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Research paper

Radon in the groundwater in the Amman-Zarqa Basin and related environments in Jordan

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ABSTRACT

The occurrence of radon (^{222}Rn) in environment (groundwater and indoor air) from geogenic sources is receiving an growing attention due to its adverse impact on human health worldwide including Jordan. Highlighting the current status of radon in Jordan, the present study of radon concentrations in ground waters in the Amman-Zarqa basin (AZB) was investigated. Groundwater samples were collected from fifteen wells located in three main areas of Ras Al-Ain, Al-Rsaifeh and Al-Hashemite. Radon concentration was measure using Liquid scintillation counting (LSC) Tri- Carb 3110 with discriminator and the highest values for radon concentration in water were observed in Al-Rsaifeh area and ranged from 4.52 up to 30.70 Bq/l with an average of 11.22 Bq/l, which were attributed to the decay of naturally distributed uranium in phosphate rock from Al-Rsaifeh mines. In Ras Al-Ain area, the radon concentration were noted ranged from 0.6 to 5.55 Bq/l with an average of 2.82 Bq/l, and also in Al-Hashemite area were ranged from 0.77 to 5.37 Bq/l with an average of 4.04 Bq/l. The overall average concentration of tested samples was 5.77 Bq/l and found within the acceptable international levels. Ground water samples of Ras Al-Ain area showed good quality as was tested of low salinity. It recorded the lowest average radon concentration of 2.82 Bq/l. Also, Radon indoor and building materials was reviewed. In conclusion, this study presented an urged need for developing national regulations and standards as well as awareness program concerning the radon status in Jordan.

1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive gas which is invisible, odorless and tasteless. The half-life time of (^{222}Rn) was estimated at 3.825 days and considered long relative to that of the other isotopes. Radon emerged from the radioactive decay of radium (^{226}Ra) and two other natural isotopes of Actinon (^{219}Rn) and Thoron (^{220}Rn). It is quite important to understand the original source of radon and its chemical and physical characteristics. ^{238}U is the parent element of radon isotope, ^{222}Rn (atomic number of 86), and it's the most common uranium isotope found in nature. ^{222}Rn has a boiling point of $-61.8\,^{\circ}$C (-79.2°F) and a density of 9.72 g/l. It is known that ^{222}Rn dissolves in water. Radon flouride (RnF) is the first compound produced from radon. Nazaroff (1992) presented a comprehensive review on the understanding of radon generation from earth surface and its migration through soil pores to the indoor and outdoor atmosphere. Fig. 1 shows the uranium series which ends with stable lead (^{206}Pb) as the final product. Skeppström and Olofsson (2007) reviewed the problem of uranium and radon in groundwater and its impact on health, who investigated the natural radioactivity of ^{222}Rn in drinking water from drilled wells in Sweden.

Natural occurrence of ^{222}Rn is observed in most rocks, soils and mainly groundwaters. However, low concentrations of radon were observed in surface water due to its ease of emission from open water. Indications showed that indoor levels of radon accumulations were orders of magnitude higher than the outdoor levels (Liendo et al., 1997). Radon (^{222}Rn) is considered as hidden killer as evident by several studies being factor for increasing risk of lung cancer (NAS, 1988; Jostes, 1996; Hofmann, 1998; Torres-Duran et al., 2014; Dempsey et al., 2018).

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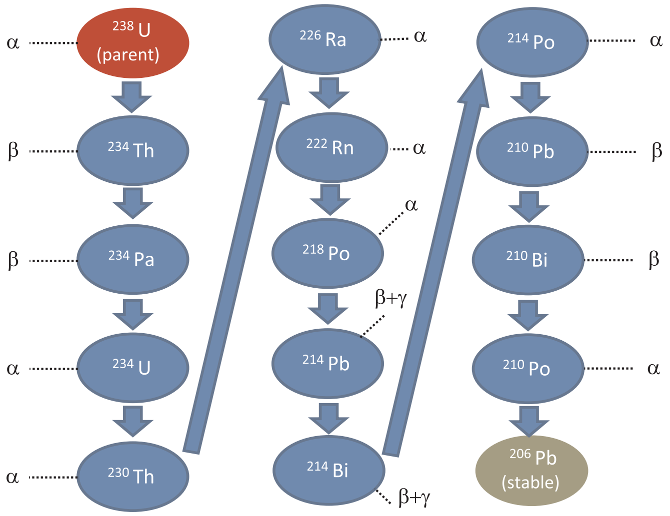

Fig. 1. The radioactive decay series of uranium (^{238}U) and the formation of radon (^{222}Rn) (modified from Skeppström and Olofsson, 2007).

Earlier, the concentrations of radon above 400 Bq/m^3 was considered to constitute a health risk. However, several recent epidemiological studies have demonstrated lung cancer risk from exposure to radon (^{222}Rn) in indoor air at levels down to 100 Bq/m^3 (Pacheco-Torgal, 2012; NAS, 1999; ICRP, 1993; European Commission, 2001; Health Canada, 2009). Moreover, a relationship was established between radon exposure and employees working in drinking water supply systems, such as well houses, conditioning plants, reservoirs, and pumping stations (Schmitz et al., 2000; Schmitz and Nickels, 2001). Trautmannsheimer et al. (2002) reported on the radon concentrations in groundwater, indoor air and the radon exposure levels to the working staff in Bavaria of Germany, and existing water supply facilities, where in the east Bavarian crystalline region, indoor radon gas concentrations of up to 300 kBq/m^3 were observed. Even, about 10% of the processing facilities workers of that region got an annual effective dose of more than 20 mSv (Trautmannsheimer et al., 2002).

