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ORIGINAL ARTICLE

Determination of radioactivity levels in Akhisar, Gördes, Gölmarmara and Sindirgi regions, Western Turkey

Sermin Çam Kaynar · Muslim Murat Saç · F. Serap Ereeş

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Abstract In this study, radioactivity measurements in the environment of Akhisar, Gölmarmara, Gördes and Sindirgi regions in Western Turkey were investigated in order to evaluate the implications of any excess radioactivity in the environment of geological formation. The radioactivity concentrations of ^{40}K, ^{238}U and ^{232}Th radionuclides in the soil samples were measured by a NaI(Tl) gamma spectrometer system, and the radium activity concentrations in the water samples were also analyzed by an ZnS(Ag) alpha counter by the collector chamber method. The radioactivity of ^{40}K, ^{238}U and ^{232}Th in soils ranged 2.80–2,347.77, 9.90–256.19 and 9.66–106.53 Bq kg^{-1}, respectively. The activity of ^{226}Ra in the water samples ranged from 0.03 Bq L^{-1} (0.89pCi/L) to 0.80 Bq L^{-1} (21.58pCi/L). In addition, the external terrestrial gamma dose rate in air (nGy h^{-1}), annual effective dose rate (mSv year^{-1}) and radium equivalent activity (Bq kg^{-1}) were calculated and compared with international standard values.

Keywords Effective dose · Radioactivity · Radium · Radon · Soil · Water

Introduction

The radioactivity in the environment depends mainly on the local geological and geographical conditions and is different in each region of the world (UNSCEAR 2000). There are three sources of environmental radioactivity: terrestrial, manmade and cosmic. The most significant terrestrial radionuclides include the uranium and thorium decay series, potassium-40 and rubidium-87 (EPA 2009). The terrestrial component is due to the radioactive nuclides that are present in air, soils, rocks, waters and building materials in amounts that vary significantly depending on the geological and geographical features of a region. The cosmic radiation from space contributes to the background changes chiefly through elevation and latitude (UNSCEAR 2000). Although background radiation is present everywhere, the component radionuclide concentrations and distributions are not constant (EPA 2009). Therefore, many studies on the background radiation level in Turkey and in the world have been carried out (Quindos Poncela et al. 2004; Bolca et al. 2007; Mora et al. 2007; Degerlier et al. 2008; Quindos et al. 2008; Jankovic et al. 2008; Taşkin et al. 2009; Al-Hamarneh and Awadallah 2009; Abd El-mageed et al. 2011).

This study aims to determine the environmental radioactivity level in Akhisar, Gördes, Gölmarmara and Sindirgi regions, Western Turkey. The following types of measurements are studied: (a) absorbed gamma dose rate in air, (b) natural radioactivity measurements in soil, and (c) radium measurements in drinking waters.

Materials and methods

Description of study region

Manisa city in Western Turkey has an area of approximately 13,830 km^2. The study area comprises Akhisar, Gördes, Gölmarmara, Köprübasi and Sindirgi districts.

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While Akhisar, Gördes, Gölmarmara and Köprübasi districts are located in the Manisa area, Sindirgi district is located in the Balikesir area; these districts are neighbors. Akhisar is 106 m above sea level (asl); Gördes is 680 m (asl); Gölmarmara is 83 m (asl); Köprübaşi and Sindirgi are 250 m (asl) (Yildirim 2008).

According to the MTA inventory of mining in the Aegean region, coal, kaolin, nickel–iron, titanium and zeolite beds are found in Gördes. In addition, feldspar, marble, chalcedony, kyanite, chrome, quartz and boron salts are mined in the region (www.gordes.bel.tr, 2013). Coal deposits are located between Akhisar and Gördes (Yağmurlu and Karayiğit 1984). One of the most important uranium deposits in Turkey is located in the town of Köprübaşi (Şaşmaz 2008). The largest kaolin field in Turkey is found in Sindirgi district. Perlite is also found there (MTA 2013). Formations of the marble are found in Demirci and Akhisar districts. The K-feldspar field in Demirci is one of the important potential fields in Turkey. Also, phosphate, sulfur, and zeolite ores are present in Demirci. Much of thermal spring water is found in Demirci and Köprübaşi (MTA 2013) (Fig. 1).

Geologic structure

In the Aegean region, various metamorphic rocks such as epimetamorphic greywacke, migmatites, mica schists, quartzites, gneiss and augen gneisses are commonly found. These metamorphic basement rocks are the rock component of the Menderes massif (Özel et al. 2006).

In the geological map of Turkey, scale 1:500,000, it is seen that the ophiolitic rocks and the structures of diorite, gabbro, and diabase are found along the Akhisar-Sindirgi route; the structures of andesite-spilite are found in Sindirgi; volcanic facies, gneisses, mica schist and amphibolite are found in Gördes and around, and the structures of andesite, spilite and porphyrite are found in Köprübaşi and Demirci (MTA 2013).

In Akhisar district, pre-neogene basement rocks include crystalline and ophiolitic rocks. Crystalline rocks are composed of the components of gneiss, mica schist, marble and phyllite (Yağmurlu 1982). There is a conglomerate of sandstone and claystone in the eastern part of Akhisar where volcanic rocks and limestones are found (Akdeniz and Ercan 1988).

Metamorphic rocks (gneiss, migmatite, mica schist and quartzite) in the Menderes massif are located in and around Gördes. The volcanic sedimentary formations known as Gördes zeolites were formed by flowing and deposition of rhyolitic, rhyo-dacitic eruptions of Kobaklar Volcanism located in the north of Gördes into the Lake Gördes which was a sedimentation basin in that period (Ulusoy and Albayrak 2009).

The Koprubasi region (Salihli Basin) in Manisa city contains uranium deposits in fluvial sedimentary rocks, which are underlaid by high-grade metamorphic rocks of the Menderes massif (Erees et al. 2006b). Detrital minerals observed in Köprübaşi uranium deposits are muscovite, quartz, feldspar, biotite, rutile, tourmaline, zircon, ilmenite-magnetite and apatite (Yilmaz 1982).

