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ORIGINAL ARTICLE

Natural and fallout radioactivity levels and radiation hazard evaluation in soil samples

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Abstract The present study aims to obtain the baseline data on natural and fallout radioactivity and to evaluate radiation hazards caused by ionizing radiation emitted from ^{226}Ra, ^{232}Th, ^{222}Rn, ^{40}K and ^{137}Cs in surface soil samples collected from Mersin province and Akkuyu nuclear power plant region. The activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were measured using a gamma spectrometer with HPGe detector. The activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs varied from 14.1 ± 0.7 to 65.4 ± 2.9, 12.0 ± 0.8–51.7 ± 2.1, 172.2 ± 15.8–511.1 ± 37.8 and <MDA to 86.2 ± 1.4 Bq kg^{-1}, respectively. The average concentrations of radon in soil and air were estimated as 23.9 kBq m^{-3} and 76 Bq m^{-3}. The radiological parameters such as absorbed gamma dose rate in outdoor air (DR_{out}), annual effective dose rate from external exposure (E_{Ext}), annual effective dose rate from inhalation of radon (E_{Inh}) and lifetime cancer risk (LTCR) were calculated to evaluate radiological hazards. The average values of DR_{out}, E_{Ext}, E_{Inh} and LTCR were found to be 51 nGy h^{-1}, 62 µSv year^{-1}, 715 µSv year^{-1} and 2.2 × 10^{-4}, respectively.

Keywords Soil · Natural radioactivity · Fallout radioactivity · Radon · Gamma dose rate · Annual effective dose rate · Lifetime cancer risk

Introduction

The inevitable ionizing radiation exposure to human being mainly stems from natural and anthropogenic radioactive sources. Natural radiation exposure is caused by cosmogenic and terrestrial radionuclides. Terrestrial radionuclides contain the radioactive series of uranium–radium (^{238}U–^{226}Ra), thorium (^{232}Th) and radioactive potassium (^{40}K) in the earth's crust. The average annual dose to human being is 2.8 mSv of which over 85 % is from natural radiation sources with about half coming from radon (^{222}Rn) decay products (UNSCEAR 2008). Soil is the most important source of the terrestrial radionuclides whose activity concentrations depend primarily on the geological and geochemical conditions of each region in the world (UNSCEAR 2008). Major anthropogenic radionuclide sources which contribute to the radionuclide contamination of the environment contain nuclear weapon tests, nuclear power plants, commercial fuel reprocessing and geological repository of high level nuclear wastes. The majority of the global fallout radionuclides resulted from atmospheric nuclear weapon tests conducted from 1945 to 1963 and nuclear accidents. Among different fallout radionuclides, ^{137}Cs (half-life 30.1 years) is the most prominent isotope detected by its gamma energy (661.8 keV) on the earth's surface. During the Chernobyl nuclear accident in 1986 about 3.8 × 10^{16} Bq of ^{137}Cs was released to the atmosphere and carried across the international boundaries (Mohapatra et al. 2015; UNSCEAR 1988). Also the nuclear accident in Fukusima plays a major role in fallout release

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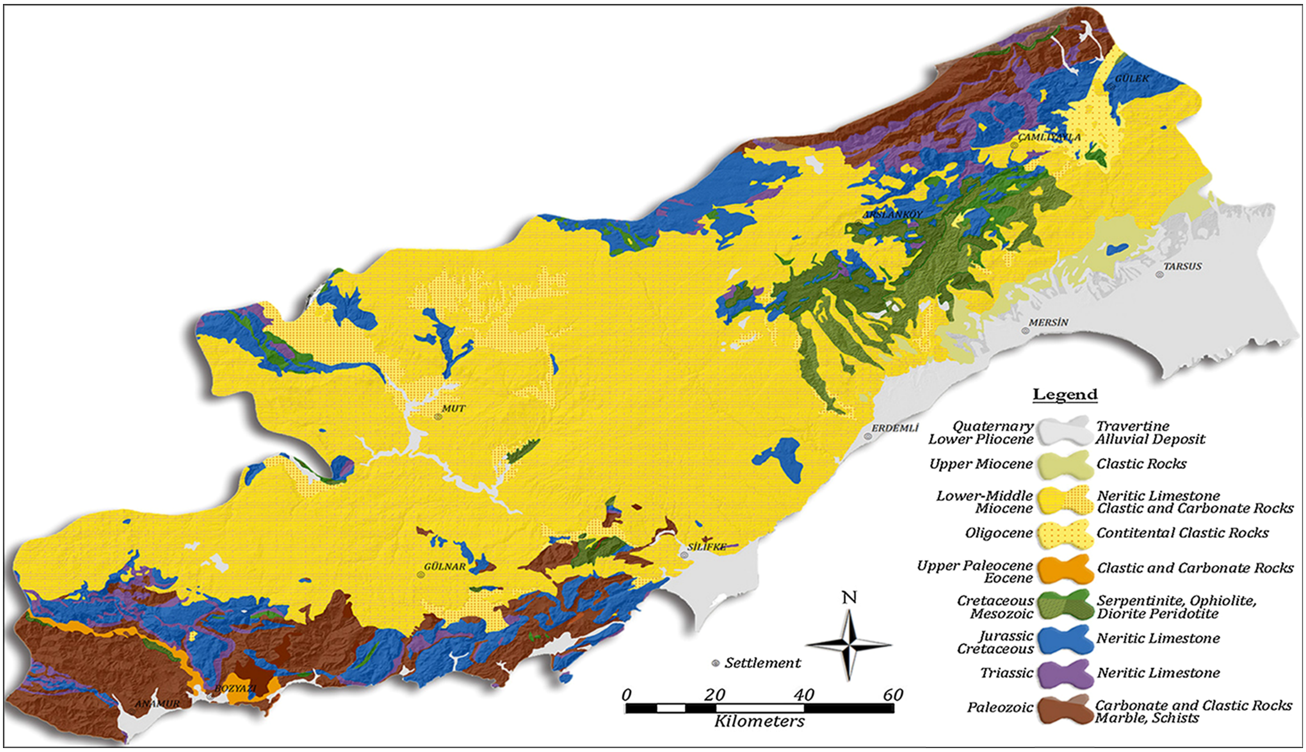