Radon concentrations were reported in several springs and well water sources in the countries neighboring Jordan, such as Lebanon and Saudi Arabia (Abdallah et al., 2007; Alabdula'aly, 1997; Tayycb et al., 1998). The concentration was as low as 0.91 Bq/l in a coastal well source, and as high as 49.6 Bq/l for a spring source in a mountainous region in Lebanon. These concentrations are considered within the lower range of the Swedish regulatory limit for radon (Skeppström and Olofsson, 2007). The drinking water distribution network of Riyadh city in Saudi Arabia was sampled and radon concentration was found to range between 0.1 and 1.0 Bq/l with an average of 0.2 Bq/l (Alabdula'aly, 1997). Tayycb et al. (1998) observed in the city of Jeddah that the radon concentration in different water sources was the highest in natural mineral water samples and the lowest in flush water. Moreover, they reported that the annual effective dose resulting from direct consumption of water is far greater than that due to inhalation of radon emanated from tap water and flushing water (Tayycb et al., 1998).

Radon gas has received an increased attention from researchers (Al-Bataina et al., 1997) in Jordan since 1995. Khalidi and Taweel (2016), found an evident lack of knowledge of radon and its health hazards in Jordan, and an overall estimate of the level of awareness on radon information among Jordanians was 63.1%, which was considered quite low. Al-Zubaidy (2012) showed an increase in the probability of lung cancer in some poorly-venilated homes in Al-Mafraq city which could be attributed to radon. The average radon concentration in Al-Mafraq city was estimated as 49.3 ± 17.4 Bq/m^3 which was comparable to the nationwide average radon concentration of 42 Bq/m^3.

Thus, the issue of ^{222}Rn in indoor facilitates and drinking water is a sensitive topic to address as it's a source of health risk, especially due to the availability of insufficient data on ^{222}Rn in groundwater. Considering the background, the main objective of the present work is to present an up to date status of the radon occurrence in groundwater and related environments in Jordan and studying the ^{222}Rn concentrations in groundwater used for drinking in one of most important basins (Amman-Zarqa Basin) in central Jordan.

Table 1
Radon concentration in indoor air in selected cities in Jordan (Khataibeh et al., 1997).

City	Radon concentration (Bq/m^3)
Irbid	30
Jerash	40
Ajloun	50
Zarka	33
Amman	41
Salt	46
Madaba	74
Karak	105
Tafilah	41

2. Radon in indoor air and building materials

The indoor ^{222}Rn concentrations (Bq/m^3) were recorded in some selected cities in Jordan (Abumurad and Al-Tamimi, 2005; Al-Zubaidy and Mohammad, 2011, 2012; Khataibeh et al., 1997). Table 1 shows radon concentration indoor for selected cities in Jordan (Khataibeh et al., 1997). Abumurad and Al-Tamimi (2005), in their study covering Soum area which is located north of Jordan, highlighted that radon levels in winter exceed that of fall or spring by about 10–12%. The average indoor radon concentration in the study area was 144 Bq/m^3 which is below the recommended level by ICRP (1993). In a different report, Al-Zubaidy and Mohammad (2011, 2012), measured indoor radon gas concentration in Hakama village in Irbid province of north Jordan and reported that the average indoor radon concentration was ranged from 18.8 Bq/m^3 to 37 Bq/m^3. In a study focusing on the dwellings of Foara and Hawar villages which were also located northern part of Jordan, Mohammad and Abumurad (2008) had reported concentrations between 36.6 ± 7.5 Bq/m^3 and 50.8 ± 5.4 Bq/m^3. In another study, Abumurad (2001) and Abumurad et al. (1997) determined indoors radon levels using passive diffusion dosimeters (using CR-39) in Al-Mazar area, northern part of Jordan in different seasons. They found that the average radon concentration during the summer season was about 62 Bq/m^3 while in winter season it was about 81 Bq/m^3. Abdullah (2012), presented a study to measure natural radioactivity concentration in the dwellings of the Umm Gais village by using a solid state nuclear track detectors. His study indicated relatively high concentration as average 80 ± 16 Bq/m^3 in stone-made buildings while relatively low concentration as average 42 ± 11 Bq/m^3 in block-made buildings. The concentrations of radon were noticed as average as 56 ± 12 Bq/m^3, 44 ± 11 Bq/m^3, and 30 ± 10 Bq/m^3 with the building aging of > 25, 15–25, and < 15 years, respectively. The overall average of radon concentration in the Umm Gais village was found to be about 58 ± 14 Bq/m^3.

Elzain (2011), investigated the variations in seasonal radon concentration levels at some commercial facilities in Zarqa city in Central Jordan. The measurements were collected using passive calibrated solid state Nuclear Track Detectors (NTD). Minimum averages were observed during summer with 18.2 ± 6.7 Bq/m^3 and 16.6 ± 3.9 Bq/m^3 in pharmacies and shops, respectively, and maximum averages during winter with 50.0 ± 4.1 Bq/m^3 and 45.1 ± 4.2 Bq/m^3 in pharmacies and shops, respectively. Ya'qoub et al. (2009), noted an average radon gas concentration in houses of 111 ± 4 Bq/m^3 in As-Salt area over the period extended from April to July of the year 2004. In addition, the concentration of radon short-lived daughters (^{222}Rn and ^{226}Ra) was estimated to be 44 ± 2 Bq/m^3. In Tafila Province which located in the southern part of Jordan, Abu-Haija et al. (2010) estimated the overall average of radon concentration level of 26.28 Bq/m^3 inside the dwelling of Tafila province.

As per report of NCRP (1984), at least 80% of the radon emitted into the atmosphere emerged from the top layers of the soil of with an average thickness of 1.5 m. Al-Shereideh et al. (2006) and Ershaidat et al. (2015) presented the ^{222}Rn concentration levels of soil, at different depths, in an area which is rich in phosphate rock deposits in the city of Irbid, northern part of Jordan by using the CR-39 dosimeters. The radon concentration were reported as 1390, 9682, 16,778, 19,817, 21,720, and 24,206 Bq/m^3 at the depths of 0, 20, 40, 60, 80 and 100 cm, respectively. Kullab (2005), conducted an assessment of radon concentrations in buildings, building materials, water and soil at various cities in Jordan.

