Asssesment of Natural Radionuclides and Associated Radiation Hazards in Water Sources of Islamabad, Pakistan

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Article

Asssesment of Natural Radionuclides and Associated Radiation Hazards in Water Sources of Islamabad, Pakistan

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Abstract: This paper reports concentrations of ^{226}Ra, ^{232}Th and ^{40}K in drinking waters in Pakistan. The aim is to estimate the radiological hazard and assess the safety of drinking water. Radiation hazard indices, and Excess Lifetime Cancer Risks are reported from all measurements. Different water samples have been collected from Islamabad (33º 38'N, 73º 09'E and analysed using a High Purity Germanium Detector (HPGe). The average concentration values of ^{226}Ra, ^{232}Th and ^{40}K were 6±0.6 Bq/L, 32±1 Bq/L and 74±2 Bq/L respectively. The radium equivalent activity was 58 Bq/L, the outdoor external dose was 0.2 nGy/h, the indoor external dose was 46 nGy/h and total average annual dose was 0.2 nGy/h. The excess lifetime cancer risk found equal to 0.8×10^{-3}. All reported values are lower than the globally calculated values and within recommended limits.

Keywords: radioactive pollutants; Ra-226; Th-232; K-40; radiation hazard index; high purity germanium detector (HPGe)

1. Introduction

Human beings are exposed to a wide range of radionuclides that are present in the environment, including water, air, soil and rock. These radionuclides originate from the earth's crust and also from man-made sources, such as residues from mining activities [1], products of the fertilizer industry [e.g. 2] and building materials [e.g. 3,4]. The natural radionuclides in the environment are very important for public health because their uninterrupted disintegration causes a continuous radiation exposure to humans and yields to radiological hazard. Radionuclides of significance are ^{226}Ra from the ^{238}U series, ^{232}Th (parent nucleus of the same name series) and ^{40}K [e.g. 5]. Apart from being present in water, air, soil, rock and building materials, they may be naturally transferred, reach water tanks and aquifers and become, hence, sources of extra exposure [1]. This exposure is mainly internal, but can be external as well via water cycle [1]. Importantly, since water is essential for all living organisms, environmental compartments, flora and fauna and all parts of biodiversity, the radiological contamination of water yields to consequent contamination of the food chain [6,7] and, as a result, to more internal exposure. All types of exposure due to these nuclides depend primarily on the geological and geographical conditions [8,9] and may be delivered both outdoors and indoors. Especially the internal contamination from ^{40}K is associated with a significant continuous constant exposure that can be altered by sports activity and diseases [10,11]. Since all aspects of environment contain ^{226}Ra, ^{232}Th and ^{40}K, it is significant that the concentrations of the nuclides are measured and the corresponding exposure and risk are estimated.

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Together with other radionuclides ^{226}Ra, ^{232}Th and ^{40}K constitute the so-called terrestrial radiation. Because of their very long half-lives (1620 y, 1.4 $\times$ 10^{10} y and 1.2 $\times$ 10^{9} y), they are still found in significant quantities in the Earth's crust and, as a result, they continue to emit radiation, expose humans and burden health. By measuring these natural sources of radiation, the background profiles of natural radioactivity can be outlined, the radiation exposure can be estimated and the corresponding health hazard risks can be appraised [12,13] . Moreover, understanding their behaviour, including concentrations and distribution, local authorities and stakeholders are assisted and, most importantly, the worldwide knowledge base of radiation information is broadened.

