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Hazard indices and annual effective dose due to terrestrial radioactivity in the urban areas in the south of Jordan

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Abstract
^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K radionuclides have been determined using gamma-ray spectrometry in soil samples collected from urban areas in the southern governorates of Jordan and showed average concentrations of (39 ± 18), (45 ± 20), (23 ± 13), and (233 ± 128) Bq kg^{-1}, respectively. The corresponding radio-elemental concentrations in the existing geological features were obtained and examined for the relative depletion/enrichment processes and state of equilibrium in soils. Radium equivalent activity, hazard indices, and annual gonadal dose equivalent do not exceed the permissible limits. Absorbed dose rates in air outdoor and external effective dose showed average values of 44.0 nGy h^{-1} and 54.4 μSv y^{-1}, respectively.

Keywords Soil radioactivity · Gamma-ray spectrometry · Activity and elemental concentrations · Radiation hazard assessment

Introduction

Naturally occurring radionuclides that belong to the decay chains of uranium and thorium and ^{40}K form the main sources of external exposure from terrestrial background radiation received by man. Exposure to natural sources of radiation is often influenced by human activities making the determination of the concentration and the distribution of the soil radioactivity an active matter of concern in providing a baseline data for ascertaining of their radiological levels.

A survey of the literature shows that the systematic data on the distribution of natural and/or artificial radioactivity available for Jordan is not yet totally established. A few number of studies have been conducted in different locations in Jordan by Al-Hamarneh and Awadallah [1] and other researchers [2–7]. Most of these studies were being local studies, concentrated on northern parts of Jordan as these are the most populated areas of the country, and based on a limited number of samples. However, studies devoted to investigating environmental radioactivity in southern parts of Jordan are very rare and were pertaining to local areas [8–10]. Hence, the southern parts of Jordan are in need for a baseline data on radiation levels that will serve as a reference to ascertain possible changes in environmental radioactivity in future. This issue is of crucial importance as the country is considering acquiring nuclear reactors for power generation as well as launching grand national projects to explore uranium and oil shale mining processes. In addition, Jordan in collaboration with regional countries is going to launch the Red Sea-Dead Sea Conveyance project in 2018. This grand project aims to provide potable water and generate electricity to the countries located along both sides of the two seas canal. It is therefore of interest to determine the current levels of naturally occurring radionuclides and determine their contribution to the annual effective dose to the population in south of Jordan.

The main aim of this work is to determine the concentrations of the natural radionuclides ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K in surface soil samples collected from populated areas

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in the governorates of Karak, Tafilah, Ma'an and Aqaba located at the southern part of Jordan. Accordingly, the measured activity concentrations were used to calculate the elemental concentrations of radium, uranium, thorium and potassium. As this knowledge provides information on geo-morphological composition and the associated environmental radioactivity of the investigated areas with a large variety of igneous and sedimentary rock types. Moreover, documenting the current background levels will help to assess the effects of the subsequent human activities. Hence, the data gathered here form a baseline for the determination of radioactivity level in the geographical region. In addition, correlations among measured radionuclides were also made to investigate the secular equilibrium in their decay chains as this condition is essential to make correct assumptions for the dose assessments.

Finally, the study included calculations of radium equivalent activity, the internal and external hazard indices, absorbed gamma dose rate in air outdoors, annual effective dose equivalent and annual gonadal dose equivalent. These calculations and the associated discussions and comparisons with the results in the literature and with internationally recommended values will help in assessing the radiological hazard due to exposure to natural radiation in the studied areas.

Experimental procedure

Study area

Jordan is a southwestern Asian country, which is situated on the eastern side of the Asian-African Great Rift Valley on about 91,000 km^2 area and located at geographic coordinates of 31°00′N and 36°00′E. The study areas are the arid to severely arid land in the south of the Jordan Valley. Around one million of inhabitants are living in the governorates of Karak, Tafilah, Ma'an, and Aqaba. Soils of these areas are characterized by high salinity and low permeability. The geology of this region includes basaltic rocks, sandstone, limestone, chalks, marls and cherts and various Pleistocene and Holocene deposits, both of alluvial and eolian origin. Moreover, phosphate formations, which are known to contain significant concentrations of uranium ores, are located mainly in the southern part of Jordan.

Soil characteristics

The region of study constitutes about 15% of the total area of Jordan. According to the USDA classification system, the following five soil taxonomic/geomorphologic units have been identified in the areas under investigation (see Fig. 1): (1) *Araba Hills Dissected Basement Plateau* constituents about 1.2% of the total area of Jordan. The region is located in the extreme southwest of Jordan to the escarpment of Ras en Naqb along the Gulf of Aqaba. It mostly lies within the aridic moisture regime except for the entire region that lies within the thermic temperature regime and characterized by heavily dissected Basement Complex granite rocks, colluvial and alluvial fans. Torriorthents soils dominant the region with small occurrences of calciorthids, torrifluvents, and torripsamments soils. (2) *Disi Ram Highlands* constituents about 5.4% of the total area of Jordan. The region consists of a very deeply dissected sandstone plateau bordered on the north by the Ras en Naqb-Jebel el Batra escarpment and on the south by the Saudi border. It lies within the aridic moisture and thermic regimes and consists of cliff-faced sandstone buttes and masses intersected by north–south valleys filled by deep colluvial and alluvial mantles including significantly large mud-flats. The dominant soils of the region are torripsamments, whereas calciorthids, camborthids, and torriorthents soils are found in some locations within the region. (3) *Central Highlands Dissected Limestone Plateau* constituents about 0.9% of the total area of Jordan. The region lies between the Wadi el Hasa in the south and the Wadi el Mujib in the north. The Xerochrepts soils occupy almost 80% of the region. In the west and north of the region, cracking vertisols with clay content in excess of 40% appear. The xerochrepts soils occupy most areas of the region with occurrence of vertisols soils. (4) *Southern Highlands Dissected Limestone Plateau* constituents about 1.0% of the total area of Jordan. The region occupies the high altitude plains and hills of Tafilah and Shobak and has the coldest winters, most frequent snowfall of Jordan and lies largely within the xeric moisture regime. It is cultivated for cereals in the north, Tafilah area, and for fruits particularly apples in the south, Shobak area. Xerochreptic soils constitutes most of the region with existence of calciorthids, camborthids, and xerochrepts soils. (5) *Jordan Highland Plateau* constituents about 6.6% of the total area of Jordan. The region extends from Qatrana in the north to Jebel el Batra in the south with a maximum width of 15 km and characterized by too low rainfall and too erratic for secure cropping. It includes the major steppe vegetation zone in the south, Qatrana area, to a grassland steppe in the north. The major soil types are transitional xerochreptic subgroups of calciorthids and camborthids.