3. Materials and method

3.1. The study area

Jordan has a Mediterranean climate, and experiences a s hot and dry summer (May-September), and cold and wet winter (October –April). The rainfall occurs in winter which extends from November to April. The main water resources in Amman-Zarqa Basin (AZB) come from groundwater, surface water and treated wastewater. The safe yield of AZB aquifer is estimated at 88 MCM/year (ARD Associates in Rural Development Inc, 2001). There are two major sources of the groundwater to AZB, namely; treated wastewater and the Zarqa river. The latter source is estimated at 68 MCM (Al-Salihi, 2006) and has two main branches; the Amman-Zarqa draining through the high rainfall areas of the Jordan rift valley, and the Wadi Dhuliel draining the Jordan highlands and plateau.

The recorded average temperature in the selected study area ranges from 4 °C in winter and up to 35 °C in the summer (Water Authority of Jordan, 2017). The area of the selected zone from the Amman–Zarqa basin covered in this study is about 850 km^2. Fig. 2 shows the location of the Amman-Zarqa basin (WAJ, 2017). The groundwater of this area is used to meet the domestic, irrigation and industrial demands. Also, the Amman-Zarqa basin is a highly urbanized area exceeding more than 60% of the total Jordan population. The study area contains hundreds of public and private wells in addition to many springs. The main source of water supply in the Amman–Zarqa basin is Ras Al-Ain spring. The average rainfall ranges from 400 to 500 mm in the west part of the basin, while declines to 150–200 mm in the east part of the basin (WAJ, 2017).

3.2. Geological characteristics of study area

The Amman Zarqa Basin is formed by basaltic eruption at the top, limestone aquifer in the middle, and sandstone aquifer at the bottom. The upper two aquifers are hydraulically connected (Al-Zyoud et al., 2015). The geological aspects of the area under study, consists of two groups, Balqa and Ajlun, which are formed during the Cretaceous period. The first group of developed areas are Al-Hasa, Amman and Wadi Ghudran. These areas, mainly contain phosphate, variable sequence of chert, limestone, dolomite and chalk, while the second group of developed areas; Wadi Sir, Shueib, Hummar, Fuhies and Naur, and they mainly contain limestone, chert, dolomitic-limestone, marl and chalk. These geological descriptions are briefly presented in Table 2. Fig. 3 shows the variety of rock types, geological mapping of the AZB area and the locations of wells being tested in yellow dots which are surrounded with limestone and phosphorite rocks (WAJ, 2017). A full environmental study of the AZB and its various springs was carried out (Awad, 1997). For further information on the outline hydrogeology of the concerned area is available through the Ministry of Water and Irrigation.

The Al-Rsaifeh area, which is located south of the Amman-Zarqa highway, is characterized by one of the oldest phosphate rock mines in Jordan. Even though it still contains large reserves of phosphate rock. However, the mines were closed in 1988 due to increased population density. It was found that there are notable concentrations of uranium at different locations in the Al-Rsaifeh area ranging from 57 up to 184 ppm with an average of 123 ppm, and the uranium content increases upwards to surface (Abed and Khalid, 1985).

3.3. Groundwater sampling

Groundwater samples were collected from 15 wells in different areas of Ras Al-Ain, Al-Rsaifeh and Al-Hashemite which represent the main water sources though the Amman-Zarqa Basin (Fig. 3). These samples were taken over the period from May to July 2017 during the season of summer. Water was allowed to flow for a few minutes from wells prior to sampling; samples from springs were collected at the mouth of the source. A water sample of 10 ml was taken from the water resource site and injected using a needle from a hypodermic syringe into scintillation vials which contains a 10 ml of cocktail Opti-fluor. The vial was shaken vigorously to ensure that radon is extracted from the water phase to the organic scintillant solution due to its greater solubility in organic liquids. The collected samples were taken directly to the laboratory for measurement and extreme caution was to minimize the loss of radon during collection and transport. Exact time and date were recorded for each group of collected samples. Each sample vial was carefully wiped from outside with a cloth and left for a minimum of three hours. This step allowed for ingrowth of the lived decay products of radon and equilibrium state.

3.4. Estimation of radon

Liquid scintillation counting (LSC) Tri- Carb 3110 with discriminator was used for measurement of radon concentration. It has an advantage of the high solubility of radon in organic solvents, which are used in cocktails for LSC, and of high counting efficiency for alpha particles. Alpha/beta discrimination using automatic PDA (Pulse Decay Analysis) separates alpha and beta radionuclides with automatic optimization of minimum spillover settings applied to each protocol. It includes automatic determination and plotting of alpha-in-beta and beta-in-alpha spillover curves (Perkin, 2018).

The chemicals and reagents were used such as HNO_3 69%, ^{226}Ra standard certified solution with 0.2086 μCi/l, and distilled water. Following the three hour ingrowth, the sample vial, handled with care and unshaked, was placed into the LSC for a suitable counting period of time using a calibrated window. Also the background of the counting system was determined by counting a vial with 10 ml of an organic solution and 10 ml of distilled water and with almost the same counting period used for water sample vials.

Beside considering the background effect of the counting system, a set of calibration solutions in LSC vials was prepared by using a Radium-226 standard certified solution. The solution was accurately diluted with 500 ml distilled water, mixed with 1 ml of HNO_3, gently evaporated to 10 ml volume and then mixed with equal 10 ml of organic scintillant. To estimate instrument performance and calculate the system efficiency, three standard solutions were tested of 10 Bq, 5 Bq and finally 2.5 Bq. Table 3 illustrates the net counts per minutes (CPM) for both standard and system background. Also the disintegrations per minutes (DPM), the activity of standard, and its error were calculated.

