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Radiation hazards and natural radioactivity levels in surface soil samples from dwelling areas of North Cyprus

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Abstract
Due to increasing concern about environmental radiological protection, radioactivity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in surface soil samples collected from the North area of Cyprus have been determined using a high-resolution HPGe gamma-spectroscopy system. The range of activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in the soil samples varies from 49.7 ± 3 to 147.6 ± 17.2, 18.1 ± 1.5 to 93.9 ± 10.7, 103.5 ± 27 to 1468.6 ± 176.1 and 4.3 ± 0.1 to 15.9 ± 1.3 Bq kg^{-1}, respectively. The obtained results and calculated values of radiation dose in the study area indicate that the relatively high background radioactivity levels.

Keywords Natural radioactivity · Soil samples · Gamma-spectroscopy · Radiation dose

Introduction

The background radiation main sources in the environment caused by terrestrial and man-made radionuclides. The main terrestrial radionuclides are ^{226}Ra and ^{232}Th series and ^{40}K. These radionuclides are a constant and inescapable feature of life on earth because these radionuclides are present everywhere in the environment of the earth's surface, such as soils, rocks, plants, water, air, building materials including the human body [1]. The long-term fall-out from the Chernobyl accident consisted mainly of the Cs isotopes, notably ^{137}Cs, which was discharged into Earth's surfaces such as terrestrial materials [2]. ^{137}Cs with long-lived ($T_{1/2} = 30.17$ years), produced in nuclear fission reactions has entered into the atmosphere in irregularly varying amounts since 1945 [3]. The fallout from the testing of nuclear weapons and the accidents at nuclear reactors and discharges of radioactive waste from the nuclear installations are the main sources of anthropogenic radionuclides in the environment. These radionuclides account for less than 0.5% of the total annual dose [1]. Knowledge of environmental radiation level present in soil enables one to assess any possible radiological hazard to occupants of the dwelling by the use of such terrestrial materials [4].

^{238}U and ^{232}Th series decay products are exist in the Earth's crust in parts per million (ppm) level [5]. ^{40}K, a single natural radionuclide, which 0.0118% of total potassium present in the Earth crust, is ^{40}K radioisotope. The level of ^{226}Ra, ^{232}Th and ^{40}K concentrations in the soil of the Earth's is different place to place because their concentrations level depended to soil originates and type of rocks [1].

To assess the radioactivity concentration in soil is significant to know their natural background contents since the soil is a major material in the environment that is used for many objectives, such as building materials [6]. The soil and its derivatives containing natural radiation is the cause of outdoor and indoor human exposure [7]. The method of gamma-ray spectrometry has been widely utilized in natural radiation level of soils [8–13], building materials [4, 14–17].

In the present study, the activity concentrations of the terrestrial (^{226}Ra, ^{232}Th and ^{40}K) and artificial (^{137}Cs) radionuclides in surface (depth range from 0 to 5 cm) soil samples collected from residential regions of North Cyprus were measured using the high-resolution gamma spectrometer with HPGe detector and evaluated their potential radiological hazards. Also, the results of this study were compared with those of similar studies related to other countries

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reported in the kinds of literature as well as worldwide mean values.

Materials and methods

Sample collection and preparation

Thirty-seven surface (up to a depth of 5 cm) soil samples from dwelling areas were collected from the Turkish Republic of Northern Cyprus (North area of Cyprus) Fig. 1. The soil samples (approximately 0.5 kg) were brought to the sample preparation laboratory. The collected soil samples were air-dried and sieved through a fine mesh < 1 mm in order to homogenise it and remove grains of big size. The samples placed then for drying at 105 °C for 1 day to completely remove moisture. Weighed each sample was placed in a polyethylene bottle of 118 cm^3 volume. Each bottle was completely sealed at least for 4 weeks to allow ^{226}Ra and its short-lived decay products to reach the radioactive equilibrium.