In Sindirgi district, basement rocks of the field consist of the complex units of the serpentine, radiolarite and recrystallized limestone. Neogene sedimentary (conglomerate, sandstone, siltstone and marl) and series of mafic volcanic (dasit and tuffs) are found on the base rock (Aksoy et al. 2009). Volcanics in Sindirgi give to crops the tuff form of these and acidic rocks (Çakir 2007).

Absorbed gamma dose rate in air

Outdoor γ dose rates were measured 1 m above the ground surface in study region using a portable radiometric instrument (TAEK Dose Rate Meter-NEB.211) as μRh^{-1}. A total of 137 measurements of gamma radiation level were carried out at the points where the soil samples and drinking waters were collected. The results include both terrestrial and cosmic ray components of gamma radiation level.

Natural radioactivity measurements in soil

A total of 137 surface soil samples (0–15 cm depths) were collected from the Akhisar, Gördes, Gölmarmara and Sindirgi regions. Soil samples were crushed in the laboratory, oven dried and sieved; 100 g of the homogenous soil samples were then packed in a polyethylene beaker, weighed and carefully sealed and stored for at least 4 weeks before counting to allow time for ^{238}U and ^{232}Th to reach equilibrium with their respective radionuclide daughters.

Each soil sample was measured by a gamma ray spectrometer using $3'' \times 3''$ NaI(Tl) detector (ORTEC-905-4). The best resolution achievable is typically <7.5 % for the 662 keV gamma ray from ^{137}Cs. In this study, the 1.76 MeV peak of ^{214}Bi, the 2.61 MeV peak of ^{208}Tl and the 1.46 MeV peak of radioactive potassium were used for quantitative determination of uranium, thorium and potassium, respectively. The 137 soil samples were counted for 7,200 s with background measurements made under the same conditions.

Concentrations of ^{238}U, ^{232}Th, and ^{40}K in the samples were determined using the concentration equations given in Erees's study (Erees et al. 2006b). Standard samples (625 ppm eU, 150 ppm eTh and 52 % K) were used for calibration to the system under appropriate conditions.