Fig. 1 Geological map of Mersin province (Duran 2014)

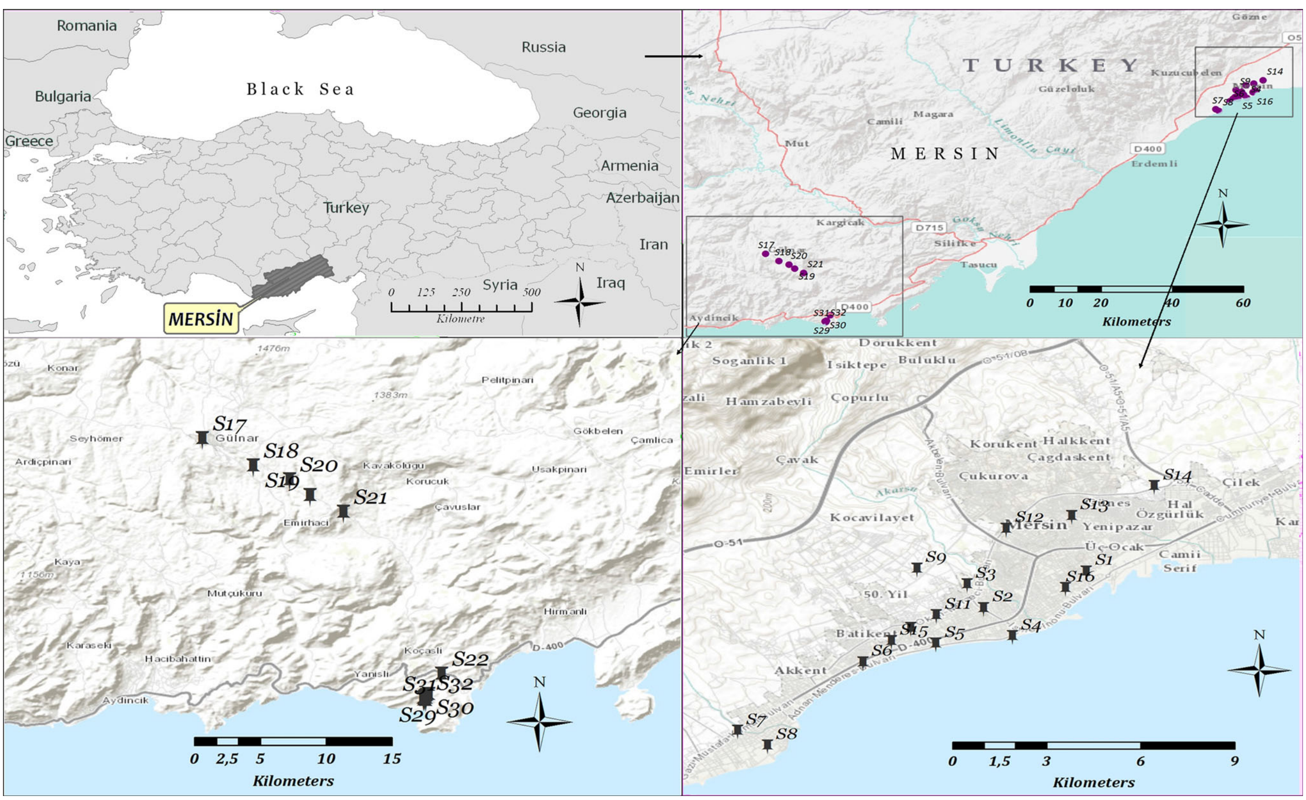

Fig. 2 Location of sampling in Mersin province and Akkuyu NPP region

Table 1 Positions of the soil samples locations in Mersin and Akkuyu NPP region

Sample code	Location	Position	
		Latitude (N)	Longitude (E)
S1	Mediterranean Municipal	36°48′10.72″	34°37′51.31″
S2	İsmet İnonu Boulevard	36°47′26.61″	34°36’5.45″
S3	Limonluk Quarter	36°47′55.09″	34°35′48.33″
S4	Palmiye Quarter	36°46′52.54″	34°36′35.13″
S5	Dumlupınar Quarter	36°46′43.48″	34°35′16.26″
S6	Eğriçam Quarter	36°46′20.71″	34°34′0.80″
S7	Mezitli Municipal	36°44′58.04″	34°31′51.24″
S8	Viranşehir Quarter	36°44′40.07″	34°32′22.07″
S9	Yenişehir Municipal	36°48′14.23″	34°34′56.55″
S10	Barbaros Quarter	36°47′2.47″	34°34′49.94″
S11	Güvenevler Quarter	36°47′17.88″	34°35′16.64″
S12	Zekiayan Quarter	36°49′2.52″	34°36′28.83″
S13	Selçuklar Quarter	36°49′17.97″	34°37′36.36″
S14	Güneş Quarter	36°49′54.08″	34°39′1.74″
S15	Tırtıl Sanayi	36°46′46.40″	34°34′30.31″
S16	Yenitaşkent Municipal	36°47′50.62″	34°37′29.96″
S17	Gülnar	36°20′25.84″	33°23′33.05″
S18	Sırsavul	36°19′14.29″	33°25′37.86″
S19	Delikkaya	36°17′55.80″	33°27′58.07″
S20	Kayabaşı	36°18′37.09″	33°27′7.47″
S21	Suyun Gözü	36°17′11.27″	33°29′19.64″
S22	Büyükeceli	36°10′2.04″	33°33′21.53″
S23	100 m from Akkuyu NPP	36°8′53.96″	33°32′37.40″
S24	200 m from Akkuyu NPP	36°8′57.16″	33°32′37.95″
S25	300 m from Akkuyu NPP	36°8′59.08″	33°32′36.49″
S26	400 m from Akkuyu NPP	36°9′1.18″	33°32′39.85″
S27	500 m from Akkuyu NPP	36°9′3.39″	33°32′41.91″
S28	600 m from Akkuyu NPP	36°9′5.52″	33°32′44.79″
S29	700 m from Akkuyu NPP	36°9′8.03″	33°32′49.12″
S30	800 m from Akkuyu NPP	36°8′52.99″	33°32′42.29″
S31	900 m from Akkuyu NPP	36°8′56.53″	33°32′40.22″
S32	1000 m from Akkuyu NPP	36°8′59.11″	33°32′43.45″

