TÜBİTAK

Turkish Journal of Engineering & Environmental Sciences

http://journals.tubitak.gov.tr/engineering/

Research Article

Turkish J Eng Env Sci
(2014) 38: 113 – 125

doi:10.3906/muh-1303-8

Measurement of activity concentration levels of radionuclides in soil samples collected from Bethlehem Province, West Bank, Palestine

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Received: 13.03.2013 • **Accepted/Published Online:** 02.09.2014 • **Printed:** 30.06.2015

Abstract: In this study, we report on the activity concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs in 50 soil samples of Bethlehem Province, West Bank, Palestine. Gamma-ray spectroscopy was employed to perform the measurements using an HPGe detector. On one hand, the activity concentrations of natural radionuclides were found to vary from 12.7 to 122.3 Bq kg^{-1} with an average value of 41.4 Bq kg^{-1} for ^{238}U, from 2.0 to 32.2 Bq kg^{-1} with an average value of 19.5 Bq kg^{-1} for ^{232}Th, and from 12.0 to 183.8 Bq kg^{-1} with an average value of 113.3 Bq kg^{-1} for ^{40}K. On the other hand, the activity concentrations of the artificial ^{137}Cs radionuclide were found between 1.0 and 12.2 Bq kg^{-1}, with an average value of 2.8 Bq kg^{-1}. The variations of the assessed radiological hazard parameters indices Ra_{eq}, D_r, H_{ex}, and I_γ of natural radionuclides were found to be as follows: 16–148, 7–65, 0.04–0.4, and 0.11–1.00, respectively. The results were found to be comparable to or lower than similar reported data worldwide. Accordingly, the investigated soil zones can be considered to have normal levels of natural background radiation.

Key words: Natural radioactivity, activity concentration, hazardous indices, Bethlehem Province

1. Introduction

Gamma radiations emitted from naturally occurring radioactive materials (NORMs) such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are generally known as terrestrial background radiation, the main external source of irradiation of the human body [1]. However, humankind can be exposed to radiation originating from artificially radioactive sources such as cesium-137 (^{137}Cs) present in the earth's environment as a result of nuclear weapon testing or nuclear fallout from nuclear technology [2].

High terrestrial background radiations zones were generally attributed to local geology, location, altitude, and geochemical effects [2–4]. Thus, the activity concentrations of radionuclides in granite locations were found to be higher than those of clay, sand stones, and limestone soils [5,6]. Normally, the presence of NORMs in soil generally originates from the disintegrating rocks that are carried to soil by rain and flows [1–3]. The assessment of radionuclide activity levels in the environment provides us with essential information about the abundance of radionuclides in the local environment [7].

Over the past half century, it has been recognized that the presence of NORMs in the environment with

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activity concentrations higher than the radiological reference levels assigned by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) is hazardous to living organisms [1]. The determination of uranium and other radionuclide concentrations in geological samples is very important in the exploration of the natural resources of these element [8]. Tremendous investigations have been made worldwide to assess activity concentrations of NORMs in soil. This is of great importance for assessing the dose to the population, which plays a vital rule in exploring the health risks due to radioactivity and paving the road to a baseline for future changes in environmental radioactivity due to human activities [9].

In Palestine, a few investigations have been performed in the southern part of the West Bank [10–12]. As far as we know, an investigation of radionuclide activity levels and radionuclide distributions in the soil of Bethlehem Province has not been performed yet. Thus, this study is devoted to reporting the activity concentration levels of both natural radionuclides (^{238}U, ^{232}Th, ^{40}K) and artificial radionuclides (^{137}Cs) in soil samples collected from different sites of Bethlehem Province. Such data are essential in establishing baseline values of radionuclides in the soil of Palestinian territories. Furthermore, the study is aimed at estimating a group of health hazard indices such as the radium equivalent activity (Ra_{eq}), the absorbed dose rate (D_r), the annual effective dose equivalent ($AEDE$), the external radiation hazard index (H_{ex}), the radioactivity level index (I_γ), and the excess lifetime cancer risk ($ELCR$).

This type of measurement is of great importance in providing us with a clear picture about the radiation health hazards due to the presence of radionuclides in Palestinian soils.

2. Experimental

In this study, the gamma-ray spectrometry technique has been employed to determine the activity concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs radionuclides and the associated radiation hazard levels in 50 soil samples collected randomly from a total of 24 different sites and locations in Bethlehem Province in West Bank, Palestine, as shown in the Figure. The site names where samples were collected are marked by ovals.