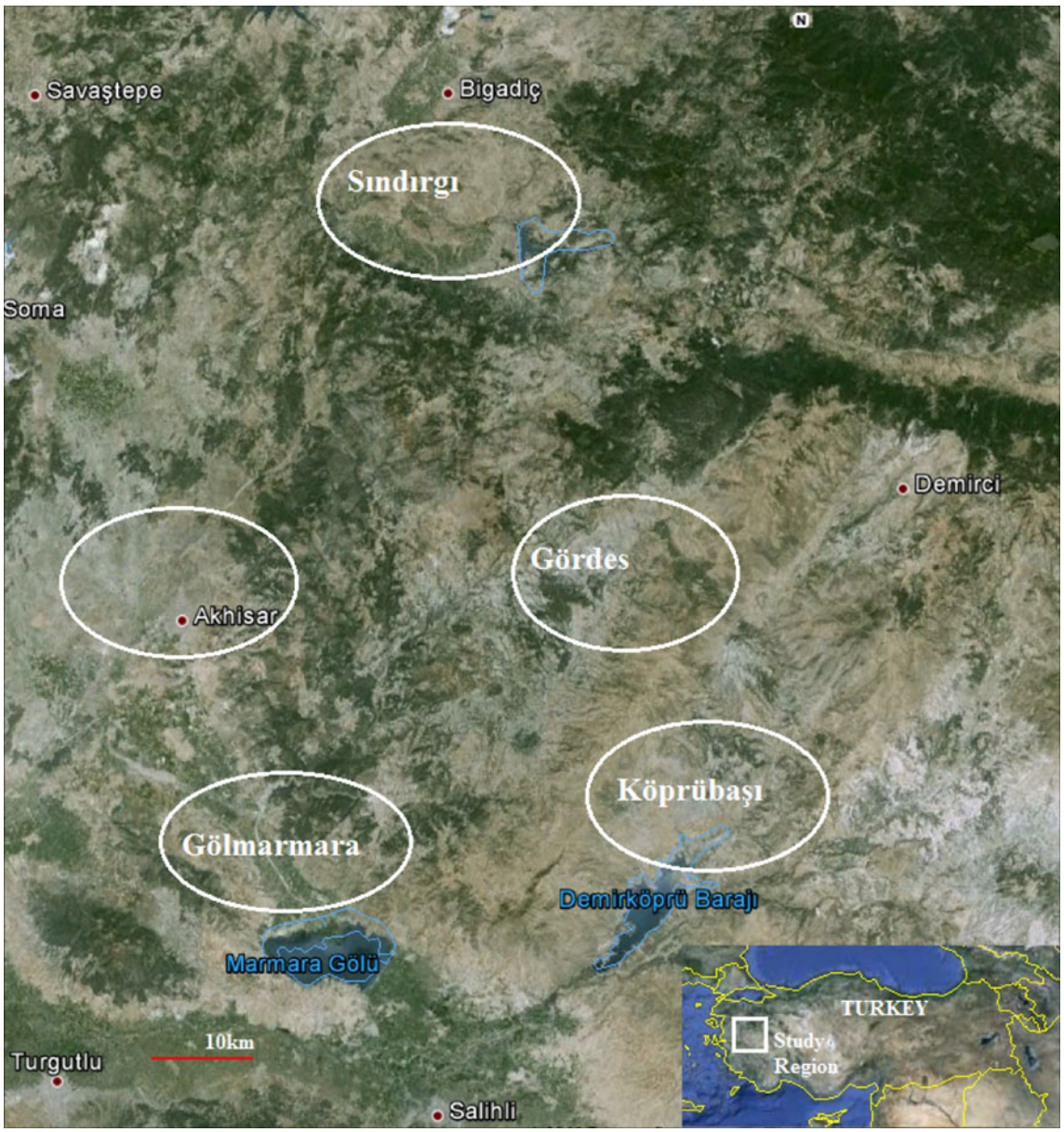

Fig. 1 The study areas

Radium measurements in waters

A total of 85 drinking water samples were collected from the Akhisar, Gördes, Gölmarmara and Sindirgi regions. They were transported to the laboratory in one liter plastic bottles. In order to determine the level of radium in the drinking water, the collector chamber method was used (Bakac and Kumru 2000). The method used here is based on the measurement of the alpha particles emitted by the radon daughters. In the laboratory, 100 ml was taken from each of the water samples. All the samples were transferred to radon bubblers and then sealed to prevent radon gas escape from bubbler and stored for about 7 days. Afterwards the bubbler bottles were connected between a pressurized aged air supply and collector chambers. Radon in the water transferred to the collector chambers about 5–10 min. The collector chambers were closed immediately and connected to an electrostatic field of 600 V DC. The collector plate used in this study is a circular plate of 4.7 cm diameter. After deamination into the collector chamber, the samples were allowed to stand for at least 4 h under a high electrostatic field. The alpha disintegration is directly measured by the alpha scintillation counter system (Eberline Model SAC-4). The counting time was 20 min for each sample. For the water samples, most of the tests were carried out with solutions containing several Bq of ^{226}Ra. Calibration

solutions, each of 100 mL volumes, were prepared by adding distilled water and HCl to 10 mL of standard ^{226}Ra solutions, containing activities of 0.185, 0.370, 0.555, 0.740, 0.925 Bq. The efficiency of the collector system for water samples was found to be 12 % in another study (Bakac and Kumru 2000; Erees et al. 2006a).

Results and discussion

Results of absorbed gamma dose rate in air

The exposure to natural radiation sources varies substantially from place to place and even locally (UNSCEAR 1982). This relates to the soil's original geochemical characteristics. The distribution maps of γ dose rates nGy h^{-1} in air (measured at a height of 1 m above the ground surface for each sampling point) are given Fig. 2. The readings are converted to nGy h^{-1} using the conversion factor of 8.7 nGy/μR.

The main sources of natural gamma radiation in the environment are origin of cosmic and terrestrial. Therefore, radionuclide concentrations in the soil and altitude of region (the height above sea level) affects the amount of gamma radiation. In this study, altitudes for the studied region vary as 83 m (Gölmarmara), 106 m (Akhisar), 125 m (Salihli), 250 m (Köprübaşi, Sindirgi) and 680 m (Gördes). According to the Fig. 1, surface gamma dose rates were high in and around Köprübaşi, Sindirgi and Gördes at high altitudes, whereas these were low at around Akhisar, Gölmarmara and Salihli. Looking at the geological structure of the region, metamorphic rocks (gneiss, migmatite, mica schist and quartzite) of the Menderes massif outcrops are basically in and around Gördes. There are the pegmatite veins, quartzite veins and the biotite gneiss from the metamorphic rocks around Köprübaşi. There are the andesite-spilite structure, conglomerate, sandstone, siltstone, marly (sedimentary rock) and mafic volcanic (dacite and tuffs) in around Sindirgi. Volcanics in the region emerged with acidic composition rocks and in

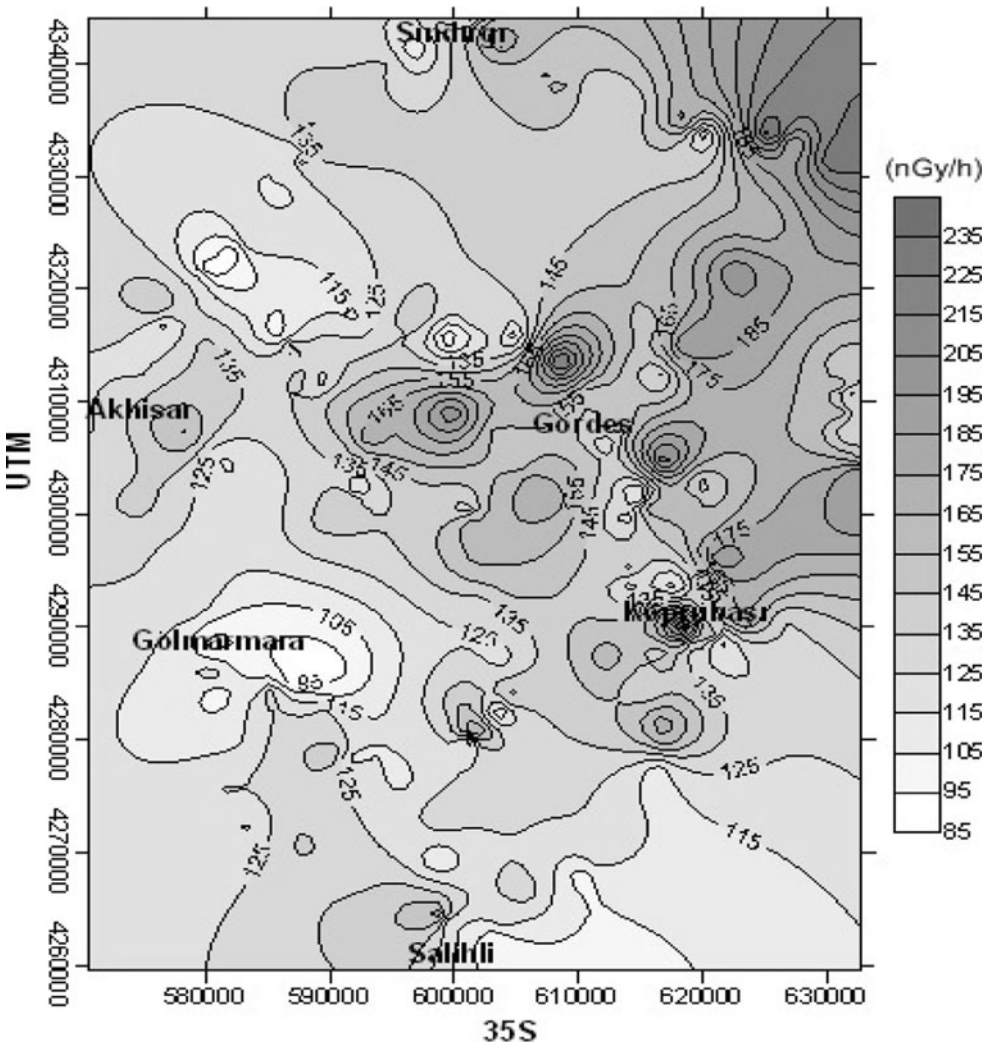

Fig. 2 Distribution map of γ dose rate in air at 1 m (contour interval: 10 nGy h^{-1})

the form of these tuffs. Rhyolite, liparit, trachyte, dacite, andesite, diabase, basalt, pikrit and tuffs are the rock types of magmatic origin and in these, there are uranium, thorium and potassium which are spontaneously in the earth's crust. It is stated that thorium is measured abundantly in granite and quartz from this rocks (Günoğlu 2008).