Sample collection

A total number of 169 surface soils on 10 cm depth were collected using a stainless steel sampler to produce approximately 2 kg wet weight per sample. The sampling locations were chosen in a representative manner from the

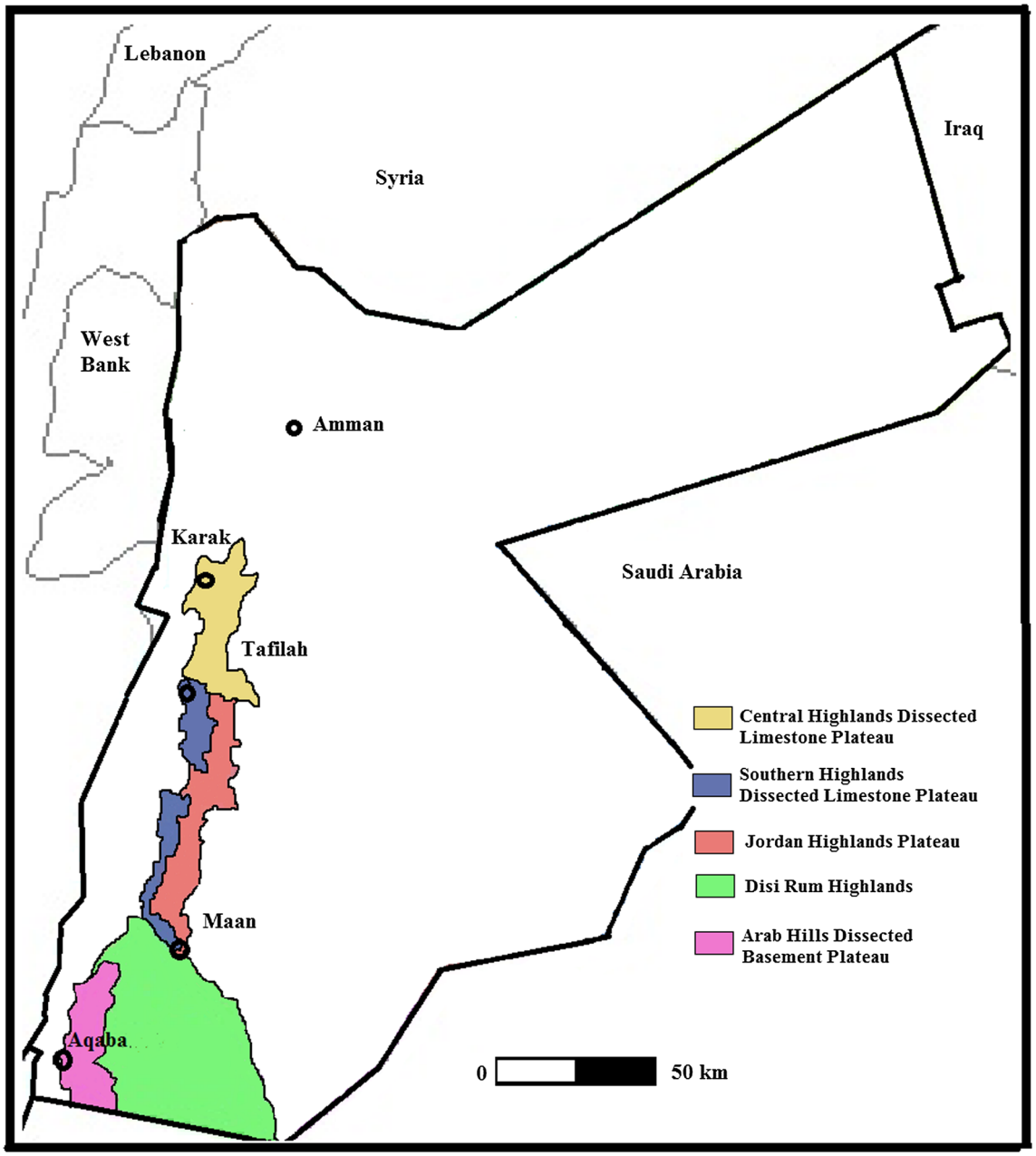


Fig. 1 Map of Jordan showing the various types of soils in the investigated areas. (Color figure online)

most populated areas within southern parts of Jordan as shown in Fig. 1. After removing the visible impurities (stones, pebbles, and organic matter), each soil sample was retained in its own secure water-tight bag to prevent cross-contamination. On return to the laboratory, the collected soils were air-dried until a constant weight was reached, thus ensuring a complete removal of residual moisture. The dried samples were then crushed, ground, and homogenized by passing through a sieve of 0.2 mm mesh size. The samples were then sealed tightly in 300 cm^3 plastic containers, with vinyl tape around its neck, and stored for at least one month, before counting by gamma-ray spectrometry, to bring ^{222}Rn and its short-lived daughters into secular equilibrium with ^{226}Ra.

Radioactivity determination

Radioactivity concentrations of radionuclides of interest in this study were determined by gamma-ray spectrometric system based on a high-purity germanium (HPGe) n-type coaxial photon detector provided by Ortec (Oak Ridge, TN, USA). The detection system consists of a GMX-type detector, with 57% nominal efficiency and about 2.0 keV resolution at 1.33 MeV. The detector was shielded by a

pre-World War II lead shield that is able to extremely reduce background radiation, and set up to cover energies from 3 keV to 10 MeV over 16 k channels. The software Gamma-Vision (A66-B32, version 5.0) was used for data analyses. Details on energy and efficiency calibration, self-absorption and true summing corrections can be found in Al-Hamarneh and Awadallah [1] and Al-Kharouf et al. [9].

The ^{238}U activity concentration was determined as the weight mean activity of the photopeaks of its daughter ^{234}Th at 63.3, 92.4, and 92.8 keV. This is because the daughter-parent ^{238}U–^{234}Th are essentially always in secular equilibrium in undisturbed or chemically untreated soil [11]. The ^{226}Ra activity was determined by considering the mean activity of the photopeaks ^{214}Pb (295.2 and 352.0 keV) and ^{214}Bi (609.3 keV). Similarly, the ^{232}Th activity was obtained from the mean activity of the photopeaks of its daughters: ^{212}Pb at 238.6 keV, ^{208}Tl at 583.1 keV and ^{228}Ac at 911.1 keV. The ^{40}K activity was directly derived from its gamma photopeak at 1460.8 keV. The "root-sum-of-squares" rule was used for overall uncertainty determination of the activity concentrations of radionuclides after taking into account the random and systematic errors. To check the accuracy of the measuring method, the activity concentrations of the IAEA-327, IAEA-375, and RGU-1 reference materials were measured, and showed good agreement with the recommended values, under the same conditions as soil samples. To reach approximately ± 5% of analytical precision of measurements, samples were counted for around 24 h.