of ^{137}Cs. Gamma radiation emitted from terrestrial and fallout radionuclides is the main external exposure to human beings. Hence determination of the terrestrial and fallout radioactivity levels in various environmental samples such as soil, plants, foods, rocks, etc. is very important for evaluation of public exposure, storage reference data records on radionuclides for producing a radiation map of the country and ascertaining possible changes in environmental radioactivity due to anthropogenic activities (Turhan et al. 2012).

Soil which contains the major sources of natural radionuclides (^{238}U, ^{232}Th, ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{40}K etc.) and fallout radionuclides (^{137,134}Cs, ^{89,90}Sr, ^{3}H, etc.) is a direct radiation source in the environment (Cho et al. 2014; Lee et al. 1995). Hence, it is critically important to assess the amount of radioactivity in the soil because of its major influence on the terrestrial ecosystem and humans (Cho et al. 2014). Moreover, the baseline concentration is needed when examining incidents in nuclear power plant facilities to determine the characteristics and behavior of the radiation environment, and to conduct research on the geological features and soil (Jun et al. 1990; Velasco et al. 2012; Cho et al. 2014). Recently, many studies related to measurement of the activity concentrations of the terrestrial and fallout radionuclides were published in the literature (Srilatha et al. 2015; Santawamaitre et al. 2014; Sivakumar 2014; Dusane et al. 2014; Aközcan 2014; Miller and Voutchkov 2014; Ajmal et al. 2014; Rajeshwari et al. 2014; Kunovska et al. 2013; Manohar et al. 2013; Dhawal et al. 2013; Khan et al. 2012). However, there are few studies related to the activity concentrations of terrestrial and fallout radionuclides in environmental samples collected from Mersin province in literature (Özmen et al. 2014; Kurt and Berker 2014).