γ dose rates in the study area ranged from 81.69 nGy h^{-1} (9.39 μRh^{-1}) to 244.12 nGy h^{-1} (28.06 μR h^{-1}) and averaging 137.40 nGy h^{-1} (15.79 μR h^{-1}). γ dose rates measured at a height of 1 m above the ground surface and comparison with literature is given in Table 1.

In the results of this study as compared to studies in the world, gamma dose rates measured at a height of 1 m from the surface have shown higher values from different cities in Turkey and from the other countries (Spain, Costa Rica, Greece) in the world except for Malaysia and Jordan. In the UNSCEAR (2000) report, gamma dose rates in air range of 24–160 nGy h^{-1} and average is 59 nGy h^{-1}. Measurement range of results in this study is higher than the range given in the UNSCEAR (2000) report. Also, the average value obtained in this study (137.40 nGy h^{-1}) is greater than the world average of 59 nGy h^{-1} and it is two times of the world average.

Table 1 γ dose rates measured in air and comparison with literature in Turkey and the world

Country	γ dose rates measured (nGy h^{-1})	References
Spain	12.1–179.5	Quindos Poncela et al. (2004)
Costa Rica	29.52	Mora et al. (2007)
Spain	75–242.3	Quindos et al. (2008)
Malaysia	39–1,039 (222)	Lee et al. (2009)
Jordan	10–2,740	Al-amairyeen (2010)
Greece	79.3–104 (90)	Papachristodoulou et al. (2010)
North and East Anatolian active faults systems, Turkey	87.8	Baykara et al. (2005)
Tekirdağ, Turkey	30.3–54.3	Yarar and Kam (2005)
Manisa, Turkey	78.30–135.72	Erees et al. (2006b)
Kastamonu, Turkey	36.1–84.6 (48.03)	Kam and Bozkurt (2007)
Şanliurfa, Turkey	60.9	Bozkurt et al. (2007)
Adana, Turkey	67	Degerlier et al. (2008)
The world average	24–160 (59)	UNSCEAR (2000)
Akhisar–Gördes–Gölmarmara–Sindirgi, Turkey	81.69–244.122 (137.40)	Present study

Results of natural radioactivity measurements in soil

The results of ^{40}K activity concentrations in 137 soil samples collected from studied area by using gamma spectrometry are as following:

^{40}K activity concentration in 23 soil samples is not detected. In 114 soil samples, it is ranged from 2.80 to 2,347.77 Bq kg^{-1} and averaging 384.80 Bq kg^{-1}. The maximum ^{40}K activity concentration is measured in soil sample taken from Gördes. Mica schist, feldspar and quartzite outcrops basically in and around Gördes. These rocks contain potassium. Figure 3 gives the frequency distribution of ^{40}K activity concentration in soil samples. According to Fig. 3, 75.4 % of the samples are ranged from 2.8 to 400 Bq kg^{-1}. 24.6 % of the samples are higher than the world average (400 Bq kg^{-1} for ^{40}K activity concentration in soil) (UNSCEAR 2000).

^{238}U activity concentrations are ranged from 9.90 to 256.19 Bq kg^{-1} and averaging 65.51 Bq kg^{-1}. Figure 4 gives the frequency distribution of ^{238}U activity concentration in soil samples. According to Fig. 4, 10.2 % of the samples are ranged from 9.9 to 35 Bq kg^{-1}. 89.8 % of the samples are higher than the world average (35 Bq kg^{-1} for ^{238}U activity concentration in soil) (UNSCEAR 2000).

^{232}Th activity concentrations range from 9.66 to 106.53 Bq kg^{-1} and average 49.29 Bq kg^{-1}. Figure 5 gives the frequency distribution of ^{232}Th activity concentration in soil samples. According to Fig. 5, 11.7 % of the samples range from 9.66 to 30 Bq kg^{-1}; 88.3 % of the

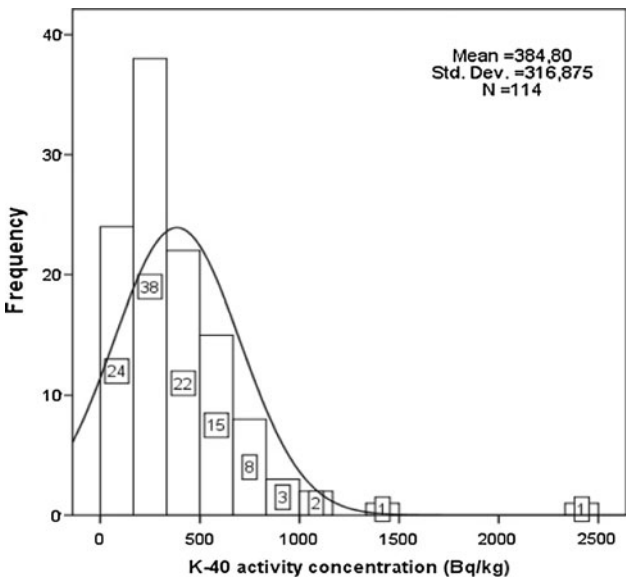

Fig. 3 The frequency distribution of ^{40}K activity concentration of the soil samples