Results and discussion

Radioactivity and elemental concentrations

The radioactivity concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K radionuclides in the 169 soil samples collected from the investigated locations in south of Jordan were obtained. The statistics of these results is presented in Table 1. All values are reported in Bq kg^{-1} dry weight. The activity concentrations of the primordial radionuclides in the investigated soils are widely varied, which can be attributed to variations in their presence in terrestrial environment as well as their physical and chemical behavior in soil. Particularly, the ^{226}Ra and ^{238}U activities show asymmetrical distributions in soils of Karak and Tafilah as indicated by the high kurtosis values with tails extending toward higher concentrations as indicated by the positive skewness coefficient. On the contrary, ^{232}Th and ^{40}K concentrations show evidence of normal distribution as their kurtosis and skewness coefficients are much closer to zero. The maximal ^{226}Ra and ^{238}U activity concentrations of 366 and 382 Bq kg^{-1}, respectively, are observed in soils of Swaqa (31°22′N and 34°04′E) in Karak governorate. This result is expected since this region belongs to the phosphate and uranium mining areas. On the other hand, soils of Rashdieh (29°34′N and 35°09′E) in Aqaba governorate showed the highest ^{232}Th and ^{40}K concentrations of 76 and 658 Bq kg^{-1}, respectively. The increased values of the activity concentrations of ^{232}Th and ^{40}K could be attributed to the presence of monazite ores in this area, which is known as a rich source of radioactive thorium.

Considering all collected soils, the average activity concentrations (± SD) of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K were found to be 39 ± 18, 45 ± 20, 23 ± 13, and 233 ± 128 Bq kg^{-1} whereas, the corresponding median values were 30, 37, 21, and 225 Bq kg^{-1}, respectively. As expected, the primordial radionuclide ^{40}K contributes to the most specific activity compared to uranium and thorium series. According to UNSCEAR [12], the worldwide average values of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K in the normal continental soil are 32, 33, 45, and 412 Bq kg^{-1}, respectively. Thus, average concentrations of ^{226}Ra and ^{238}U in soils of south Jordan were found, respectively, to be 17.9 and 26.7% above the worldwide average values. Whereas, ^{232}Th and ^{40}K average concentrations were found, respectively, to be 48.9 and 45.4% below the worldwide average values.

It is worth to mention that the average activities of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K in south Jordan did not show significant difference from the corresponding average activities of (42 ± 13), (49 ± 15), (27 ± 9), and (291 ± 98) Bq kg^{-1}, respectively, that were previously registered in soils collected from northern Jordan [1]. Moreover, the obtained average concentrations in soils of Ma'an (Table 1) seem to be in range with those of 58, 45, 18, and 138 Bq kg^{-1}, respectively, that were recorded by Saleh and Abu Shayeb [8] for soil samples collected at five sites in Ma'an. Abusini et al. [10] determined the natural radioactivity in six different locations in Araba valley, south of Jordan and their results were in the range of 21.0–38.7, 15.1–35.0 and 96.0–762 Bq kg^{-1}, respectively. Moreover, Al-Jundi et al. [7] found that the natural radioactivity in soil samples collected along the Amman-Aqaba highway to be in the range of 22–104 Bq kg^{-1} for ^{238}U, 21–103 Bq kg^{-1} for ^{232}Th and 138–601 Bq kg^{-1} for ^{40}K. In regional countries, Srilatha et al. [13] found mean concentrations of 33.8, 77.4, and 791.6 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively, in soils of Ramanagara and Tumkur districts, India using gamma spectrometry. Activity concentrations of 45, 59, and 648 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively, were registered by Tufail et al. [14] in soils of Peshawar basin in northern Pakistan using HPGe gamma spectrometer. Reddy et al. [15] measured soil samples in 30 places around Kolar Gold fields in India for their natural radioactivity content using

Table 1 Statistics on the ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K activities in the investigated soils

Governorate	Statistics	Average activity concentrations (Bq kg^{-1})			
		^{226}Ra	^{238}U	^{232}Th	^{40}K
Aqaba (30[a])	Activity	21.4	34.6	33.7	290.3
	Range	6.9–40.1	14.3–77.0	8.8–78.9	34.2–684.2
	SD[b], SE[c]	11.8, 2.2	20.2, 3.7	20.2, 4.3	236.5, 43.2
	Median	18.1	31.3	30.9	232.1
	Kurtosis, skewness	− 1.5, 0.3	0.1, 1.1	− 0.7, 0.7	− 1.4, 0.4
Karak (57)	Activity	54.3	61.0	20.2	234.1
	Range	3.4–365.7	8.6–381.6	4.0–49.4	44.9–471.4
	SD[b], SE[c]	75.9, 10.0	77.2, 10.2	9.2, 1.2	78.1, 14.3
	Median	33.2	39.1	20.4	254.7
	Kurtosis, skewness	10.0, 3.2	10.6, 3.2	2.0, 0.9	− 0.2, − 0.1
Ma'an (40)	Activity	31.9	37.4	19.7	203.7
	Range	12.6–72.2	10.5–69.1	9.5–32.4	96.6–362.3
	SD[b], SE[c]	16.1, 2.5	15.7, 2.5	7.7, 1.2	79.0, 12.5
	Median	30.7	38.0	18.3	180.8
	Kurtosis, skewness	1.3, 1.3	− 0.3, 0.1	− 1.3, 0.4	− 0.7, 0.7
Tafilah (42)	Activity	36.4	39.9	20.8	217.7
	Range	13.9–143.0	8.2–186.6	10.5–31.3	34.0–345.0
	SD[b], SE[c]	26.3, 4.1	33.8, 5.2	6.1, 0.9	74.0, 11.4
	Median	29.5	34.1	36.9	227.1
	Kurtosis, skewness	10.3, 3.1	15.4, 3.7	− 1.1, 0.1	0.4, − 0.6

[a]Number of samples

[b]Standard deviation

[c]Standard error of the mean

gamma ray spectrometry and found ^{226}Ra, ^{232}Th and ^{40}K concentrations of 27.3, 63.1 and 818 Bq kg^{-1}, respectively. These results are in general agreement with the corresponding results presented in Table 1.

