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ASSESSMENT OF RADIOACTIVITY STATUS IN COASTAL WATERS OF TÜRKIYE

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Anatolia has a geopolitical location between Europe and Asia, surrounded by sea on three sides. The Black Sea washes the northern coast of Türkiye, stretching 1,700 km from the suburbs of Istanbul to the town of Hopa. Following the Chernobyl Nuclear Power Plant accident, the dust cloud containing radioactive elements (first of all, an artificial radionuclide ^{137}Cs) reached western Türkiye in May 1986 and affected Thrace, Istanbul, and the western Black Sea. Upon the increase in radioactive fallout in these regions, a nationwide radiation monitoring program was initiated by the Turkish Atomic Energy Agency to determine the nuclear and radiological hazard status and geographical distribution of radionuclides. Many studies were focused on environmental radioactivity measurements in air, water, soil, rocks, and sediments in order to reveal the possible health effects of their radioactive pollution on the population of Türkiye after the Chernobyl NPP accident.

Keywords: Türkiye, the Black Sea water, the Chernobyl NPP accident, natural and artificial radionuclides

Radioactivity is the spontaneous disintegration of atomic nuclei, and occurs naturally or artificially [Bayrak, 2018; TAEK, 1988]. Until the beginning of the 20th century, living beings were only under the effect of natural radiation sources, such as ionizing radiations from natural radioactive materials and cosmic rays emanating from the Sun and space. However, with the discovery of radioactivity, radioactive sources began to be used in medicine, industry, agriculture, and research. The nuclear technology applications, atmospheric, aquatic, and underground nuclear weapon tests, as well as nuclear reactor explosions, are factors that initiate radioactive pollution and can cause releasing of artificial radionuclides – iodine-131 (^{131}I), iodine-129 (^{129}I), strontium-90 (^{90}Sr), cesium-137 (^{137}Cs), cesium-134 (^{134}Cs), and plutonium-239 (^{239}Pu) – into the environment [IAEA, 2011; TAEK, 2013]. By-products and waste of nuclear sources can be another source of artificial radioisotopes. Environmental toxicity risk may occur due to leakages that may arise from underground or undersea warehouses which are used for storing nuclear wastes for a long period. All these reasons have led researchers to focus on environmental radioactivity measurements in air, water, soil, rocks, and sediments to reveal possible effects of radioactive pollution on human health and environmental quality. World Health Organization (hereinafter WHO) determined the gross alpha and gross beta radioactivity limits in drinking water as 0.5 and 1.0 Bq·L^{-1}, respectively, and the annual effective dose limit as 0.1 mSv·year^{-1} [WHO, 2004]. Also, in the Republic of Türkiye, within the scope of the “Regulation on Water Intended for Human Consumption” published by the Ministry of Health, the annual effective dose limit has been determined as 0.1 mSv·year^{-1} [Ministry of Health, 2005]. In cases where gross alpha and gross beta in drinking water are above the limit values, the total dose calculation, which is a detailed radionuclide analysis, is performed.

The main radioactive substances frequently encountered in groundwater are potassium-40 (^{40}K), thorium-232 (^{232}Th), and uranium-238 (^{238}U). In addition, radon-222 (^{222}Rn) and radium-226 (^{226}Ra), which are formed as a result of ^{238}U decay, can be found in groundwater. It is known that ^{238}U, ^{232}Th, ^{40}K and their decay products, which are the key sources of radioactivity, are most enriched in granitic rocks [Abdel Hady et al., 1994]. For this reason, water taken from granitic aquifers is always approached with close attention.

The main source of environmental radioactivity is radioactive fallout after a nuclear or radiological accident. It is extremely important to know the dimensions of the radioactive fallout to accurately determine the possible effects of radiation and radioactive contamination on human health and the environment [TAEK, 2013]. As several European countries, Türkiye began raising these issues after the Chernobyl disaster in 1986. Shortly after the Chernobyl Nuclear Power Plant (NPP) accident, the dust cloud containing radioactive elements reached western Türkiye and affected especially Thrace, Istanbul, and the western Black Sea region through rain. Another important area affected by this accident was the eastern Black Sea region, where the dust cloud left its radioactive content along the coast after heavy rain. Conducted studies showed that artificial radionuclide ^{137}Cs originating from Chernobyl was detected in the Black Sea region [Environmental Radioactivity, 2020; Gokmen et al., 1995; Kapdan et al., 2012a].

Anatolia has a geopolitical location between Europe and Asia, and is surrounded by seas on three sides. The Black Sea is situated in the north of Türkiye, between Asia and Europe, and covers an area of approximately 497.000 km^2 together with the Sea of Azov. The Black Sea is connected to the Mediterranean Sea in the south after the Bosphorus Strait and the Sea of Marmara and next after the Dardanelles Strait and the Aegean Sea [Akengin et al., 2016]. Although Türkiye is surrounded by seas on three sides, it has limited water resources, and the protection of water quality in the country is very important. Following the Chernobyl NPP accident, a major radioactive fallout (^{137}Cs, a common fission product with its high water solubility) was released from the atmosphere. It affected the Eastern Europe, the Black Sea, and northern coasts of Türkiye [Kulahci, Doğru, 2006; Özmen, Güven, 2021]. After radioactive fallout resulting from the Chernobyl NPP accident, the increase of the specific activity of artificial radionuclides in natural environments in Türkiye was recorded.

