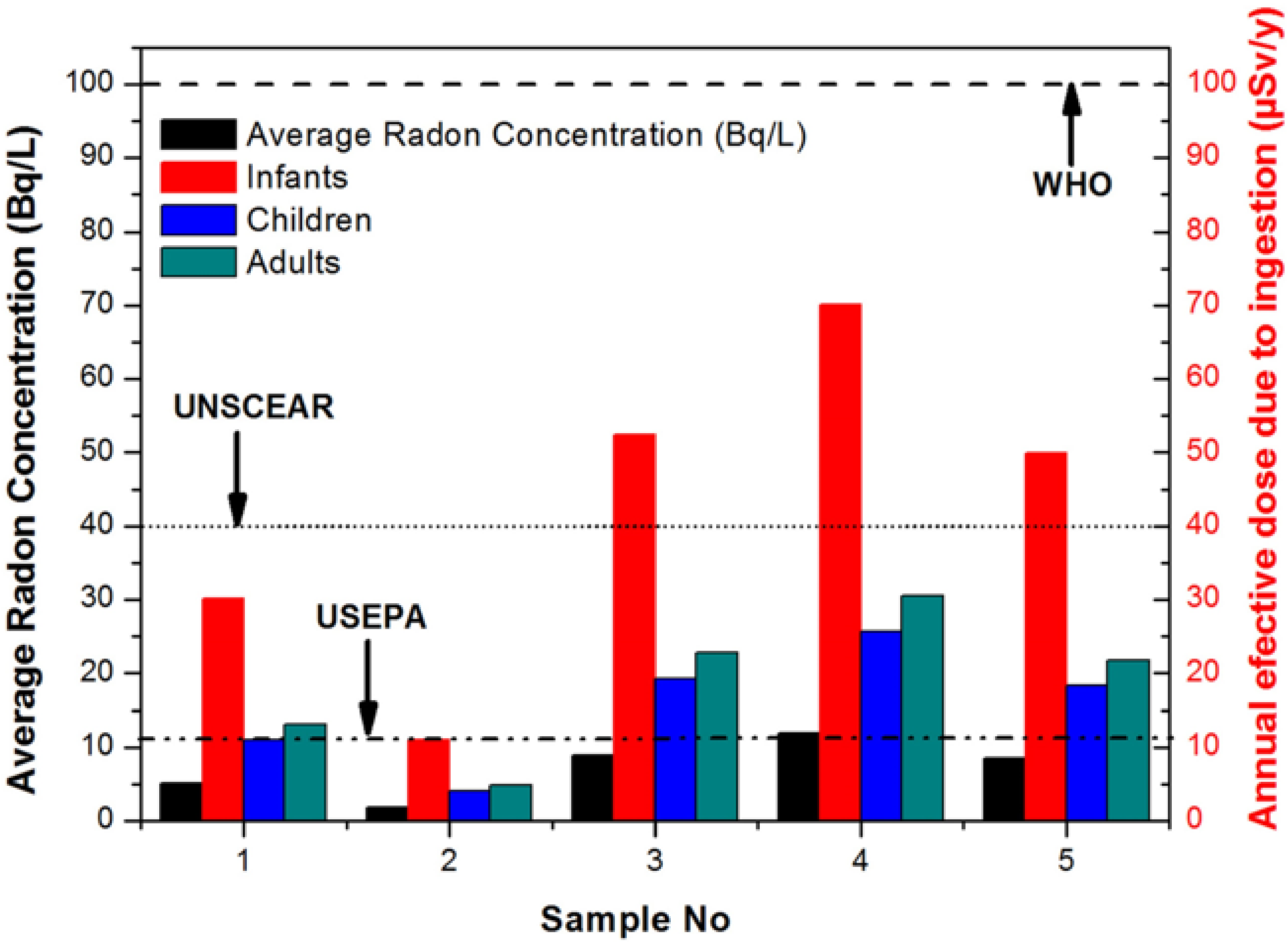

Figure 4

Average ^{222}Rn concentrations of measuring points and annual effective doses for ingestion

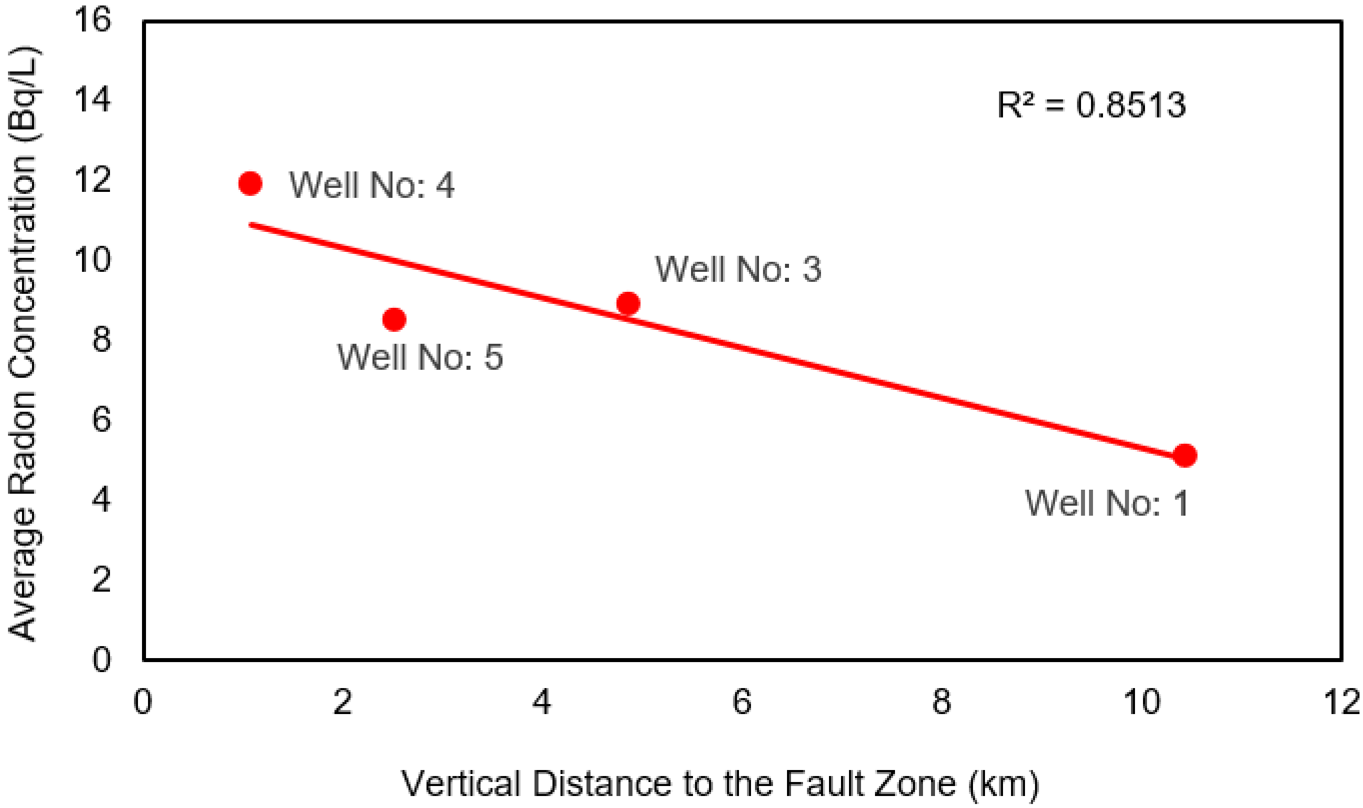

Figure 5

Correlation between the mean radon concentrations of the wells and their vertical distance from the ASFS