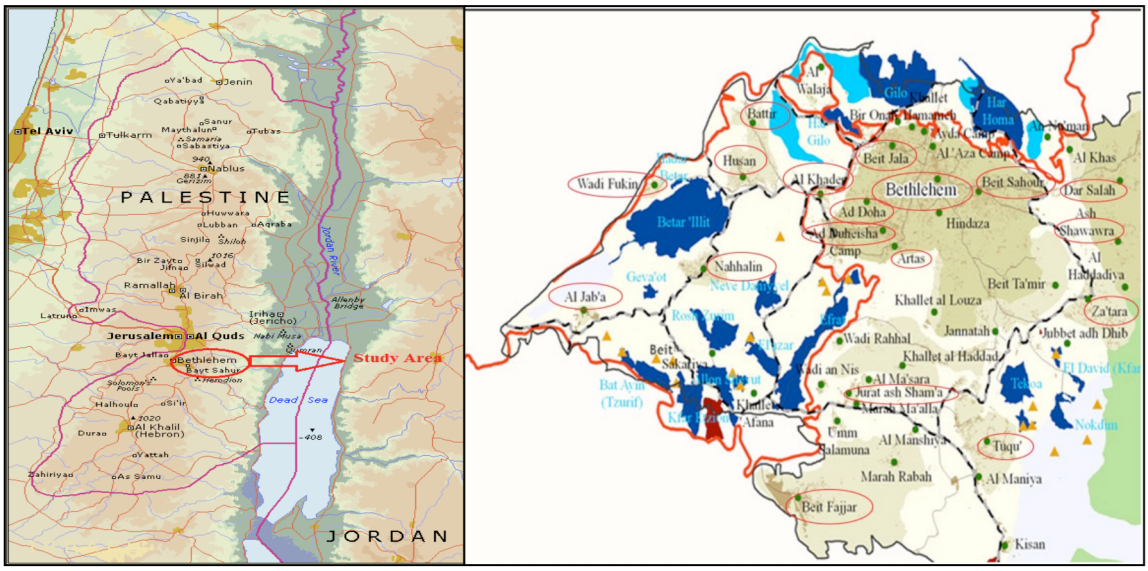

Figure. On the left, West Bank map including Bethlehem Province (http://looklex.com/e.o/map_westbank.htm), and on the right, map of Bethlehem Province where the investigated soil sites are marked by ovals (http://vprofile.arij.org/Bethlehem).

2.1. Sample collection and sample processing

The samples were collected randomly during the spring season of 2011. The collection procedures were as follows: for each sample, the soil position was determined and the ground was cleared of stones, pebbles, vegetation, and roots. A total of 1.5–2.0 kg of soil material was then collected from a soil position 10 cm below the soil surface. The collected soil material was placed in a coded polythene bag and sent to the laboratory for activity measurements. In the laboratory, the samples were first dried in air and then ground into a fine powder of 200 μm in size. After removing foreign materials, the samples were weighed, mixed well, and dried in an oven at 110 $^{\circ}$C to ensure material homogeneity [12,13]. The prepared samples were then sealed in 1000-mL dry-weighed Marinelli beakers and stored for a period of 30 days to assure radioactive secular equilibrium between ^{226}Ra and ^{232}Th with their daughters [14]. The activity concentration for each sample was measured using an HPGe gamma spectrometer connected to a coaxial high-purity germanium detector [11].

2.2. Calibration and energy lines

The activity concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs radionuclides in the samples were determined by well-known standard gamma-ray spectrometry using an HPGe detector (Ortec). The detector has a relative efficiency of 15% and a resolution of 1.85 keV for the 1332.5 keV ^{60}Co gamma lines and MCA with 8000 channel. The detector is shielded using three inner concentric shells of lead, cadmium, and copper on all sides to reduce the background level of the system.

Energy calibration in the energy range of 59.5–1836 keV was attained using standard reference mixed material ^{60}Co (1173.5 and 1332.5 keV), ^{241}Am (59.5 keV), ^{226}Ra (186.2, 242.0, 295.2, 351.9, and 609.3 keV), ^{137}Cs (661.3 keV), and ^{88}Y (898 and 1836 keV). Beyond 1850 keV, the calibration efficiency curve was constructed by using different energy peaks of ^{226}Ra in order to cover the energy range from 60 to 2500 keV [11]. The background radiation and the samples were counted between 5×10^4 and 7×10^4 s.

The activity concentrations for ^{238}U were calculated from the mean value of six γ-ray lines obtained from the photopeaks of ^{226}Ra (186.2 keV), ^{214}Pb (295.2 and 351.9 keV), and ^{214}Bi (609.3, 1120.3, and 1764.8 keV), while the ^{232}Th activity concentrations were calculated from the mean value of four γ-ray lines obtained from the photopeaks of ^{212}Pb (238.6 keV), ^{228}Ac (338.5 and 911.1 keV), and ^{208}Tl (583.1 keV). The ^{40}K and ^{137}Cs activity concentrations were measured from their own γ-ray energies of 1461.8 keV and 661.6 keV, respectively [12–15]. The net count rates under the most prominent photopeaks of radionuclides' daughter peaks were calculated by subtracting the respective count rate from the background spectrum obtained for the same counting time. The activity of the radionuclide was then calculated from the background subtracted area prominent gamma ray energies [9].