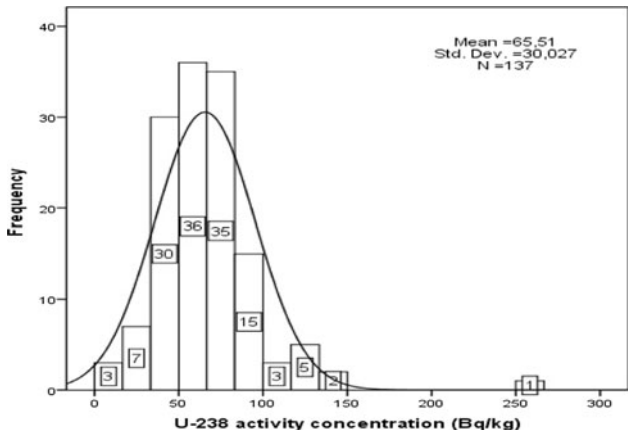

Fig. 4 The frequency distribution of ^{238}U activity concentration of the soil samples

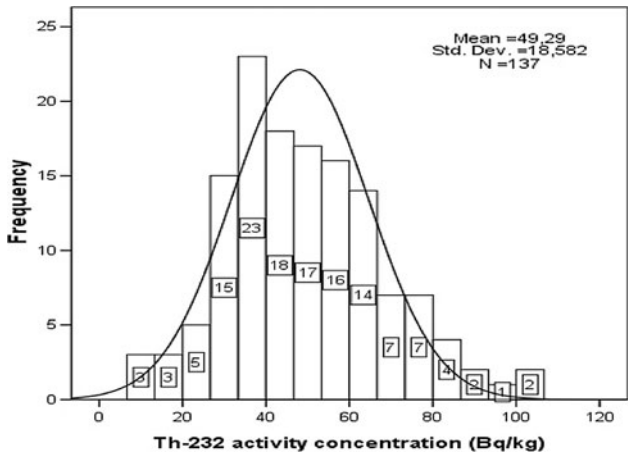

Fig. 5 The frequency distribution of ^{232}Th activity concentration of the soil samples

samples are higher than the world average (30 Bq kg^{-1} for ^{232}Th activity concentrations in soil) (UNSCEAR 2000).

From studies, concentrations of natural radionuclide in soil in Turkey and in the world are given in Table 2.

The results of this study as compared to studies in the world have got higher values than the other countries except China. Average values for ^{238}U and ^{232}Th in this study exceeded the average values given for the world (35 Bq kg^{-1} for ^{238}U and 30 Bq kg^{-1} for ^{232}Th). The highest ^{40}K activity concentration is approximately six times the world average (400 Bq kg^{-1}). This soil sample is taken from Gördes district. A structure from gneiss, migmatite, mica schist and quartzite has been seen in and around Gördes. There are large and small scales of mica deposits depending on pegmatite formations in Gördes. Mica, found in magmatic rocks of granite composition and in metamorphic rocks such as schist and gneiss, is a mineral. Pegmatite rocks of granite composition are the main source of sheet micas (DPT 2001). Mica is found in nature in the form of thin sheets and flakes. Although micas are separated in three structures such as muscovite (white mica), biotite (black mica) and lepidolite (purple mica), potassium is found in the mica structure (Vardar et al. 2009). High concentration of ^{40}K activity in the soil sample taken from Gördes district can be due to the mica deposits around Gördes.

Radium equivalent activities of the soil samples were calculated by using ^{40}K, ^{238}U and ^{232}Th activity concentrations.

To represent the activity levels of ^{226}Ra, ^{232}Th and ^{40}K by a single quantity, which takes into account the radiation hazards associated with each component, a common

Table 2 ^{40}K, ^{238}U and ^{232}Th activity concentrations of the soil samples taken from different countries

Country	^{40}K (Bq kg^{-1})	^{238}U (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	References
Republic of Serbia	60–821	6.5–228	6.8–72	Jankovic et al. (2008)
Jordan	291.1	49.9	26.7	Al-Hamarneh and Awadallah (2009)
Thailand	393–478	55.3–65.2	60.7–69.1	Santawamaitre et al. (2011)
Yugoslavia	554	51	53	Bikit et al. (2005)
China	441.8–913 (672)	40.2–442 (112)	32.6–88.1 (71.5)	Yang et al. (2005)
Egypt	433	13	6	Sroor et al. (2001)
Botswana	33.5–1,085.7 (432.7)		7.4–110 (41.8)	Murty and Karunakara (2008)
India	363.4–1,002.2		61.2–140.3	Singh et al. (2009)
Yemen	822.7	58.2	44.4	Abd El-mageed et al. (2011)
Gediz, Turkey	240.4–403.1		7.40–38.5	Bolca et al. (2007)
Kirklareli, Turkey	667	28	40	Taşkin et al. (2009)
İstanbul, Turkey	322	27	35	Karahan and Bayulken (2000)
The world average	400	35	30	UNSCEAR (2000)
Akhisar–Gördes–Gölmarmara–Sindirgi, Turkey	2.80–2,347.8 (384.80)	9.9–256.2 (65.51)	9.66–106.5 (49.29)	Present study

radiological index has been introduced (Agbalagba and Onoja 2011). The equivalent radium activity or simply equivalent radium (Ra_{eq}), is a parameter utilized to estimate the external exposure due to the contribution of gamma emitters from the ^{238}U (^{226}Ra), ^{232}Th and ^{40}K series (Santos Junior et al. 2010).

This index is called the Radium Equivalent activity (Ra_{eq}) and is mathematically defined by (UNSCEAR 2000):

$$e(\mathrm{Ra}) = C_{\mathrm{Ra}} + 1.43C_{\mathrm{Th}} + 0.077C_{\mathrm{K}} \quad (1)$$

where C_{Ra}, C_{Th} and C_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively. In the above relationship, it has been assumed that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce equal gamma doses (Diab et al. 2008; El-Daly 2008; Santos Junior et al. 2010).

Figure 6 gives the frequency distribution of Ra_{eq} concentration in soil samples. It can be seen from Fig. 6 that the radium equivalent for all the 137 soil samples in the present study ranged between 53.28 Bq kg^{-1} in Gördes and 373.21 Bq kg^{-1} in Sindirgi at an average value of 160.65 Bq kg^{-1}, which is lower than the allowed maximum value of 370 Bq kg^{-1} (Santos Junior et al. 2010; Lu and Zhang 2008; Mehra and Singh 2011). Only one soil sample taken from Sindirgi has got a high radium equivalent activity from the allowed maximum value (370 Bq kg^{-1}).