Measurement equipment

The radioactivity measurements were carried out by using a gamma-ray spectrometer with a high-resolution coaxial p-type vertical HPGe detector. The detector resolution is 1.9 keV at full-width half maximum of the 1332.5 keV gamma-ray photopeak from ^{60}Co and has a relative efficiency of 50% relative to NaI (Tl) (3 × 3) detector. The energy calibration of the gamma-ray spectrometer was carried out by using point sources. Full energy peak (FEP) efficiency calibration of the gamma-ray spectrometer was performed using reference materials RGU-1 (U-ore), RGTh-1 (Th-ore), RGK-1 (K_2SO_4) and IAEA-375 supplies by International Atomic Energy Authority. Each of these reference materials was placed in the same polyethylene bottles of 118 cm^3 volume and counted until a good counting statistic was obtained. Then, the FEP efficiency (ε_γ) for each interested gamma-ray energy was calculated using the formula given below:

$$\varepsilon_\gamma = \frac{\mathrm{CR}}{P_\gamma \cdot A} \tag{1}$$

where CR is the net count rate of the gamma-ray photopeak of region of interest, P_γ is the probability of the gamma-ray of interest, and A is the radioactivity of reference material in Bq. Each soil sample was placed on the top of the detector and counted for approximately 1 day. Background radiations were taken under the same conditions of sample measurements and subtracted to get net counts for the sample. The activity concentrations were averaged from gamma-ray photopeaks at several energies assuming secular equilibrium in the ^{238}U and ^{232}Th decay series. The gamma-ray line of the 351.9 keV from ^{214}Pb and the 609.3 keV from ^{214}Bi were used to determine the activity concentration of ^{226}Ra. The weighted average of the gamma-ray photopeaks of 911.2 keV from ^{228}Ac and 583.2 keV from ^{208}Tl was used

Fig. 1 Geographical location of the North section of Cyprus and sampling points (source: Google Maps)

to determine the activity concentration of ^{232}Th. The activity concentration of ^{40}K and ^{137}Cs was measured directly by their gamma-ray line at 1460.8 keV and 661.7 keV, respectively.

Uncertainty calculation

Uncertainty assessment was performed to activity calculation, the activity concentration uncertainty (U_A) calculated by the following equation [3]:

$$\frac{U_A}{A} = \sqrt{\left(\frac{U_N}{N}\right)^2 + \left(\frac{U_B}{B}\right)^2 + \left(\frac{U_\varepsilon}{\varepsilon}\right)^2 + \left(\frac{U_M}{M}\right)^2 + \left(\frac{U_{P_\gamma}}{P_\gamma}\right)^2} \quad (2)$$

where U_N is sample counting uncertainty; U_B, background counting uncertainty; U_ε, efficiency uncertainty, U_M, mass measurements uncertainty and U_{P_γ}, gamma line energy uncertainty (for example this uncertainty for ^{137}Cs is 0.24% of intensity) [18].

Determination of radiation doses

Annual gonadal equivalent dose

According to UNSCEAR 1982, the activate bone marrow and the bone surface cells are considered as the organs of interest. So, the Annual Gonadal Equivalent Dose (AGED μSv year^{-1}) for the residents of the study area by the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K was obtained using the following equation [19]:

$$\mathrm{AGED}\left(\mu\mathrm{Sv\ year}^{-1}\right) = 3.09A_{\mathrm{Ra}} + 4.18A_{\mathrm{Th}} + 0.314A_{\mathrm{K}} \quad (3)$$

where A_{Ra}, A_{Th} and A_{K} (Bq kg^{-1}) are the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K, respectively.

Ambient dose equivalent rate ($H^*(10)$)

$H^*(10)$ is a measurable quantity providing a conservative assessment of the effective dose, which quantifies the risk to human health associated to radiation exposure. The ambient dose equivalent rate of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in 1 m above the ground surface was computed. The ambient dose equivalent rate ($H^*(10)$) calculation equation is as the following [20]:

$$H*(10)\left(\mathrm{nSv\ h}^{-1}\right) = 0.674A_{\mathrm{Ra}} + 0.749A_{\mathrm{Th}} + 0.0512A_{\mathrm{K}} + 0.192A_{\mathrm{Cs}} \quad (4)$$

where A_{Ra}, A_{Th}, A_{K} and ^{137}Cs (Bq kg^{-1}) are the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K, respectively.

