



Radioactivity levels and radiological risk assessment in west Antalya beach sands

Caner Yalçın¹ · Osman Günay² · Recep Taygun Güray¹

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Abstract

A radiological baseline study was carried out by means of a computational analysis to evaluate the distribution of ^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs in samples of beach sand collected from the coastal areas of Antalya, Turkey. The results of the radiological risk assessment indicated that the calculated radiological risk for workers and tourists was below the level that could pose an endangerment to life or the safe operation. There was also no evidence of recent migration of ^{137}Cs or other isotopes through precipitation, dust transport, or by indirect means such as sea currents.

Keywords Mediterranean Sea beaches · Natural radioactivity · Beach sand · ^{137}Cs · Radiological risk

Introduction

Naturally occurring radioactive elements, including uranium, thorium, and potassium, are present in sand grains in varying amounts. Radiation levels from these sources typically remain low. However, especially in coastal areas, radiation levels may increase due to geological factors or human activities such as mining, waste disposal or nuclear weapons tests. Certain locations have deposits of uranium and thorium, both naturally occurring radioactive elements. It is possible that beaches situated in close proximity to geological formations may exhibit elevated levels of radiation within their sands, as a consequence of the presence of radioactive substances. Some mineral sands, such as monazite, contain elevated levels of radioactive elements [1]. Mining and processing of these sands can cause localized contamination of beach areas with high radiation levels. In regions of geothermal activity, levels of naturally occurring radioactive substances, such as radon gas, may be elevated. This can result in the release of radioactive decay products, into the environment, including beach sand. Certain beaches around the world are known to have elevated levels

of natural radioactivity due to specific geological conditions. Guarapari Beach in Brazil is often cited as one of the most radioactive beaches in the world [2]. This is attributed to its black sand, which contains naturally occurring monazite deposits that are rich in thorium. Similar to Guarapari, several beaches along the Indian coast of Kerala also have monazite-rich sands [3]. Ramsar, a city in Iran, has a beach with naturally high radiation levels. The presence of radioactive hot springs is the primary factor contributing to this phenomenon [4]. This area exposes its population to elevated levels of background radiation that exceed those of any other region in the world.

In addition to natural radiation, a wide range of man-made radionuclides can be released into the atmosphere and oceans as a result of both nuclear weapon tests and nuclear accidents. In the 1960s, radioactive materials emitted by nuclear tests conducted in the Sahara Desert were transported to western Turkey via atmospheric phenomena [5]. Beaches along the Black Sea coast near the Krasnokamenka radioactive waste disposal facility in Odessa, Ukraine, have high radiation levels [6]. Furthermore, the level of radioactivity may be elevated as a consequence of industrial activities [7].

Together, these factors contribute to increased levels of radioactivity in the environment, resulting in increased radiation doses to organisms. Prolonged exposure to radiation can result in significant health effects, including damage to the kidneys, bones, lungs, liver, and pancreas [8]. One of the main risk factors is the inhalation of radon gas

✉ Caner Yalçın
caner.yalcin@kocaeli.edu.tr

¹ Department of Physics, Kocaeli University, 41001 Izmit, Kocaeli, Turkey

² Department of Biomedical Engineering, Yıldız Technical University, 34220 Istanbul, Turkey

and its daughter products, and the consumption of radioactive foods [9]. Therefore, determining the levels of natural and artificial radiation doses on the beach sands is crucial.

Radioactivity concentration measurements for beach sands in Turkey [10–13] and around the world [14–24] have been reported in the literature. However, this study is the first to be carried out on the west coast of Antalya. The research area was selected for two reasons. Firstly, monozite minerals are prevalent in the Mediterranean beaches and sediments [5, 25]. Secondly, the area is situated in close proximity to the geologically active Kahramanmaraş region, which experienced earthquakes with magnitudes of 7.8 and 7.6 in Turkey in 2023 [26]. To ascertain the impact of geological and anthropogenic factors, the specific activity concentrations of 28 sand samples collected from six beaches in West Antalya were measured using a gamma spectroscopy system (see Table 1 for details). The results provide valuable data for monitoring environmental radioactivity in the region. To assess the radiological hazard from natural radioactivity, the radioactivity equivalent activity, the external hazard index, the average annual effective dose equivalent (AEDE), and the excess lifetime risk of cancer (ELCR) were calculated for west Antalya beaches. The artificial radioisotope ^{137}Cs was also detected in the samples and dose calculations were performed in addition to the natural radioactivity. The resulting data will serve as a reference point for future monitoring activities to detect any changes in the background levels of radioactivity.