Mersin province is near the Mediterranean Sea in southern of Turkey. It is located at the Çukurova region and situated between 32 56′–35 11′E and 37 26′–36 01′N (Fig. 1). Mersin has a population of 1,727,255 as of 2014 and occupies 15,853 km^2. Mersin is one of Turkey's most important cities with its economy determined by agriculture, trade, tourism and industry. Akkuyu nuclear power plant (NPP) having 4 × 1200 MW VVER units to be the first nuclear power plant in Turkey will be built in Büyükeceli which is one of the districts of Mersin (Özmen et al. 2014). The aim of the study is to determine the activity concentrations of ^{226}Ra, ^{232}Th, ^{222}Rn, ^{40}K and ^{137}Cs in soil samples collected from Mersin and Akkuyu nuclear power plant (NPP) region. The measurements of the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were performed by high-resolution gamma-ray spectrometer with a hyper pure germanium (HPGe) detector. An evaluation of the radiation hazards for human beings due to the natural and fallout radioactivity arising from soil samples was determined in terms of the absorbed gamma dose rate in outdoor air (DR_{out}), annual effective dose rate from external exposure (E_{Ext}), annual effective dose rate from inhalation of radon (E_{Inh}) and lifetime cancer risk (LTCR).

Materials and methods

Sample processing and activity measurements

Surface soil (0–5 cm) samples were collected randomly from 32 undisturbed sites in Mersin province and around Akkuyu NPP region (Fig. 2). The surface soil samples were properly coded according to the location of the sampling site (Table 1). The soil samples were dried in a temperature-controlled furnace at 105 °C for 24 h to remove moisture. After homogenization, samples were sieved, placed in plastic containers, weighed and hermetically sealed. Before starting the gamma spectrometric measurements, the sealed samples were stored for 4 weeks to reach radioactive equilibrium of the ^{226}Ra, ^{232}Th and their decay products.

Activity measurements were performed by a high-resolution gamma-ray spectrometer at the Gülten Günel Nuclear Physics Research laboratory in Physics Department of Çukurova University. The gamma-ray spectrometer is equipped with a coaxial p-type HPGe detector (GX5020) with a relative efficiency of 50 %. The HPGe detector's energy resolution is 2.0 keV at 1332.5 keV. For gamma-ray shielding, a front opening split-top shield was used to reduce the background. The detector was interfaced to the digital spectrum analyzer (DSA-1000), which was a full-featured 16K channel multichannel analyzer on advanced digital signal processing (DSP) techniques. DSA-1000 operates through Genie-2000 gamma spectroscopy software including peak searching, peak evaluation, energy/efficiency calculation mode, nuclide identification (Uğur et al. 2013). Each soil sample was placed on the top of the detector and counted for 24 h. Background measurements were taken under the same conditions of sample

Table 2 The activity concentrations of terrestrial and fallout radionuclides in the soil samples