3.5. Statistical analysis

The LSC-Tri-Carb 3110 is capable of conducting Instrument Performance Assessment (IPA) which measures background, counting efficiency and sensitivity. The background correction ($CPM_{corrected}$) is

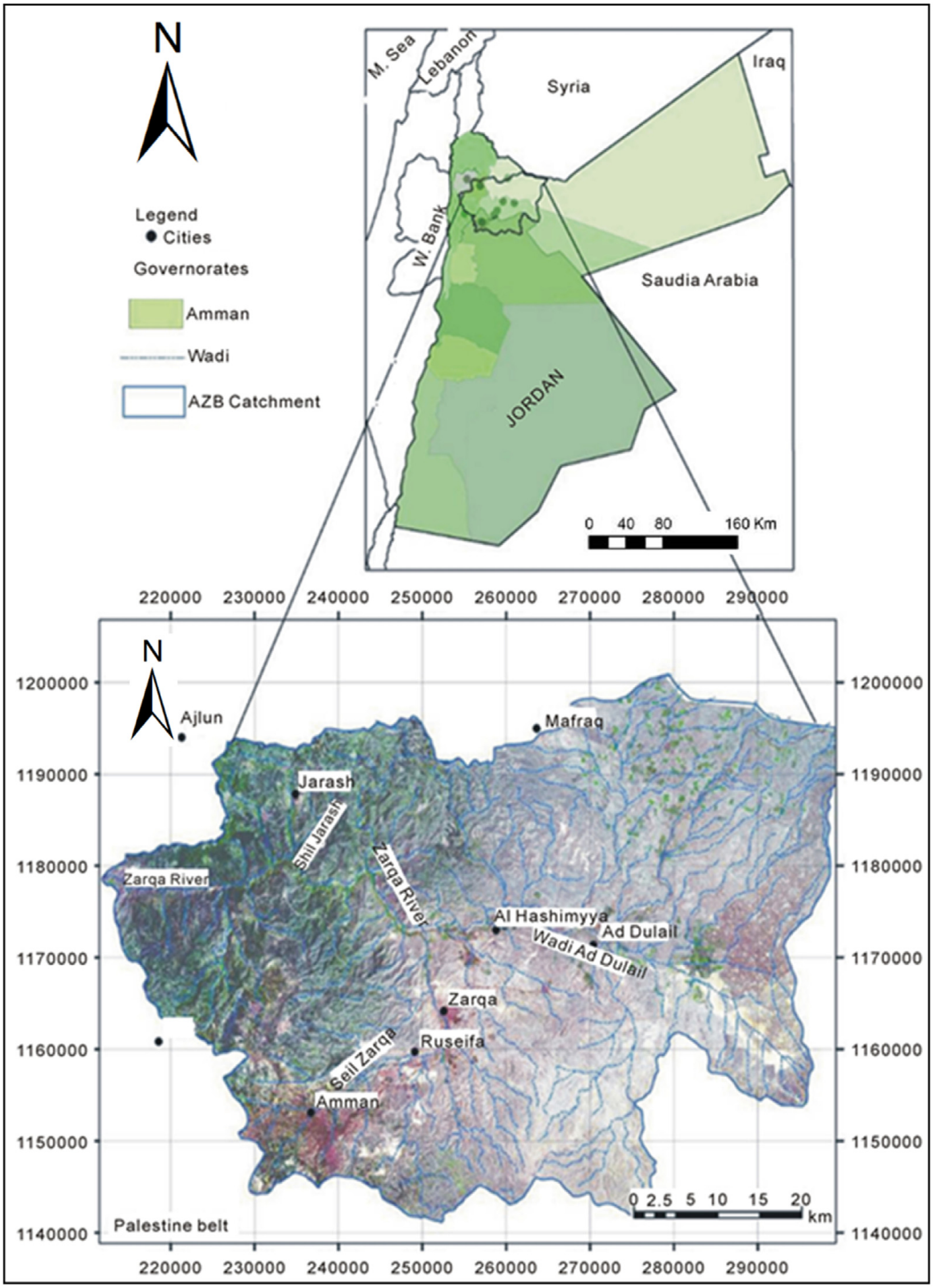

Fig. 2. Map of Jordan and the location of the Amman-Zarqa Basin in North Jordan (Al Kuisi et al. (2014)).

Table 2
Geological description of study area (WAJ, 2017).

Period	Group	Formation	ID	Ideal thickness	Aquifers
Late Cretaceous	Balqa	AlHisa Phosphorite	B2	40–60 m in mid	Upper Carbonate (B2-A7)
		Amman Silicified		100 in Mujab	
		Wadi Ghudran	B1	50 m rbed	
	Ajlun	Wadi Sir LS	A7	120 m North Amman	
		Shueib Formation	A5–6	65 m Ajlun, 60 m Um dananeer	Aquiclude
		Hummar LS	A4	60–65 Hummar	Lower carbonate
		Fuheis Formation	A3	80–90 m Irbid	Aquiclude
		Naur LS	A1–2	86 m Amman	Aquifer
Early Cretaceous		Kurnub sandstone	KS	320 m Al Arda	Deep sand aquifer

