Measurement of gross alpha and beta activity concentration in groundwater of Jordan: groundwater quality, annual effective dose and lifetime risk assessment

Ahmad Hussein Alomari, Muneer Aziz Saleh, Suhairul Hashim, Amal Alsayaheen, Ismail Abdeldin and Refaat Bani khalaf

ABSTRACT

The current study was conducted to measure the activity concentration of the gross alpha and beta in 87 groundwater samples collected from the productive aquifers that constitute a major source of groundwater to evaluate the annual effective dose and the corresponding health impact on the population and to investigate the quality of groundwater in Jordan. The mean activity concentration of gross alpha and beta in groundwater ranges from 0.26 ± 0.03 to 3.58 ± 0.55 Bq L^{-1} and from 0.51 ± 0.07 to 3.43 ± 0.46 Bq L^{-1}, respectively. A very strong relationship was found between gross alpha and beta activity concentrations. The annual effective dose for alpha and beta was found in the range of 0.32–2.40 mSv with a mean value of 0.89 mSv, which is nine times higher than the World Health Organization (WHO) recommended limit and one and half times higher than the national regulation limit. The mean lifetime risk was found to be 45.47×10^{-4} higher than the Jordanian estimated upper-bound lifetime risk of 25×10^{-4}. The data obtained in the study would be the baseline for further epidemiological studies on health effects related to the exposure to natural radioactivity in Jordan.

Key words | effective dose, gross alpha beta, groundwater quality, internal hazard, Jordan, natural radioactivity

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INTRODUCTION

Natural radioactivity in drinking water is of great concern worldwide because it is consumed daily and because of the water's ability to transport pollutants (Subramani *et al.* 2010). The radioactivity in groundwater comes mainly from radionuclides of the natural decay chains ^{238}U and ^{232}Th in soil and bedrock (Dinh Chau *et al.* 2011). Besides that, the levels of naturally occurring radionuclides in drinking water may be increased through human activities. Uranium exploration and mining started in Jordan in 2008 (Xoubi 2015). Mining of solid minerals has been linked with the dispersion of primordial radionuclides in the environment and may result in a build-up of radionuclides in groundwater (Aliyu *et al.* 2015). Groundwater is the main source for drinking and other uses in Jordan. Consequently, these radionuclides transported in groundwater can enter the food chain through irrigation waters and the water source through groundwater wells. Thus, the ingestion of radionuclides in drinking water causes human internal exposure.

Humans are exposed naturally to ionizing radiation from a number of sources which include cosmic rays and natural radionuclides in air, food, and drinking water (UNSCEAR 2000). The presence of radionuclides in

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drinking water poses a number of health hazards (IAEA 1989). The process of identifying individual radionuclides and determining their concentration is time-consuming and expensive due to their low concentrations in drinking water (WHO 2011). Gross alpha and beta activities are very useful parameters for the preliminary screening of waters; the activity concentration of gross alpha and beta gives essential information about the natural radionuclides in water and their corresponding health hazards associated with water consumption (Zikovsky 2006). The recommended guideline activity concentrations are 0.5 Bq L^{-1} for gross alpha activity, 1 Bq L^{-1} for gross beta activity for drinking water and an effective dose criterion of 0.1 mSv $year^{-1}$ (WHO 2011). Below these reference levels of gross activity, drinking water is acceptable for human consumption.

Physicochemical properties of groundwater such as temperature, hydrogen ion concentrations and electrical conductivity (EC) may affect the source of natural radioactivity in groundwater as well as the quality of drinking water (Srilatha *et al.* 2014; Abdurabu *et al.* 2016a). Several studies in recent years have focused on the physicochemical properties of water to evaluate the physical and chemical factors that may affect the source and mobility of natural radionuclides in groundwater (Idriss *et al.* 2011; Ramadan *et al.* 2014; Calin *et al.* 2015; Reddy *et al.* 2017). Concentrations of natural radionuclides in water can be related to the physicochemical conditions (Sarvajayakesavalu *et al.* 2018).

In recent decades, studies of the natural radioactivity in groundwater have received attention worldwide (Kleinschmidt 2004; Kovács *et al.* 2005; Bonotto & Bueno 2008; Damla *et al.* 2009; Kabir *et al.* 2010; Canu *et al.* 2011; Görür *et al.* 2011; Gorur & Camgoz 2014; Saleh *et al.* 2014, 2015; Kobya *et al.* 2015; Abdurabu *et al.* 2016b; Korkmaz *et al.* 2016; Abbasi & Mirekhtiary 2017; Le *et al.* 2017). Most of these studies were focused on determining the levels of radioactivity in drinking water and related health risks resulting from consuming water. The annual effective dose due to the ingestion of gross alpha and beta activities in groundwater in Nevsehir province in Turkey ranged from 0.04 to 0.20 mSv (Turhan *et al.* 2013). In Guilan province in Iran, the mean annual effective dose and lifetime risk assessment due to intake of gross alpha and beta activities in drinking water were found to be 0.0289 mSv and 1.44×10^{-4}, respectively (Abbasi & Mirekhtiary 2017). These types of studies are essential for the assessment of the doses and health risks resulting from consuming water. Drinking water is considered to be an important factor in increasing the natural radiation exposure in humans (UNSCEAR 2000).

Based on existing literature, extensive field measurement of the radioactivity of public water supplies and in particular measurements of gross alpha and beta activity concentration in groundwater and the corresponding excess lifetime cancer risk have yet to be conducted in Jordan. The relationships between groundwater physicochemical properties and gross alpha and beta activity concentrations in Jordan have not yet been studied. Therefore, this study aims to determine the gross alpha and beta activity concentration in groundwater and to estimate the corresponding annual effective dose and excess lifetime risk due to water consumption. Also, this study aims to investigate the quality of groundwater in Jordan. It can provide a baseline to identify groundwater sources that need further investigation with respect to radiation exposure and their suitability for drinking water. The results may also be used as reference data for monitoring possible radioactivity pollution in anticipation that Jordan will have a nuclear power plant in the future (Xoubi 2015).