Although a significant amount of the related research is on the concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil and building materials [4,14–16], the corresponding concentrations in water samples are of equal importance [e.g. 1,8, and references therein]. This is reinforced by the fact that both ^{226}Ra and ^{232}Th are parent radionuclides for the generation of the most harmful isotopes of environmental radon, viz., ^{222}Rn (from ^{226}Ra) and ^{220}Rn (from ^{232}Th). Both isotopes have been acknowledged [see e.g. 8,17] as serious environmental carcinogenic factors with ^{222}Rn being separated as the most significant natural cause of lung cancer incidence, both at high and, most importantly, at low residential concentrations. Moreover, both ^{222}Rn and ^{220}Rn are found in waters and aquifers, making them very critical for radiological protection. Regarding their physical properties ^{222}Rn, hereafter called radon, is a noble gas with a half-life of 4.5 $\times$ 10^{9} y whereas ^{220}Rn, hereafter called thoron, has only 55.6 s which means that usually is disintegrated quickly. However the radiological value is not mainly due to the above radon isotopes, but rather because of their short lived progeny. Although the related contribution of thoron in atmosphere is low, this can be altered dramatically in waters rich in ^{232}Th. It becomes hence evident, that the presence of ^{226}Ra and ^{232}Th in waters is a health threat not only due to these precise nuclides, but also due to their daughter nuclei, ^{222}Rn and ^{220}Rn. Specially regarding these latter nuclides, there are people that use groundwater as potable and this imposes significant risk because radon is more enriched in groundwater. This is prolonged more, because during periods of high temperature gradients, radon in groundwater raises abnormally to hundreds of Bqm^{-3}, due to the high amounts of radioactive minerals in the ground. This may yield to abnormal radon anomalies as for example, in the village of Villar de la Yegua in Spain, where significantly higher mean deviation of radon concentration (as high as 15,000 Bqm^{-3}) was recorded, while the difference between this village and the surrounding regions, was about 818 Bqm^{-3} [18]. For integrity it should be mentioned, that there are contradictory interpretations regarding the causal relationship between radon in drinking water and gastrointestinal malignancy, with studies reporting no correlation between radon in water and stomach cancer while others, positive relationship [19,20]. All these facts provide additional evidence regarding the significance of the measurement of concentrations of ^{226}Ra and ^{232}Th in waters.

In Pakistan, the radionuclide content of drinking waters has not been investigated so-far at a national scale. Only some individual limited efforts exist, by few organisations or institutions and for educational purposes only. In view of this situation, measurements have been conducted of the content of ^{226}Ra, ^{232}Th and ^{40}K of waters of Islamabad, Pakistan. The scope was to assess the short-term exposure of inhabitants, to estimate the concentration variations and to find the related health-hazards. Towards this, samples were collected from different sectors of Islamabad along with samples from the most populous areas around the city. Mean annual effective doses are calculated together with exposure and risk estimations via different hazard indices.

In the following, the study area is given together with information of sample collection and measurement via High Purity Germanium (HPGe) x-ray spectrometer measurements. The mathematical aspects of exposure, dose and risk estimations are given next. Finally the results are given and their implications are discussed.

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2. Materials and Methods

2.1. Experimental Aspects

2.1.1. Area of Study

The study area is Islamabad which is the capital of Pakistan, located at 33° N, 73° E at the edge of the Potohar Plateau in the vicinity of the foothills of Malaria elevated at 507 *m* above mean sea level. The leading feature controlling the geology of the Islamabad area is the convergence of the Indo-European and Eurasian tectonic plates which began about 20 million years ago. This process produced a complex structure and stratigraphy in the Islamabad area that has been investigated by many local and international geologists. The study area tectonically lies along the significant faults of Margalla and Fateh Jang which form an arc length of several hundred miles (**Figure 1**).

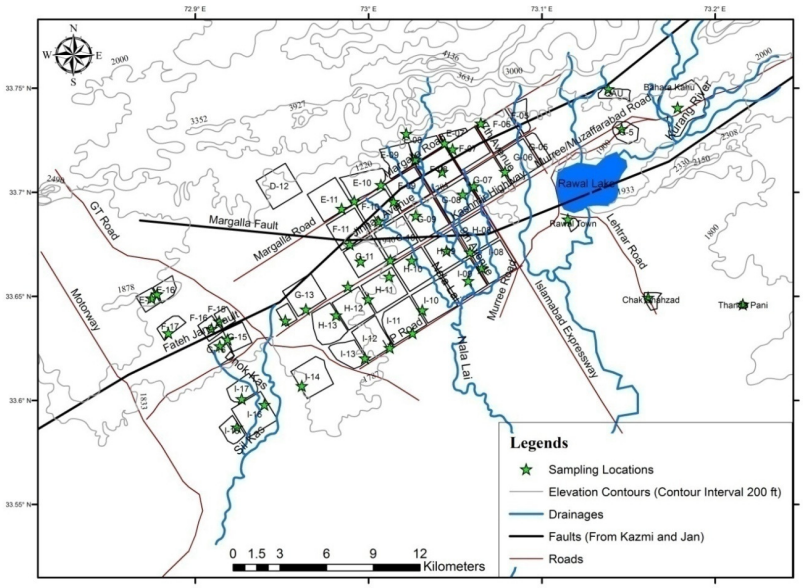

Figure 1. The map shows the location of sampling sites. The elevation contours marking the topography of the study area have been digitised from the topo-sheet NI-43-9 series U-502.