Experimental

Study area

Antalya, a significant tourist destination in Turkey, lies on the Mediterranean coastline. It is bordered by Mersin on the east, Konya, Isparta, and Burdur to the north, Muğla on the west, and the Mediterranean Sea on the south. The Mediterranean climate and extended coastline, featuring beaches like Çıralı, Adrasan, Beykonak, Kumluca, Finike, Hasyurt, Patara, Kleopatra, Lara, Konyaaltı, Kemer, İncekum, Kaputaş, Kundu, Phaselis, etc., are the primary driving forces behind tourism development in Antalya. Tourism season in Antalya is further prolonged with an approximate 300 sunny days a year and high average temperatures.

Natural and artificial radioactivity levels were assessed at six beaches situated in Kemer, Kumluca and Finike districts on the west coast of Antalya. Çıralı beach is located in Kemer district, while Adrasan and Beykonak beaches are situated in Kumluca district, and Hasyurt Beach is located in Finike district (see Fig. 1 and Table 1 for details).

Table 1 Information about the location where the samples were collected

Sample no	Sub sample no	Sampling site	Longitude	Latitude
1	A1	Adrasan	36°18'41"	30°27'53"
2	A2		36°18'26"	30°27'55"
3	A3		36°18'13"	30°27'56"
4	A4		36°18'01"	30°28'01"
5	A5	Beykonak	36°17'55"	30°28'05"
6	A6		36°17'46"	30°28'13"
7	B1		36°18'10"	30°19'03"
8	B2		36°18'23"	30°18'39"
9	B3	Çıralı	36°18'36"	30°18'05"
10	B4		36°18'46"	30°17'21"
11	Ç1		36°25'10"	30°29'07"
12	Ç2		36°24'57"	30°28'51"
13	Ç3	Finike	36°24'34"	30°28'46"
14	Ç4		36°24'10"	30°28'39"
15	F1		36°18'42"	30°10'26"
16	F2		36°18'37"	30°10'08"
17	F3	Hasyurt	36°18'33"	30°09'53"
18	F4		36°18'25"	30°10'40"
19	F5		36°18'15"	30°10'21"
20	F6		36°18'09"	30°10'04"
21	H1	Kumluca	36°18'56"	30°12'54"
22	H2		36°18'57"	30°12'25"
23	H3		36°18'59"	30°12'00"
24	H4		36°18'55"	30°11'27"
25	K1	Kumluca	36°18'56"	30°16'04"
26	K2		36°18'57"	30°15'48"
27	K3		36°18'58"	30°15'32"
28	K4		36°18'58"	30°15'19"

Sample collection and preparation

A total of twenty-eight sand samples were collected from six beaches: six from Finike Beach, four from Kumluca Beach, six from Adrasan Beach, four from Çıralı Beach, and four from both Beykonak Beach and Hasyurt Beach. The sampling sites were selected based on the length of the shorelines. The comprehensive findings of the sand's properties and characteristics for each location were determined using a weighted average calculation method. The samples were obtained via the template methodology within a predefined one-square-meter area, with a depth of six centimeters. Four separate subsamples were blended thoroughly to create approximately 3 kg of homogenized sample profiles. Following the collection of the samples, they were initially dried at room temperature and subsequently in an oven maintained at 105 °C for a period of 48 h, with the objective of eliminating all traces of