Upon seeing the rising values, a nationwide radiation monitoring program was started by the Turkish Atomic Energy Agency [1988]. Recently, a comprehensive study was conducted by the Agency to determine the nuclear and radiological hazard status and geographical distribution of radionuclides present in surface soils and in drinking and utility waters in 81 provinces in Türkiye between 2002 and 2011 [TAEK, 2013].

The aim of the research is to assess the current quality of coastal ecosystems of the Black Sea along the coast of Türkiye in relation to natural and artificial radionuclides based on a generalized analysis of our own and literature data.

MATERIAL AND METHODS

This study was carried out to assess the quality of Turkish coastal ecosystems in terms of natural and artificial radionuclides. In the research, the analysis results of Turkish coastal waters, sediment, and soil samples given in the literature between 2000 and 2021 were evaluated. The most commonly used methods in the literature for determining the activities of natural and artificial radionuclides are alpha/beta counters, gamma spectroscopy, alpha spectroscopy, liquid scintillation spectroscopy, and nuclear track detectors.

The data evaluated also include the results of gross alpha and gross beta analysis, conducted by N. Dogan, one of the authors of this article, on water samples taken from various parts of Türkiye in 2017. The collected water samples are prepared for measurements as described in EPA method 900.0 [2025].

The water sample is evaporated on a heater until approximately 10–15 mL remains, providing sufficient residue for counting (5 $mg \cdot cm^{-2}$ for alpha and 10 $mg \cdot cm^{-2}$ for beta). The remaining water is transferred to ~ 5-cm (2-inch) diameter steel planchets under an infrared lamp, dried in an oven at +105 °C until a constant weight is obtained, and then counted. Total alpha and total beta activity values from the residual water sample are measured with a 10-channel multi-detector system (Berthold LB 770) with low natural background counting and calculated using equation 1:

$$A_{\alpha,\beta}(Bq/L) = \frac{N}{(60 \times Eff \times V)}\,, \tag{1}$$

where $A_{\alpha,\beta}$ is total alpha/beta activity of the sample ($Bq \cdot L^{-1}$);

N in net count rate of the sample (counts *per* minute, cpm);

Eff is counting efficiency of the system ($cpm \cdot dpm^{-1}$);

V is volume of the sample (L);

60 is conversion factor ($min \cdot s^{-1}$).

The Berthold LB 770 system is a proportional gas counter operating on the principle that both alphas and betas are counted independently of each other simultaneously [Dogan, 2017; EPA Method 900.0, 2025].

RESULTS AND DISCUSSION

Radioactivity status of coastal waters in Türkiye. The first effects of the Chernobyl NPP accident occurred on 30 April, 1986, in the North-Western (Thrace) region and the Black Sea coast of Türkiye with increases in environmental natural gamma radiation levels. In the meantime, radioactive substances in the air descended to the earth with heavy rains, which caused significant contamination in the region. According to the measurements made, the gross beta activity accumulated in the soil in Istanbul and its surroundings in the first two weeks of May was 3,000 $Bq \cdot m^{-2}$. The gross beta activity concentration of the rainwater collected in Kapıkule (Edirne) on 4 May was found to be around 9,000 $Bq \cdot L^{-1}$, and the gross beta activity of rainwater collected in Istanbul on 10 May was around 3,500 $Bq \cdot L^{-1}$. These activity increases in rain water did not affect the groundwater in Edirne region, but caused minor activity increases in surface waters around Istanbul. As a matter of fact, in the gross beta activity measurements made on 5–22 May in Istanbul drinking and tap water, the highest activity concentration was found to be around 9 $Bq \cdot L^{-1}$ on 5 May. In the following days, it gradually decreased to its normal level [TAEK, 1988].

The data of studies conducted in order to determine gross alpha and gross beta radioactivity levels in water ($Bq \cdot L^{-1}$) at different locations in Türkiye are given in Table 1. High gross alpha activity values were observed in Izmir Golcuk Lake [Akyil et al., 2009] and the Mediterranean Sea water near Adana (Karatas and Incirli regions) [Degerlier, Karahan, 2010].

High gross beta activity values were observed in the Canakkale Strait [Kam et al., 2017], seawater near Istanbul, Kucuk Cekmece Lake [Karahan et al., 2000], the Marmara Sea water [Karahan et al., 2000; Otansev et al., 2016], the Black Sea and the Boshporus Strait water [Karahan et al., 2000], Izmit Bay seawater [Bayrak, 2018], Izmir Karagol Lake, Izmir Golcuk Lake, Izmir Cakalbogaz Lake [Akyil et al., 2009], and the Mediterranean Sea water near Adana, Karatas, and Incirli regions [Degerlier, Karahan, 2010]. Spatial concentrations of gross alpha and beta activity values in surface waters of Turkish coastal area are shown in Figs 1 and 2, respectively.