2.1.2. Sample Collection and Measurement

A total of 50 water samples were obtained from different sectors of the Islamabad region as shown in **figure 1**. Specifically, the distance between each sector was kept 2×2 km^2, to remove sample overlapping among different sectors. These sectors are denoted by, E, F, G, H, I together with their adjacent areas, namely, Chak Shehzad (CSD), Nilore (NLR), Barakahu (BKH), Rawal-dam (RWD) and Quaid-e-Azam University (QAU). The activity concentration of the collected samples was measured by a High Purity Germanium (HPGe), x-ray spectrometer. As mentioned, the nuclides of analysis were ^{226}Ra, ^{232}Th, and ^{40}K. The geometry of the detector was a vertical dipstick with a nitrogen cooling arrangement. The length of the HPGe detector was 53.4 *mm* and its diameter was 59 *mm*. The detector efficiency is 52.3%, the energy resolution is is 1.85 *keV*, for the 1.33 *MeV* photo peak and the Full-Width Half Maximum (FWHM) equals to the x-ray transition of a Cobalt ^{60}Co point source in a 5 *cm* × 5 *cm* Sodium Iodide NaI (TI). The background level of radioactivity is measured periodically in the laboratory. The activity concentration of ^{226}Ra is measured by the 351 *keV* peak of ^{214}Pb and the 609*keV*, 1120*keV* and 1749 *keV* peaks of ^{214}Bi. The activity concentration of ^{232}Th is measured the 238.63 *keV* peak of ^{212}Pb, the 338 *keV* and 911 *keV* peaks of ^{228}Ac and the 585 *keV* peak of ^{208}Tl. The activity concentration of ^{40}K was measured from its single peak of 1460 *keV*. Spectra acquisition time was 20,000 *s*. All spectra were stored on a computer. After collection, each of the water samples was acidified with 11 M HCL solution at the rate of 10 ml/L in reference to the sample's volume.

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This procedure was followed to avoid absorption of radionuclides as reported by IEAE [21], while it also releases any radionuclides already absorbed, back into the samples. In the laboratory, Marinelli beakers were used to collect the water samples. First of all, each Marinelli beaker with a volume of 1 L was rinsed with dilute sulfuric acid (H_2SO_4) and then the samples were turned into each beaker with proper labelling, sealed and left for about four weeks. The purpose of this was to achieve a state of secular equilibrium between the parent and daughter nuclides within each sample. After radioactive equilibrium, water samples were analysed and the activity concentration of the radionuclides present in each sample was measured. The soil sample was collected under the well water when it settled down.

2.2. Mathematical Aspects

The Gamma index I_x measures the total gamma-ray radiation emitted by a water sample. It can be calculated by equation (1):

$$I_x = \frac{A_{Ra^{226}}}{300} + \frac{A_{Th^{232}}}{200} + \frac{A_{K^{40}}}{3000} \tag{1}$$

The $A_{Ra^{226}}$, $A_{Th^{232}}$ and $A_{K^{40}}$ correspond to the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K as (Bq/L) respectively.

Radium equivalent activity (Ra_{eq}) was obtained by equation (2):

$$Ra_{eq} = \left(\frac{A_{Ra^{226}}}{370} + \frac{A_{Th^{232}}}{259} + \frac{A_{K^{40}}}{4810}\right) \times 370 \tag{2}$$

If sample has known content of ^{226}Ra, ^{232}Th and ^{40}K ,the external hazard index, H_{IN}, can be calculated by equation (3):

$$H_{IN} = \left(\frac{A_{Ra^{226}}}{370} + \frac{A_{Th^{232}}}{259} + \frac{A_{K^{40}}}{4810}\right) \tag{3}$$

Again $A_{Ra^{226}}$, $A_{Th^{232}}$ and $A_{K^{40}}$ are the activity concentrations as in equation 1. A radiation-safe sample has H_{IN} less than unity.