MATERIALS AND METHODS

Study area

Jordan is situated in the southwest of Asia and is classified as a Mediterranean country with a total area of about 90,000 km^2 and a population of around 10 million people (Jordan Department of Statistics 2017). It lies between latitudes 29° 11′ and 33° 22′ N and between longitudes 34° 59′ and 39° 18′ E. The wells investigated cover most of Jordan, distributed in Amman, Alzarqa, Almafraq, Albalqa, Ajloun, Irbid, Alkarak, Aqaba, and Maan governorates. Most of the wells in the current study constitute the main source of drinking water in Amman-Zarqa basin, which is home to more than 60% of the population of Jordan. Amman-Zarqa basin is one of most important groundwater systems which supplies the three largest cities in Jordan (Al-Zyoud *et al.* 2015).

Climate of Jordan

Jordan has a transition from a Mediterranean to a semi-arid to an arid climate. Rainfall occurs from November to April. From May to October there are dry summers. The Mediterranean climate dominates in the north and north-west of Jordan and rainfall in the winter exceeds 300 mm. In the semi-arid area, the rainfall is between 50 mm and 300 mm, while the annual rainfall in the arid area is less than 50 mm (Bender 1974).

Collection and preparation of groundwater samples

A total of 87 groundwater samples were collected from different drilled water supplies from different governorates in Jordan. Samples were collected in 1-L polyethylene bottles for radioactivity analysis. Samples were preserved at the laboratory upon receipt by adding 2 ml of concentrated HCL assay 35% to bring pH below 2. The gentle evaporation method was applied to prepare water samples for gross alpha and beta measurements; sampling and preparing were implemented based on the recommended methodology (Standard Methods 2012). The prepared samples were then transferred to liquid scintillation counter (LSC) for counting and analysis.

Activity concentration measurement using liquid scintillation counter

The Tri-Carb 3110 LSC from Perkin Elmer was used. Alpha/beta discrimination was constructed by counting separately standards of ^{90}Sr as pure beta and ^{241}Am as pure alpha emitters using the Ultima Gold LLT scintillation cocktail. Efficiency calibration which is considered a first step in calculating activity for all tests was carried out by using standards ^{241}Am and ^{90}Sr. The background of the counting system was determined by preparing 10 ml of Ultima Gold LLT scintillation cocktail into 10 ml of distilled water in the LSC vial.

The activity concentration of gross alpha or gross beta in a certain volume V is then calculated by Equation (1) (L'Annunziata 2003):

$$A_{\alpha\beta}(\mathrm{Bq\,L^{-1}}) = \frac{N_{cpm}}{\varepsilon \times V \times 60} \tag{1}$$

where N_{cpm} is the true count rate, ε is the detection efficiency, V is the sample volume in L, and 60 is the conversion factor to change from decay per minute (dpm) to decay per second (dps).

In low-level radioactivity measurements, it is important to quantify the minimum activity that can be detected reliably. The minimum detectable activity (MDA) is the lowest activity that can be achieved when a sample is measured with a detection system. MDA depends on several factors that include the sample size, the counting time, the counting efficiency and the background. MDA can be increased by increasing counting time or increasing sample size (L'Annunziata 2003). The MDA for the LSC detection system can be calculated as given in Equation (2) (Currie 1968; L'Annunziata 2003):

$$\mathrm{MDA}(Bq\,L^{-1}) = \frac{2.71 + 4.65\sqrt{B(\mathrm{cpm}) \times t(\mathrm{min})}}{\varepsilon \times t \times V \times 60} \tag{2}$$

where MDA is the lowest activity concentration in Bq L^{-1} that yields a net count above background with a 95% probability, ε is the detection efficiency, V is the sample volume (L), B is the background count rate, and t is the counting time. The MDA for gross alpha and beta activities was determined and found to be 0.11 Bq L^{-1} and 0.28 Bq L^{-1}, respectively. The guidance levels below which no further action is necessary are 0.5 Bq L^{-1} and 1 Bq L^{-1} for gross alpha and beta activity, respectively (JISM 2008).

In situ measurements of physicochemical properties in groundwater

Physiochemical parameters such as pH, EC and temperature of groundwater were measured *in situ*. The water was run by the pump for about 10 minutes to assure a representative well sample, the water sample was collected in a plastic container with a capacity of approximately 1 L. The physicochemical properties pH and temperature were measured directly during sampling by placing the probe into the sampling container. Measurement of pH was carried out using the 888-Titrando model of Metrohm instruments. Three standard reference materials from Orion for pH 4, 7 and 10 were used for calibration. The instrument is equipped with an auto sampler and PC to read out results directly. EC was measured directly during sampling by placing the probe into the plastic sampling container. EC was measured by thermo instrument. The instrument was calibrated using 1,413 μS cm^{-1} Standard Reference Material manufactured by Orion.

Annual effective dose and health impact due to ingestion of gross alpha and beta activities in the water

The annual effective dose due to the ingestion of both alpha and beta emitters through drinking water for adults was calculated using Equation (3) (Sajo-Bohus *et al.* 1997):

$$\mathrm{AED}(mSv\,y^{-1}) = A(Bq\,L^{-1}) \times \mathrm{WC}(L\,y^{-1}) \times \mathrm{DCF}(mSv\,Bq^{-1}) \quad (3)$$

where AED is the annual effective dose due to ingestion of alpha and beta emitters, A is the gross alpha and beta activity concentration, WC is the annual water consumption per person and DCF is the ingestion dose conversion factor for gross alpha and beta. The annual water intake adopted in this study is 730 L for adults (JISM 2008; WHO 2011). This value may change based on the outdoor temperature. According to Regnier *et al.* (2015), a hot climate is responsible for additional water consumption and is considered the most significant factor affecting total water consumption.