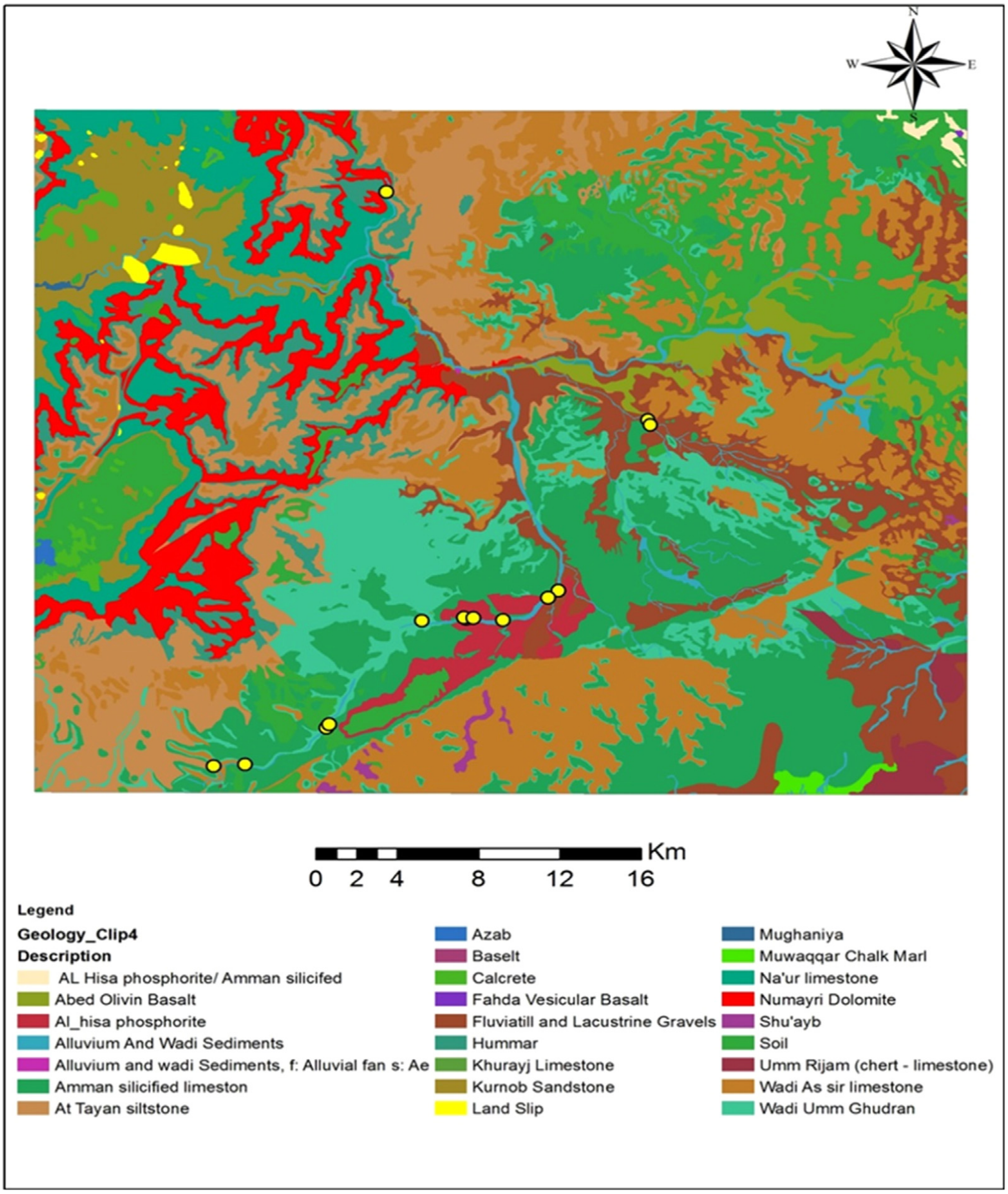

Fig. 3. Geological map of the AZB area with the location of the 15 groundwater sampling sites marked as yellow circles (●) (WAJ, 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difference between $CPM_{sample} - CPM_{Background}$. Whereas the efficiency of the instrument is the ratio of CPM/DPM. The efficiency of the narrow alpha window is approximately 300% due to the presence of the three alpha emitters, ^{222}Rn, ^{218}Po, ^{214}Po The discriminator setting of the used LSC is shown in Fig. 4. The Alpha /Beta discrimination was tested by using standard of Sr-90 as Beta emitters and Am −241 as Alpha emitters.

The main critical values of the operated system are the pulse decay discriminator (PDD) = 136, % Alpha spillover = 3.84, and % Beta spillover = 2.55. The calculated average efficiency is around 0.769 with an average error of 0.0195. The analysis of the data obtained from both water samples and standard samples was carried out at 2 sigma percent value which represents the percent of uncertainty in a gross count value (with 95% confidence limits).

4. Results and discussion

4.1. Environmental parameters of water

Jordan is facing real water crisis, and AZB is one of the most important groundwater systems which are already exploited beyond their estimated safe yield (Al-Zyoud et al., 2015). The Water Authority of Jordan (WAJ) conducts regular water quality tests as an important part of environmental monitoring and helps in constructing a proper management system. Jordan contains of 15 surface water basins and 12 groundwater basins with more than 3000 operational wells. The safe yield abstraction of non renewable groundwater for 50 years is about 143 MCM annually based on the Ministry of Water and Irrigation report for 2015 estimation. Table 4 represents some physical and chemical analyses of raw water of selected wells in AZB. Water sampling were carried out biweekly during the months of October and November 2017. Samples from Awajan area showed the highest levels of bicarbonates, chloride, sodium and hardness when compared with other resources. Whereas, samples of Qunah spring indicated low levels of contaminants. The pH values range from 7.0 – 8.0. These changes in ground water quality is expected. This is due to the wide variety of deep rock distribution within AZB ranging from chalk-marl, phosphorite and silicified limestone. Therefore, to accommodate such wide variety, Ain Ghazal Pump Station was established to provide the nearby population with adequate drinking water quality. Table 5 presents water analysis for samples of the final product from Ain Ghazal Pump Station. The analyzed results were compatible with the Jordanian drinking water

Table 3
Testing system performance using the certified solution of ^{226}Ra.