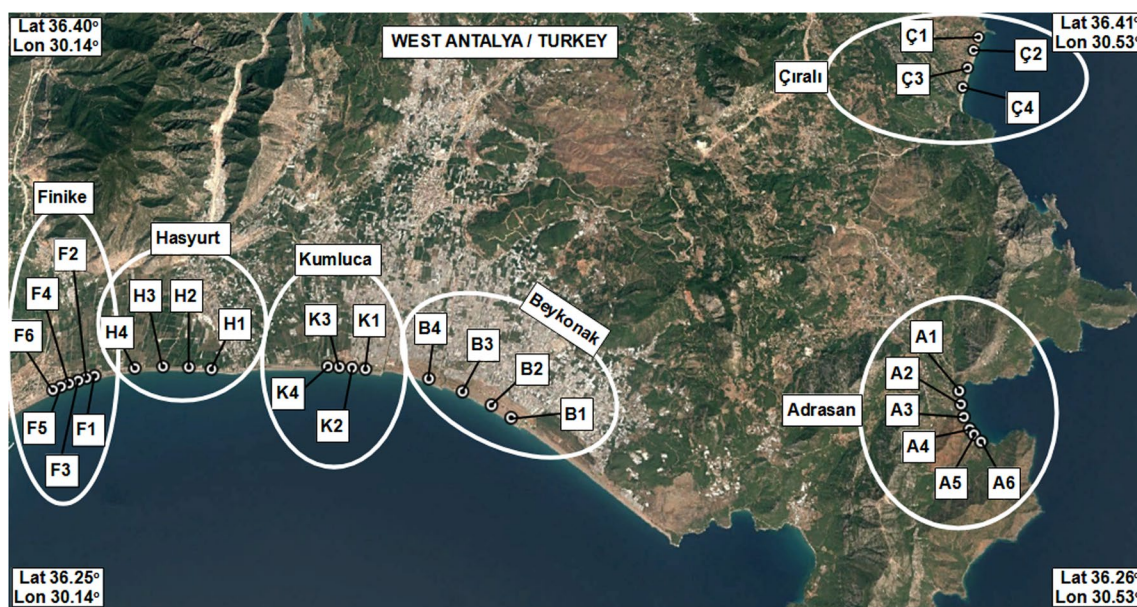


Fig. 1 Study area: West Antalya, Turkey. The coordinates of each sample shown on the map are listed in Table 1

moisture. The moisture content of the samples within the oven was monitored through the observation of the color change of the silica gel within the oven. Additionally, the samples were removed from the oven at regular intervals and weighed with a precision scale to assess whether the mass change had ceased. To prevent re-moistening of the samples, they were stored in a desiccator when they required further processing. Subsequently, the samples were sifted using a 1-mm mesh sieve to remove visible impurities such as stones and pebbles. After homogenizing, the samples were transferred into 170 ml hermetically sealed PVC containers and sealed with parafilm to prevent the escape of gaseous ^{222}Rn and ^{220}Rn from the samples. Additionally, the containers were stored in a secure manner for about 40 days to achieve radioactive equilibrium between ^{226}Ra and ^{232}Th and their corresponding decay products.

Radioactivity concentration measurements

The radioactivity measurements were performed at the Nuclear Physics Research Laboratory of Kocaeli University. A HPGe detector with a relative efficiency of 25% and an energy resolution of 1.71 keV for the 1332 keV gamma energy of ^{60}Co was used. The detector was shielded with a 10 cm thick lead armor with 1 mm tin and 1.5 mm copper plating to minimize natural background radiation. A mixed radioactive reference source from ECKERT & ZIEGLER ISOTOPE PRODUCTION GMBH (Source no: 85548A-443) with an energy range from 47 to 1836 keV, identical to the sample geometry, was employed to calibrate the detector

efficiency. The calibration source contains the following isotopes: ^{210}Pb , ^{241}Am , ^{109}Cd , ^{57}Co , ^{139}Ce , ^{203}Hg , ^{113}Sn , ^{85}Sr , ^{137}Cs , ^{60}Co and ^{88}Y . Samples were counted between approximately 75 000 and 200 000 s. An example spectrum is shown in Fig. 2.

The activities of ^{226}Ra were assessed by measuring gamma rays at the 609 keV and 1120 keV levels of ^{214}Bi peak, as well as at the 295 keV, and 352 keV levels of ^{214}Pb peak. Similarly, the activities of ^{232}Th were evaluated by measuring gamma rays at the 338 keV, and 911 keV levels of ^{228}Ac , and the 583 keV level of ^{208}Tl peak. Finally, the weighted averages of the measured activities for both ^{226}Ra

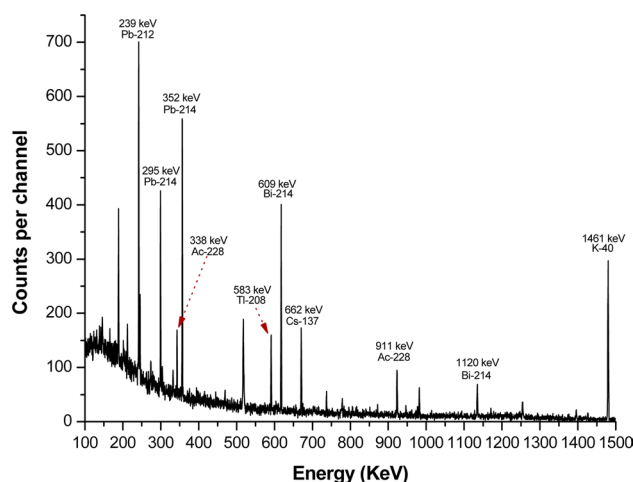


Fig. 2 The spectrum of sand sample number 12 (Çıralı Beach) measured for 85 000 s