Table 1. Gross alpha and gross beta radioactivity levels (Bq·L^{-1}) in water of the seas along the Turkish coast and inland waters at different locations of Türkiye

Таблица 1. Уровни суммарной альфа- и бета-активности (Бк·л$^{-1}$) в воде морей вдоль турецкого побережья и внутренних водоёмов в различных районах Турции

Area	Gross alpha	Gross beta	References
Canakkale Strait	0.05–0.06	10.53–14.33	Kam et al., 2017
Seawater near Istanbul	0.4	4.9	Karahan et al., 2000
Kucuk Cekmece Lake	0.06	3	
Buyuk Cekmece Lake	0.05	0.3	
Terkos Lake	0.02	0.2	
Omerli Dam Lake	0.034	0.04	
The Marmara Sea water	0.5	5.0	
The Black Sea water	0.4	5.6	
The Black Sea and the Boshporus Strait water	0.3	5.3	
The Marmara Sea	0.01–0.09	6.51–19.09	Otansev et al., 2016
Izmit Bay seawater	0.03	9.74	Bayrak, 2018
Surface waters in Kastamonu near the Black Sea	0.001–0.026	0.016–2.241	Kam, Bozkurt, 2007
Surface waters in Samsun near the Black Sea	0.024–0.116	0.041–0.191	Görür et al., 2011
The Yesilırmak River	0.128	0.170	
The Kızılırmak River	0.156	0.191	
The Fırtına River	0.012–0.066	0.028–0.133	Küçükömeroğlu et al., 2008
Surface waters in Hatay near the Mediterranean Sea	0.010–0.086	0.014–0.949	Turgay et al., 2016
Surface waters in Giresun near the Black Sea	0.003–0.011	0.040–0.264	Damla et al., 2006
Surface waters in Trabzon near the Black Sea	0.004–0.039	0.022–0.191	Damla et al., 2006; Küçükömeroğlu et al., 2021
Surface waters in Rize near the Black Sea	0.0002–0.042	0.025–0.238	Damla et al., 2006; Islam, 2016
Surface waters in Adana near the Mediterranean Sea	0.0003–0.023	0.019–0.291	Degerlier, Karahan, 2010
The Mediterranean Sea water near Adana (Karatas)	0.8463	3.7395	
The Mediterranean Sea water near Adana (İncirli)	0.703	6.81	
Seyhan Lake (Adana)	0.012	0.0426	
The Seyhan River (Adana)	0.005	0.2453	
Karagol Lake (Izmir)	0.03	2.62	Akyil et al., 2009
Golcuk Lake (Izmir)	0.75	2.35	
Cakalbogaz Lake (Izmir)	0.03	1.77	
Surface waters in Zonguldak near the Black Sea	0.0029–0.1705	0.0154–0.2443	Aytekin, Bayraktaroğlu, 2017
SHW Bursa Regional Directorate	0.022–0.302	0.06–0.32	Dogan, 2017
SHW Izmir Regional Directorate	0.098–0.193	0.15–0.46	
SHW Adana Regional Directorate	0.031–0.096	0.04–0.18	
SHW Samsun Regional Directorate	0.027–0.070	0.05–0.12	
SHW Edirne Regional Directorate	0.040–0.100	0.01–0.24	
SHW Antalya Regional Directorate	0.008–0.083	0.02–0.18	
SHW Istanbul Regional Directorate	0.035–0.178	0.06–0.43	
SHW Aydın Regional Directorate	0.025–0.054	0.05–0.15	
SHW Trabzon Regional Directorate	0.011–0.086	0.03–0.17	
SHW Kastamonu Regional Directorate	0.030–0.131	0.01–0.11	
SHW Balıkesir Regional Directorate	0.047–0.233	0.06–0.31	

Note: SHW, State Hydraulic Works.

Примечание: SHW — Государственное управление гидротехнических сооружений.

Fig. 1. Spatial concentration of gross alpha activity in surface waters along the Turkish coast

Рис. 1. Пространственное распределение суммарной альфа-активности в поверхностных водах вдоль турецкого побережья

Fig. 2. Spatial concentration of gross beta activity in surface waters along the Turkish coast

Рис. 2. Пространственное распределение суммарной бета-активности в поверхностных водах вдоль турецкого побережья

The concentrations of environmental radioactivity were investigated in sediment cores sampled at different depths (5–5.5, 10–10.5, and 15–15.5 m at the same point) from Kulakcayırı Lake situated in Istanbul. While ^{40}K concentrations increased with depth, the maximum value was found as 367 Bq·kg^{-1} d. w. (dry weight). Maximum ^{232}Th concentration was registered as 43 Bq·kg^{-1} d. w. at the middle depth, while maximum ^{226}Ra was found as 29 Bq·kg^{-1} d. w. at the first depth. It was reported that the activity of ^{137}Cs was below the minimum detectable activity value [Kam et al., 2018].

The specific activity of natural and artificial radionuclides was determined in bottom sediments of the Golden Horn Bay located in the center of Istanbul. The specific activity values of these radionuclides were the following: 7.18–20.16 Bq·kg^{-1} d. w. for ^{238}U; 6.41–27.25 Bq·kg^{-1} d. w. for ^{232}Th; 281.9–683 Bq·kg^{-1} d. w. for ^{40}K; and 1.12–67.92 Bq·kg^{-1} d. w. for ^{137}Cs [Kılıç, Çotuk, 2011].