Results and discussion

Radioactivity of the soil samples

The activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs measured in the soil samples together with the measurement uncertainty (1σ), and average, standard deviation (SD), minimum and maximum values are given in Table 1. The radioactivity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in soil samples ranged from 49.7 to 147.6 Bq kg^{-1} with a mean of 83.7 Bq kg^{-1}, 18.1 to 93.9 Bq kg^{-1} with a mean of 53.6 Bq kg^{-1}, 103.5 to 1468.6 Bq kg^{-1} with a mean of 593.9 Bq kg^{-1} and 4.3 to 15.9 Bq kg^{-1} with a mean of 7.1 Bq kg^{-1}, respectively. It is demonstrated in Table 1 that the highest and lowest radioactivity concentration was measured in the soil samples of S-17 and S-34 (^{226}Ra), S-6 and S-33 (^{232}Th), S-30 and S-34 (^{40}K) and S-29 and S-19 (^{137}Cs). The frequency distribution of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs concentration in the soil samples are demonstrated in Fig. 2. The activity concentration of ^{226}Ra and ^{232}Th obtained in 80% and 86% of the total soil samples are between 40 and 100 Bq kg^{-1}, respectively. The range of 300-700 Bq kg^{-1} measured for ^{40}K include most of the samples (74%). Also, the activity concentration of ^{137}Cs measured in 77% of the total soil samples is between 4 to 8 Bq kg^{-1}. Whereas the range of ^{238}U, ^{232}Th and ^{40}K measured by Tzortzis et al. [21] are 0.9 to 90.3 Bq kg^{-1}, 1.3 to 52.8 Bq kg^{-1} and 13 to 894 Bq kg^{-1}, respectively. Those values are lower than the results of this study Table 3. The difference of north part and south part can be due to differences geological formations (Fig. 3). Cyprus is divided into four geological zones: the *Pentadaktylos* (*Keryneia*), the *Troodos Ophiolite*, the *Mamonia* and the *autochthonous* sedimentary rocks [22]. The northern part consists of the Pentadaktylos (Keryneia) and the autochthonous sedimentary rocks parts. Whereas, the maximum and minimum concentration of ^{226}Ra and ^{40}K were measured in sedimentary rocks (*Terrace Deposits, Fanglomerate*) and sedimentary rocks (*Kythrea Formation*), respectively. The maximum and minimum concentration of ^{232}Th was obtained in sedimentary rocks (*Terrace Deposits, Fanglomerate*) and sedimentary rocks (*Apalos Formations*). The ^{137}Cs distribution was in surface soils and different concentration can be due to natural factors such as wind and rain. The world average of ^{226}Ra, ^{232}Th and ^{40}K in soil are 35, 30 and 400 Bq kg^{-1}, respectively [1]. It has been observed that the average activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in this study was higher than the world average values.

Table 1 The Activity concentration of terrestrial radionuclides (^{226}Ra, ^{232}Th, ^{40}K) and artificial radionuclides (^{137}Cs), the Annual Gonadal Equivalent Dose (AGED), ambient dose equivalent rate, $H^*(10)$ for soil samples