Sample no.	Activity concentration (Bq kg^{-1})			
	^{226}Ra	^{232}Th	^{40}K	^{137}Cs
S1	14.1 ± 0.7	13.7 ± 0.6	255.0 ± 14.2	<MDA
S2	14.8 ± 1.2	12.0 ± 0.8	365.9 ± 16.8	21.8 ± 1.1
S3	19.9 ± 1.1	24.8 ± 1.2	352.9 ± 15.8	4.6 ± 0.6
S4	23.6 ± 1.0	32.2 ± 1.0	424.0 ± 15.6	3.2 ± 0.4
S5	16.7 ± 0.9	24.7 ± 1.3	326.0 ± 14.7	2.3 ± 0.4
S6	19.3 ± 1.4	29.2 ± 1.5	388.4 ± 17.8	5.4 ± 0.7
S7	22.8 ± 0.7	41.3 ± 1.2	368.5 ± 14.8	5.1 ± 0.3
S8	23.2 ± 1.4	28.5 ± 1.6	438.2 ± 18.3	<MDA
S9	21.1 ± 0.8	38.1 ± 1.3	370.7 ± 15.1	5.0 ± 0.4
S10	21.4 ± 1.3	36.3 ± 1.0	367.2 ± 16.9	10.4 ± 1.2
S11	20.9 ± 0.8	41.0 ± 1.4	383.2 ± 15.5	<MDA
S12	17.4 ± 0.9	24.1 ± 1.9	284.9 ± 15.3	4.5 ± 0.6
S13	26.7 ± 0.9	41.9 ± 1.4	437.1 ± 15.5	5.6 ± 0.3
S14	14.8 ± 1.2	13.8 ± 1.7	370.6 ± 16.6	<MDA
S15	22.1 ± 0.8	38.6 ± 1.2	425.5 ± 15.1	<MDA
S16	21.0 ± 1.5	34.8 ± 1.9	382.5 ± 17.4	7.4 ± 0.8
S17	65.4 ± 2.9	50.0 ± 1.1	490.7 ± 45.3	3.1 ± 0.2
S18	40.7 ± 2.0	36.5 ± 2.1	342.7 ± 27.6	10.6 ± 1.0
S19	41.6 ± 1.6	51.7 ± 2.1	412.6 ± 41.1	7.7 ± 1.8
S20	36.0 ± 1.7	40.4 ± 1.9	356.8 ± 27.1	19.1 ± 1.5
S21	22.4 ± 0.9	40.3 ± 1.3	371.1 ± 26.3	19.0 ± 1.0
S22	25.3 ± 1.1	31.6 ± 1.4	172.2 ± 15.8	<MDA
S23	39.0 ± 1.9	27.1 ± 1.1	184.0 ± 31.2	28.5 ± 0.9
S24	36.4 ± 1.3	38.2 ± 1.9	385.4 ± 40.2	49.3 ± 1.4
S25	22.0 ± 1.4	41.0 ± 1.6	431.7 ± 33.6	49.8 ± 1.0
S26	32.5 ± 1.5	35.0 ± 1.0	495.2 ± 36.5	7.5 ± 0.3
S27	27.9 ± 1.1	34.1 ± 1.8	511.1 ± 37.8	18.7 ± 1.2
S28	25.5 ± 1.6	35.3 ± 1.1	391.9 ± 32.0	12.7 ± 1.1
S29	36.2 ± 1.4	36.5 ± 1.7	365.9 ± 36.9	86.2 ± 1.4
S30	40.5 ± 1.5	45.4 ± 1.5	232.5 ± 31.9	27.2 ± 1.9
S31	24.9 ± 1.7	36.3 ± 1.3	386.1 ± 32.0	57.0 ± 1.7
S32	30.4 ± 1.3	44.8 ± 1.3	384.8 ± 35.5	11.2 ± 0.8
Min	14.1	12.0	172.2	<MDA
Max	65.4	51.7	511.1	86.2
Average	27.1	34.3	370.5	18.6
SD	10.7	9.6	78.1	20.6
SE	1.9	1.7	13.8	3.6

measurements and subtracted in order to get net counts for the sample. The HPGe detector was calibrated for energy and efficiency using reference materials RGU-1 (U-ore), RGTh-1 (Th-ore) and RGK-1 (K_2SO_4) supplies by International Atomic Energy Authority (IAEA). The activity concentration of ^{226}Ra was derived from the average of the activities of the gamma-ray line of 609.3 keV from ^{214}Bi and 351.9 keV from ^{214}Pb, while the gamma-ray lines of 911.2 keV from ^{228}Ac and 583.2 keV from ^{208}Tl were used to determine the activity concentration of ^{232}Th. The activity concentrations of ^{40}K and ^{137}Cs were measured from 1460.8 and 661.6 keV direct gamma-ray lines, respectively.

The combined standard uncertainty of the activity concentration is calculated by the next formula:

$$\Delta A = A \times \sqrt{\left(\frac{\Delta C_R}{C_R}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \quad (1)$$

where A and ΔA is the activity concentration and its uncertainty; C_R and ΔC_R is the count rate and its uncertainty; I and ΔI is the gamma emission probability and its uncertainty, ε and $\Delta\varepsilon$ is the absolute efficiency of the detector and its uncertainty; M and ΔM is the mass and its uncertainty.

The minimum detectable activity (MDA) of the gamma-ray measurement system at 95 % confidence level was calculated using the following formula:

$$\text{MDA} = \frac{4.66 \times \sqrt{B}}{\varepsilon \times I \times T \times M} \quad (2)$$

where B is the background counts, ε is the absolute efficiency of the detector, I is the gamma emission probability and T is the counting time (s) and M is the mass of the sample (kg). The average value of the MDA for ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs was found as 0.3, 0.4, 5.4 and 1.8 Bq kg^{-1}, respectively.