The estimated dose conversion factor was 0.28 μSv Bq^{-1} for alpha and 0.69 μSv Bq^{-1} for beta (WHO 2011). Lifetime risk assessment was calculated using Equation (4) (Kim *et al.* 2004):

$$\text{Lifetime Risk} = \mathrm{AED}(Sv) \times \mathrm{LE}(y) \times \mathrm{RF}(Sv^{-1}) \quad (4)$$

where AED is the annual effective dose (Sv), assuming a life expectancy (LE) of 70 years, and RF is the risk factor (Sv^{-1}). For risk assessment, the nominal probability coefficient recommended by the International Commission on Radiological Protection for radiation-induced stochastic health effects, which include fatal cancer and severe hereditary effects for the whole population, is 7.3×10^{-2} Sv^{-1} (WHO 2011). Multiplying this by the recommended reference dose level of 0.1 mSv year^{-1} via drinking water gives an estimated upper-bound lifetime risk of approximately 10^{-4}.

RESULTS AND DISCUSSION

Gross alpha and beta activity concentrations in groundwater in governorates of Jordan

Basic descriptive statistics such as minimum, maximum, mean, standard deviation, skewness, and kurtosis of gross alpha and beta activity concentrations in groundwater in Jordan are presented in Table 1. Gross alpha activity concentration in the groundwater of governorates of Jordan recorded a mean value of 1.57 ± 0.24 Bq L^{-1}. Jordanian standards for drinking water quality recommend a limit of gross alpha activity concentration of 0.5 Bq L^{-1} (JISM 2008). These, in turn, rely on the World Health Organization (WHO) guidelines for drinking water quality and ICRP and International Atomic Energy Agency (IAEA) basic safety standards recommendations. The mean gross alpha activity concentration is three times higher than the national regulation limit while 51% of gross alpha activity concentrations are higher than the national regulation limit.

Table 1 | Statistical analysis of gross alpha and beta activity concentration of groundwater in Jordan

Statistical analysis	Activity concentrations of gross alpha (Bq L^{-1})	Activity concentrations of gross beta (Bq L^{-1})
Mean	1.57	1.62
Std error of mean	0.24	0.22
Std deviation	1.92	1.73
Skewness	1.83	1.68
Std error of skewness	0.25	0.25
Kurtosis	3.46	2.24
Std error of kurtosis	0.50	0.50
Minimum	0.18	0.36
Maximum	9.46	7.48
Percentile 95	5.11	5.64
Percentile 98	8.50	7.14

Gross beta activity concentration in the groundwater of governorates of Jordan shows a mean value of 1.62 ± 0.22 Bq L^{-1}. Jordanian standards for drinking water quality recommend a limit of gross beta activity concentrations of 1 Bq L^{-1} (JISM 2008). The mean gross beta activity concentration in groundwater is one and a half times higher than the national regulation limit while 35% of gross beta activity concentrations are higher than the national regulation limit.

The mean gross alpha and beta activity concentrations of the groundwater in governorates of Jordan are presented in Table 2. The mean value of gross alpha activity concentration ranges from 0.26 ± 0.03 to 3.58 ± 0.55 Bq L^{-1}, while the mean gross beta activity concentration ranges from 0.51 ± 0.07 to 3.43 ± 0.46 Bq L^{-1}.

The highest mean activity concentrations of 3.58 ± 0.55 Bq L^{-1} for gross alpha were found for the Maan governorate, which is seven times higher than the national and WHO recommended value (JISM 2008; WHO 2011). The wells in Maan governorate are composed of sandstone and shale (El-Naser & Gedeon 1996). The lowest mean activity concentration of 0.26 ± 0.03 Bq L^{-1} for gross alpha was found for Alkarak governorate, which is half the national recommended value. The host rock of groundwater in Alkarak governorate, locally known as Kurnub sandstone, is composed of sandstone interceded with clay, sand, and gravel.

The highest mean activity concentration of 3.43 ± 0.46 Bq L^{-1} for gross beta was found for Aqaba governorate; the results in the current study were found to be in good agreement with literature studies (Vengosh et al. 2009; El-Naser et al. 2016; Al-Absi et al. 2019). According to El-Naser et al. (2016), sandstone rock contains abundant thorium-enriched heavy mineral aggregation, which may be the source of radioactive elements. The lowest mean activity concentration of 0.51 ± 0.07 Bq L^{-1} for the gross beta was found in Amman governorate, which is lower than the national and WHO recommended value (JISM 2008; WHO 2011).

Albalqa governorate shows a low mean activity concentration of gross beta considered lower than the WHO limits. The host rock of the wells in Albalqa governorate is Kurnub sandstone consisting of sandstone and shale (Bender 1974). Almafraq governorate shows relatively low activity concentrations of gross alpha and beta. The wells in this governorate are composed of basalt, gravel, clay, and conglomerates locally known as the basalt aquifer. According to Othman & Yassine (1995) and Arnedo et al. (2017) basalt rocks have low contents of radioactive materials.

Irbid governorate in the north of Jordan shows a higher mean gross alpha activity concentration than the Jordanian limit of 0.5 Bq L^{-1}, while gross beta activity concentrations were lower than the Jordanian limit; the wells in Irbid governorate are composed of limestone, marl and chert. The activity concentrations of gross alpha and beta in Alzarqa governorate were lower than the WHO and Jordanian limits. The host rock is formed from chert, chalk, limestone, and phosphate. The results were in agreement with Gedeon et al. (1995).

The activity concentrations of gross alpha and beta varied among the governorates of Jordan. The variations in activity concentrations could be related to the diversity of bedrocks containing the groundwater; in other words, the difference in the content of radioactive materials in the aquifer solids.