The global average of the radium equivalent for soil is given as 128.7 Bq kg^{-1} in the study by Santos Junior et al. (2010); 65.69 % of radium equivalent results from the soil samples in this study are greater than this value (128.7 Bq kg^{-1}).

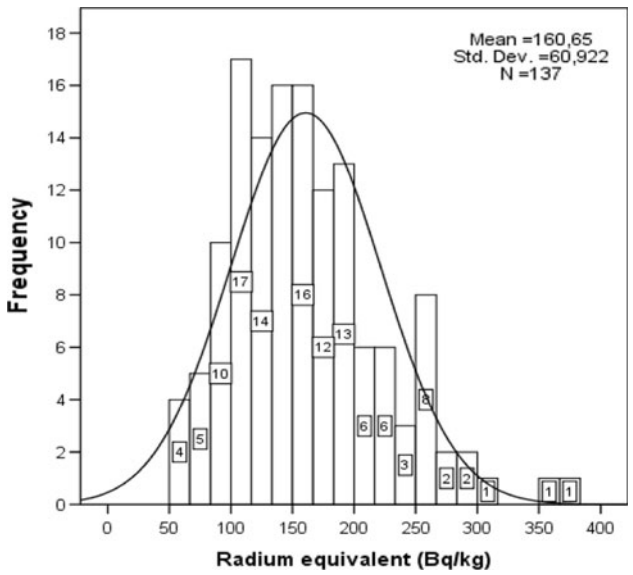

Fig. 6 The frequency distribution of Ra_{eq} activity concentration of the soil samples

The external terrestrial γ-radiation absorbed dose rate in air at a height of about 1 m above the ground is calculated to UNSCEAR (2000):

$$D(\mathrm{nGy\,h^{-1}}) = 0.462C_{\mathrm{U}} + 0.604C_{\mathrm{Th}} + 0.0417C_{\mathrm{K}} \quad (2)$$

where, C_U, C_{Th} and C_K are the activity concentrations (in Bq kg^{-1}) for ^{238}U, ^{232}Th and ^{40}K, respectively. The external terrestrial γ-radiation absorbed dose rate ranged between 22.90 and 174.69 nGy h^{-1} at an average value of 76.09 nGy h^{-1}, which is higher by a factor 1.26 than the world's average value of 60 nGy h^{-1}. The contributions of ^{40}K, ^{238}U and ^{232}Th in the average value are in the ratio 16.05:30.27:29.77.

The distribution maps of γ-radiation absorbed dose rates calculated from ^{40}K, ^{238}U and ^{232}Th activity concentrations (nGy h^{-1} in air) are given Fig. 7. According to Fig. 7, gamma dose rates were high at Sindirgi, east of Sindirgi, Köprübaşi, east of Köprübaşi and Gördes. Distribution map of γ dose rate calculated (Fig. 7) is similar to the other distribution map of γ dose rate measured by using a portable instrument (Fig. 2).

The annual effective dose rates were calculated utilizing the conversion coefficient from absorbed dose in air to effective dose (0.7 SvGy^{-1}) and an outdoor occupancy factor (0.2) proposed by UNSCEAR (2000). Therefore, the annual effective dose rate (mSv year^{-1}) was calculated by the formula (UNSCEAR 2000):

$$\text{Effective dose rate } (\mathrm{mSv\,year^{-1}}) = \mathrm{D(Gy\,h^{-1})} \times 0.7(\mathrm{SvGy^{-1}}) \times (8,760\mathrm{h\,year^{-1}}) \times 0.2 \quad (3)$$

The calculated results show that the annual effective dose rates in air varied from 0.028 to 0.214 mSv year^{-1} with an average value of 0.093 mSv year^{-1} (Table 3), which is higher than the worldwide average (0.070 mSv year^{-1}). The calculated results of external gamma dose rates and annual effective dose rates in soil samples taken from Turkey and at different locations in the world can be seen in Table 3.

According to Table 3, results of the average external terrestrial γ-radiation absorbed dose rate and of the average annual effective dose calculated for all of the study area were higher than the other countries (India, Spain, Republic of Serbia, Republic of Botswana, Jordan, and Serbia) except China, Yemen and Thailand. Also, result of the average external gamma dose rate was lower than the other cities in Turkey except Istanbul and Isparta.

Looking at the region, it was seen that values of the average external gamma dose rate were passed to the world average (60 nGy h^{-1}) in Gördes district (85.42 nGy h^{-1}),