Table 2 Gamma rays used to determine the specific activity

Radionuclide	Energy (keV), gamma intensity (%)
^{226}Ra	295.22 (18.42), 351.93 (35.60) 609.32 (45.49), 1120.29 (14.92)
^{232}Th	338.32 (11.27), 911.20 (25.8) 583.19 (30.4)
^{40}K	1460.82 (10.66)
^{137}Cs	661.66 (89.90)

and ^{232}Th were determined by considering data from different gamma lines (Table 2). The activity concentration of ^{40}K was directly determined from its peak at 1461 keV, while ^{137}Cs activity was determined using its own peak at 662 keV. To determine the radionuclide activity concentration at a sampling site, we considered the net photo peak area, absolute peak efficiency, counting time, gamma intensity, and sample mass.

Assessment of radiological hazard effects

For radiological evaluation, the Radium Equivalent Activity (Ra_{eq}), the External Hazard Index (H_{ex}), the absorbed dose rate, the Average Annual Effective Dose (AED), and the Excess Lifetime Risk of Cancer (ELCR) were determined based on the specific activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K .

The radium equivalent activity is an index that has been introduced with the purpose of representing the specific activities of ^{226}Ra , ^{232}Th , and ^{40}K by a single quantity. This facilitates comparisons and ensures that the total radiological hazard of different radioactive materials can be uniformly assessed. It is particularly useful in evaluating the safety and regulatory aspects of materials that contain uranium, thorium, or radium. The radium equivalent activity (Ra_{eq}) indicator is frequently employed to ascertain the potential health risks associated with radiation exposure. In order to ensure that the annual effective dosage of the population remains below 1 mSv, it is recommended that Ra_{eq} values be maintained at $< 370 \text{ Bq kg}^{-1}$. The Ra_{eq} is calculated using the following equations [15]:

$$Ra_{eq} = \left(\frac{C_{Th}}{259} + \frac{C_{Ra}}{370} + \frac{C_K}{4810} \right) \times 370 \quad (1)$$

where C_{Th} , C_{Ra} , and C_K represent that specific activity concentration of ^{232}Th , ^{226}Ra and ^{40}K , respectively.

An External Hazard Index (H_{ex}) shall be used as a radiological parameter to assess the potential risk of radiation to individuals exposed to gamma radiation from naturally occurring radionuclides in the vicinity. The increase in total radiation risk from external gamma radiation is expressed in

H_{ex} . In assessing the potential health risk of external radiation exposure, the gamma dose rate at a particular location shall be taken into consideration. The International Commission on Radiation Protection (ICRP) recommends a dose equivalent value of 1 mSv per year. A radium equivalent activity of 370 Bq kg^{-1} is equivalent to the limit value of the external hazard index of 1. Hex values were calculated using the following equation (Eq. 2).

$$H_{ex} = \frac{C_{Th}}{259} + \frac{C_{Ra}}{370} + \frac{C_K}{4810} \leq 1 \quad (2)$$

The gamma dose rate absorbed by the environment at the height of 1 m above the ground surface, with the consideration of radionuclides even distribution, was computed through Eq. (3) and (4) and is expressed in nGy h^{-1} .

$$D_{natural} = \frac{C_{Th}}{1.51} + \frac{C_{Ra}}{2.34} + \frac{C_K}{23.25} \quad (3)$$

$$D_{total} = \frac{C_{Th}}{1.51} + \frac{C_{Ra}}{2.34} + \frac{C_K}{23.25} + \frac{C_{Cs}}{33.33} + 30 \quad (4)$$

where C_{Th} , C_{Ra} , C_K , and C_{Cs} represent that specific activity concentration (in Bq kg^{-1}) of ^{232}Th , ^{226}Ra , ^{40}K , and ^{137}Cs , respectively. The term " $D_{natural}$ " is used to indicate the gamma dose rate resulting from the presence of naturally occurring radioactive materials (measured in nGy/h). D_{Total} represents the absorbed dose rate resulting from terrestrial gamma radiation. This encompasses both natural and artificially-induced radionuclides, as well as cosmic rays. At sea level, this rate is reported to be approximately 30 nGy/h [27].