The radioactivity concentrations in sediment and seawater samples of the Marmara Sea were determined. Seawater samples were collected from various depths: surface samples, from 5 m below the water line, and bottom samples, from depths of 47–89 m. As revealed, the gross alpha and beta activity levels rose with increasing water depth. The mean gross alpha and beta activity concentrations in seawater samples from the Marmara Sea were 0.042 and 13.402 Bq·L^{-1}, respectively. The radionuclide activity was also determined in sediment samples. The maximum values were found for ^{226}Ra (34.2 Bq·kg^{-1} d. w.), ^{238}U (25.9 Bq·kg^{-1} d. w.), ^{232}Th (31.1 Bq·kg^{-1} d. w.), ^{40}K (693.6 Bq·kg^{-1} d. w.), and ^{137}Cs (16.3 Bq·kg^{-1} d. w.). The obtained results revealed that the mean amounts of ^{226}Ra, ^{238}U, and ^{232}Th were below the limit value; however, the mean amount of ^{40}K was higher than the world mean level [Otansev et al., 2016].

The natural and artificial radionuclide levels in the Marmara Sea region were studied both in Izmit Bay Yalova and Kocaeli. Surface sediment samples were analyzed in Izmit Bay, which is located in industrialized zone of the Marmara Sea. The mean activity concentration of ^{137}Cs was detected as 21 Bq·kg^{-1} d. w., while that of natural radioisotopes, ^{40}K and ^{226}Ra, as 568 and 18 Bq·kg^{-1} d. w., respectively. The highest value for natural radionuclide activities was recorded near petrochemical, phosphate, and fertilizer processing facilities. The mean ^{137}Cs activities were 10 times higher than those in marine sediments in the Middle East and lower than in sediments in Northern Europe [Ergül et al., 2013]. Marine sediments in the Yalova region were sampled from 6 different points ranging 7 to 38 m; mean activities of ^{40}K, ^{232}Th, ^{226}Ra, and ^{137}Cs of sediment samples were found as 589.2, 32.7, 19.7, and 4.17 Bq·kg^{-1} d. w., respectively. Mean activities of gross alpha and beta of three seawater samples were 0.028 and 9.739 Bq·L^{-1}, respectively [Bayrak, 2018].

Soil samples from 27 points in Kocaeli Basin were analyzed in terms of radionuclides. The concentrations determined were as follows: 2–25 Bq·kg^{-1} d. w. for ^{137}Cs; 11–49 Bq·kg^{-1} d. w. for ^{238}U; 161–964 Bq·kg^{-1} d. w. for ^{40}K; 10–58 Bq·kg^{-1} d. w. for ^{226}Ra; and 11–65 Bq·kg^{-1} d. w. for ^{232}Th [Karakelle et al., 2002]. The Canakkale Strait has a strategic position between the Gallipoli and Biga peninsulas and is connected with the Sea of Marmara and the Aegean Sea. Within the study conducted in the Canakkale Strait, the levels of gross alpha and beta radioactivity in seawater were of 0.046–0.064 and 10.53–14.325 Bq·L^{-1}, respectively. The gross alpha values in the study area were lower compared to gross beta values in the same area [Kam et al., 2017].

The effect of radioactive pollution on the habitat of benthic Foraminifera was analyzed in another study conducted in the Canakkale Strait [Yümün, Kam, 2017]. The radionuclide concentrations were measured on 7 core samples and 1 drilling sample from the shallow marine environment. The values for different radionuclides were in the following ranges: 17.5 to 58.3 Bq·kg^{-1} d. w. for ^{232}Th; 16.9 to 48.6 Bq·kg^{-1} d. w. for ^{226}Ra; 443.7 to 725.6 Bq·kg^{-1} d. w. for ^{40}K; and < 2 to 20 Bq·kg^{-1} d. w. for ^{137}Cs. While ^{226}Ra values remained within normal limits, ^{40}K and ^{232}Th values were above the world mean limits defined by the United Nations Scientific Committee on the Effects of Atomic Radiation [2000]: for ^{226}Ra, it is 35 Bq·kg^{-1} d. w.; for ^{40}K, 400 Bq·kg^{-1} d. w.; and for ^{232}Th, 30 Bq·kg^{-1} d. w.

The Balıkesir province situated in the northwest of Türkiye was investigated in terms of activity levels of radionuclides in the soil. ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs activities were within the ranges of 7.7–71.9, 10.1–94.9, 96.3–1,831.9, and 0.59–27.80 Bq·kg^{-1} d. w., respectively [Kapdan et al., 2012b].

Environmental radioactivity has been studied by different researchers in various points of the Black Sea coastal area. In 1997–1998, the activity levels of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs radionuclides were investigated in sediments sampled from different points along the Turkish Black Sea coast. The activities of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs in the sediment samples were within the ranges of < 13 to 56; 17 to 37; 301 to 833; and 11 to 138 Bq·kg^{-1} d. w., respectively. It was reported that ^{137}Cs activity in the sediment sample is an indication that the eastern shore of the Black Sea was more affected by Chernobyl NPP accident than the western shore [Topcuoglu et al., 2001].