In developing surveys for geological mapping using gamma-ray spectrometry, it would be useful to use the elemental concentrations of natural radioactivity. The elemental concentrations of radium, uranium, thorium and potassium (denoted here as: eRa, eU, eTh, and eK, respectively), can be calculated from ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K activity concentrations according to IAEA–TEC-DOC–1363 [16] as: 1 ppm of eRa, eU and eTh, and 1% of eK are equivalent to 11.10, 12.35, 4.06, and 313 Bq kg^{-1} of ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K, respectively. Accordingly, the radio-elemental concentrations of radium, uranium, thorium and potassium for the 169 soil samples collected from all over the study areas were calculated and plotted in Fig. 2. It can be seen from Fig. 2 that the elemental concentrations of the measured radionuclides are distributed in a relatively wide interval of values. The overall geometric mean (GM) along with the geometric standard deviation (GSD) of elemental concentrations were: 2.52 (1.24), 2.83 (1.25) and 4.85 (1.12) ppm and 0.63 (1.19)% for eRa, eU, eTh and eK, respectively. The worldwide elemental concentrations of these natural radionuclides in the upper crust of the Earth as reported by UNSCEAR [17] vary from 1.3 to 8.9 ppm with an average value of 2.8 ppm for ^{238}U, from 2.7 to 15.8 ppm with a world average of 7.4 ppm for ^{232}Th, and from 0.5 to 2.7% with an average of 1.3% for ^{40}K. These elemental concentrations were derived by converting the Bq kg^{-1} concentrations reported in UNSCEAR [17] into ppm concentrations using the foregoing conversion. If compared to the worldwide limits, soils of south Jordan showed elemental concentrations within the range of the worldwide elemental concentrations. In soils collected from five locations in Ma'an, Jordan, the U elemental concentrations was determined to be in the range of 2.4–4.8 ppm with an average of 3.6 ppm [8]. The elemental concentrations of U, Th, and K in various rock types in Cyprus, of mean values 1.3, 2.8 ppm and 0.6%, respectively have been determined by Tzortzis et al. [18]. Also, Chiozzi et al. [19] have found elemental concentrations in the range of 0.3–5.6, 0.3–16.7 ppm, and 0.14–5.14% for U, Th, and K, respectively, in different rock types at the Alps–Apennines transition. These findings fit to our results, which appear to fall within the range of most worldwide reported values.

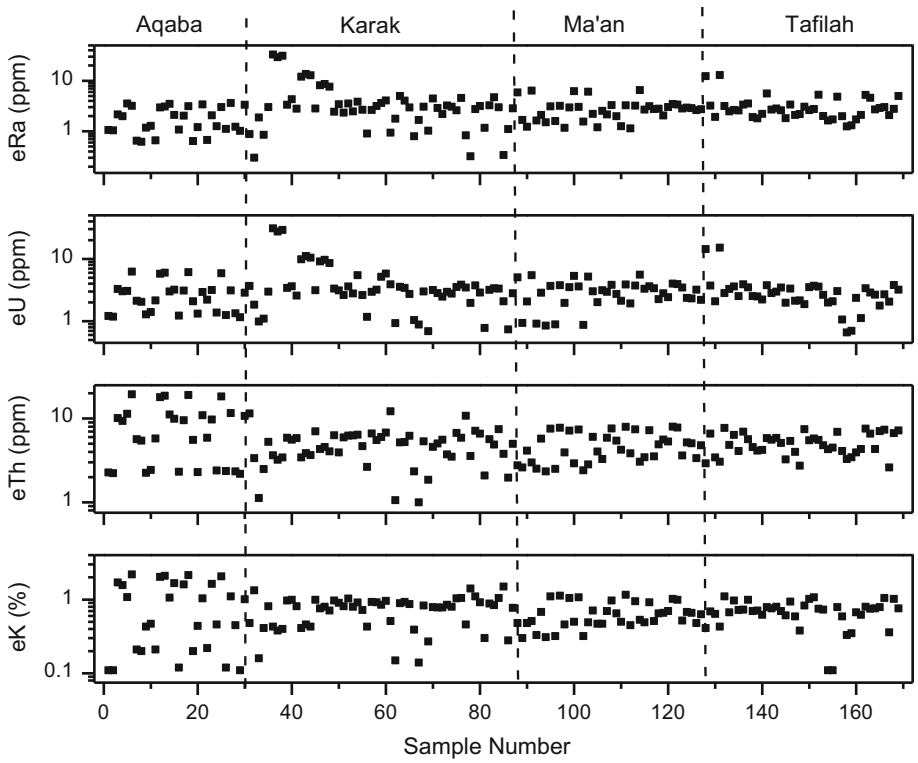


Fig. 2 Radium, uranium, thorium and potassium elemental concentrations for all soil samples. Vertical dashed lines correspond to various governorates from which samples have been collected

It was known that natural radioactivity in soils is similar to that in the bedrocks from which it derives [20]. And taking into account the geological diversity of the study area in south Jordan, differences in elemental concentrations are expected to occur. Within the study regions, two distinct rock types can be categorized: granitic and basaltic rocks of igneous origin that are available at the Arab Hills Dissected Basement Plateau and Disi Ram Highlands, and limestone rocks of sedimentary origin that are available at the Central Highlands Dissected Limestone Plateau and Southern Highlands Dissected Limestone Plateau (see Fig. 1). Consequently, the frequency distribution of the elemental concentrations of Ra, U, Th, and K in soils of basalt and granite, and limestone origin are shown in Fig. 3 a–d. The histograms of Fig. 3 show that the considerable part of the data is contained within the range of 0–5 and 2–4 ppm for eRa (Fig. 3a); 0–5 and 2–4 ppm for eU (Fig. 3b); 3–4, 5–6 and 4–6 ppm for eTh (Fig. 3c); and 0.8–1.0 and 0.6–0.8% for eK (Fig. 3d) in soils of limestone, and granitic and basaltic origin, respectively. Moreover, the range of elemental concentrations of Ra, U, Th, and K along with their average values in the two rock types investigated in south Jordan are presented in Table 2. For comparison, the corresponding values previously obtained by Al-Hamarneh and Awadallah [1] for north Jordan are also included in Table 2. It can be concluded from this quantitative analysis that, on average, limestone rocks of sedimentary origin in south Jordan has more U and less Th contents than that in north Jordan, whereas no significant difference in U and Th contents in basaltic rocks of igneous rocks in the north and south of Jordan.

It is also of interest to identify the relative depletion or enrichment of natural radionuclides in soils of the two investigated geological formations in south Jordan. Therefore, the linear dependence between eRa, eU, eTh and eK were studied by means of the Pearson correlation coefficient. The highest correlations between the elemental concentrations were found for Ra versus U ($R = 0.97$ and 0.87), then for K versus Th ($R = 0.88$ and 0.86) for soils of limestone, and granite and basalt origin, respectively. Lower correlations appeared to be between Th and U and between K versus U. The best ones of these correlation relations are shown in Fig. 4 and its inset. The elemental ratios of Ra versus U was distributed in a wide interval of 0.59–1.79 with a GM (GSD) ratio of 0.95 (1.21) for soils of limestone origin, whereas the corresponding GM (GSD) ratio of 0.88 (1.37) with values distributed in the range from 0.31 to 1.89 for soils of granite and basalt origin. Leaching and weathering processes are the main causes for the primordial ^{226}Ra to not always be in secular equilibrium with its parent ^{238}U radionuclide. However, the abovementioned values indicate that a state of equilibrium is most probably to exist on both types of soils in south Jordan and these values are also very close to the ratio of 0.88 obtained in soils of north Jordan [1]. On the other hand, the elemental ratio of Th/U showed a GM (GSD)