The mean activity concentration of gross alpha and beta in the groundwater found in the present study were compared with values recommended by WHO and those found in other countries as presented in Table 3. The average activity concentrations of gross alpha in this study are in good agreement with the results obtained by El-Naser et al. (2016) in a study conducted in Aqaba zone in the southern part of Jordan, and consistent with the results obtained by Le et al. (2017) in Ho Chi Minh city in

Table 2 | Mean gross alpha and beta activity concentration of groundwater in governorates of Jordan

Governorate	Mean activity concentrations of gross alpha (Bq L^{-1})	Mean activity concentrations of gross beta (Bq L^{-1})
Albalqa	0.55 ± 0.08*	0.62 ± 0.08
Amman	0.34 ± 0.05	0.51 ± 0.07
Irbid	0.81 ± 0.12*	0.65 ± 0.08
Ajloun	0.43 ± 0.06	1.40 ± 0.19*
Alzarqa	0.43 ± 0.06	0.53 ± 0.07
Almafraq	0.38 ± 0.05	0.55 ± 0.08
Alkarak	0.26 ± 0.03	0.68 ± 0.09
Maan	3.58 ± 0.55*	2.90 ± 0.39*
Aqaba	3.34 ± 0.52*	3.43 ± 0.46*
JISM (2008), WHO (2011)[a]	0.5	1

[a]Standard reference, where * indicates the values exceeding the standard.

Table 3 | Comparison of the gross alpha and beta activity concentration results of this study and other studies from different countries

Country/location	Gross alpha activity (Bq L^{-1})	Gross beta activity (Bq L^{-1})	References
Jordan	1.57	1.62	Current study
Bangladesh/Dhaka	0.001	0.08	Ferdous et al. (2016)
Romania/Galati	0.02	0.07	Pintilie et al. (2016)
Ghana	0.04	0.17	Darko et al. (2015)
Spain	0.54	0.22	Duenas et al. (1998)
Italy	0.18	0.21	Forte et al. (2007)
USA/New Jersey	0.19	0.11	Szabo & Zapecza (1987)
USA/Los Angeles	0.05	1.85	Weigand et al. (1987)
Iran/Gulian	0.05	0.11	Abbasi & Mirekhtiary (2017)
Saudi Arabia/Tabuk	5.39	3.15	Alkhomashi et al. (2016)
Saudi Arabia/Hail	2.15	2.6	Shabana & Kinsara (2014)
Turkey/Karaman	0.037	0.045	Korkmaz et al. (2016)
Malaysia/Johor	0.01	0.23	Saleh et al. (2015)
Brazil/Guarani	0.009	0.26	Bonotto & Bueno (2008)
Australia	0.05	0.08	Kleinschmidt (2004)
Turkey/ Eastern Black Sea	0.006	0.1	Damla et al. (2006)
Vietnam/Ho Chi Minh	1.5	84	Le et al. (2017)
Turkey/Nevsehir	0.19	0.58	Turhan et al. (2013)
Turkey/Samson	0.05	0.08	Görür et al. (2011)
Jordan/Aqabazone	2.5	3.4	El-Naser et al. (2016)
WHO	0.5	1	WHO (2011)

Vietnam. The mean activity concentration of gross beta was in agreement with a value measured in Los Angeles (Weigand et al. 1987). Most studies have found low levels but earlier studies in Jordan (El-Naser et al. 2016), Saudi Arabia (Shabana & Kinsara 2014; Alkhomashi et al. 2016), and Vietnam (Le et al. 2017) have found elevated levels.

Annual effective dose and lifetime risk assessment

The annual effective dose and excess lifetime risk due to gross alpha and beta activity concentration in the groundwater of Jordan are determined and presented in Table 4. The annual effective dose ranged from 0.323 to 2.408 mSv with a mean value of 0.890 mSv. The highest mean value was found for the Aqaba governorate, while the lowest mean annual effective dose was found for the Amman governorate. The annual effective dose from water samples in Ajloun and Alzarqa governorates are higher than the Jordanian limit (JISM 2008). This could cause health risks to certain consumers in Ajloun and Alzarqa governorates who depend on drinking water supplies derived from groundwater as their primary source of drinking water. This demands continuous monitoring of radioactivity in water supplies from these governorates.

Water samples from Albalqa, Irbid, Amman, Almafraq, and Alkarak governorates have a mean annual effective dose that exceeds the WHO recommended limit of 0.1 mSv but is still below the Jordanian limit of 0.5 mSv. The lifetime risk assessment due to ingestion of gross alpha and beta activities in groundwater in these governorates was lower than the standard limit value of 25×10^{-4} (JISM 2008), while the limit was exceeded in Ajloun, Alzarqa, Maan and Aqaba governorates by 26% in Alzarqa governorate to 392% in Aqaba governorate as shown in Table 4.

Descriptive statistics of quality parameters of groundwater

The physicochemical properties pH, EC, temperature and depth of groundwater were statistically analyzed. pH

Table 4 | Annual effective dose and lifetime risk due to ingestion of gross alpha and beta activities of groundwater in governorates of Jordan

Governorate	Annual effective dose (alpha and beta) (mSv)	Lifetime cancer risk (alpha and beta) ($\times 10^{-4}$)	Percentage exceedance of mean values over the standard
Albalqa	0.421	21.51	–
Amman	0.323	16.50	–
Irbid	0.489	24.98	–
Ajloun	0.792	40.47	61
Alzarqa	0.617	31.52	26
Almafraq	0.356	18.19	–
Alkarak	0.393	20.08	–
Maan	2.192	112.01	348
Aqaba	2.408	123.04	392
Jordan	0.890	45.47	81

Table 5 | Correlations between gross alpha and beta activity concentrations and physicochemical properties of groundwater in Jordan