Zonguldak city, which has the richest hard coal mines in Türkiye, is located on the Black Sea coast and occupies an important place in the maritime trade between Türkiye and the Black Sea countries, especially with those having ports. In order to determine the radiological status of spring waters in Zonguldak city, 49 different water samples were analyzed, and gross alpha and beta levels were found to be 0.003–0.171 and 0.015–0.244 $Bq \cdot L^{-1}$, respectively. The measured gross alpha and beta activity concentrations were lower than the limit values suggested by WHO [Aytekin, Bayraktaroğlu, 2017].

Kastamonu is in the northern part of Türkiye, and it is in the Black Sea region. Natural and artificial radionuclide activities were measured in water and soil, which were sampled from Kastamonu province. The gross alpha and beta activity concentrations recorded in water samples were 0.001–0.026 and 0.016–2.241 $Bq \cdot L^{-1}$, respectively. The radioactivity levels of soil samples were assessed as well (on d. w.); the mean concentrations were found as 32.9 $Bq \cdot kg^{-1}$ for ^{238}U; 27.2 $Bq \cdot kg^{-1}$ for ^{232}Th; 431.4 $Bq \cdot kg^{-1}$ for ^{40}K; and 8.0 $Bq \cdot kg^{-1}$ for ^{137}Cs [Kam, Bozkurt, 2007].

The gross alpha and beta levels of tap water samples were determined in a study conducted in the Eastern region of Türkiye. The activity values ranged 0.004 to 0.01 $Bq \cdot L^{-1}$ for alpha and 0.032–0.191 $Bq \cdot L^{-1}$ for beta in the province of Trabzon. In Giresun, the gross alpha and beta levels ranged 0.003 to 0.011 $Bq \cdot L^{-1}$ and 0.04 to 0.264 $Bq \cdot L^{-1}$, respectively. The values ranged 0.0002 to 0.015 $Bq \cdot L^{-1}$ for alpha and 0.025 to 0.238 $Bq \cdot L^{-1}$ for beta in the province of Rize. These results indicated that the lowest gross alpha and beta values were obtained in tap water samples from Trabzon. Rize showed the highest gross alpha activity, while the Giresun had the highest gross beta activity. This analysis provided evidence that the gross alpha and beta activity levels in tap waters in Eastern region of Türkiye were in good condition and below the limit values given by WHO [2004] and Turkish regulations [Ministry of Health, 2005] for drinking water [Damla et al., 2006]. A recent study determined the gross alpha and beta concentrations in water samples collected from different areas of Rize Province with the values ranging 0.012 to 0.042 $Bq \cdot L^{-1}$ for gross alpha and 0.027 to 0.211 $Bq \cdot L^{-1}$ for gross beta [Islam, 2016]. The radionuclides values were measured in the drinking water samples of Trabzon region and found as 0.008–0.654 $Bq \cdot L^{-1}$ for ^{238}U; 0.007–0.067 $Bq \cdot L^{-1}$ for ^{232}Th; 0.010–0.337 $Bq \cdot L^{-1}$ for ^{40}K; and 0.0002–0.056 $Bq \cdot L^{-1}$ for ^{137}Cs [Küçükömeroğlu et al., 2021].

The gross alpha and beta radioactivity and annual effective doses were investigated in various waters of Samsun city situated in the central part of the Black Sea coastline, between the deltas of the Yesilırmak and the Kızılırmak rivers. Activity concentrations of gross alpha and beta in tap water samples were detected as 0.024–0.1156 and 0.0408–0.1905 $Bq \cdot L^{-1}$, respectively. The radioactivity concentrations measured for the Yesilırmak and the Kızılırmak rivers were 0.128 and 0.1556 $Bq \cdot L^{-1}$ for gross alpha and 0.170 and 0.191 $Bq \cdot L^{-1}$ for gross beta, respectively. The calculated annual effective doses of alpha- and beta-emitters were found to be below the reference value recommended by WHO (0.1 $mSv \cdot year^{-1}$) for all water samples [Görür et al., 2011]. The radionuclides status in soil and sediment of the Kızılırmak River delta was measured in another study. The following mean values were determined: 28.59 $Bq \cdot kg^{-1}$ d. w. for ^{238}U; 17.48 $Bq \cdot kg^{-1}$ d. w. for ^{232}Th; 150.59 $Bq \cdot kg^{-1}$ d. w. for ^{40}K; and 5.32 $Bq \cdot kg^{-1}$ d. w. for ^{137}Cs; those are below the worldwide mean values given by UNSCEAR. It is stated that ^{137}Cs could result from the Chernobyl NPP accident and nuclear weapon tests conducted by several countries until 1980 [Arıman, Gümüş, 2018; UNSCEAR, 2000].