For a sample, further from equation (3), the indoor external dose, D_{IN}, can be calculated using equation (4)

$$D_{IN} = 0.92A_{Ra^{226}} + 1.1A_{Th^{232}} + 0.08A_{K^{40}} \tag{4}$$

and the corresponding Annual effective dose, E_{IN}, from equation (5):

$$E_{IN} = 4.905 \times 10^{-3} D_{IN} \tag{5}$$

Finally, the excess lifetime cancer risk ($ELCR_{IN}$) was calculated based on the values of annual effective dose E_{IN} by the relationship given in equation (6):

$$ELCR_{IN} = E_{IN} \times LE \times RF \tag{6}$$

In this equation E_{IN} is the annual effective dose and LE is the life expectancy which is on average 66 years for Pakistan. RF is the fatal risk factor per Sievert, which is 0.05 according to a previous study carried out in this region.

3. Results and Discussion

According to the HPGe measurements, the activity concentrations in the various sectors of Islamabad, ranged from (0.87±0.001) to (17.89±1.02) Bq/L for ^{226}Ra, from (12.44±0.99) to (47.74±3.02) Bq/L for ^{232}Th, and from (50.09±3.04 to (98.09±6.00) Bq/L ^{40}K respectively. The average values obtained from the analysis of samples were (6.35±0.59) Bq/L for ^{226}Ra, (32.09 ±2.87) Bq/L for ^{232}Th and (73.87±5.40) Bq/L for ^{40}K respectively. Accounting that 1 L of water weights 1 kg, the above values can be compared to the specific activity (Bq/kg) reported by several researchers. In this sense

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the above value ranges are comparable the corresponding ranges reported in Turkey [13], however, with significantly lower maximum values. The ranges of all nuclides are within the corresponding ranges of some sites in Russia [16], with higher maximum values. On the other hand, only the ranges of ^{226}Ra and ^{232}Th are comparable with the ones of other sites in Russia, whereas the ranges of ^{40}K are significantly lower [5]. The value range of ^{226}Ra and ^{232}Th are similar to those reported in Nigeria, however the range of ^{40}K are significantly lower [22]. The ranges of ^{232}Th are similar to those of sediments of rivers in Morocco, but very higher than the samples of the river's waters [1]. All are within the corresponding global ranges [8,24,27].

The summary of every radionuclide analysis is shown in **Table 1**. The discrepancies of the activity concentration against sample number are shown in **figure 2**. Comparing the activity concentrations within each sample point, the partial concentration values of ^{40}K are higher than the corresponding activity concentration values of ^{232}Th which, in turn, are higher than the ones of ^{226}Ra. Namely, within each sample, $A_{Ra^{226}} > A_{Th^{232}} > A_{K^{40}}$. The reader should note here in relation, that a different order, namely $A_{K^{40}} > A_{Ra^{226}} > A_{Th^{232}}$ has been observed in Russia [16], viz. $A_{Ra^{226}} > A_{Th^{232}}$. On the other hand, similar association with this paper, viz. $\frac{A_{Th^{232}}}{A_{Ra^{226}}} < 1$ is reported for other sites in Russia [5]. More significant, however, than the intra-nuclide associations, are the intra-activity relations of each nuclide, namely the the comparisons of the activity concentration distribution between the nuclides. At first, by visually observing the curve activity concentration profiles of **figure 2**, it may be supported that the distribution within samples 1-4 and 26-50 is comparable between the three nuclides (^{226}Ra, ^{232}Th and ^{40}K). This can be attributed to the relative positions of these points in association to the Margalla and Fateh Jang arcs. By analytically going trough the values of **Table 1**, it can be observed that the activity concentration values of F-sector (G-10, G-11, and H-10) in Islamabad are relatively higher when compared with the corresponding values of the other sectors. This is possibly because the Fateh Jang fault is passing through the F-sector, as shown in **1**. The total activity concentration ($A_{Ra^{226}} + A_{Th^{232}} + A_{K^{40}}$) in these sectors was 163.72 Bq/L, which is very prominent, at least when compared to the total activity concentration values of other parts of the study area. The total activity concentration (153.01 Bq/L) was also high for the combination of sectors H-8 and H-9 as well. A possible reason for that, is that these sectors lie on opposite sides of the fault. The total activity concentration ($A_{Ra^{226}} + A_{Th^{232}} + A_{K^{40}}$) varied from 80.74 Bq/L to 163.72 Bq/L for all the sectors of Islamabad.