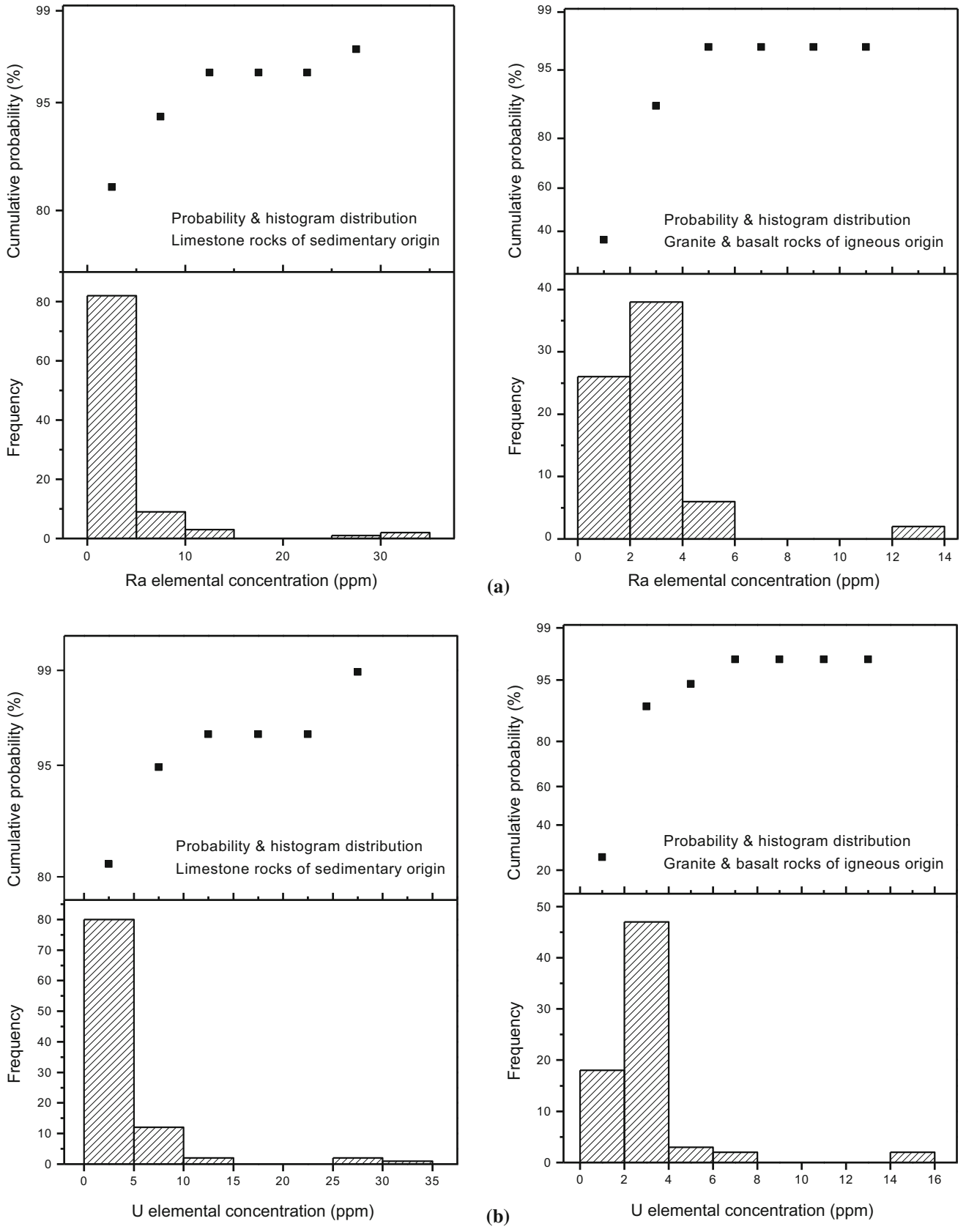
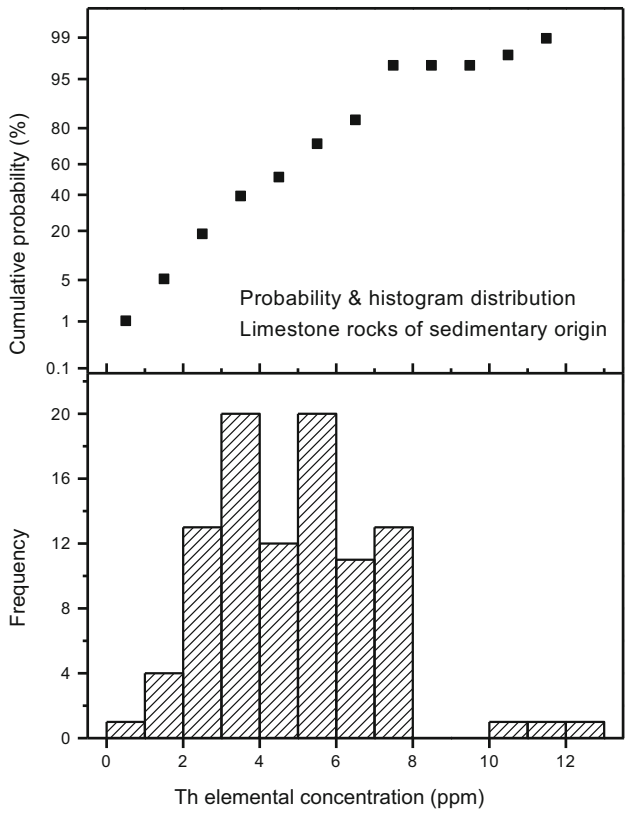
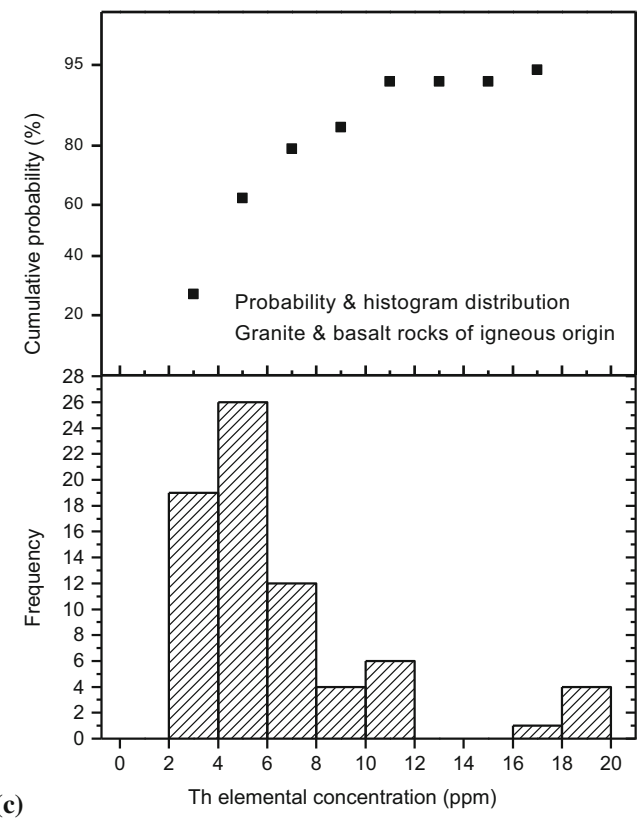