The Fırtına River, one of the important rivers in the eastern Black Sea region, arises from the slopes of the Kackar Mountains and is connected to the eastern Black Sea near 2 km to Ardesen town in the west of Rize. The natural radioactivity concentrations of water, sediment, and soil samples were investigated in several expeditions. The mean concentration levels (on d. w.) for ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs in soils and bottom sediment samples were as follows: 50, 42, 643, and 85 $Bq \cdot kg^{-1}$ and 39, 38, 573, and 6 $Bq \cdot kg^{-1}$, respectively. The presence of ^{137}Cs in soil and sediment samples was related to the Chernobyl NPP accident, as well as to atmospheric nuclear weapon tests carried out by several countries [Kurnaz et al., 2007].

Other radioactivity studies on water and sediment samples of the Fırtına River stated that the natural gross alpha and beta levels in water samples were between 0.012–0.066 and 0.028–0.133 Bq·L^{-1}, respectively. The mean specific activities of gamma-emitting radionuclides in bottom sediments (on d. w.) were as follows: 47.41 Bq·kg^{-1} for ^{226}Ra; 39.93 Bq·kg^{-1} for ^{238}U; 38.55 Bq·kg^{-1} for ^{232}Th; 573.34 Bq·kg^{-1} for ^{40}K; and 6.15 Bq·kg^{-1} for ^{137}Cs. The existence of ^{137}Cs was also related to the Chernobyl NPP accident, the same as in the previous investigation [Küçükömeroğlu et al., 2008]. The radioactivity concentrations of seawater and bottom sediments sampled from five different locations in the Rize province of the Eastern Black Sea were measured in recent study. The concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in bottom sediment samples (on d. w.) and water samples (data presented in parentheses) varied in the following ranges: 9–23 Bq·kg^{-1} (0.16–0.63 Bq·L^{-1}); 6–34 Bq·kg^{-1} (0.07–0.17 Bq·L^{-1}); 223–765 Bq·kg^{-1} (3.44–6.20 Bq·L^{-1}); and 5–12 Bq·kg^{-1} (no values for seawater), respectively [Baltas et al., 2017].

Studies carried out in 2015 and 2019 were focused on the radioactivity status of the Coruh River in Artvin. In 2015, sediments were sampled from 3 different dam reservoirs on the Coruh River. The mean concentrations (on d. w.) of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs were determined: in Deriner Dam Lake, 15.8, 13.9, 551.5, and 18.1 Bq·kg^{-1}; in Borcka Dam Lake, 3.7, 12.5, 473.8, and 6.8 Bq·kg^{-1}; and in Muratlı Dam Lake, 14.4, 30.0, 491.7, and 18.2 Bq·kg^{-1}, respectively. It was reported that activity levels of radionuclides decreased from the upper parts of Çoruh River to coastal area [Kobya et al., 2015]. In 2019, the concentrations of radionuclides in sediment samples (on d. w.) collected from the Borcka Dam Lake were determined. The mean activity concentrations were found to be below worldwide mean values given by UNSCEAR [2000]: 12.19 Bq·kg^{-1} for ^{226}Ra; 14.05 Bq·kg^{-1} for ^{232}Th; 396.41 Bq·kg^{-1} for ^{40}K; and 4.20 Bq·kg^{-1} for ^{137}Cs [Şirin, 2019].

Izmir, which is located in the western part of Türkiye, was investigated in terms of gross alpha and beta and uranium levels in surface water of lakes. The mean gross alpha and beta activity levels were determined as 0.03 and 2.62 Bq·L^{-1} for Karagol Lake; 0.75 and 2.35 Bq·L^{-1} for Golcuk Lake; and 0.03 and 1.77 Bq·L^{-1} for Cakalbogaz Lake, respectively. It was also found that the uranium concentration ranged 0.05 to 900 μg·L^{-1} for Karagol Lake; 0.05 to 0.95 μg·L^{-1} for Golcuk Lake; and 3.33 to 10 μg·L^{-1} for Cakalbogaz Lake [Akyil et al., 2009]. In another study aimed at detecting radionuclides in beach sand samples, the following results were obtained: 5.70–38.83 Bq·kg^{-1} d. w. for ^{226}Ra; 3.870–292.7 Bq·kg^{-1} d. w. for ^{232}Th; and 120.4–377.6 Bq·kg^{-1} d. w. for ^{40}K [Gür, Tarakçı, 2018].

The specific activity levels of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were determined very recently to evaluate the radiological status of the fisheries ground sediments in the Antalya Bay situated on the Mediterranean Sea coastline. The activity values ranged 10.65 to 23.76 Bq·kg^{-1} for ^{226}Ra; 11.63 to 24.15 Bq·kg^{-1} for ^{232}Th; 316.35 to 414.83 Bq·kg^{-1} for ^{40}K; and 1.48 to 8.58 Bq·kg^{-1} for ^{137}Cs in the sediment samples (on d. w.) where the values were below the world mean activity levels defined by UNSCEAR [Özmen, Güven, 2021; UNSCEAR, 2000].

The natural radioactivity status in different surface waters of Adana, which is located in the southern part of Türkiye, was investigated in 2010. The mean gross alpha and beta levels in drinking water samples were detected as 0.0096 and 0.086 Bq·L^{-1}, respectively. During the studies on sea samples, gross alpha and beta levels were measured as 0.8463 and 3.7395 Bq·L^{-1} in the Karatas Sea and 0.703 and 6.81 Bq·L^{-1} in the Incirli Sea, respectively. The gross alpha and beta levels in other sampling points, Seyhan Dam Lake and the Seyhan River, were found to be below WHO limit values [Degerlier, Karahan, 2010].