The Annual Effective Dose (AED) is calculated as the product of $0.7 \text{ (Sv Gy}^{-1})$ the conversion factor, $OF_{outdoor}$ the outdoor occupancy factor, T the number of hours spent in the beach per year (1440 h for workers and 170 h for tourists), and 10^{-3} nano to micro conversion factor (Eq. 5). The resultant unit is expressed in microSieverts per year ($\mu\text{Sv/year}$).

$$AED_{outdoor} = D_{total} \times T \times 0.7 \times OF_{outdoor} \times 10^{-3} \quad (5)$$

Most of the radiation from beach sands affects the public due to the amount of time spent on the beach. Individuals were classified into two categories based on their beach activities. The first category, tourists, includes individuals who visit the beach for leisure and are assumed to stay for an average of three weeks and an average of eight hours per day. The second category, workers or residents, includes individuals who work on the beach for eight hours per day and stay for a period of six months. The estimated occupancy factor ($OF_{outdoor}$) for workers and tourists is 0.3 and T is 1440 h for workers and 170 h for tourists per year [15, 27].

Gamma rays emitted by the samples can cause cancer with prolonged exposure, both indoors and outdoors. The

Excess Lifetime Cancer Risk (ELCR) refers to the probability of cancer incidence in a specific population due to exposure to radiation. ELCR was calculated using the Eq. (6).

$$ELCR = AED_{\text{outdoor}} \times RF \times DL \quad (6)$$

where AED represents the annual effective dose rate (μSv^{-1}), RF denotes the cancer risk factor set by the

ICRP (0.05 Sv^{-1}), and DL indicates the life expectancy of 70 years.

Results and discussion

Specific activity concentrations of twenty-eight sand samples from six beaches were measured, six samples from Adrasan and Finike Beaches and four samples from Kumluca, Çıralı, Beykonak and Hasyurt Beaches. The activity results of each sample are shown in Fig. 3. The activity of ^{137}Cs was measured 2–4 times higher in Çıralı beach compared to other beaches. The highest activity of ^{232}Th and ^{40}K was measured at Adrasan beach. At ^{226}Ra activity concentration, very similar results were obtained in almost all samples.

The average specific activity concentrations were determined by calculating the weighted average of the specific activity concentrations of multiple samples collected from each beach. The specific activity of ^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs ranged from 6.8 ± 0.1 to $8.1 \pm 0.2 \text{ Bq kg}^{-1}$ (mean of $7.3 \pm 0.2 \text{ Bq kg}^{-1}$), 3.6 ± 0.1 to $6.8 \pm 0.2 \text{ Bq kg}^{-1}$ (mean of $4.7 \pm 0.2 \text{ Bq kg}^{-1}$), 67 ± 2 to $116 \pm 3 \text{ Bq kg}^{-1}$ (mean of $84 \pm 2 \text{ Bq kg}^{-1}$), and 0.05 ± 0.01 to $1.4 \pm 0.1 \text{ Bq kg}^{-1}$ (mean of $0.44 \pm 0.04 \text{ Bq kg}^{-1}$), respectively. The results and simple statistical calculations are given in Table 3 and Fig. 4.

Figure 5 shows frequency distribution plots of the specific activity measurements of ^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs in 28 samples of beach sand. The results show that ^{226}Ra and ^{40}K exhibit normal distributions. However, ^{232}Th and ^{137}Cs show significant multimodalities. These multimodalities indicate the varying mineralogical composition of the sampled beach sands. ^{232}Th shows a multimodal characteristic due to the complexity of the radioelements in these samples. Furthermore, studies have shown that thorium is less prone to leaching compared to uranium, so the increase of thorium levels is typically greater due to the fact that thorium minerals resist weathering [28].