Results and discussion

Radioactivity measurement

Thirty-two surface soil samples collected from the study area were analyzed for terrestrial and fallout radionuclides using the gamma-ray spectrometer with the HPGe detector. The activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs measured in the soil samples are given in Table 2. The average concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were measured as 27.1 ± 1.9 Bq kg^{-1} (range 14.1 ± 0.7–65.4 ± 2.9 Bq kg^{-1}), 34.3 ± 1.7 Bq kg^{-1} (range 12.0 ± 0.8–51.7 ± 2.1 Bq kg^{-1}), 370.5 ± 13.8 Bq kg^{-1} (range 172.2 ± 15.8–511.1 ± 37.8 Bq kg^{-1}) and 18.6 ± 3.6 Bq kg^{-1} (range <MDA to 86.2 ± 1.4 Bq kg^{-1}), respectively. The highest value of ^{226}Ra, ^{232}Th and ^{40}K was observed at the location of Gülnar (S17), Delikkaya (S19) and Akkuyu (S27), while the lowest value of ^{226}Ra, ^{232}Th and ^{40}K was found at the location of Mediterranean Municipal (S1), Ismet Inonu Boulevard (S2) and Kayabaşı (S22), respectively. The world average value of ^{226}Ra, ^{232}Th and ^{40}K is 33, 45 and 420 Bq kg^{-1}, respectively (UNSCEAR 2008). The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K measured in the soil samples are lower than the world average values because the significant part of the province

Table 3 Comparison of the activity of ^{226}Ra, ^{232}Th and ^{40}K in soil samples with those reported for different regions of Turkey and other countries

Country	Activity concentration (Bq kg^{-1})			References
	^{226}Ra	^{232}Th	^{40}K	
Algeria	50	25	370	UNSCEAR (2008)
Armenia	51	30	360	UNSCEAR (2008)
Azerbaijan	25	33	120	UNSCEAR (2008)
Bulgaria	45	30	400	UNSCEAR (2008)
Greece	29	28	383	UNSCEAR (2008)
Croatia	43	37	423	UNSCEAR (2008)
Egypt	17	18	320	UNSCEAR (2008)
India	29	64	400	UNSCEAR (2008)
Iran	30	39	640	UNSCEAR (2008)
Turkey (Kastamonu)	37	27	431	Kam and Bozkurt (2007)
Turkey (Kırklareli)	37	40	667	Taşkın et al. (2009)
Turkey (Sanliurfa)	21	25	299	Bozkurt et al. (2007)
Turkey (Osmaniye)	10	12	243	Uğur et al. (2013)
Turkey (Kilis)	16	15	206	Canbazoğlu et al. (2013)
Turkey (Yalova)	22	27	419	Kapdan et al. (2011)
Turkey (Mersin)	27	34	371	Present study

is formed by the limestone related to the geological process (Duran 2014). It is known that the activity concentration levels of terrestrial radionuclides are related to the types of rock from which the soils originate (UNSCEAR 2000). In general, basalts and most limestones have relatively low radium contents (UNSCEAR 2000). The measured average activity of ^{226}Ra, ^{232}Th and ^{40}K were compared with the values reported in different parts of Turkey and other countries as shown in Table 3. As seen in Table 3, the natural radionuclide concentrations were comparable with the other reported values. It can be seen from Table 2 that the activity concentrations of ^{137}Cs were below the lower the MDA measured for six soil samples (S1, S8, S11, S14, S15 and S22). The activity concentrations of ^{137}Cs varied from MDA (<1.8 Bq kg^{-1}) to 86.2 ± 1.4 Bq kg^{-1} with an average of 18.6 ± 3.6 Bq kg^{-1}. The highest value of ^{137}Cs was observed at location of Akkuyu (S29).

Estimation of radon concentration in soil and air

The concentration of radon in soil gas (A_{Rnsoil} in Bq m^{-3}) in the absence of radon transport is as follows (UNSCEAR 2000):

$$A_{\mathrm{Rnsoil}} = \frac{A_{\mathrm{Ra}} \times f \times \rho \times (1-\varepsilon)}{\varepsilon} \tag{3}$$

where A_{Ra} is the activity concentration of ^{226}Ra measured for the soil samples, f is the emanation factor (0.21), ρ is the density of soil (1800 kg m^{-3}) and ε is the total porosity (0.3).

The concentration of radon in the air (A_{Rnair} in Bq m^{-3}) was estimated by the below equation:

$$A_{\mathrm{Rnair}} = A_{\mathrm{Rnsoil}} \sqrt{\frac{d_{\mathrm{Soil}}}{D_{\mathrm{Air}}}} \tag{4}$$

where A_{Rnsoil} is the concentration of ^{222}Rn in the soil given in Eq. (3), d_{Soil} is the diffusion rate constant of ^{222}Rn in the soil (0.5 × 10^{-4} m^2 s^{-1}) and D_{Air} is the diffusion rate constant of ^{222}Rn in the air (5 m^2 s^{-1}). The activity concentrations of ^{222}Rn estimated for the soil samples and air are given in Table 4. The values of A_{Rnsoil} and A_{Rnair} varied from 12.4 to 57.7 kBq m^{-3} with an average of 23.9 kBq m^{-3} and 39–182 Bq m^{-3} with an average of 76 Bq m^{-3}, respectively. Results show that 75 % of the A_{Rnair} values are lower than the reference level of 100 Bq m^{-3} recommended by WHO (2009).