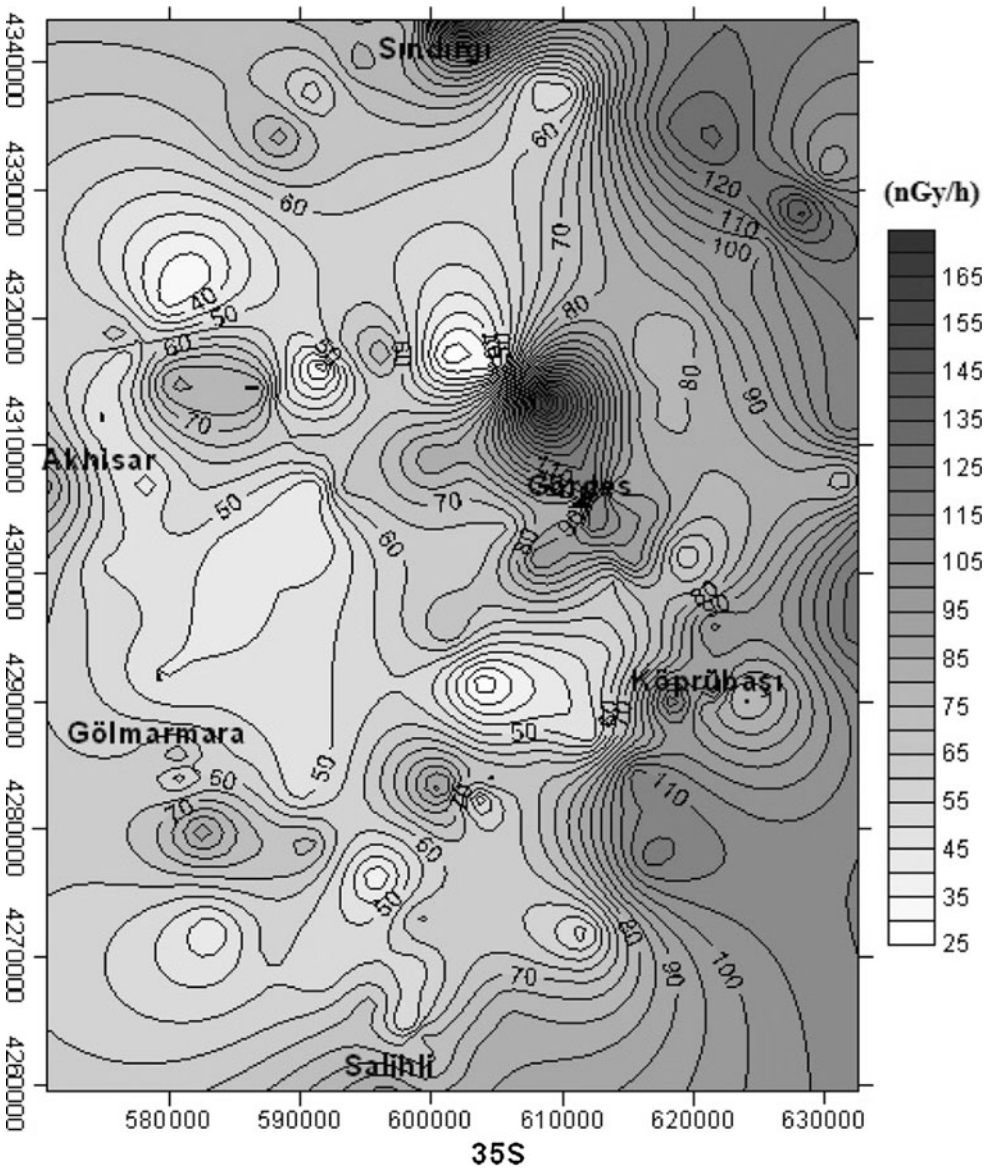

Fig. 7 Distribution map of γ dose rate calculated from K, U and Th activity concentrations in soil samples. (contour interval: 5 nGy h^{-1})

Köprübaşi district (88.59 nGy h^{-1}), Sindirgi district (100.9 nGy h^{-1}) and region of between Köprübasi and Demirci (108.16 nGy h^{-1}). Values of the average annual effective dose in the same regions have passed to value of the world average annual effective dose (0.07 mSv $year^{-1}$).

A widely used hazard index (reflecting external exposure) called the external hazard index H_{ex} is defined as follows (Diab et al. 2008; Agbalagba and Onoja 2011):

$$H_{ex} = C_{Ra}/370 + C_{Th}/259 + C_K/4,810 \quad (4)$$

In addition to the external hazard index, radon and its short lived progeny are also hazardous to the respiratory organs. The internal exposure to radon and its daughter progenies is quantified by the internal hazard index H_{in}, which is given by the equation:

$$H_{in} = C_{Ra}/185 + C_{Th}/259 + C_K/4,810 \quad (5)$$

The values of the indices (H_{ex}, H_{in}) must be less than unity for the radiation hazard to be negligible (Diab et al. 2008; Agbalagba and Onoja 2011).

In this study, the regional values of the indices (H_{ex}, H_{in}) for soil samples taken from study area were calculated using the above formulas (Table 4).

According to Table 4, while value of the external hazard index ranged from 0.10 to 1.01 with a mean of 0.43, value of the internal hazard index varied from 0.14 to 1.70 and averaged 0.61 for all of the study area. The values of the indices (H_{ex}, H_{in}) must be less than unity for the radiation hazard to be negligible (Diab et al. 2008). In the present study, while the maximum value of H_{ex} is the limit value

Table 3 The calculated results of external gamma dose rates and annual effective dose rates in soil samples

Study	External gamma dose rates (nGy h^{-1})	Annual effective doses (mSv $year^{-1}$)	References
India	74.3	0.46	Selvasekarapandian et al. (2000)
India	18–144		Sadasivan et al. (2003)
Spain	47.3		Quindos et al. (2004)
Brazil	62–126	0.08–0.15	Alencar and Freitas (2005)
China	124	0.15	Yang et al. (2005)
India	83.28	0.07–0.13	Rani and Singh (2005)
Republic of Serbia	69	0.08	Jankovic et al. (2008)
Republic of Botswana	8.7–156.7 (59.4)	0.01–0.19 (0.07)	Murty and Karunakara (2008)
Jordan	51.5	0.063	Al-Hamarneh and Awadallah (2009)
Serbia	73.4	0.09	Dugalic et al. (2010)
Yemen	89.45		Abd El-mageed et al. (2011)
Thailand	81.6–90.4	0.1–0.11	Santawamaitre et al. (2011)
Istanbul, Turkey	65	0.08	Karahan and Bayulken (2000)
North and East Anatolian active faults systems, Turkey	100–107.7		Baykara and Doğru (2009)
Eskişehir, Turkey	87.14–531.81		Örgün et al. (2005)
Rize, Turkey	19.1–149.6		Kurnaz et al. (2007)
Kirklareli, Turkey	118		Degerlier et al. (2008)
Isparta, Turkey	26.67–86.97	0.13–0.42	Mavi and Akkurt (2010)
The world average	60	0.07	UNSCEAR (2000)
Akhisar	55.11	0.068	Present study
Gördes	85.42	0.104	Present study
Gölmarmara	55.11	0.068	Present study
Köprübaşi	88.59	0.109	Present study
Sindirgi	100.9	0.124	Present study
Between Gölmarmara and Salihli and Köprübaşi	65.1	0.080	Present study
Region between Köprübasi and Demirci	108.16	0.133	Present study
All of the study area	22.90–174.69 (76.09)	0.028–0.214 (0.093)	Present study

Table 4 External and internal hazard indexes (H_{ex}, H_{in}) calculated as district

Area	Sample number	External hazard index (H_{ex})			Internal hazard index (H_{in})		
		Min.	Max.	Average	Min.	Max.	Average
Akhisar	36	0.14	0.51	0.33	0.17	0.77	0.47
Gördes	30	0.10	0.96	0.46	0.14	1.20	0.68
Gölmarmara	15	0.20	0.53	0.33	0.32	0.70	0.47
Köprübaşi	19	0.32	0.70	0.52	0.44	1.06	0.71
Sindirgi	12	0.31	1.01	0.60	0.48	1.70	0.86
All of the study area	137	0.10	1.01	0.43	0.14	1.70	0.61

for Sindirgi, the maximum values of H_{in} for Gördes, Köprübaşi and Sindirgi are higher than unity.