STD Bq/vial	STD CPM		BKGR CPM	
10 Direct	1373		2	
	1400		2	
	1414		2	
	1447		1	
	1428		2	
	1421		2	
	1437		2	
	1439		3	
	1434		3	
	1418		2	
Average value	1421.1		2.1	
Standard deviation	14.604		0.568	
Error	0.0143			
Efficiency	0.79			
Net CPM	Efficiency error	DPM error	DPM	Error
1419	0.0048	6	600	14.593
5 Direct	666		2	
	684		2	
	691		2	
	689		1	
	700		2	
	700		2	
	700		2	
	686		3	
	701		3	
	686		2	
Average value	690.3		2.1	
Standard deviation	10.884		0.568	
Error	0.0187			
Efficiency	0.77			
Net CPM	Efficiency error	DPM error	DPM	Error
788.2	0.085	6	300	10.869
2.5 Direct	333		2	
	330		2	
	339		2	
	338		1	
	347		2	
	346		2	
	329		2	
	340		3	
	353		3	
	340.2		2	
Average value	340.2		2.1	
Standard deviation	8.011		0.568	
Error	0.026			
Efficiency	0.75			
Net CPM	Efficiency error	DPM error	DPM	Error
338.1	0.0155	6	150	7.991

Table 4
Water quality parameters measured in raw water samples from selected wells in AZB (WAJ, 2017).

Water parameter	Concentration of water quality parameter in different well			
	Awajan No. 23	Awajan 21 Zerqa Municipality B	Qunah Spring	Muhajereen
Bicarbonate (mg/l)	353.4	341.3	282	309
Calcium (mg/l)	139.4	142.6	81	122.3
Chloride (mg/l)	385.6	378.6	83.3	123.3
Hardness as $CaCO_3$ (mg/l)	500	533	330	375
Magnesium (mg/l)	37	43.2	31	17
Nitrate (mg/l)	46.2	40.6	33	94.8
Potassium (mg/l)	8.4	6.8	6	4.9
Sodium (mg/l)	193.8	219.6	47.2	63
Sulfate (mg/l)	50.5	89.7	63.8	18
EC (uS/cm)	1920	2070	878	1114
Thorium 232 (ppt)	< 0.85	< 0.85	< 0.85	< 0.85
Uranium 238 (ppt)	2348.18	3154.38	1004.25	2228.37

standards no. JS 286/1997.

4.2. Radon in groundwater

The international acceptable level of radon concentration in drinking water is below 11 Bq/l. All examined samples from different wells are shown in Table 6. These results divided into three groups based on the location of the tested wells. Table 6 shows radon concentrations of Ras Al-Ain area which ranges from 0.6 Bq/l at Ras Al-Ain deep well to 5.55 Bq/l at Ain Gazal well with an overall average value of 2.82 Bq/l for this tested area. The radon concentrations of Al-Rsaifeh area which ranges from 4.52 Bq/l at the Al-Rsaifeh well-1–30.70 Bq/l at the Al-Rsaifeh Well-8 with an overall average of 11.22 Bq/l of this tested area (Table 6). The radon concentrations of Al-Hashemite area which ranges from 0.77 Bq/l at the Al-Hashemite 2 well to 5.37 Bq/l at the Auajan 21 well with an average of 4.04 Bq/l for the examined area (Table 6). The ground waters of the Ras Al-Ain area has the lowest radon concentrations. Based on hydrochemical studies of the Zarqa river, it showed that the salinity increases along the direction of flow of the river, and ranges between 320 ppm at Ras Al-Ain and 1100 ppm at Sukhneh (Zarqa) (Awad, 1997). The Ras Al-Ain area (Amman) usually has the highest rainfall in AZB estimated around 400–500 mm when compared with the Rsaifeh and Al-Hashemite areas which have a lower rainfall estimated around 150–200 mm. Therefore, waters of the Ras Al-Ain area can be considered as very good quality water. The radon

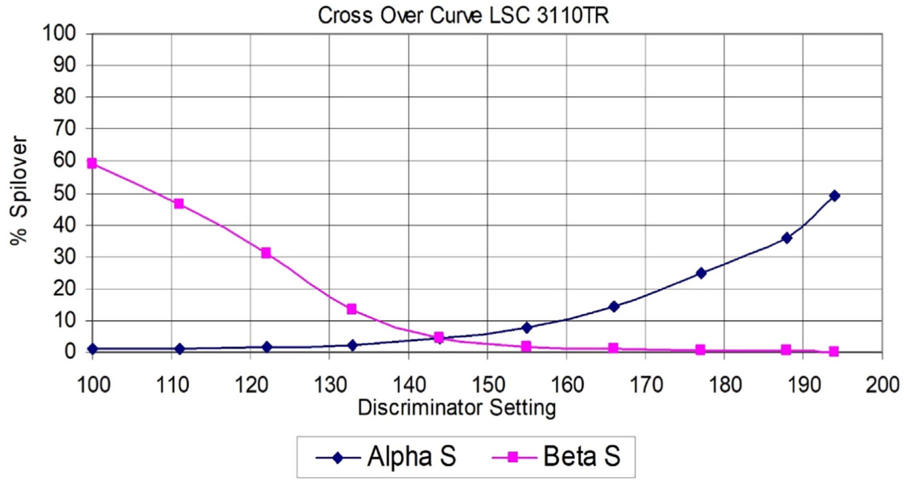

Fig. 4. Discriminator settings of the used LSC.

Table 5
Water property analysis as a final product from Ain Ghazal Pump Station (WAJ, 2017).