Sample code	Activity concentration (Bq kg^{-1})				Dose	
	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	AGED (μSv year^{-1})	$H^*(10)$ (nSv h^{-1})
S-1	68.6 ± 8.3	61.9 ± 7.4	561.2 ± 43.5	4.6 ± 0.7	646.93	114.67
S-2	67.3 ± 7.4	54.8 ± 6.2	1119.9 ± 48.9	5.5 ± 0.8	788.67	137.40
S-3	89.0 ± 10.6	46.9 ± 5.6	595.9 ± 46.0	5.3 ± 0.8	658.16	116.85
S-4	79.9 ± 8.7	49.0 ± 5.4	526.4 ± 53.3	7.3 ± 0.9	617.00	110.12
S-5	56.4 ± 6.8	32.7 ± 3.8	572.8 ± 56.4	8.2 ± 0.9	490.82	87.20
S-6	115.1 ± 13.7	93.9 ± 10.7	585.0 ± 64.6	13.4 ± 1.2	931.85	167.77
S-7	118.7 ± 14.2	56.0 ± 6.7	466.5 ± 41.9	4.4 ± 0.7	747.34	133.62
S-8	93.1 ± 10.2	61.0 ± 8.0	541.9 ± 46.7	6.3 ± 0.8	712.82	127.15
S-9	75.7 ± 9.1	59.4 ± 6.5	413.2 ± 45.8	5.7 ± 0.8	611.95	109.44
S-10	93.5 ± 11.1	51.0 ± 5.6	455.2 ± 50.4	6.1 ± 0.8	645.03	115.41
S-11	112.5 ± 13.5	91.1 ± 10.4	662.4 ± 59.5	5.8 ± 0.8	936.42	166.71
S-12	85.7 ± 9.4	45.2 ± 5.8	492.0 ± 54.4	8.7 ± 0.9	608.24	109.05
S-13	55.8 ± 6.4	33.0 ± 4.2	468.8 ± 54.3	9.1 ± 0.9	457.57	81.94
S-14	110.3 ± 12.7	71.5 ± 7.7	559.8 ± 55.8	5.2 ± 0.7	815.47	145.42
S-15	63.9 ± 7.1	42.3 ± 4.3	1235.8 ± 51.0	6.9 ± 0.8	762.31	132.32
S-16	81.4 ± 9.6	56.6 ± 6.5	410.3 ± 38.6	6.2 ± 0.8	616.95	110.50
S-17	147.6 ± 17.2	63.4 ± 7.5	419.5 ± 34.8	5.9 ± 0.8	852.82	153.34
S-18	86.8 ± 10.3	48.0 ± 8.2	1368.6 ± 55.0	5.8 ± 0.8	898.59	156.09
S-19	83.7 ± 9.2	56.6 ± 6.1	402.1 ± 39.0	4.3 ± 0.7	621.48	111.01
S-20	62.5 ± 6.8	71.9 ± 7.8	425.6 ± 37.2	12.5 ± 1.1	627.31	113.29
S-21	80.7 ± 9.2	75.0 ± 8.3	485.5 ± 39.6	6.8 ± 0.8	715.31	127.85
S-22	127.9 ± 14.6	79.4 ± 8.8	409.0 ± 39.2	4.7 ± 0.7	855.53	153.45
S-23	98.5 ± 11.2	64.8 ± 6.9	407.6 ± 35.6	5.4 ± 0.8	703.22	126.00
S-24	76.4 ± 8.4	46.8 ± 5.2	470.8 ± 56.4	6.0 ± 0.7	579.53	103.40
S-25	67.7 ± 7.3	42.1 ± 4.5	903.1 ± 108.2	6.0 ± 0.7	668.74	117.11
S-26	52.9 ± 5.7	44.9 ± 5.3	423.1 ± 46.4	7.3 ± 0.9	484.00	86.53
S-27	85.7 ± 8.7	42.4 ± 5.1	369.8 ± 40.6	6.2 ± 0.8	558.16	100.22
S-28	61.9 ± 7.1	47.9 ± 5.2	467.1 ± 51.2	5.4 ± 0.7	538.16	95.74
S-29	83.2 ± 9.0	42.8 ± 5.0	464.7 ± 51.0	15.9 ± 1.3	581.91	105.83
S-30	74.1 ± 7.5	34.6 ± 3.7	1468.6 ± 176.1	6.5 ± 0.8	834.74	144.15
S-31	121.5 ± 14.3	63.0 ± 7.4	601.9 ± 66.0	5.3 ± 0.7	827.77	147.55
S-32	61.5 ± 6.1	42.4 ± 4.6	582.6 ± 64.1	6.0 ± 0.8	550.20	97.42
S-33	84.2 ± 4.2	18.1 ± 1.5	957.4 ± 48.5	8.2 ± 0.4	636.46	111.64
S-34	49.7 ± 3.0	60.5 ± 4.2	103.5 ± 77.6	12.0 ± 0.8	438.96	80.95
S-35	101.0 ± 6.2	51.2 ± 5.0	550.2 ± 38.5	6.2 ± 0.5	698.87	124.67
S-36	57.5 ± 4.9	37.5 ± 2.1	318.5 ± 27.0	10.7 ± 0.3	434.43	78.88
S-37	64.3 ± 5.0	46.3 ± 3.5	709.8 ± 56.8	5.2 ± 0.1	615.10	108.28
Average	83.7 ± 9.0	53.6 ± 5.9	593.9 ± 54.0	7.1 ± 0.8	669.43	119.16
SD	23.25	15.90	291.53	2.67	136.48	23.81
Min	49.7 ± 3	18.1 ± 1.5	103.5 ± 27	4.3 ± 0.1	434.43	78.88
Max	147.6 ± 17.2	93.9 ± 10.7	1468.6 ± 176.1	15.9 ± 1.3	936.42	167.77
Kurtosis	0.26	0.71	2.61	0.53	–	–
Skewness	0.79	0.55	1.67	0.71	–	–