Fig. 3 Frequency distribution of **a** radium, **b** uranium, **c** thorium and **d** potassium elemental concentrations in soils of limestone, and granite and basalt origins collected from the study areas





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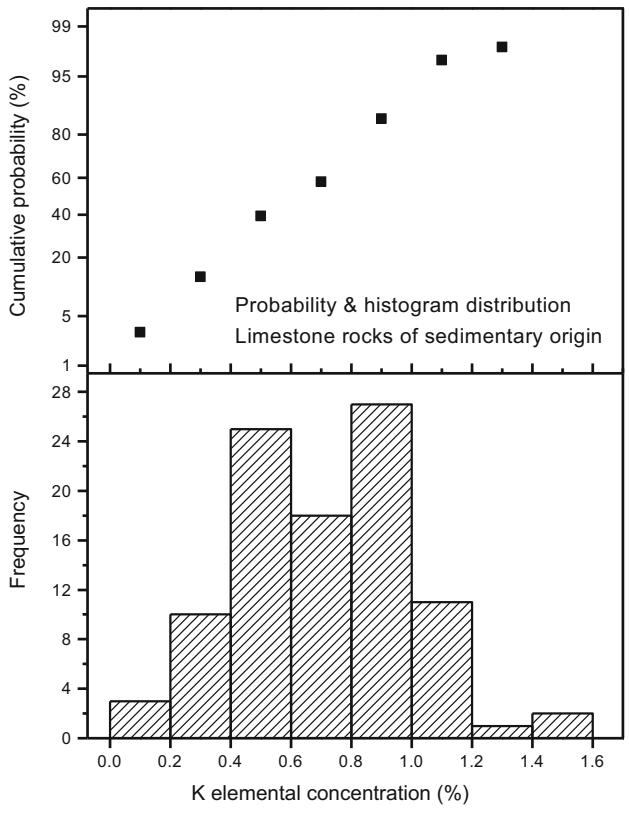

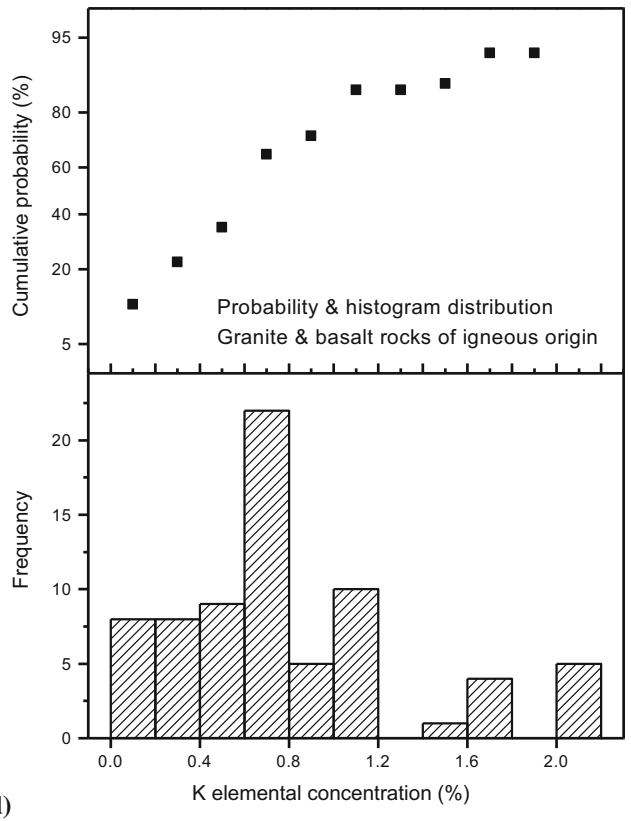

(d)

Fig. 3 continued

Table 2 Comparison of the elemental concentrations of Ra, U, Th and K in soils of south Jordan with that of North Jordan

		South Jordan (Results from this study)		North Jordan (Results from [1])	
		Limestone rocks of sedimentary origin	Granite and basalt rocks of igneous origin	Limestone rocks of sedimentary origin	Basalt rocks of igneous origin
eRa (ppm)	Range	0.3–33.0	0.6–12.9	–	–
	Average ± SD	4.1 ± 2.4	2.7 ± 2.0	–	–
eU (ppm)	Range	0.7–30.9	0.7–15.1	0.7–14.2	1.3–5.8
	Average ± SD	4.2 ± 1.9	3.0 ± 1.3	2.8 ± 1.6	2.7 ± 1.0
eTh (ppm)	Range	1.0–12.2	2.2–19.4	1.1–11.4	4.2–9.1
	Average ± SD	4.9 ± 2.1	6.4 ± 2.2	6.9 ± 2.1	6.9 ± 1.5
eK (%)	Range	0.1–1.5	0.1–2.2	0.1–1.6	0.6–1.5
	Average ± SD	0.7 ± 0.3	0.8 ± 0.3	0.9 ± 0.3	1.1 ± 0.3

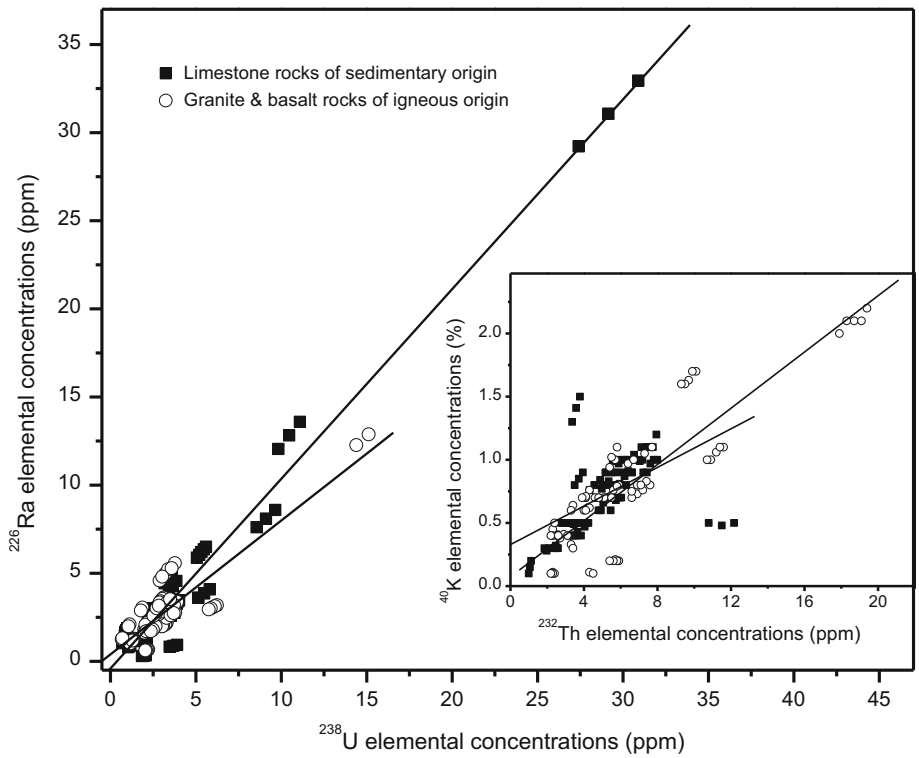

Fig. 4 Linear regression of the elemental concentrations of eU versus eRa and eTh versus eK (the inset) for soils of limestone rocks of sedimentary origin and soils of granite and basalt rocks of igneous origin