The specific activity results of ^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs obtained in this study are compared in Table 4 with the data

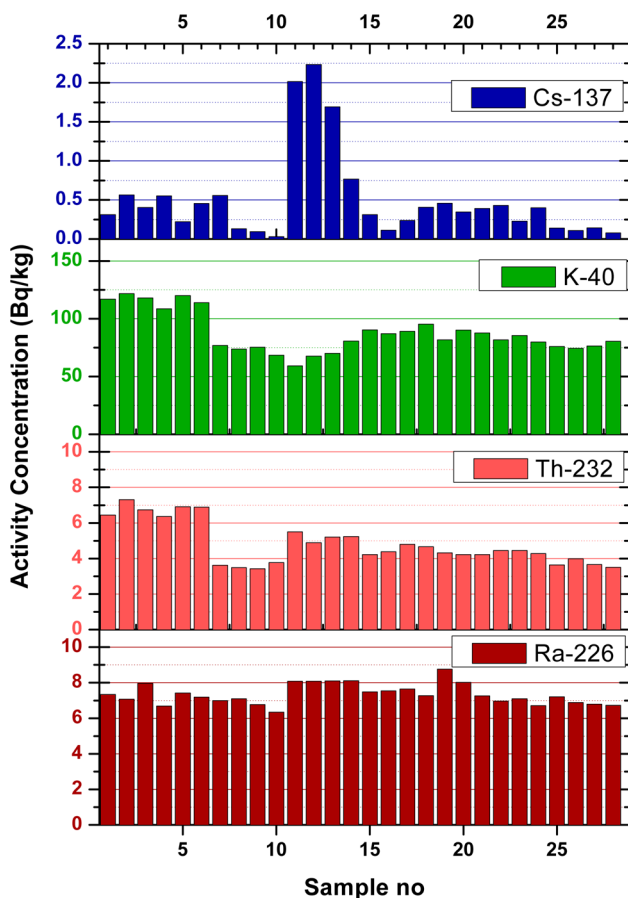


Fig. 3 The specific activities of ^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs for the sampling points given in Table 1

Table 3 Average specific activity concentration results on the beaches of West Antalya

Beaches	Ra-226 (Bq kg^{-1})	Th-232 (Bq kg^{-1})	K-40 (Bq kg^{-1})	Cs-137 (Bq kg^{-1})
Adrasan	7.2 ± 0.1	6.8 ± 0.2	116 ± 3	0.40 ± 0.03
Beykonak	6.9 ± 0.1	3.6 ± 0.1	73 ± 2	0.05 ± 0.01
Çıralı	8.1 ± 0.2	5.2 ± 0.2	67 ± 2	1.4 ± 0.1
Finike	7.8 ± 0.1	4.4 ± 0.2	88 ± 2	0.32 ± 0.04
Hasyurt	7.0 ± 0.2	4.3 ± 0.2	83 ± 2	0.37 ± 0.04
Kumluca	6.8 ± 0.1	3.7 ± 0.1	77 ± 2	0.11 ± 0.02
Minimum	6.8 ± 0.1	3.6 ± 0.1	67 ± 2	0.05 ± 0.01
Maximum	8.1 ± 0.2	6.8 ± 0.2	116 ± 3	1.41 ± 0.07
Mean	7.3 ± 0.2	4.7 ± 0.2	84 ± 2	0.44 ± 0.04