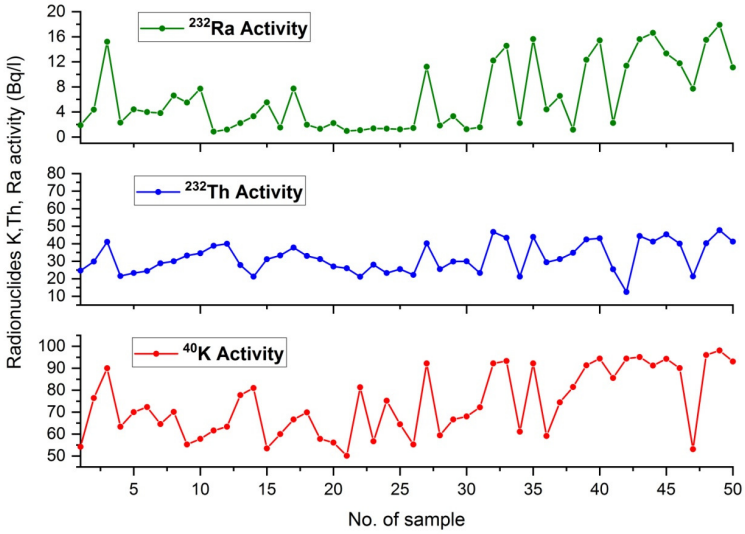

Figure 2. Variation of activity concentration of ^{226}Ra,^{232}Th, and ^{40}K in different samples of the study area.

As far as the radiological potential of Islamabad's waters concerns, all average activity concentrations are higher than the maximum proposed limit of 11.1 Bq/L of the United States Environmental

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protection Agency (EPA) [23], but are within the corresponding value range reported in the related publications of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for the worldwide ranges of activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in drinking water [8,24,27]. The hazard of these values is estimated by the radiological indices of section 2.2. The reader should note here in relation, that similar radiological indices have been followed by other researchers as well. In specific the quantities I_x, Ra_{eq} and E_{IN} are mentioned by Abd Elkader et al. [4]. All quantities are employed for dosimetry by Aközcan et al. [13]. Many of the related quantities are mentioned by Azeez et al. [2] and elsewhere [3,14,16,22,25,26]. From this point of view, it can be supported hence that the employed quantities are adequate for reference comparisons and dosimetric estimations. The values of the radiological hazard indices are shown in last two columns of **Table 1** and in **Table 2**. The Gamma index has a value less than 0.33 which is lower than the global average value of 1.17 [8,24,27]. The average value of the Radium equivalent activity (Ra_{eq}) was 57.89 Bq/L whereas, the maximum value reached up to 163.72 Bq/L. The global average value is 370 Bq/L [8,24,27], therefore, both values are significantly lower. The external hazard index H_{IN} was 0.17 which is significantly less than 1 and this implies low radiological hazard [2,16,25,26]. The value is also within the value range reported by Azeez et al. [2]. The maximum value of D_{IN} calculated via equation (4) was 76.83 nGy/h, which is lower than the global average of 279.64 nGy/h [8,24]. That means that the maximum dose rate due water is considered low. The value range of D_{IN} is within the range mentioned by Azeez et al. [2] and other references [25,26]. The effective dose includes the effect of ^{226}Ra, ^{232}Th, and ^{40}K in different samples of water. The maximum value of the annual effective dose E_{IN} is calculated to be 0.30 mSv/y. The range of the annual effective dose comes out to be 0.10-0.30 mSv/y. The global value of E_{IN} as per the UNSCEAR report comes out to be 1.37 mSv/y. The variation of E_{IN} is shown in the **figure 3**. The $ELCR_{IN}$ calculated in this study has an average value of $0.76 10^{-3}$ is lower than the average world value of $4.8 10^{-3}$, which is the probability of cancer incidence due to radioactivity in the indoor environment. All these values are comparable to the international comparison values reported by by Aközcan et al. [13, see Table 4]. All values are also within the value range reported by Azeez et al. [2]. The E_{IN} values are within the range reported by Inoue etal. [12, see Figures 2 and 3]. They are also comparable to the ranges reported by Yakovlev et al. [16], Abdullahi et al. [3] and Stojanovska and Blazho [14].