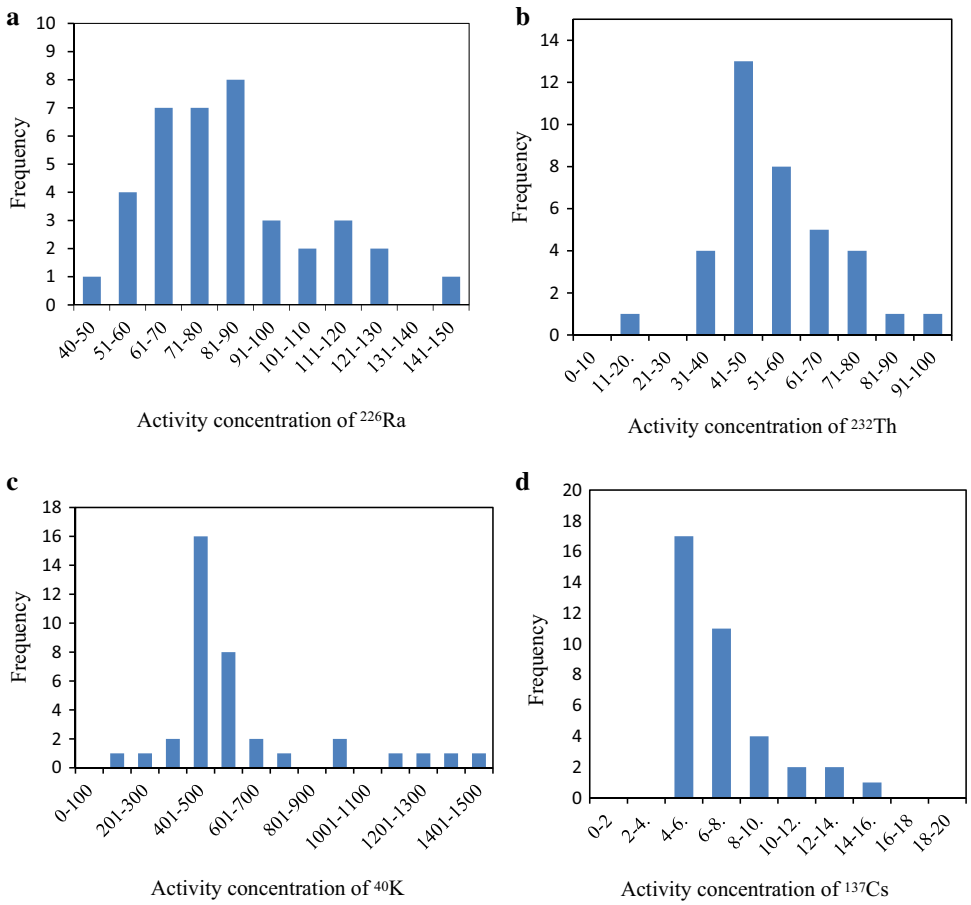

Fig. 2 Frequently distribution of the radioactivity concentration of **a** ^{226}Ra, **b** ^{232}Th, **c** ^{40}K and ^{137}Cs **d** in study area soil samples

Hazard indices

The annual gonadal equivalent dose (AGED) and ambient dose equivalent rate, $H^*(10)$ for each sample were calculated and reported in Table 1. The obtained average values for studied samples are 669.43 µSv year^{-1}, 119.16 nSv h^{-1} for AGED and $H^*(10)$, respectively.

The average value of AGED parameter was obtained twice higher than the world average of 300 µSv year^{-1} [1]. These values reported between 132.62 to 466.99 µSv year^{-1} in liagunmodi, Nigeria [23].

The measured values of ^{226}Ra, ^{232}Th and ^{40}K activity concentration have been compared with the other studies in some countries' values and shown in Table 2.

Statistics analysis

Concerning statistical analysis, the skewness parameter of activity concentrations demonstrates that deviation from mean value will be positive or negative. While this statistical parameter is a symmetry requirement for the mean value [13]. In this study, the skewness of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs activity concentration in surface soil samples is positive, which reveals their distribution is asymmetric.