values of 1.50 (1.35) and 2.12 (1.32) for the soil of limestone and basalt origin, respectively. It can be pointed out that the Th/U elemental ratio in both soil types stemming from the limestone and basalt plateaus was less than the corresponding values of 2.93 and 2.88 obtained by Al-Hamarneh and Awadallah [1] for soils of north Jordan. It is also lower than the expected Th/U ratio of 3.0 for normal continental crust, which can be used as an indicative for the relative uranium enrichment in both soil types [21]. Moreover, the observed eTh/eU ratios were lower than Clark's vaue of 3.5 [22], which points out for the feasibility of the economic use of uranium for mining and extraction in the investigated regions [17]. However, the deduced Th/U ratios in soils of south Jordan are still acceptable compared to the distribution of values available in the literature by other researchers. For example, Tzortzis and Tsertos [23] registered a value of 2.0 for the Th/U ratio in surface soils in Cyprus. We attributed this result to the fact that ^{238}U and ^{232}Th series occur commonly together in nature and this weak correlation may be due to soil processes that affect differently the mobility of the two radionuclides in soil. Other correlations showed GM of the eK/eU and eK/eTh elemental ratios of 0.22 and 0.14 for soil of limestone origin and 0.24 and 0.11 for the soil of basalt origin,

respectively. These values are comparable to the corresponding values obtained in the soils of north Jordan [1]. The aforementioned elemental ratios clearly indicate a quite different depletion/enrichment process of the two types of soils recognized in south Jordan.

Assessment of radiation hazard indices

The ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K activity concentrations shown in Table 1 were varied in wide ranges of inhomogeneous distributions in most cases, as can be indicated by the clear differences between their average and median values. With respect to radiation exposure, the uniformity in the concentrations can be performed in terms of radium equivalent (Ra_{eq}) activity, which is a common hazard index used to represent the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides by a single quantity and to compare the relative significance of these radionuclides. Ra_{eq} is calculated by assuming that 370 Bq kg^{-1} of ^{226}Ra, 259 Bq kg^{-1} of ^{232}Th and 4810 Bq kg^{-1} of ^{40}K produce the same gamma dose rate [24, 25]:

$$Ra_{eq}(Bq\,kg^{-1}) = \left(\frac{A_{^{226}Ra}}{370} + \frac{A_{^{232}Th}}{259} + \frac{A_{^{40}K}}{4810}\right) \times 370, \qquad (1)$$

where $A_{^{226}Ra}$, $A_{^{232}Th}$ and $A_{^{40}K}$ are the ^{226}Ra, ^{232}Th and ^{40}K activity concentrations in Bq kg^{-1}, respectively.

The individual Ra_{eq} values for all soil samples were distributed from (26.6 ± 5.1) to (397.1 ± 115.1) Bq kg^{-1}, whereas the overall average was (89.0 ± 53.7) Bq kg^{-1}, which is about 24% lower than the UNSCEAR [17] Ra_{eq} activity limit of 370 Bq kg^{-1} that is equivalent to an external dose of 1.5 mGy y^{-1} [24]. This implies that using these soils in building materials might present no significant radiological health risk. The average Ra_{eq} values for each of the four governorates along with their statistical analyses are listed in Table 3. These results show that Ra_{eq} activities in Karak soils are slightly higher than in other governorates. Particularly, in soils of Swaqa region, which belongs to the phosphate and uranium mining areas that are characterized by elevated levels of radium, Ra_{eq} activities slightly exceeding the safe limit of 370 Bq kg^{-1}. Moreover, Table 3 lists also the average values of the relative contribution of ^{226}Ra, ^{232}Th and ^{40}K to Ra_{eq} activity for soils collected from the four governorates, and hence the radiological risk from using these soils in building constructions. These findings lead to conclude that the most contribution to the effective natural radioactivity comes from ^{232}Th in Aqaba soils and from ^{226}Ra in soils of Karak, Ma'an, and Tafilah. Whereas, ^{40}K contributes the least in spite of its high concentrations in all regions. These results are consistent with the distribution of soils radioactivity in the four governorates.

Comparing to others' results, the calculated Ra_{eq} activities in the measured soils are in range with those reported from other regions in Jordan and other countries [1, 8, 26], but are lower than others [3, 27]. For example, the overall average value of this work is similar to 94.2 Bq kg^{-1} that was obtained in Ma'an soil by Saleh and Abu Shayeb [8], but is slightly lower than the average value of 103 Bq kg^{-1} that was registered by Al-Hamarneh and Awadallah [1] in soils of north Jordan and much lower than the average value of 319 Bq kg^{-1} that was obtained by Hamideen and Sharaf [3] in soils collected from phosphate hills in Russaifa, Jordan. In middle Jordan, cultivated soils of Khan Al-Zabeeb area, which lies above superficial uranium deposits, showed Ra_{eq} activities in the range of (121.8–702.5) Bq kg^{-1} [9] that exceeds the range of activities present in south Jordan. In neighboring countries, average values of 166.3 Bq kg^{-1} were found in soils in Fırtına Valley in Rize, Turkey [24], 493.8 Bq kg^{-1} in Eastern Desert of Egypt [27], and 366.9 Bq kg^{-1} in southeastern Eskisehir (Turkey) [28], which are also higher than those presented in this study.