Results of radium measurements in waters

Radium activity in 85 water samples collected from the studied area was determined by using the collector method. The distribution map of radium activity in the water samples is shown in Fig. 8.

The radium activity concentrations of the water samples ranged from 0.03 Bq L^{-1} (0.89 pCi/L) to 0.80 Bq L^{-1} (21.58 pCi/L), averaging 0.28 Bq L^{-1} (7.51 pCi/L). About 40 % of the results were $\leq$0.185 Bq L^{-1}, about 34.1 % were between 0.185 and 0.37 Bq L^{-1}, about 15.3 % were

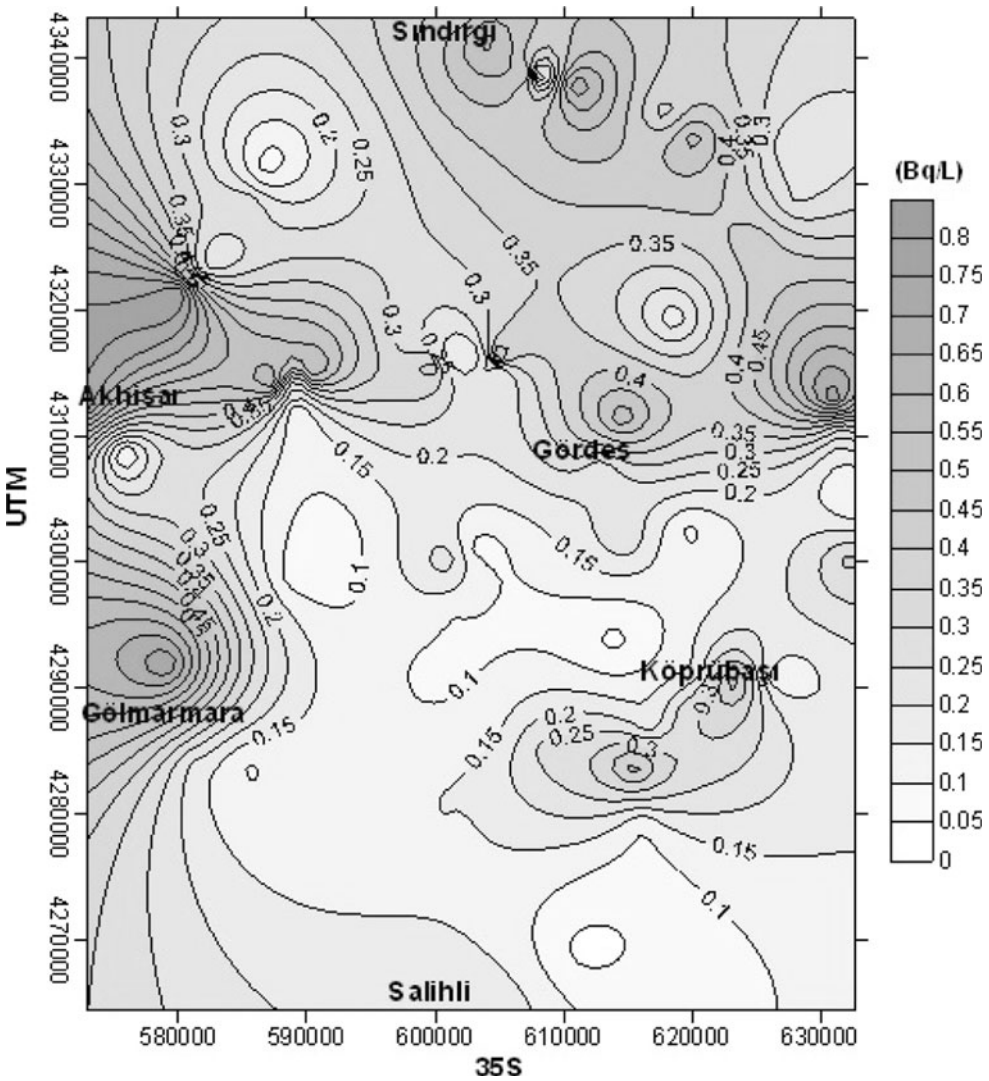

Fig. 8 Distribution map of radium contents in drinking waters. (contour interval: 0.05 Bq L^{-1})

between 0.37 and 0.555, about 7.1 % were between 0.555 and 0.74, and about 3.5 % were between 0.74 and 0.925. According to the Maximum Contaminant Level for Radium (5 pCi/L), the result showed that 60 % of the water samples have the radium contamination more than this level (EPA 2004).

Conclusion

In this study, absorbed gamma dose rate in air, natural radioactivity measurements in soil, and radium measurements in drinking water have been determined in Akhisar, Gördes, Gölmarmara and Sindirgi regions, Western Turkey. The average absorbed gamma dose value (137.40 nGy h^{-1}) is greater than the world average of 59 nGy h^{-1} and it is two times that of the world average. The average external terrestrial gamma absorbed dose rate and of the average annual effective dose calculated from the radioactivity measurements in soils were higher than the other countries in world; 60 % of the water samples have the radium contamination higher than the Maximum Contaminant Level (5 pCi/L) for radium given by EPA (2004).

The results from our study show that the studied area has a background radiation level that exceeds the natural limits.

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