The kurtosis parameter in statistical analysis is a measure of peakedness. Regarding the concept of peakedness, it is named as mesokurtic, leptokurtic and platykurtic state. When the value of kurtosis equal zero, it indicates a normal curve (mesokurtic). If the kurtosis value is positive, the curve is more peaked than the normal curve (leptokurtic), whereas the negative value of kurtosis indicates less peaked than the normal curve (platykurtic) [24]. According to the finding of the present study, the kurtosis values of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs activity concentration in soil are positive, and it indicates that the curve is more peaked than the normal curve.

Spearman correlation coefficients among variables are shown in Table 3. A strong positive correlation was observed between the activity concentration of ^{226}Ra in soil with $H^*(10)$ ($\rho = 0.740$) and AGED ($\rho = 0.720$) due to Uranium-series radionuclides. Whereas, the ^{232}Th series correlates with less than ^{238}U series. According to the Spearman correlation, analyzes ^{40}K has the lowest correlation in hazard indices compared to ^{226}Ra and ^{232}Th series in Table 2 and the cluster analysis of variables presented in Fig. 4.

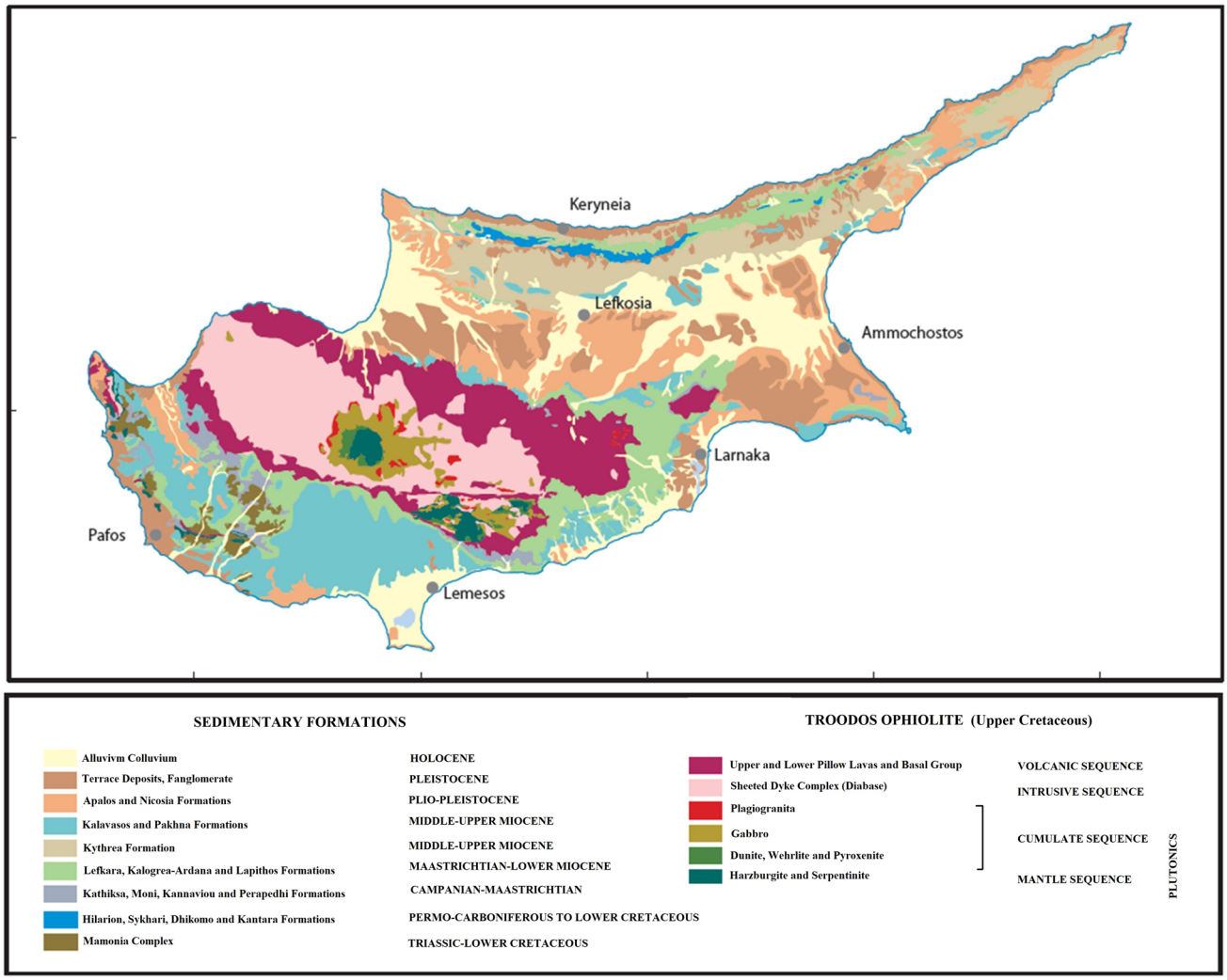

Fig. 3 Geological map of Cyprus and basin formations (Source: Cyprus Geological Survey Department Offices; http://www.moa.gov.cy)