Activity concentrations vs. activity concentration and/or physicochemical properties	Pearson's correlation	Outcome
Activity concentration of gross alpha vs. gross beta	0.891	Very strong
Activity concentration of gross alpha vs. depth	0.460	Moderate
Activity concentration of gross beta vs. depth	0.563	Moderate
Activity concentration of gross alpha vs. pH	−0.244	Weak
Activity concentration of gross beta vs. pH	−0.120	Negligible
Activity concentration of gross alpha vs. temperature	0.688	Strong
Activity concentration of gross beta vs. temperature	0.712	Strong
Activity concentration of gross alpha vs. EC	0.199	Weak
Activity concentration of gross beta vs. EC	−0.002	Negligible

varied from 5.51 to 8.32 with a mean value of 7.35. Jordanian standards for drinking water quality recommend a pH limit value range of 6.5–8.5. pH is a measure of hydrogen ion concentration in water, indicating whether the water is acidic or alkaline. The pH of 96.9% of the groundwater samples was within the national recommended range value (JISM 2008), while the rest (3.1%) of the groundwater samples were slightly acidic. EC varied from 6 to 3,446 μS cm^{-1} with a mean value of 1,007 μS cm^{-1}, which is higher than the recommended value of 640 μS cm^{-1} (JISM 2008). EC indicates the salinity of the water. A high value of EC in drinking water influences the taste of the water and can cause health problems. Most of the samples (80%) had an EC value between 200 μS cm^{-1} and 400 μS cm^{-1} while 11% of the water samples had an EC value higher than the national recommended level (JISM 2008). To check the suitability of the groundwater for drinking and irrigation uses, a set of determinants were studied. According to Wilcox (1955), to ascertain the suitability of groundwater for any purpose, it is essential to classify the groundwater depending upon its hydrochemical properties based on its EC values. The EC values in the range 250–750 μS cm^{-1} are considered good for drinking water, while values in the range 750–2,250 μS cm^{-1} are permissible for drinking water. Physicochemical analysis

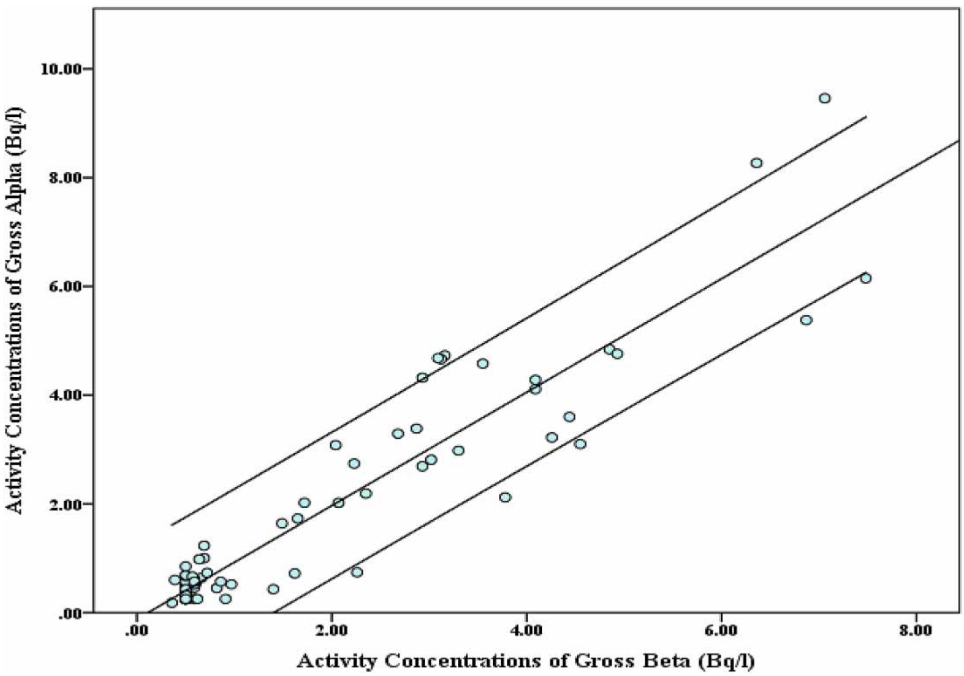

Figure 1 | The correlation between gross alpha and beta activity concentration (Bq L^{-1}).

indicates that most groundwater of Jordan (98.9%) is suitable for drinking water, while 1.1% of the total exceeded the permissible limit for drinking water and is considered not suitable for drinking. The temperature of groundwater samples ranged from 11 to 36 °C with a mean value of 27 °C. Jordanian standards for drinking water quality recommend temperature less than 25 °C (JISM 2008). Depth of the wells ranges from 28 to 1,259 m, with a mean value of 394 m.

The relationship between gross alpha and beta activity concentrations and physicochemical properties in groundwater

The physicochemical properties pH, EC, temperature and depth of groundwater were correlated to activity concentration in groundwater in terms of possible effects of physicochemical properties on gross alpha and beta activity