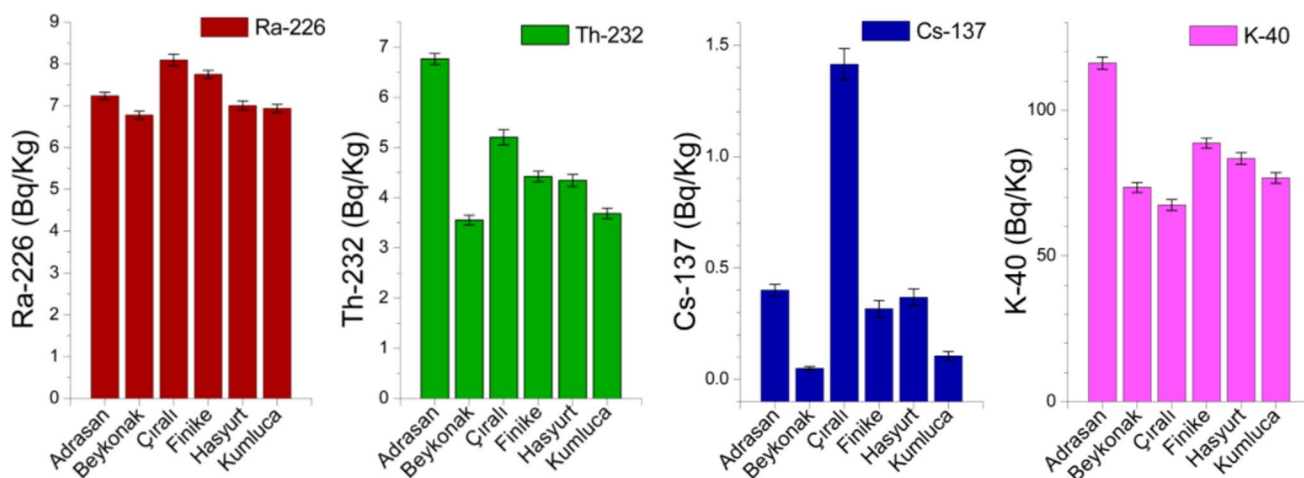


Fig. 4 Average specific activity concentration results on the beaches of West Antalya

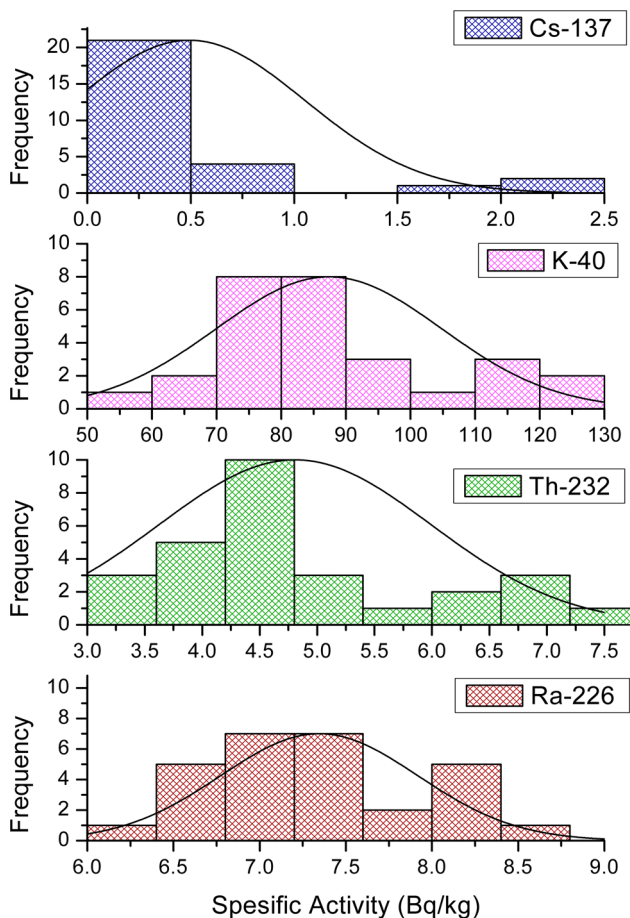


Fig. 5 The frequency distribution of ^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs specific activities of total 28 samples

of previous studies on beaches around the world. The results, obtained from measurements conducted in various locations around the globe, indicate that the specific activities

of radioactive materials are largely influenced by the geological characteristics of the investigated area. The values of the activity concentrations of ^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs measured in this study are mostly lower than the previously published data. They are quite similar to those measured in Spanish sands [22, 29].

The annual effective doses of radiation exposure that workers and tourists received while on the beaches of western Antalya were found to be between 11.61 and 12.88 μSv per year and between 1.37 and 1.52 μSv per year, respectively. The annual effective dose to be expected at each of the locations is shown in Table 5. The annual effective dose for beach workers and tourists does not exceed the UNSCEAR recommended limit of 70 μSv per year. There are no adverse health effects, such as tissue damage, genetic mutation, cancer, or cardiovascular disease, from prolonged exposure below these limits [35].

The ELCR values for workers range from 40.65×10^{-6} to 45.07×10^{-6} , with a mean value of 42.34×10^{-6} . On the other hand, the ELCR values for tourists range from 4.80×10^{-6} to 5.32×10^{-6} , with a mean value of 5.00×10^{-6} . Although the ELCR for workers is four times higher than that for tourists, both results are well below the recommended limit (290×10^{-6}) [36].

Conclusions

A radiological baseline study was conducted by determining the activity concentrations of natural and man-made radionuclides, including ^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs , in beach sand samples collected from the Antalya Coast in Turkey.