The radioactivity level in water samples of Hatay city located in the southeastern region of Türkiye was investigated in 2015. While the mean alpha activity was obtained as 0.037 Bq·L^{-1}, the mean beta activity was assessed as 0.116 Bq·L^{-1}. The annual effective doses were calculated as 7.50 and 58.61 μSv from alpha- and beta-emitting radionuclides, respectively, which were lower than 0.1 mSv·year^{-1} suggested by [Turgay et al., 2016; WHO, 2004].

The gross alpha and beta radioactivity values were investigated in various water samples at 11 different coastal regions of Türkiye. According to the results obtained, the gross alpha radioactivity concentrations ranged between 0.008 Bq·L^{-1} (Antalya) and 0.302 Bq·L^{-1} (Bursa), while the gross beta ranged between 0.01 Bq·L^{-1} (Edirne and Kastamonu) and 0.46 Bq·L^{-1} (İzmir). They were below WHO values [2004]. As observed, the gross beta radiation results were higher than the gross alpha radiation ones, which was related to the difference in geological formation of studied areas [Dogan, 2017].

The summary of the activity concentration of radionuclides in bottom sediment and soil samples at different locations in Türkiye is presented in Table 2.

Table 2. Activity concentration of radionuclides in bottom sediment and soil samples (Bq·kg^{-1} dry weight) at different locations in Türkiye

Таблица 2. Удельная активность радионуклидов в пробах донных отложений и почв (Бк·кг$^{-1}$ сухой массы) из различных районов Турции

Area	^{238}U	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	References
Trabzon (soil)	11.5–115	–	8.5–49	153–548	1–201	Küçükömeroğlu et al., 2021
Fırtına River (bottom sediments)	16.10–113.25	15.20–116.55	17.26–87.45	51.41–1,605.26	0.87–41.72	Küçükömeroğlu et al., 2008
Fırtına Valley (soil)	11–188	15–188	10–105	105–1,235	19–232	Kurnaz et al., 2007
Rize (soil)	52.44–240.71	58.4–193.7	14.29–83.83	118.43–520.37	0–219.19	Islam, 2016
Rize (bottom sediments)	–	9–23	6–34	223–765	5–12	Baltas et al., 2017
Borçka Dam Lake (bottom sediments)	–	4.79–21.46	9.36–20.65	238.01–721.26	0.79–6.81	Şirin, 2019
Kızılırmak delta (bottom sediments)	7.00–52.14	–	11.55–34.83	149.24–287.36	12.90–21.39	Arıman, Gümüş, 2018
Kızılırmak delta (soil)	19.64–42.88	–	13.67–33.83	204.91–633.72	1.11–4.11	
Balıkesir (soil)	7.70–71.90	–	10.10–94.90	96.30–1,831.90	0.59–27.80	Kapdan et al., 2012b
Istanbul (soil)	3–59	–	8–91	117–1,204	2–81	Karahan et al., 2000
Kocaeli (soil)	11–49	10–58	11–65	161–964	2–25	Karakelle et al., 2002
Çanakkale (soil)	82–167	–	152–275	1,015–1,484	0.37–36.03	Kurnaz et al., 2007; Merdanoğlu, Altınsoy, 2006
Çanakkale (bottom sediments)	–	16.90–48.60	17.50–58.30	443.70–725.60	< 2 to 20	Yümün, Kam, 2017
Deriner Dam Lake (bottom sediments)	15.8	–	13.9	551.5	18.1	Kobya et al., 2015
Borcka Dam Lake (bottom sediments)	3.7	–	12.5	473.8	6.8	
Muratlı Dam Lake (bottom sediments)	14.4	–	30.0	491.7	18.2	
Kulakcayırı Lake (bottom sediments)	–	26–29	38–43	325–367	–	Kam et al., 2018
Antalya Bay (bottom sediments)	–	10.65–23.76	11.63–24.15	316.35–414.83	1.48–8.58	Özmen, Güven, 2021
The Golden Horn and the Bosphorus (bottom sediments)	7.18–20.16	–	6.41–27.25	281.9–683	1.12–67.92	Kılıç, Çotuk, 2011
The Marmara Sea (bottom sediments)	6.40–25.90	13.80–34.20	6.30–31.10	378.80–693.60	4.8–16.3	Otansev et al., 2016

Continued on the next page…

Area	^{238}U	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	References
The Izmit Bay (bottom sediments)	–	18	–	568	21	Ergül et al., 2013
Yalova Altınova (bottom sediments)	–	19.70	32.70	589.20	4.17	Bayrak, 2018
Kastamonu (soil)	32.93	37.40	27.17	431.43	8.02	Kam, Bozkurt, 2007
Igneada (bottom sediments)	41	–	17	316	11	Topcuoglu et al., 2001
Kilyos (bottom sediments)	26	–	19	350	23	
Amasra (bottom sediments)	17	–	27	301	50	
Sinop (bottom sediments)	40	–	34	501	94	
Persembe (bottom sediments)	< 13	–	36	833	138	
Rize (bottom sediments)	56	–	37	358	104	
Izmir (beach sand)	–	5.70–38.83	3.87–292.7	120.4–377.6	–	Gür, Tarakçı, 2018
Worldwide mean values	35	35	30	400	–	UNSCEAR, 2000