3. Radiometric analysis and assessment

3.1. Activity concentration results

The activity concentration of a certain radionuclide, C, in the soil samples was calculated using the following equation [11,16].

$$C(Bqkg^{-1}) = \frac{C_a}{\varepsilon \times I_{eff} \times M_s} \tag{1}$$

Here C_a is the net gamma counting rate (counts per second) for a peak at energy E, ε is the detected efficiency of a specific γ-ray, I_{eff} is the intensity of the γ-line in radionuclides, and M_s is the mass of the soil sample under consideration measured in kilograms.

3.2. Radiation hazards

3.2.1. Radium equivalent activity

The radium equivalent activity, Ra_{eq}, measured in Bq kg^{-1}, was introduced to identify the uniformity to radiation exposure. The calculated values of Ra_{eq} are generally used to compare the specific activity of materials containing different amounts of ^{238}U, ^{232}Th, and ^{40}K. Besides, Ra_{eq} data can be used to assess the health hazard effects produced from the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K radionuclides in soil. The measured values of Ra_{eq} were obtained by making use of the following equation [15,17].

$$\underset{eq}{Ra}(Bqkg^{-1}) = AU + 1.43 \times ATh + 0.077 \times Ak \tag{2}$$

Here A_U, A_{Th}, and A_K are the average activity concentrations of ^{238}U, ^{232}Th, and ^{40}K, respectively. In calculating Ra_{eq} values, the average activity concentrations of 370 Bq kg^{-1}, 259 Bq kg^{-1}, and 4810 Bq kg^{-1} used for ^{238}U, ^{232}Th, and ^{40}K radionuclides, respectively, were assumed to produce the same gamma dose rate [18].

3.2.2. Absorbed dose rate in air

The effects of gamma radiation originating from radioactive sources in the environment are generally expressed in terms of the total gamma radiation absorbed dose rate in air, D_r. The values of D_r in air and 1 m above the ground level are calculated from the measured activity concentrations of ^{238}U, ^{232}Th, and ^{40}K radionuclides using the following semiempirical formula [19,20].

$$D_r(nGyh^{-1}) = 0.427 \times A_U + 0.662 \times A_{Th} + 0.043 \times A_K \tag{3}$$

Eq. (3) was modified to include the contributions of artificial radionuclides of cesium, ^{137}Cs, as well as cosmic radiation via the following equation [19].

$$D_\gamma(nGyh^{-1}) = 0.427 \times A_U + 0.662 \times A_{Th} + 0.043 \times A_K + 0.03 \times A_{Cs} + 34 \tag{4}$$

Here 0.427, 0.662, and 0.043 are the dose rate conversion factors to convert the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K and ^{137}Cs radionuclides into absorbed dose rates as proposed by UNSCEAR [4]. Basically, these factors are representative of the absorbed dose rates in air per unit activity per unit of soil mass, in units of nGy h^{-1} per Bq kg^{-1}.

3.2.3. Annual effective dose equivalent

The annual effective dose equivalent ($AEDE$) received by individuals was calculated from the calculated values of D_r by applying the dose rate conversion factor of 0.7 Sv Gy^{-1} and the occupancy factors of 0.2 (5/24) and 0.8 (19/24) for outdoors and indoors, respectively [4]. The annual effective outdoor doses, D_{out}; the annual

effective indoor doses, D_{in}; and total annual effective doses, D_{tot}, were calculated according to the following equations [21].

$$D_{out}(mSvy^{-1}) = D_r(mGyh^{-1}) \times 24h \times 365.25d \times 0.2 \times 0.7SvGy^{-1} \times 10^{-6} \quad (5)$$

$$D_{in}\,(mSvy^{-1}) = D\,_r(mGyh^{-1}) \times 24h \times 365.25d \times 1.4 \times 0.8 \times 0.7SvGy^{-1} \times 10^{-6} \quad (6)$$

$$D_{tot}\,(m\ Sv\,y^{-1}) \;=\; D_{out} \;\;+\;\; D_{in} \quad (7)$$

3.2.4. External and internal radiation hazard indices

$$Hex = \frac{AU}{370Bqkg^{-1}} + \frac{ATh}{259Bqkg^{-1}} + \frac{AK}{4810Bqkg^{-1}} \quad (8)$$

The external radiation hazard index, H_{ex}, corresponding to ^{238}U, ^{232}Th, and ^{40}K natural radionuclides, was calculated using the following equation [22].

The results of H_{ex} should be less than or equal to unity, i.e. $H_{ex} \leq 1$. Normally, the maximum value of H_{ex} ($H_{ex} = 1$) corresponds to the upper limit of Ra_{eq} (370 Bq kg^{-1}). In order to keep the radiation hazard insignificant, the values of H_{ex} should be lower than 1 [15,18].