The radiation hazard can also be assessed by other indices that are calculated from the knowledge of the activity concentrations of the measured samples. The most important ones are the external hazard index (H_{ex}) and the

Table 3 Average values of radium equivalent (Ra_{eq}) activity, external radiation hazard index (H_{ex}), internal radiation hazard index (H_{in}), absorbed dose rate (D), annual effective dose equivalent rate (E), and annual gonadal dose equivalent (AGDE) in soil samples

	Aqaba	Karak	Ma'an	Tafilah
Ra_{eq} (Bq kg^{-1})	92.0 ± 61.1	101.3 ± 73.4	75.8 ± 23.9	82.9 ± 29.4
Contribution of Ra, Th, K to Ra_{eq} (%)	26.9, 51.7, 21.4	43.8, 34.1, 22.1	41.5, 37.8, 20.7	41.2, 37.8, 21.0
H_{ex}	0.25 ± 0.16	0.27 ± 0.20	0.20 ± 0.06	0.22 ± 0.01
H_{in}	0.31 ± 0.19	0.42 ± 0.40	0.29 ± 0.10	0.32 ± 0.15
D (nGy h^{-1})	49.5 ± 33.7	49.4 ± 32.7	37.7 ± 12.3	40.1 ± 15.2
E (μSv y^{-1})	60.7 ± 41.3	60.7 ± 40.2	46.3 ± 15.2	47.7 ± 16.2
AGDE (μSv y^{-1})	298.3 ± 200.4	325.9 ± 225.8	245.0 ± 77.6	267.7 ± 92.5

internal hazard index (H_{in}). The prime objective of these two indices is to measure the radiation dose and limit it to the permissible dose equivalent of 1 mSv y^{-1} set by ICRP 60 [29]. The two indices are given as [25]:

$$H_{ex} = \frac{A_{^{226}Ra}}{370} + \frac{A_{^{232}Th}}{259} + \frac{A_{^{40}K}}{4810}, \quad (2)$$

$$H_{in} = \frac{A_{^{226}Ra}}{370} + \frac{A_{^{232}Th}}{259} + \frac{A_{^{40}K}}{4810}. \quad (3)$$

The above definitions were used to calculated the values of H_{ex} and H_{in} indices at each governorate and the average values are presented in Table 3. The overall average H_{ex} and H_{in} indices were found to be 0.24 ± 0.08 and 0.35 ± 0.12, respectively. It is seen from these results that both indices are below the permissible limits. Thus, the investigated soils can be used for building constructions without restrictions. However, only one location (Swaqa in Karak governorate) was found to be hazardous, with its H_{ex} and H_{in} indices of values up to 1.07 ± 0.04 and 2.06 ± 0.04, respectively, mainly because of its high radium content relative to other regions. All other locations have their maximum ^{226}Ra activities below half of the 370 Bq kg^{-1} limit, which confirms that H_{in} will be less than unity, and consequently the examined soils exhibited low levels of gamma radiation.

In the literature, it was reported that the average H_{ex} and H_{in} are found to be 0.25 and 0.41 for the soil of Ma'an, Jordan [8] and 0.28 and 0.39 for soils of north Jordan [1], respectively. These findings are very similar to the results reported in Table 3.

Calculations of effective dose

The annual effective dose (E) received by an adult due to soil radioactivity can be estimated by the following relation [30]:

$$E(\mu Sv\ y^{-1}) = D(nGy\ h^{-1}) \times 24\ h \times 365.25\ d \times 0.2 \times 0.7\ Sv\ Gy^{-1} \times 10^{-3}. \quad (4)$$

In this relation, 0.2 is the outdoor occupancy factor [17], 0.7 is a conversion factor (in Sv Gy^{-1}) from gamma absorbed dose rate in air outdoors D to E. Where D can be calculated as [30]:

$$D\ (nGy\ h^{-1}) = 0.427 \times A_{^{238}U} + 0.662 \times A_{^{232}Th} + 0.0432 \times A_{^{40}K}, \quad (5)$$

where $A_{^{238}U}$, $A_{^{232}Th}$ and $A_{^{40}K}$ are the ^{238}U, ^{232}Th and ^{40}K activity concentration (in Bq kg^{-1}), respectively. Table 3 gives the average values of D and E for the areas under investigation. In the present work, D and E values are distributed in the range from 9.2 to 179.1 nGy h^{-1} and from 11.3 to 219.8 μSv y^{-1}. The highest values are registered in Swaqa in Karak governorate. However, the overall average values of the dose rate in air outdoors from terrestrial gamma-rays and annual effective dose of (44.4 ± 19.2) nGy h^{-1} and (54.4 ± 32.5) μSv y^{-1}, respectively, for south Jordan are still below the worldwide average values of 57 nGy h^{-1} and 70 μSv, respectively, reported by UNSCEAR [17] under normal circumstances. Saleh and Abu Shayeb [8] registered an average value of absorbed dose 37.2 nGy h^{-1} for Ma'an soil and Al-Hamarneh and Awadallah [1] found overall average values of D and E of about 52 nGy h^{-1} and 63 μSv for soils of north Jordan. Thus, it can be concluded that the present results are in good agreement with the average worldwide limits and other regions of Jordan.

Finally, the gonads, the female breast, the active bone marrow and the bone surface cells are the organs of interest as considered by UNSCEAR [30]. Therefore, the annual gonadal dose equivalent (AGDE) due to ^{226}Ra, ^{232}Th, and ^{40}K activity concentrations can be deduced from the Mamont-Ciesla et al. [31] relation:

$$AGDE\ (mSv\ y^{-1}) = 3.09 \times A_{^{226}Ra} + 4.18 \times A_{^{232}Th} + 0.314 \times A_{^{40}K}. \quad (6)$$

Table 3 presents also the average values AGDE for the four governorates under study. The AGDE values were distributed in the range of 82.6–1233.6 μSv y^{-1}. The highest value, which was found in Swaqa region, is four times greater than the worldwide average AGDE value of 300 μSv y^{-1} [32], but the overall average value of (287.4 ± 191.4) μSv y^{-1} is still below the world average value. In the literature, it was reported that the average value of AGDE was found to be 2398 μSv y^{-1} for Eastern Desert of Egypt [27]. This value is higher than our results.

Conclusions

The levels and distribution of terrestrial natural radionuclides in surface soil samples from south of Jordan (Karak, Tafilah, Ma'an, and Aqaba governorates) were determined by using gamma-ray spectrometry system. The activity and elemental concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K in the studied regions are found to be normal. The extracted values are, in general, comparable to the corresponding ones obtained from other regions in Jordan and other countries and they all fall within the average worldwide ranges. Thus, the background in these areas is exactly the same as the value range typical of the upper part of the Earth's crust. In soils at Swaqa (Karak governorate), the uranium and radium contents slightly exceeded values typical of the upper part of the Earth's crust due to the existence of phosphate and uranium rocks. In this context,

a comparison of median activities of ^{226}Ra, ^{232}Th, and ^{40}K indicates that ^{40}K is the dominant gamma-emitting source in the soil. Accordingly, the correlations and elemental ratios between measured radionuclides have been assessed to investigate the state of secular equilibrium as well as the relative depletion/enrichment processes in the investigated soils.

The overall average annual effective dose was found to be below the corresponding worldwide average value of 70 μSv. This implies that inhabitants of the southern governorates Jordan are subjected to low level of radiation exposure in relative to other areas worldwide. In addition to that, the estimations made for radium equivalent activity, external and internal hazard indices, and annual gonadal dose equivalent showed values, except for soils of Swaqa region where the phosphate and uranium mining processes exist, that do not exceed internationally recommended limits. Hence, all the samples investigated can be considered as safe materials for use in building constructions.

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