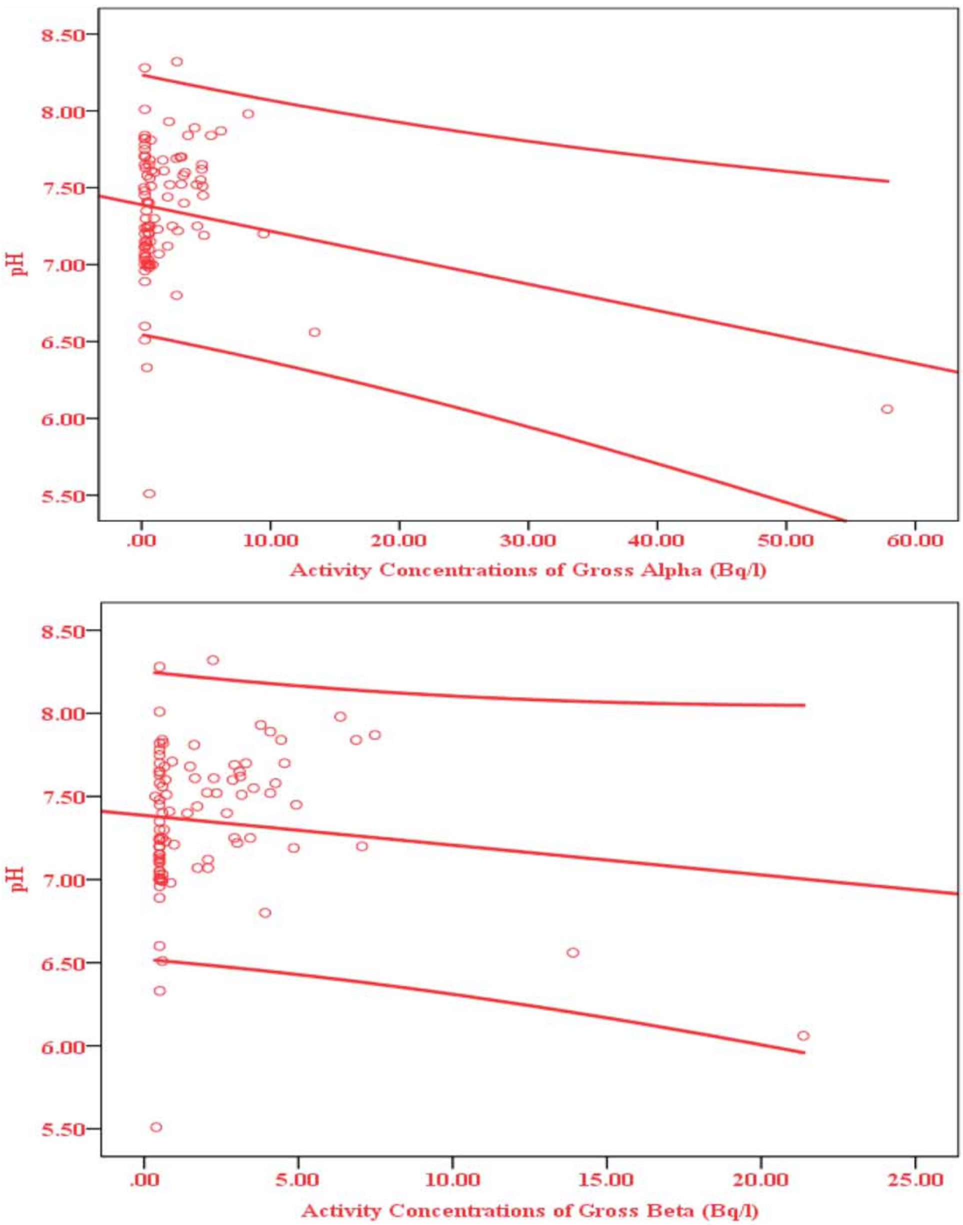

Figure 2 | Relationship between gross alpha and beta activity concentrations (Bq L^{-1}) and pH in groundwater.

concentrations. The relationship matrix using Pearson's correlation is presented in Table 5.

Gross alpha and beta activity concentrations have a very strong relationship as shown in Figure 1. This indicates that gross alpha activity correlation results show high validity for prediction of the gross beta activity concentrations.

Gross alpha and beta activity concentrations show an insignificant relationship with pH values of groundwater as given in Figure 2. The pH values above 8.3 show low gross alpha and beta activity concentrations.

Gross alpha and beta activity concentrations show an insignificant relationship with EC values of groundwater as shown in Figure 3. The scattered gross alpha and beta may be due to the mixing of groundwater from different lithologies in an aquifer, which may affect the correlation between natural radioactivity and physicochemical properties of groundwater.