The hazard levels from the inhalation of alpha particles emitted from the radon short-lived radionuclides such as ^{222}Rn, the daughter product of ^{226}Ra, and ^{220}Rn, the daughter product of ^{224}Ra, can be quantified by the internal hazard index, H_{in}. This index can be calculated using the following semiempirical formula [22,23].

$$Hin = \frac{AU}{185\ Bqkg^{-1}} + \frac{ATh}{259\ Bqkg^{-1}} + \frac{AK}{4810\ Bqkg^{-1}} \quad (9)$$

The measured values of H_{in} should also be less than or equal to unity, i.e. $H_{in} \leq 1$. This of great importance to keep the concentration levels of radon and its short-lived daughters low enough for the respiratory organs of humans living in the dwellings, comparable to or even lower than the assigned international levels of 40 Bq m^{-3} [1].

3.2.5. Radioactivity level index

The radioactivity level index, I_γ, is generally used to assess the hazardous level of radionuclides in the human body when exposed to an amount of external (indoor or outdoor) annual effective doses of γ-radiations decayed from radioactive nuclides in soils. This index is very important for quality control of γ-radiation annual effective doses and in monitoring radiation inside human body, to ensure that such radiation does not exceed the worldwide permissible high dose values [24]. Values of I_γ can be calculated according to the following semiempirical formula [11,22].

$$I\gamma = \frac{AU}{150Bqkg^{-1}} + \frac{ATh}{100Bqkg^{-1}} + \frac{AK}{1500Bqkg^{-1}} \quad (10)$$

The assessed values of I_γ must be less than or equal to 1 to make sure the soil environment is generally safe or hazard-free.

3.3. Excess lifetime cancer risk

The excess lifetime cancer risk ($ELCR$) values are calculated using the below equation [2].

$$ELCR = D_{tot} \times \mathrm{D_L} \quad \times R_F \tag{11}$$

Here D_L is the duration of life (approximately 70 years), and R_F is the risk factor (Sv^{-1}), which reflects the fatal cancer risk per sievert. For stochastic effects, ICRP 60 uses values of 0.05 for the public [3].

4. Results and discussion

4.1. Activity concentration results

The statistical parameters of the measured activity concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs radionuclides for a total of 50 soil samples collected from Bethlehem Province are presented in Table 1.

Table 1. The activity concentration levels of natural radionuclides in soil samples collected from different sites located in Bethlehem Province, West Bank, Palestine.

Zone	Samples codes	No. of samples	Activity concentration (Bq kg^{-1})								
			^{238}U			^{232}Th			^{40}K		
			Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Bethlehem city	BLSS	3	18.8	41.8	30.8	11.2	23.9	17.9	69.4	149.8	115.5
Beit Jala	BJSS	2	13.4	31.6	22.5	7.5	12.3	9.9	61.4	74.8	68.1
Beit Sahour	BSSS	3	27.4	55.5	43.4	16.9	23.6	21.3	88.2	127.8	111.6
Al Doha	DSS	1	----	----	32.4	----	----	24.3	----	----	92.5
Duheisha Camp	DCSS	1	----	----	47.1	----	----	27.2	----	----	155.6
Al Khader	KSS	2	45.1	52.0	48.6	18.9	30.9	24.9	123.7	175.6	149.7
Artas	ASS	2	12.7	37.0	24.9	7.3	23.2	15.3	50.8	176.4	113.6
Tuku'	TSS	2	30.0	40.9	35.5	27.3	31.2	29.3	166.4	183.8	173.0
Za'tara	ZSS	1	----	----	36.7	----	----	18.9	----	----	183.8
Freedees Mount	FSS	1	----	----	45.8	----	----	12.1	----	----	81.9
Al Shawawra	SSS	4	21.2	89.7	55.7	13.8	24.4	20.0	99.5	156.2	126.0
Dar Salah	DSSS	2	41.8	122.3	82.1	11.4	14.9	13.2	56.2	61.0	58.6
Al Obeidiya	OSS	3	27.0	71.4	42.9	12.4	20.6	16.8	136.9	163.6	149.9
Wad Al Nar	WNSS	3	88.5	99.4	93.9	8.1	12.4	10.3	33.0	48.3	38.9
Al Sawahra	ASSS	2	42.5	69.8	56.2	19.4	22.0	20.7	101.8	108.2	105.0
Abu Dies	ADSS	1	----	----	33.9	----	----	25.4	----	----	157.3
Sur Bahir	SBSS	2	44.6	50.9	47.8	18.1	30.7	24.4	86.9	128.7	107.8
Jurat Al Sham'a	JSSS	2	13.2	40.8	27.0	2.0	27.9	14.9	16.5	133.8	70.2
Beit Fajjar	BFSS	3	14.3	22.0	17.9	3.0	12.3	6.9	12.0	64.0	29.6
Al Jab'a	AJSS	2	47.3	51.0	49.2	27.3	31.4	29.4	162.3	168.0	165.2
Nahhalin	NSS	2	33.2	43.9	38.6	7.7	20.8	14.3	92.9	114.9	103.9
Wadi Fukin	WFSS	2	34.2	63.9	49.1	27.4	30.5	29.0	122.6	136.1	129.4
Husan	HSS	2	25.1	39.9	32.5	7.6	32.2	19.9	78.1	134.9	106.5
Battir	BSS	2	18.5	36.2	27.4	17.1	21.5	19.3	137.2	149.7	143.5
Total		50	12.7	122.3	41.4	2.0	32.2	19.5	12.0	183.8	113.3