The measured average natural radiation activities were found to be below the standard world average values. While the ^{40}K isotope was found at comparable

Table 4 Results of previous studies on beaches around the world

Location	^{226}Ra (Bq kg^{-1})		^{232}Th (Bq kg^{-1})		^{40}K (Bq kg^{-1})		^{137}Cs (Bq kg^{-1})		References
	Min	Max	Min	Max	Min	Max	Min	Max	
India, Ulla	374		184		2158		–	–	[30]
Spain, Valencia	4	16	1	11	30	253	–	–	[29]
Jordan	14.8	59.4	3.5	31.2	65.8	379	–	–	[16]
Bangladesh, Cox's Bazar	10.8	27.3	27.4	49.4	117	688	–	–	[17]
India, Kalpakkam	36	258	352	3872	324	405	–	–	[24]
Spain, Mazagon	3.8	7.0	2.4	6.1	175	291	–	–	[22]
France, Camargue	1180	2240	1915	3470	45	80	–	–	[31]
Brazil	5	4043	7	55,537	25	888		–	[6]
Turkey, Çanakkale	79	1885	96.6	4360	687	1421	0.6	5.9	[13]
Egypt, Red Sea	7.2	40.9	3.7	37.9	159	2412	0.45	2.3	[23]
China, Rizhao,	7.6	17.2	7.8	25.1	883	1314	–	–	[32]
Turkey, Bodrum	9.5	71.5	25.8	42.8	510	835	–	–	[12]
NWFP, Pakistan	15.7	55.1	26.3	75.5	416	541	–	–	[33]
Thailand, Andaman	2.7	23.5	3.0	34.5	10.7	654	–	–	[34]
Turkey, Kocaeli	4.41	14.0	2.62	16.55	11.6	513	0.56	5.43	[11]
Malaysia, Langkawi	451.4	2411	232.2	1271	60.9	136	–	–	[1]
Egypt, North Sinai	1.2	16.7	23.3	60.9	25.0	182	–	–	[19]
Cyprus, Morphou Bay	12	37	18	71	411	720	0.8	3.1	[15]
Worldwide	35		30		400		–		[27]
Antalya, Turkey	6.8	8.1	3.6	6.8	67	116	0.05	1.41	This Study

Table 5 Estimated radiation risk parameters for workers and tourists for each beach

Beaches	Ra_{eq} (Bq/kg)	H_{ex}	D_{total} (nGy/h)	AED ($\mu\text{Sv}/\text{year}$)		$\text{ELCR} \times 10^{-6}$	
				Tourist	Workers	Tourist	Workers
Adrasan	25.85	0.07	42.59	1.52	12.88	5.32	45.07
Beykonak	17.50	0.05	38.41	1.37	11.61	4.80	40.65
Çıralı	20.71	0.06	39.85	1.42	12.05	4.98	42.17
Finike	20.89	0.06	40.06	1.43	12.11	5.01	42.40
Hasyurt	19.62	0.05	39.46	1.41	11.93	4.93	41.77
Kumluca	18.09	0.05	38.70	1.38	11.70	4.84	40.96
Minimum	17.50	0.05	38.41	1.37	11.61	4.80	40.65
Maximum	25.85	0.07	42.59	1.52	12.88	5.32	45.07
Mean	20.75	0.06	40.01	1.43	12.10	5.00	42.34

concentrations in other beaches, it was measured at a significantly higher level in Adrasan Beach compared to other beaches. The artificially produced ^{137}Cs isotope was detected in all sand samples, with an average specific activity concentration of 0.44 ± 0.04 Bq kg^{-1} . Furthermore, ^{137}Cs was measured at significantly higher levels at Çıralı Beach compared to other beaches. It is thought that this isotope is a product of the Chernobyl disaster or nuclear weapons testing. There is no indication of current transfer of ^{137}Cs or other isotopes via precipitation or indirect avenues, including sea runoff.

External radiation hazard indexes (H_{ex}) were estimated to range from 0.22 to 0.49 with an average of 0.34, while

radium equivalent activities (Ra_{eq}) were found to range from 82.78 to 182.97 Bq kg^{-1} with an average of 127.52 Bq kg^{-1} .

The estimated average annual effective doses and outdoor gamma dose rates for both tourists and workers were determined to be well below the global average. It should be noted that the calculated gamma dose measurement was taken at a height of 1 m above the ground, however, it is important to consider that most tourists spend their time much closer to the sand when on the beaches. Thus, the gamma dose they receive may be higher. However, the estimated lifetime excess cancer risk for tourists and workers spending time in this region is lower than the world average.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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