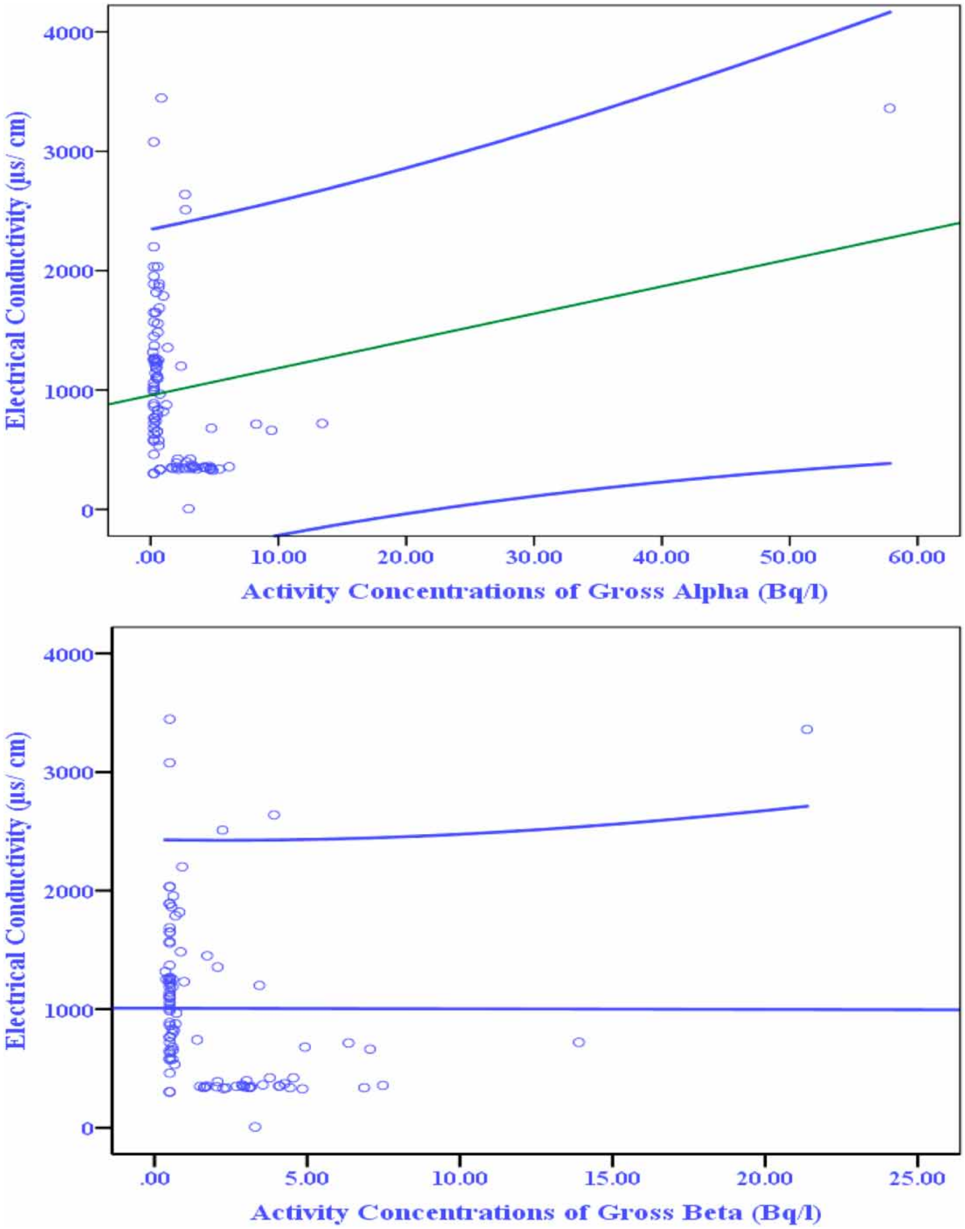

Figure 3 | Relationship between gross alpha and beta activity concentrations and (Bq L^{-1}) EC in groundwater.

A moderate relationship was found between gross alpha and beta activity concentrations and depth of the wells, with coefficients 0.460 and 0.563, respectively. As shown in Figure 4, the increase in gross alpha and beta activity concentrations was noted from 28 m to 750 m depth. Some water samples show low activity concentrations of gross alpha and beta for depth values higher than 750 m, in other words the effects of depth values on gross alpha and beta activity concentrations above 750 m is not linear.

Pearson's correlation revealed that gross alpha and beta activity concentrations show a strong relationship with the temperature of groundwater with coefficients 0.688 and 0.712, respectively. This indicates a possible cause–effect relationship; it can be noted from Figure 5 that activity

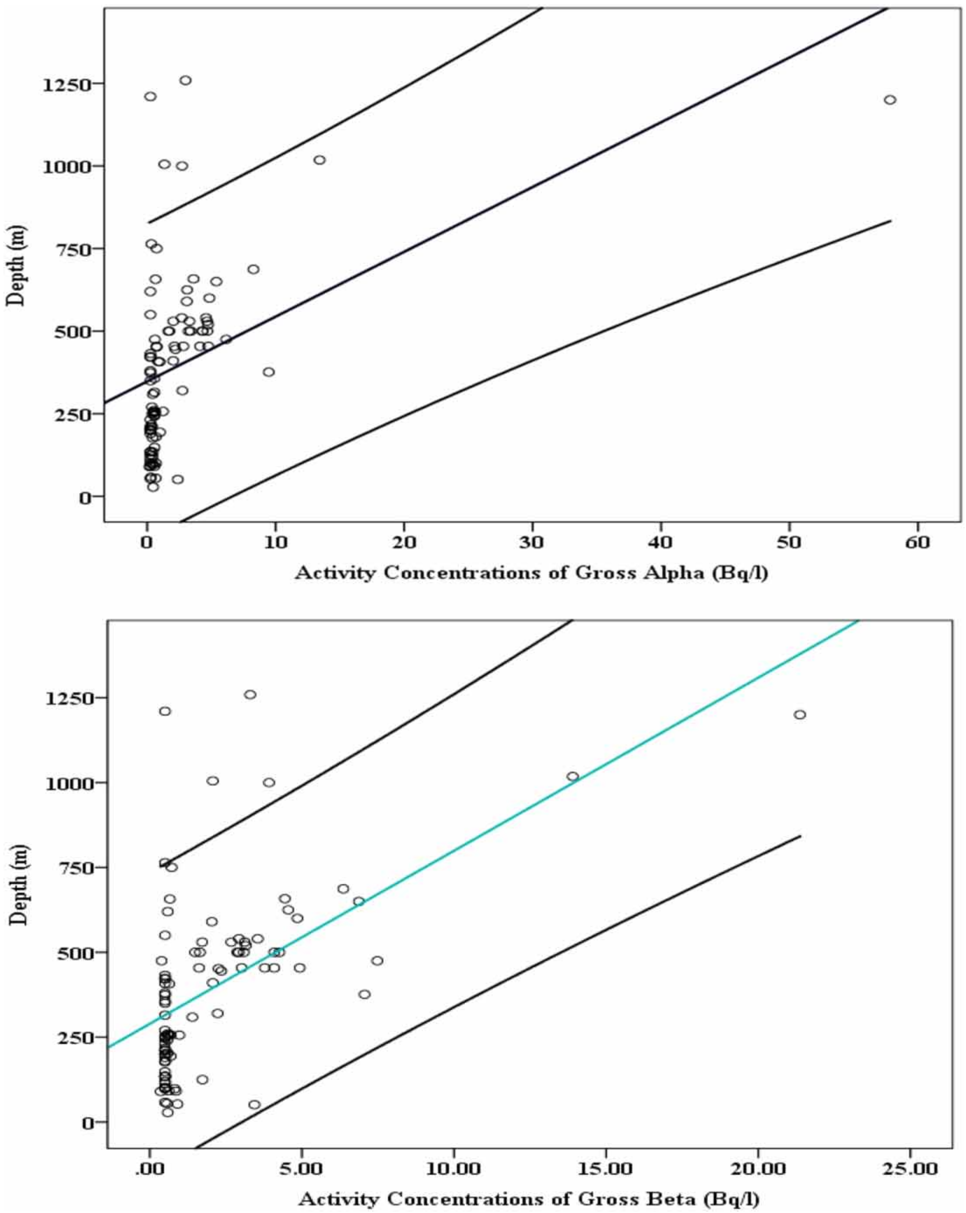

Figure 4 | Relationship between gross alpha and beta activity concentrations (Bq L^{-1}) and well depth in groundwater.

concentrations of gross alpha and beta in most water samples show a strong relationship with temperature.