Parameter	Concentration/ value	Parameter	Concentration/ value
pH	7.37	Fluoride (ppm)	0.41
EC (uS/cm)	1007	Silver (mg/l)	< 0.01
Color (CU)	15	Residual Chlorine (mg/l)	1.5
Anionic Surfactants (mg/l)	< 0.02	Ammonia (mg/l)	< 0.10
Aluminum (mg/l)	< 0.01	Turbidity (NTU)	0.55
Arsenic (mg/l)	< 0.005	Iron (mg/l)	< 0.01
Boron (mg/l)	0.2	Mercury (ppb)	< 0.15
Barium (mg/l)	0.13	Manganese (mg/l)	0.005
Bicarbonate (mg/l)	277.9	Molybdenum (mg/l)	0.01
Cadmium (mg/l)	< 0.003	Nitrite (mg/l)	< 0.20
Calcium (mg/l)	93.4	Lead (mg/l)	< 0.005
Chloride (mg/l)	127.8	Antimony (mg/l)	< 0.005
Hardness as $CaCO_3$ (mg/l)	326	Selenium (mg/l)	< 0.005
Magnesium (mg/l)	22.5	Zinc (mg/l)	0.04
Nitrate (mg/l)	48.9	Chromium (mg/l)	< 0.005
Potassium (mg/l)	4.9	Copper (mg/l)	< 0.02
Sodium (mg/l)	68.3	*Escherichia coli* (MPN/100 ml)	Absence
Sulfate (mg/l)	31.3	Total Coliforms (MPN/100 ml)	Absence

Table 6
Calculated ^{222}Rn by using LSC for well in Ras Al-Ain area, Al-Rsaifeh area and Al-Hashemite area.

Location name	Average CPM	Radon (Bq/l)
Wells in Ras Al-Ain area		
Ain Gazal Well	181	5.55 ± 0.5
Ras Al-Ain deep well	20	0.60 ± 0.1
Al-Mohagreen well	142	4.40 ± 0.4
Amman mills	24	0.74 ± 0.1
Wells in Al-Rsaifeh area		
Al-Rsaifeh Well-1A	199	6.09 ± 0.6
Al-Rsaifeh well-1	169	4.52 ± 0.5
Al-Rsaifeh well-11	256	6.85 ± 0.7
Al-Rsaifeh well-9A	115	14.79 ± 0.3
Al-Rsaifeh Well-8	263	30.70 ± 0.7
Wells in Al-Hashemite area		
Auajan 21	175	5.37 ± 0.5
Auajan 23	66	1.76 ± 0.2
Al-Hashemite 2	29	0.77 ± 0.1
Al-Hashemite 5	37	1.00 ± 0.1
The spring of Qeneh	18	2.34 ± 0.1
Well Karam/ Qaneh	8	0.89 ± 0.1

CPM = Count per minute.

concentrations in water are considered within the acceptable levels except in two wells (8 and 9 A) in the Al-Rsaifeh area having values reaching 14.8 and 30.7 Bq/l. These increased values were attributed to the presence of phosphate mines in the area where it contains noticeable amount of U in the rocks at an average of 123 mg/kg. The highest recorded value in AZB was 30.7 Bq/l and lowest was 0.60 Bq/l with an average value of 5.77 Bq/l (Fig. 5). Spatial variability of radon concentration in the groundwater samples in AZB gradually decrease outward from the Al-Rsaifeh area (Fig. 6).These levels drop gradually as samples were taken far away from the Al-Rsaifeh area. However, the health and safety considerations indicate that these values do not assume important concern regarding health safety. The physical treatment steps applied to the groundwater involving aeration, mixing, handling and pumping resulted in dramatic drop in these values.

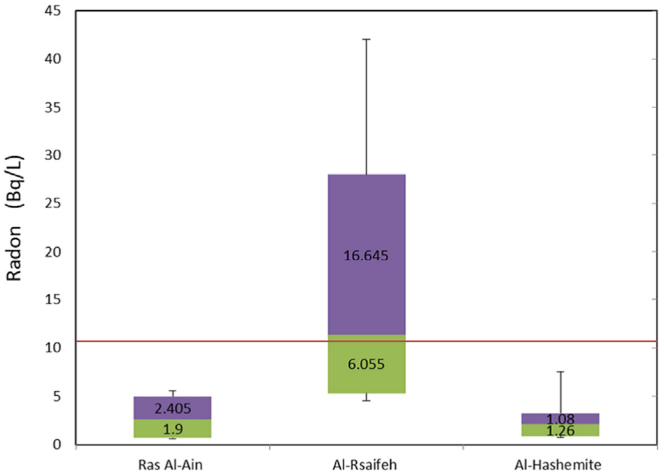

Fig. 5. Radon concentration in groundwater samples from the three investigated areas in AZB, Jordan.

The data and results presented by this study for AZB followed standard procedures of selection, sampling, and analyzing. Unfortunately, the comparison was found challenging with other attempts to study the same area as those attempts were lacking accuracy and confidence. Few unpublished data were found scattered and taken randomly following old and uncalibrated systems, therefore, their results were over-exaggerated and too high. However, the present work conducted systematic investigation on radon present in groundwater in Jordan with joint collaboration with Water Authority of Jordan (WAJ) using up to date instrumentation and calibrated systems. The obtained results were within the acceptable range as compared to known and trusted results concerning other groundwater resources in the city of Amman and in Al-Mufraq province. An early attempt to measure radon concentrations in water was conducted by Al-Bataina et al. (1997). Their attempt involved studying radon levels in natural water sampled from various basins as result showed that cold spring water has the highest average of 5.4 Bq/l, while tap water has 3.7 Bq/l. Also, they reported an overall average for radon level in natural waters in Jordan as 4.5 ± 0.9 Bq/l, which is in agreement with the one obtained in this study of 5.5 Bq/l. Al-Kazwini and Hasan (2003) investigated radon activity in Jordanian drinking water and hot springs throughout Jordan as shown in Table 7. The two sources of the highest radon activity are those at Awajan (Zarka province, northern region) and at Umm-Al-O′rooq in Shafa Badran (Amman Suburbs, central region). Fortunately, limited number of inhabitants depend on these sources of water supply. The third source with radon activity larger than 37 Bq/l is at Al-Khaldiyah and Dlail. This source supply water to several small towns in Al-Mafraq province (Al-Kazwini and Hasan, 2003). A concise review of radon and its existence in ground water in Jordan was presented by (Abu-Khader et al., 2017).