As can be seen from Table 1, the range of measured activity concentration of ^{238}U varies from 12 .7 to 122.3 Bq kg^{-1} with an average of 41.4 Bq kg^{-1}. The maximum value of the activity concentration of ^{238}U

radionuclide has been reported in some soil samples collected from Dar Salah village, whereas the minimum concentration value was measured in a soil sample collected from Artas village. This noticeable difference may be attributed to the geochemical composition and origin of soil types in such particular areas [11,12].

The measured activity concentrations of ^{232}Th were found to range from 2.0 to 32.2 Bq kg^{-1} with an average of 19.5 Bq kg^{-1}. Moreover, the range of activity concentration of ^{40}K was found to vary from 12.0 to 183.8 Bq kg^{-1}, with an average value of 113.3 Bq kg^{-1}. The reported differences were also attributable to the differences in soil type.

Clearly, the results show that the activity concentration of ^{238}U is higher than that of ^{232}Th in all samples. The average activity levels of ^{238}U are about 1.5 times higher than that of ^{232}Th in the soil of this particular region of the world. Another observation revealed that the measured activity concentration of ^{40}K significantly exceeds the measured activity concentration values of both ^{238}U and ^{232}Th. This is an indication that ^{40}K is a more abundant radioactive element than the other elements in the soils under consideration [12].

All of the obtained average values are within the attainable worldwide ranges except the activity concentration average value of ^{238}U, which was found to be higher than the reported international radioactivity levels of ^{238}U in UNSCEAR reports [1,4]. The reported high values of the activity concentration belong to soil samples collected from sites near radioactive-rich granite, phosphate, sandstone, and quartzite [1,4].

4.2. Assessment of radiation hazards

The calculated data for Ra_{eq}, H_{ex}, and I_{γ} of the collected soil samples are shown in Table 2.

As can be observed from Table 2, the calculated values of Ra_{eq} for the same soil samples were found to vary from 16.3 Bq kg^{-1} to 147.9 Bq kg^{-1}, with an average value of 77.6 Bq kg^{-1}. For most inspected soil samples, Ra_{eq} values are comparable to or lower than the assigned international allowed limit of 370 Bq kg^{-1} [1,4].

The calculated values of H_{ex} were found to vary from 0.04 to 0.40, with an overall average value of 0.21. These values are much less than unity ($H_{ex} < 1$) and below the measured values in other countries. The values of H_{in} were found to range between 0.08 and 0.73 with an average value of 0.32. The obtained values of H_{in} are less than 1, as recommended for construction materials [11].

The calculated values of I_{γ} were found to range from 0.11 to 1.00 with an average of 0.55. In most soil samples, the calculated values of I_{γ} were found to be lower than 1, corresponding to an annual effective dose of generally less than 0.3 mSv year^{-1} [12].

The activity concentrations of the artificial radionuclide ^{137}Cs were measured for all collected soil samples in order to assess the amount of fallout radionuclide in such locations; they are given in Table 3.

The obtained activity concentration values of ^{137}Cs in all collected soil samples were found to range from 1.0 Bq kg^{-1} to 12.2 Bq kg^{-1} with an average value of 2.8 Bq kg^{-1}. The minimum activity concentration value of ^{137}Cs was obtained for a soil sample collected from Jurat Al Sham'a village, whereas the maximum value was measured in a soil sample collected from Al Jab'a village. Thus, the impact of the artificial radionuclide and the corresponding additional external radiation exposure to the population were almost negligible. Consequently, the measured activities of ^{137}Cs confirmed no hazard effects due to ^{137}Cs radionuclides to the people living in the vicinity of the sites where soil samples were collected.

The calculated values of D_r were found to vary from 7.1 to 64.5 nGy h^{-1}, with an average value of

Table 2. The radium equivalent (Ra_{eq}), the external (H_{ex}) and the internal (H_{in}) hazard indices, and radioactivity level index (I_γ) of soil samples collected from Bethlehem Province, West Bank, Palestine.