Table 2 Comparison of mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in surface soil samples reported for different region and countries

Region	Activity concentration (Bq kg^{-1})			References
	^{226}Ra	^{232}Th	^{40}K	
Lambapur, India	48.07	230.77	807.08	[11]
Balkan National Park, Bulgaria	47.8	37.7	597.3	[25]
Eastern province, Saudi Arabia	16.73	10.40	419.78	[7]
Gümüşhane, Turkey	40.8	33.5	638.5	[8]
Southern Coast of the Caspian Sea, Iran	61	49	537	[26]
Osmaniye Province, Turkey	10.4	12.2	243.4	[27]
South area, Cyprus	13.2	9.3	146.9	[28]
Patras, Greece	28	30	483	[29]
Armenia	46.0	30.0	360.0	[1]
Buenos Aires, Argentina	60–92	37–46	540–750	[30]
Kocaeli, Turkey	11–49	11–65	161–964	[31]
Rize, Turkey	17.3	8.2	465.8	[32]
Alkharje, Sudi Arabia	2.8–18.8	5.3–16.4	211.3–378.9	[33]
North area, Cyprus	83.7	53.6	593.9	Present study
Worldwide mean	35	30	400	[1]

Table 3 Correlations of ^{226}Ra, ^{232}Th and ^{40}K activity concentration in the risk parameters (Spearman's Correlation coefficients)

Parameters	^{226}Ra	^{232}Th	^{40}K	AGED	H*(10)
^{226}Ra	1.000				
^{232}Th	0.548	1.000			
^{40}K	0.024	−0.229	1.000		
AGED	0.720	0.551	0.467	1.000	
H*(10)	0.740	0.577	0.436	0.997	1.000

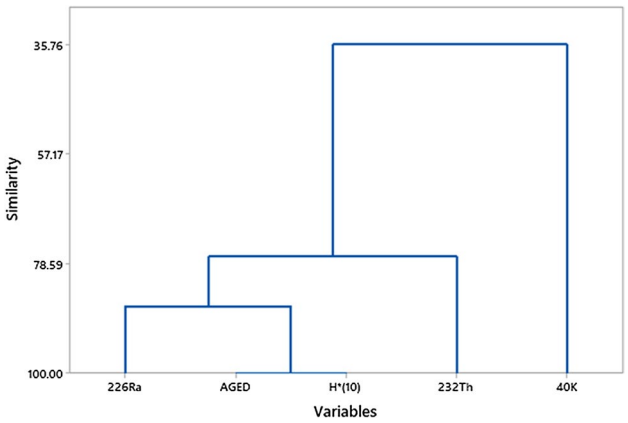

Fig. 4 Cluster analysis of variables of ^{226}Ra, ^{232}Th and ^{40}K activity concentration vis. AGED and *H**(10) hazard indices

Conclusions

The concentration of terrestrial (^{226}Ra, ^{232}Th and ^{40}K) and man-made (^{137}Cs) radionuclides in the surface soil samples from the North area of Cyprus were measured using a high-resolution HPGe gamma-spectrometry system. The obtained results for average values of ^{226}Ra, ^{232}Th and ^{40}K were higher than the world average reported by UNSCEAR 2000. The measurement of the man-made radionuclide of ^{137}Cs indicates that this radionuclide is existing in soil samples due to nuclear weapons testing and the Chernobyl reactor accident. The average value of AGED was found higher than the world limit. The ambient dose equivalent rate, *H**(10) were obtained for all the soil samples analyzed. The mean values of the *H**(10) fall within the worldwide average range. In conclusion, the soil of the studied area can be used as a construction material without any radiological hazards except AGED index to the residents. The unusual AGED index should be more investigated in the future.

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