Health assessment. Ionizing radiation can cause physical, chemical, and biological changes in living things at molecular and cellular levels [Varol, 2011]. These changes may be temporary or permanent depending on the type, intensity, amount of ionizing radiation, duration of the exposure, and also the area of the body exposed [Gökoğlan et al., 2020]. Since alpha particles are heavier than beta particles, they can be absorbed by the skin of the body. When taken into the body by inhalation or ingestion, it can cause serious damage to tissues of lung or stomach walls. Beta particles are faster than alpha particles and can penetrate more into tissue or materials. Skin burns can be seen in cases of excessive exposure to high-energy beta radiation. The major concern with ionizing radiation is its cancer effect and the transmission of defects, called delayed effects, to future generations by genetic means [Varol, 2011]. Therefore, the effect of radiation on human health is still being investigated. In recent years, many analyses have been made on vital water resources. The obtained results are compared with the permissible limit values given by WHO: 0.5 $Bq \cdot L^{-1}$ for gross alpha and 1 $Bq \cdot L^{-1}$ for gross beta. If the measured values are lower than the limits, the sample is considered suitable for drinking water. In case of exceeding the given limits, it is necessary to determine the radionuclide species in the samples. The determined dose amounts of these radionuclides are compared with the effective dose amount (0.1 $mSv \cdot year^{-1}$) that can be taken in a year determined by WHO [2004]. If the dose amounts do not exceed the limit value, the sample complies with the drinking water criteria in terms of radioactivity. Regarding soil samples, the worldwide mean values reported by UNSCEAR are used for comparison: 35 $Bq \cdot kg^{-1}$ d. w. for ^{238}U; 30 $Bq \cdot kg^{-1}$ d. w. for ^{232}Th; and 400 $Bq \cdot kg^{-1}$ d. w. for ^{40}K. If the worldwide mean values are exceeded, the annual mean effective dose is calculated and compared with the value of 70 μSv determined by UNSCEAR [2000].

Conclusions. Türkiye has a geopolitical location between Europe and Asia and is surrounded by sea on three sides. As several European countries, Türkiye, especially Thrace, Istanbul, the western Black Sea region, and the eastern Black Sea region, have experienced the effects of radioactivity shortly after the occurrence of the Chernobyl NPP accident. The presence of the artificial radionuclide cesium-137 in natural samples taken from these regions confirms this. Not only the Chernobyl NPP accident, but also technological developments can cause radioactive pollution from industrial and nuclear wastes, and all living things are exposed to both natural and artificial radiation. Therefore, sustainable monitoring system should be developed in order to assess the radioactivity status in the environment. Studies conducted throughout Türkiye show that the recorded gross alpha and beta levels in coastal waters are generally below the limit values suggested by World Health Organization. However, higher values of gross beta were observed in seawater samples from the Marmara region, the Straits, and Adana. This may be due to the high salinity of seawater and a dissolved form of the radioactive isotope ^{40}K, which causes high beta radioactivity in seawater. Natural radionuclides, such as ^{238}U series, ^{232}Th series, and ^{40}K, were found at various levels in soil and sediment samples. In general, the values remained below the world mean values stated by the United Nations Scientific Committee on the Effects of Atomic Radiation. However, the presence of ^{137}Cs at some points of Türkiye was related to the Chernobyl NPP accident and nuclear weapon tests conducted by several countries. Any radioactive pollution in the environment requires careful monitoring in terms of human health and taking the necessary precautions.

This work is a review study which includes an assessment of the quality of coastal ecosystems along the Turkish coast of the Black Sea in relation to natural and artificial radionuclides. The authors declare no conflict of interest.

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ОЦЕНКА УРОВНЯ РАДИОАКТИВНОСТИ В ПРИБРЕЖНЫХ ВОДАХ ТУРЦИИ

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Анатолия занимает геополитическое положение между Европой и Азией. С трёх сторон она окружена морями. Чёрное море омывает северное побережье Турции на протяжении 1700 км, от пригородов Стамбула до городка Хопа. После аварии на Чернобыльской атомной электростанции пылевое облако, содержащее радиоактивные элементы (прежде всего, искусственный радионуклид ^{137}Cs), в мае 1986 г. достигло западной Турции и затронуло Фракию, Стамбул и западную часть Черноморского региона. В связи с увеличением радиоактивных выпадений в этих районах Турецкое агентство по атомной энергии инициировало общенациональную программу радиационного мониторинга для определения ядерного и радиологического статуса опасности и для анализа географического распределения радионуклидов. Большое количество исследований было сосредоточено на измерении радиоактивности окружающей среды в воздухе, воде, почве, горных породах и осадках с целью выявления возможного влияния их радиоактивного загрязнения на здоровье местного населения после аварии на Чернобыльской АЭС.

Ключевые слова: Турция, воды Чёрного моря, авария на Чернобыльской АЭС, природные и искусственные радионуклиды