Zone	Ra_{eq} (Bq kg^{-1})			H_{ex}			H_{in}			I_γ		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Bethlehem city	40.1	87.5	65.0	0.11	0.24	0.18	0.16	0.35	0.26	0.28	0.62	0.46
Beit Jala	29.9	53.8	41.9	0.08	0.15	0.12	0.12	0.23	0.18	0.21	0.37	0.29
Beit Sahour	70.0	99.1	82.4	0.19	0.27	0.22	0.26	0.42	0.34	0.50	0.69	0.58
Al Doha	----	----	74.2	----	----	0.20	----	----	0.29	----	----	0.52
Duheisha Camp	----	----	98.1	----	----	0.26	----	----	0.39	----	----	0.69
Al Khader	88.6	102.7	95.7	0.24	0.28	0.26	0.38	0.40	0.39	0.62	0.73	0.68
Artas	27.1	83.7	5 5.4	0.07	0.23	0.15	0.11	0.33	0.22	0.19	0.60	0.40
Tuku'	87.4	93.7	90.6	0.24	0.25	0.25	0.32	0.36	0.34	0.62	0.67	0.65
Za'tara	----	----	77.9	----	----	0.21	----	----	0.31	----	----	0.56
Freedees Mount	----	----	69.4	----	----	0.19	----	----	0.31	----	----	0.48
Al Shawawra	57.3	132.4	94.0	0.15	0.36	0.25	0.21	0.60	0.40	0.41	0.91	0.66
Dar Salah	62.7	147.9	105.3	0.17	0.40	0.29	0.28	0.73	0.51	0.43	1.00	0.72
Al Obeidiya	66.8	101.6	78.5	0.18	0.27	0.21	0.25	0.47	0.33	0.48	0.71	0.56
Wad Al Nar	106.1	120.9	111.7	0.29	0.33	0.30	0.53	0.60	0.56	0.72	0.82	0.76
Al Sawahra	82.3	105.4	93.9	0.22	0.28	0.25	0.34	0.47	0.41	0.58	0.73	0.66
Abu Dies	----	----	82.4	----	----	0.22	----	----	0.31	----	----	0.59
Sur Bahir	77.2	104.8	91.0	0.21	0.28	0.25	0.33	0.42	0.38	0.54	0.73	0.64
Jurat Al Sham'a	16.3	91.0	53.7	0.04	0.25	0.15	0.08	0.36	0.22	0.11	0.64	0.38
Beit Fajjar	21.7	44.6	30.1	0.06	0.12	0.08	0.10	0.18	0.13	0.15	0.31	0.21
Al Jab'a	102.6	105.1	103.9	----	----	0.28	----	----	0.41	----	----	0.73
Nahhalin	51.4	82.4	66.9	0.14	0.22	0.18	0.23	0.34	0.29	0.36	0.58	0.47
Wadi Fukin	83.8	117.0	100.4	0.23	0.32	0.28	0.32	0.49	0.41	0.59	0.81	0.70
Husan	42.0	96.3	69.2	0.11	0.26	0.19	0.18	0.37	0.28	0.30	0.68	0.49
Battir	59.7	72.1	65.9	0.16	0.19	0.18	0.21	0.29	0.25	0.43	0.51	0.47
Total	16.3	147.9	77.6	0.04	0.40	0.21	0.08	0.73	0.32	0.11	1.00	0.55

35.3 nGy h^{-1}. The measured average absorbed dose rate in the air and the measured average value of the representative level index are lower than the recommended international levels of 55 nGy h^{-1}. The weighted mean value of 35.3 nGy h^{-1} represents 64% of the world average outdoor exposure due to terrestrial gamma radiation (55 nGy h^{-1}) [1,4]. The measured values of D_γ range from 41.1 to 98.7 nGy h^{-1} and have an average value of 69.4 nGy h^{-1}. Obviously, radiation backgrounds in some inspected places were found to be higher than the recommended world average of 55 nGy h^{-1}. Such locations are not suitable for human residency, and constructed homes should be removed.

The calculated indoor, outdoor, and total *AEDE* values are exhibited in Table 4.

The calculated values for D_{out}, D_{in}, and D_{tot} averages were respectively 0.04, 0.24, and 0.28 mSv year^{-1}. In comparison to global measured values, these values were all below the assigned worldwide values of 0.08, 0.42, and 0.50 mSv year^{-1}, respectively [1].

As all measured values were lower than unity (Table 2), the locations from which the soil samples were collected were all safe according to the Radiation Protection 112, and such locations can be classified as hazard-free [25]. Accordingly, such places can be used as agricultural lands, dwelling areas, and sources of construction material without posing any significant radiological threat to the population.

Table 3. The activity concentrations, the absorbed dose rate (D_r), and the total dose rate of ^{137}Cs and cosmic radiation of the soil samples collected from Bethlehem Province, West Bank, Palestine. ND: Not detected.