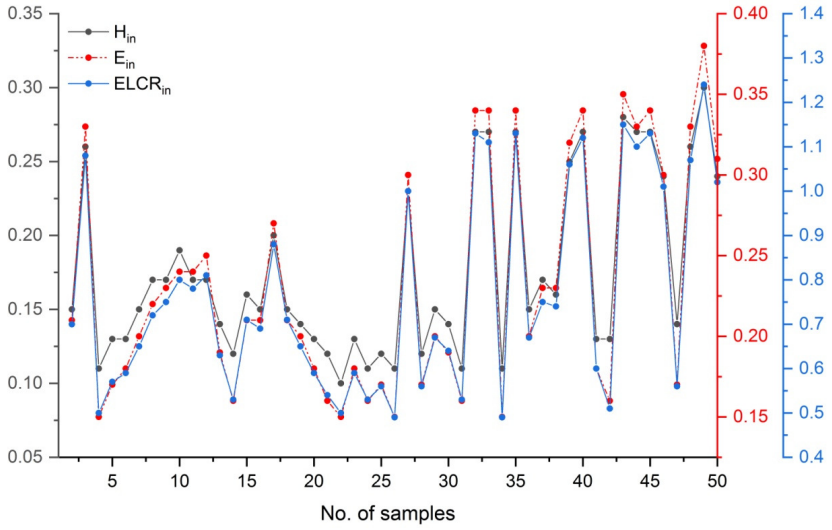

Figure 3. Variation of activity concentration of H_{IN} represented by black line,E_{IN} represented by red dashed line and cancer risk Hazard $ELCR_{IN}$ with blue line, calculated by internal hazard index and annual effective index of the study area.

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Table 1. Table 1 Calculation of Gamma activity (Bq/L) concentration of ^{226}Ra, ^{232}Th, and ^{40}K, radiation indices, and the Radium equivalent activity in water samples for the region of Islamabad, Pakistan with indoor internal doses from safe building material index.

No. of sample	Sample location	^{226}Ra (Bq/L)	^{232}Th (Bq/L)	^{40}K (Bq/L)	Ra_{eq} (Bq/L)	D_{in} (nGy/h)
1	QAU	1.88	24.65	54.21	41.26	33.18
2	NLR	4.36	29.9	76.44	52.95	43.02
3	RWD	15.21	41.11	90.03	80.86	66.42
4	E-7	2.31	21.56	63.33	37.98	30.91
5	E-9	4.41	23.33	69.99	43.12	35.32
6	CSD	3.98	24.44	72.33	44.46	36.33
7	E-8	3.82	28.88	64.56	50.04	40.45
8	BKH	6.61	29.99	70.09	54.84	44.68
9	E-9	5.51	33.3	55.23	57.33	46.12
10	G-16	7.71	34.56	57.77	61.53	49.73
11	E-16	0.87	38.88	61.61	61.15	48.5
12	E-17	1.19	39.99	63.33	63.19	50.15
13	E-10	2.21	27.88	77.77	48.02	38.92
14	E-12	3.31	21.23	80.99	39.87	32.88
15	I-13	5.53	31.21	53.46	54.23	43.7
16	I-11	1.52	33.33	59.99	53.75	42.86
17	I-14	7.72	37.87	66.66	66.95	54.09
18	I-8	1.96	33.09	69.87	54.61	43.79
19	I-17	1.31	31.23	57.77	50.37	40.18
20	I-9	2.21	27.04	56.09	45.15	36.26
21	I-15	0.96	26.05	50.09	42.03	33.55
22	I-10	1.08	21.11	81.33	37.49	30.72
23	I-16	1.36	28.08	56.66	45.83	36.67
24	I-12	1.33	23.33	75.22	40.44	32.9
25	G-5	1.22	25.54	64.44	42.66	34.37
26	G-6	1.44	22.22	55.23	37.43	30.19
27	G-10	11.21	40.2	92.21	75.73	61.91
28	G-7	1.83	25.55	59.4	42.9	34.54
29	G-14	3.32	29.87	66.66	51.12	41.24
30	G-12	1.25	30	68.03	49.34	39.59
31	G-15	1.56	23.3	72.22	40.4	32.84
32	G-11	12.21	46.76	92.22	86.1	70.05
33	G-13	14.56	43.44	93.33	83.8	68.65
34	G-8	2.21	21.22	61.11	37.23	30.26
35	G-9	15.63	43.89	92.22	85.42	70.04
36	H-12	4.41	29.44	59.11	51.01	41.17
37	H-11	6.55	31.23	74.44	56.89	46.33
38	H-10	1.16	34.87	81.44	57.24	45.94
39	H-8	12.32	42.44	91.32	79.97	65.32
40	H-9	15.43	43.14	94.44	84.32	69.2
41	H-13	2.24	25.44	85.58	45.17	36.89
42	F-8	11.37	12.44	94.44	36.41	31.7
43	F-9	15.61	44.41	95.12	86.37	70.82
44	F-10	16.61	41.23	91.22	82.53	67.93
45	F-15	13.33	45.33	94.31	85.34	69.67

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Table 1. Table 1 Calculation of Gamma activity (Bq/L) concentration of ^{226}Ra, ^{232}Th, and ^{40}K, radiation indices, and the Radium equivalent activity in water samples for the region of Islamabad, Pakistan with indoor internal doses from safe building material index.