Table 4 The activity concentrations of ^{222}Rn estimated for soil samples and air

Sample no.	Radon concentration (Bq m^{-3})	
	Soil	Air
S1	12436	39
S2	13054	41
S3	17552	56
S4	20815	66
S5	14729	47
S6	17023	54
S7	20110	64
S8	20462	65
S9	18610	59
S10	18875	60
S11	18434	58
S12	15347	49
S13	23549	74
S14	13054	41
S15	19492	62
S16	18522	59
S17	57683	182
S18	35906	114
S19	36656	116
S20	31726	100
S21	19757	62
S22	22288	70
S23	34354	109
S24	32131	102
S25	19386	61
S26	28665	91
S27	24590	78
S28	22491	71
S29	31928	101
S30	35677	113
S31	21944	69
S32	26848	85
Min	12436	39
Max	57683	182
Average	23878	76
SD	9412	30
SE	1664	5

Evaluation of the radiation hazards

Absorbed gamma dose rate in outdoor air (DR_{out})

The external terrestrial gamma dose rate in outdoor air at 1 m height from the ground in each sampling locations was estimated using data and formulae provided by the UNSCEAR report (2008).

$$\mathrm{DR_{Out}}\left(\mathrm{nGy\ h^{-1}}\right) = 0.462 \times A_{\mathrm{Ra}} + 0.604 \times A_{\mathrm{Th}} + 0.0417 \times A_K + 0.1243 \times A_{\mathrm{Cs}} \tag{6}$$

where A_{Ra}, A_{Th}, A_K and A_{Cs} are the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in Bq kg^{-1}, respectively. The estimated values of $\mathrm{DR_{out}}$ are given in the second

Table 5 Outdoor absorbed gamma dose rate, annual effective dose rates and lifetime cancer risk

Sample no.	DR_{out} (nGy h^{-1})	Annual effective dose rate (μSv $year^{-1}$)		LTCR
		E_{Ext}	E_{Inh}	
S1	26	31	372	1.1E-04
S2	32	39	391	1.4E-04
S3	39	48	525	1.7E-04
S4	48	59	623	2.1E-04
S5	37	45	441	1.6E-04
S6	43	53	510	1.9E-04
S7	51	63	602	2.2E-04
S8	46	57	613	2.0E-04
S9	49	60	557	2.1E-04
S10	48	59	565	2.1E-04
S11	50	62	552	2.2E-04
S12	35	43	459	1.5E-04
S13	57	69	705	2.4E-04
S14	31	38	391	1.3E-04
S15	51	63	584	2.2E-04
S16	48	58	555	2.0E-04
S17	81	100	1727	3.5E-04
S18	56	69	1075	2.4E-04
S19	69	84	1097	2.9E-04
S20	58	71	950	2.5E-04
S21	53	64	591	2.3E-04
S22	38	47	667	1.6E-04
S23	46	56	1028	2.0E-04
S24	62	76	962	2.7E-04
S25	59	73	580	2.5E-04
S26	58	71	858	2.5E-04
S27	57	70	736	2.5E-04
S28	51	63	673	2.2E-04
S29	65	79	956	2.8E-04
S30	59	73	1068	2.5E-04
S31	57	69	657	2.4E-04
S32	59	72	804	2.5E-04
Min	26	31	372	1.1×10^{-4}
Max	81	100	1727	3.5×10^{-4}
Average	51	62	715	2.2×10^{-4}
SD	12	14	282	5.0×10^{-5}
SE	2	2	36	6.5×10^{-6}

column of Table 5. The values of DR_{out} varied from 26 to 81 nGy h^{-1} with an average of 51 nGy h^{-1}. The minimum and maximum value of DR_{out} was estimated for the samples of S1 (Mediterranean Municipal) and the sample of S17 (Gülnar), respectively. The average percentage contribution of the natural and fallout radionuclides to the outdoor absorbed gamma dose rate is shown in Fig. 3. The average value of DR_{out} is 14 % lower than the world average outdoor absorbed gamma dose rate of 59 nGy/h (UNSCEAR 2008).

Annual effective dose rates due to external exposure and inhalation of radon

The annual effective dose rate due to external exposure (E_{Ext}) was estimated from outdoor external gamma radiation dose rate (DR_{out}) taking into account the conversion factor for adults (0.7 Sv Gy^{-1}) and the outdoor occupancy (0.2) implying that 20 % of time is spent outdoors. The E_{Ext} was estimated using the following equation proposed by the UNSCEAR report (1982).