Zone	^{137}Cs			D_r (nGy h^{-1})			D_γ (nGy h^{-1})		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Bethlehem city	2.2	4.3	2.9	18.4	40.1	29.8	52.4	74.3	63.9
Beit Jala	1.2	1.3	1.3	13.9	24.2	19.1	47.9	58.2	53.1
Beit Sahour	1.2	1.7	1.4	32.3	44.8	37.4	66.3	78.9	71.4
Al Doha	----	----	1.5	----	----	33.9	----	----	68.0
Duheisha Camp	----	----	ND	----	----	44.8	----	----	78.8
Al Khader	2.9	5.0	4.0	40.1	47.2	43.7	74.2	81.4	77.8
Artas	2.5	5.5	4.0	12.5	38.7	25.6	46.6	72.9	59.7
Tuku'	2.6	2.8	2.7	40.6	43.2	41.9	74.7	77.3	76.0
Za'tara	----	----	ND	----	----	36.1	----	----	70.1
Freedees Mount	----	----	3.0	----	----	31.1	----	----	65.2
Al Shawawra	3.2	4.5	3.7	26.6	59.1	42.5	60.7	93.2	76.6
Dar Salah	1.3	3.9	2.6	28.0	64.5	46.3	62.0	98.7	80.4
Al Obeidiya	1.1	2.3	1.9	30.9	45.7	35.9	64.9	79.8	70.0
Wad Al Nar	3.1	4.3	3.5	46.2	52.8	48.7	80.3	86.9	82.8
Al Sawahra	3.3	4.2	3.8	37.4	47.0	42.2	71.5	93.6	76.3
Abu Dies	----	----	1.0	----	----	38.1	----	----	72.1
Sur Bahir	1.1	1.2	1.2	34.8	47.6	41.2	68.8	81.6	75.2
Jurat Al Sham'a	1.0	1.2	1.1	7.1	41.7	24.5	41.1	75.7	58.5
Beit Fajjar	1.1	1.3	1.2	9.4	20.3	13.5	43.4	54.4	47.5
Al Jab'a	7.5	12.2	9.9	46.8	48.2	47.5	81.0	82.6	81.8
Nahhalin	3.2	7.6	5.4	23.3	37.4	30.4	57.4	71.6	64.6
Wadi Fukin	1.4	1.6	1.5	38.5	52.8	45.7	72.5	86.9	79.8
Husan	1.5	2.6	2.1	19.1	44.1	31.6	53.2	78.2	65.7
Battir	5.9	6.1	6.0	28.0	33.2	30.6	62.2	67.4	64.8
Total	1.0	12.2	2.8	7.1	64.5	35.3	41.1	98.7	69.4

4.3. Excess lifetime cancer risk

The calculated values of the excess lifetime cancer risk ($ELCR$) for all the samples are presented in Table 4. As seen from Table 4, the range of all $ELCR$ values is between 0.21×10^{-3} and 1.82×10^{-3} and the average value is about 1.02×10^{-3}. The calculated average value of $ELCR$ for all samples is higher than the world average of 0.29×10^{-3} [3]. This indication of the possibility of developing cancer cases among individuals cannot be neglected.

For comparison purposes, the reported values of the activity concentrations of natural radionuclides' absorbed dose rates in the investigated soil samples and similar soil data reported by research groups from some other countries are listed in Table 5.

As shown in Table 5, the average values of ^{238}U, ^{232}Th, and ^{40}K obtained in this study were found to be comparable to or lower than similar results of other countries. The average activity concentration of ^{238}U,

Table 4. The outdoor ($D_{outdoor}$), indoor (D_{indoor}), and total annual effective dose equivalent (D_{total}) and excess lifetime cancer risk ($ELCR$) of the soil samples collected from Bethlehem Province, West Bank, Palestine.