CONCLUSION

The mean gross alpha and beta activity concentrations in groundwater in Jordan were determined. They were found to be 1.57 ± 0.24 Bq L^{-1} and 1.62 ± 0.22 Bq L^{-1}, respectively. The results showed that 51% of gross alpha activity concentrations and 35% of gross beta activity concentrations in groundwater were higher than the WHO limit. The highest mean annual effective dose due to ingestion of gross alpha and beta activity concentrations was found in the Aqaba governorate. The highest lifetime risks due to gross alpha and beta activity concentration in water were

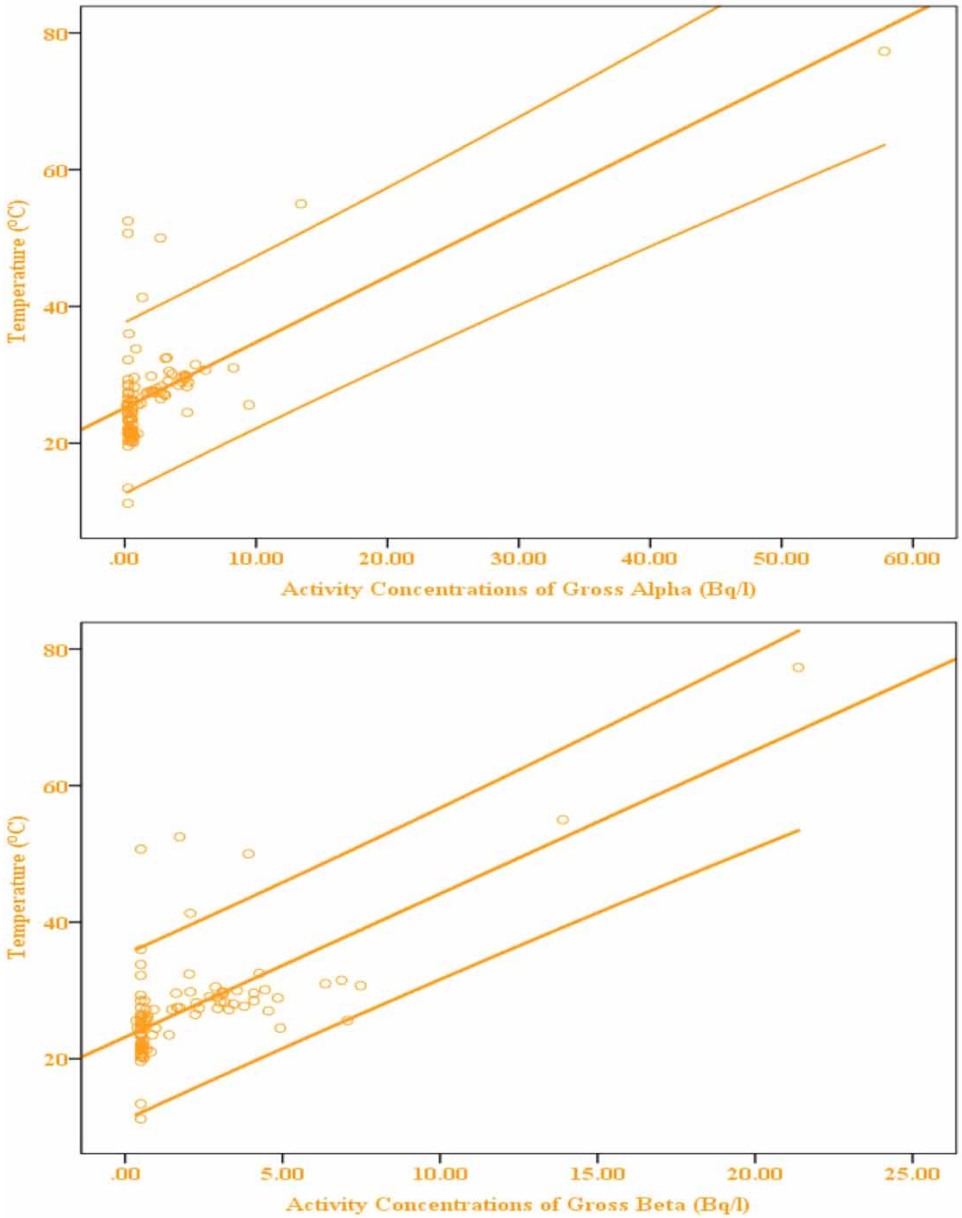

Figure 5 | Relationship between gross alpha and beta activity concentrations (Bq L^{-1}) and temperature in groundwater.

found in Aqaba and Maan governorates, which exceeded the Jordanian limit. Continuous monitoring of radioactivity in water supplies from Aqaba and Maan governorates is important to avoid the health risks to the population residing in these governorates due to the gross alpha and beta activity concentrations. A very strong relationship was found between gross alpha and beta activity concentrations. Gross alpha and beta activity concentrations show a strong relationship with temperature and moderate relationship with depth values, but an insignificant relationship with pH and EC values of groundwater. The current results can be used as baseline data in investigating any future changes in environmental radiation caused by nuclear, industrial or other human activities.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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