The phosphate rock in Jordan covers a widespread area starting from the far northwest to its south. Fig. 7 shows the main locations of high P_2O_5 content phosphate rock in Jordan. The Uranium concentrations, present within the crystal structure of francolite (carbonate

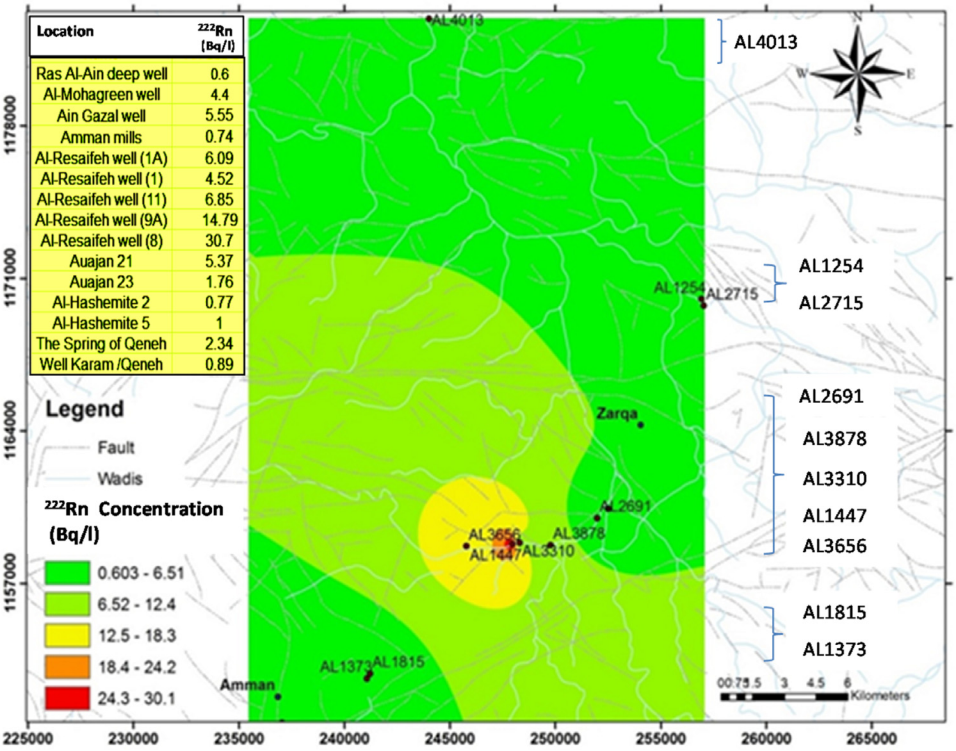

Fig. 6. Spatial variability of radon concentration levels in the investigated areas in AZB.

Table 7
Radon activity in Jordanian drinking water and hot springs (Al-Kazwini and Hasan, 2003).

No. water resources	Radon concentration
10	Less than 11 Bq/l
12	Between 11 and 37 Bq/l
3	Greater than 37 Bq/l.

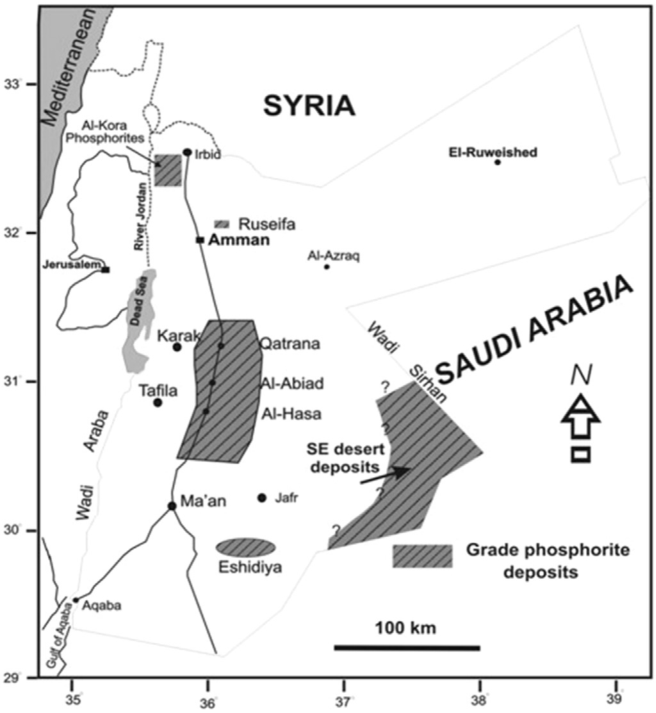

Fig. 7. Main locations of high P_2O_5 deposits of phosphate rock in Jordan (Abed, 2011).

flourapatite) substituting for Ca, varies as low as 7 ppm and up to 379 ppm widely depending on the location in Jordan. However, it was observed that the uranium content in the various localities increases northwards (Abed, 2011; Abed and Khalid, 1985). The expected source of the radioactive gas comes from the breakdown of uranium in phosphate rock. The ^{222}Rn is a decay product of ^{226}Ra which is a decay product of ^{238}U. The latter can be found in uranium ores, phosphate rock, shales, igneous and metamorphic rocks (Kusky, 2003). It is evident that radon emmision from the soil varies with soil type. Thus, present investigation along with previous study report on radon occurance in Jordan, will support the for public awareness and establishment of national legislations and guidelines that strongly needed for public health protection.

5. Conclusion

During the last decade, radon has gained great attention at the national level due to its serious health impact. The Al-Rsaifeh area has recorded the highest values for radon water concentrations reaching up to 14.8–30.7 Bq/l due to the presence of uranium in the phosphate rocks in the Al-Rsaifeh mines. The overall average value of all the tested samples from Amman-Zarqa Basin was 5.77 Bq/l. The groundwaters of the Ras Al-Ain area has the lowest radon concentrations with an average value of 2.82 Bq/l and complemented with low salinity. Based on this brief investigation along with a review on indoor and building materials in Jordan, it is clear that radon health risk problem is not well addressed within the community, and there is a lack of knowledge of how such problem exists and can be minimized or treated. There is a need to develop national regulations, standards and, awareness program.

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