Zone	$D_{outdoor}$ (mSv year^{-1})			D_{indoor} (mSv year^{-1})			D_{total} (mSv year^{-1})			$ELCR$ ($\times 10^{-3}$)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Bethlehem city	0.02	0.05	0.04	0.13	0.28	0.20	0.15	0.33	0.24	0.53	1.16	0.84
Beit Jala	0.02	0.03	0.02	0.10	0.17	0.13	0.12	0.20	0.15	0.42	0.70	0.53
Beit Sahour	0.04	0.05	0.05	0.22	0.31	0.26	0.26	0.36	0.31	0.91	1.26	1.09
Al Doha	----	----	0.04	----	----	0.23	----	----	0.27	----	----	0.95
Duheisha Camp	----	----	0.05	----	----	0.31	----	----	0.36	----	----	1.26
Al Khader	0.05	0.06	0.05	0.28	0.32	0.30	0.33	0.38	0.35	1.16	1.33	1.23
Artas	0.02	0.05	0.03	0.09	0.27	0.18	0.11	0.32	0.21	0.39	1.12	0.74
Tuku'	0.04	0.05	0.05	0.28	0.30	0.29	0.32	0.35	0.34	1.16	1.23	1.19
Za'tara	----	----	0.04	----	----	0.25	----	----	0.29	----	----	1.02
Freedees Mount	----	----	0.04	----	----	0.21	----	----	0.25	----	----	0.88
Al Shawawra	0.03	0.07	0.05	0.18	0.41	0.29	0.21	0.48	0.34	0.74	1.68	1.19
Dar Salah	0.03	0.08	0.06	0.19	0.44	0.32	0.22	0.52	0.38	0.77	1.82	1.33
Al Obeidiya	0.04	0.06	0.04	0.21	0.31	0.25	0.25	0.37	0.29	0.88	1.30	1.02
Wad Al Nar	0.05	0.06	0.06	0.32	0.36	0.33	0.37	0.42	0.39	1.33	1.47	1.37
Al Sawahra	0.05	0.06	0.05	0.26	0.32	0.29	0.31	0.38	0.34	1.09	1.33	1.19
Abu Dies	----	----	0.05	----	----	0.26	----	----	0.31	----	----	1.09
Sur Bahir	0.04	0.06	0.05	0.24	0.33	0.28	0.28	0.39	0.33	0.98	1.37	1.16
Jurat Al Sham'a	0.01	0.05	0.03	0.05	0.29	0.17	0.06	0.34	0.20	0.21	1.19	0.70
Beit Fajjar	0.01	0.02	0.02	0.06	0.14	0.09	0.07	0.16	0.11	0.25	0.56	0.39
Al Jab'a	0.05	0.07	0.06	0.32	0.33	0.33	0.37	0.40	0.39	1.33	1.37	1.35
Nahhalin	0.03	0.05	0.04	0.16	0.26	0.21	0.19	0.31	0.25	0.67	1.09	0.88
Wadi Fukin	0.05	0.06	0.06	0.26	0.36	0.31	0.31	0.42	0.37	1.09	1.47	1.30
Husan	0.02	0.05	0.04	0.13	0.30	0.22	0.15	0.35	0.26	0.53	1.23	0.91
Battir	0.03	0.04	0.04	0.19	0.23	0.21	0.22	0.27	0.25	0.77	0.95	0.88
Total	0.01	0.08	0.04	0.05	0.44	0.24	0.06	0.52	0.28	0.21	1.82	1.02

^{232}Th, and ^{40}K in the Bethlehem region represents, respectively, 60%, 40%, and 20% of the average activity concentrations obtained for radionuclides in soil samples collected from Hebron Province south to Bethlehem Province [11,12].

5. Conclusions

The measured average activity concentrations in Bq kg^{-1} for ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs are respectively 41.4, 19.5, 113.3, and 2.8. On one hand, the average activity concentrations of ^{232}Th and ^{40}K are found to be lower than the world averages of 30 Bq kg^{-1} and 400 Bq kg^{-1}. On the other hand, the average activity concentration of ^{238}U is found to be higher than the corresponding world average of 35 Bq kg^{-1}.

The measured average absorbed dose rate in the air and the measured average value of the representative level index are found to be lower than the recommended international levels. The estimated average of total

Table 5. A comparison of the average activity concentration (in Bq kg^{-1}) and the absorbed dose rate in air (in nGy h^{-1}) in soil samples under investigation with those in other countries.

Country	^{238}U	^{232}Th	^{40}K	D_r	Reference
Jordan	49.9	26.7	291.1	52	[26]
Saudi Arabia	14.5	11.2	225.0	23	[7]
Iran	28.5	53.7	490.9	69	[5]
Turkey	17.6	21.1	297.5	67	[27]
Malaysia	57.0	68.0	427.0	88	[28]
Pakistan	45.0	67.0	878.0	107	[6]
China	26.0	49.0	440.0	60	[29]
Libya	7.5	4.5	28.5	4.4	[30]
Hungary	33.3	32.1	418.0	41	[31]
Oman	14.4	10.0	158.2	19	[32]
Ghana	13.6	24.2	162.1	0.2	[33]
Thailand	67.7	45.0	213.1	68	[34]
South WB (Hebron)	69	48	630.0	88	[11]
North WB (Tulkarem)	35	24	120.0	36	[12]
Bethlehem region	41.4	19.5	113.3	35	Present study
Worldwide	35	30	400.0	51	[1]
					WB: West Bank.

annual effective dose equivalent (0.28 mSv $year^{-1}$) is lower than the 0.5 mSv $year^{-1}$ dose recommended by UNSCEAR reports for public radiation exposure control [1]. The impact of the artificial radionuclide and the corresponding additional external radiation exposure to the population were almost negligible.

In conclusion, the inspected sites and locations in the Bethlehem governorate are found to have either comparable or higher activity concentration of natural background radiation. Thus, no harmful radiation effects are posed to the population living in the vicinity of the investigated locations, except in regions having high activity concentrations of ^{238}U (>40 Bq m^{-3}). Locations with higher activity concentrations should have special management and immediate treatment to reduce radioactive pollution in accordance with the environmental protection regulations and to maintain the activity levels around the accepted levels.

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