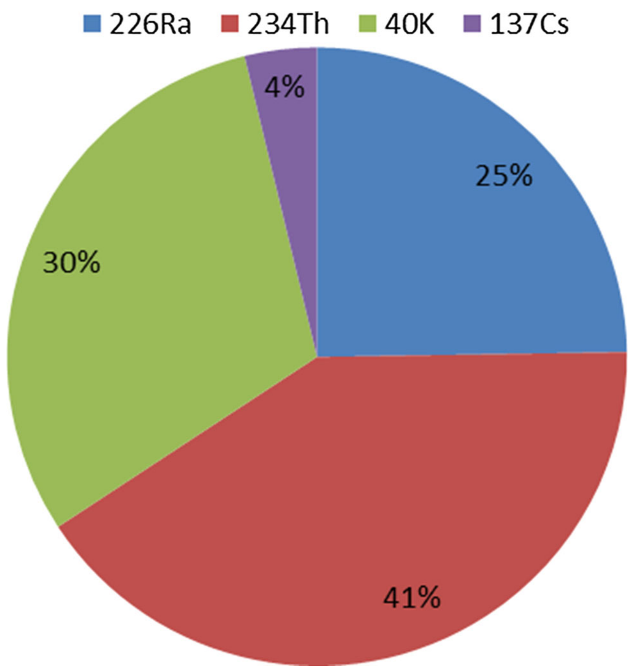

Fig. 3 Percentage contribution of natural and fallout radionuclides in the soil samples to the outdoor absorbed gamma dose rate

$$E_{Ext} = DR_{Out} \times 0.7 \times 8766 \times 0.2 \times 10^{-3} \quad (6)$$

where DR_{Out} is the outdoor gamma absorbed gamma dose rate given in Eq. (5).

Annual effective dose rates due to inhalation of radon (E_{Inh})

The annual effective dose rate (E_{Inh}) coming from inhalation of radon gas was estimated taking into account the equilibrium factor (0.6 for outdoors), the conversion factor for radon (9 nSv h^{-1} per Bq m^{-3}) and the outdoor occupancy (0.2) implying that 20 % of time is spent outdoors (UNSCEAR 2008).

$$E_{Inh} = A_{Rnair} \times 0.6 \times 9 \times 8766 \times 0.2 \times 10^{-3} \quad (7)$$

where A_{Rnair} is the concentration of ^{222}Rn in the air given in Eq. (4).

The estimated values of E_{Ext} and E_{Inh} are given in the third and fourth column of Table 5. The values of E_{Ext} varied from 31 to 100 µSv $year^{-1}$ with an average of 62 µSv $year^{-1}$ which is lower than the world average of 70 µSv $year^{-1}$ (UNSCEAR 2008). The values of E_{Inh} varied from 372 to 1727 µSv $year^{-1}$ with an average of 715 µSv $year^{-1}$ which is lower than the UNSCEAR (2008) recommended radon dose.

Lifetime cancer risk (LTCR)

The LTCR caused by the annual effective dose rate due to external exposure (E_{Ext}) was estimated using following equation (ICRP 1990):

$$LTCR = E_{Ext} \times AL \times RF \quad (8)$$

where E_{Ext} is the annual effective dose rate given in Eq. (6), AL is the average life time (70 years) and RF is the risk factor (0.05). The estimated values of LTCR are given in the fifth column of Table 5. The values of LTCR varied from 1.1×10^{-4} to 3.5×10^{-4} with an average of 2.2×10^{-4} which is less than the world average (2.9×10^{-4}).

Conclusions

The activity concentrations of natural and fallout radionuclides (^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs) in the soil samples collected from Mersin and Akkuyu NPP region were determined to evaluate the possible changes in environmental radioactivity caused by nuclear activities in the future. The activity concentrations of radon in soil gas and air were estimated using the activity concentrations of ^{226}Ra measured in the soil samples. The results of the activity measurements have shown that the average activity concentrations of natural radionuclides are lower than the world average values reported UNCEAR (2008) as the significant part of the province is formed by the limestone. As known, ^{137}Cs is released into the environment and can be transferred by some meteorological events such as wind to thousands of kilometers. In the study the average concentration of ^{137}Cs due to Chernobyl accident and around 500 atmospheric nuclear weapons tests conducted until 1980 was 18.6 Bq kg^{-1}. The highest value of ^{137}Cs was observed at the location of Akkuyu (S29).

The radiological hazard information of the average outdoor absorbed gamma dose rate, annual effective dose rate from external exposure, annual effective dose rate from inhalation of radon and lifetime cancer risk for each adult person living in the region was 51 nGy h^{-1}, 62 µSv $year^{-1}$, 715 µSv $year^{-1}$ and 2.2×10^{-4}, respectively. These values do not exceed the recommended values.

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