46	F-16	11.76	40.11	90.09	75.99	62.15
47	F-17	7.71	21.33	53.11	42.27	34.81
48	F-6	15.51	40.33	96.01	80.51	66.31
49	F-11	17.89	47.74	98.09	93.64	76.82
50	F-7	11.11	41.22	93.07	77.15	63.01

Table 2. Calculation of excessive life-time cancer risk by using internal hazard index and annual effective index for different locations of Islamabad, Pakistan.

No. of sample	**Sample Name**	**H_{in}**	**E_{in} (mSv)**	**$ELCR_{in}$ $\times 10^{-3}$**
1	QAU	0.12	0.16	0.54
2	NLR	0.15	0.21	0.7
3	RWD	0.26	0.33	1.08
4	E-7	0.11	0.15	0.5
5	E-9	0.13	0.17	0.57
6	CSD	0.13	0.18	0.59
7	E-8	0.15	0.2	0.65
8	BKH	0.17	0.22	0.72
9	E-9	0.17	0.23	0.75
10	G-16	0.19	0.24	0.8
11	E-16	0.17	0.24	0.78
12	E-17	0.17	0.25	0.81
13	E-10	0.14	0.19	0.63
14	E-12	0.12	0.16	0.53
15	I-13	0.16	0.21	0.71
16	I-11	0.15	0.21	0.69
17	I-14	0.2	0.27	0.88
18	I-8	0.15	0.21	0.71
19	I-17	0.14	0.2	0.65
20	I-9	0.13	0.18	0.59
21	I-15	0.12	0.16	0.54
22	I-10	0.1	0.15	0.5
23	I-16	0.13	0.18	0.59
24	I-12	0.11	0.16	0.53
25	G-5	0.12	0.17	0.56
26	G-6	0.11	0.15	0.49
27	G-10	0.23	0.3	1
28	G-7	0.12	0.17	0.56
29	G-14	0.15	0.2	0.67
30	G-12	0.14	0.19	0.64
31	G-15	0.11	0.16	0.53
32	G-11	0.27	0.34	1.13
33	G-13	0.27	0.34	1.11

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Table 2. Calculation of excessive life-time cancer risk by using internal hazard index and annual effective index for different locations of Islamabad, Pakistan.

34	G-8	0.11	0.15	0.49
35	G-9	0.27	0.34	1.13
36	H-12	0.15	0.2	0.67
37	H-11	0.17	0.23	0.75
38	H-10	0.16	0.23	0.74
39	H-8	0.25	0.32	1.06
40	H-9	0.27	0.34	1.12
41	H-13	0.13	0.18	0.6
42	F-8	0.13	0.16	0.51
43	F-9	0.28	0.35	1.15
44	F-10	0.27	0.33	1.1
45	F-15	0.27	0.34	1.13
46	F-16	0.24	0.3	1.01
47	F-17	0.14	0.17	0.56
48	F-6	0.26	0.33	1.07
49	F-11	0.3	0.38	1.24
50	F-7	0.24	0.31	1.02

This investigation is a radiological study carried out in Islamabad, Pakistan. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were measured in water samples collected from different sites of Islamabad. The concentrations varied between the measurement sites, most possibly, due to the distance of the main fault across the capital city, which could enhance these perturbations. The concentrations and the corresponding doses were within the ranges reported from various papers and are also within the international ranges. The average concentrations and doses are considered low. This may be attributed to the non-igneous formation around the fault zone in Islamabad. Therefore, the drinking water from wells and tube wells in Islamabad, Pakistan is of relatively low risk. Th radiological estimation was based on samples collected from different wells around Islamabad and therefore it is a characteristic summary of the analysis of drinking water. The direct exposure of the individuals to radionuclides in wells could assess the concentration in the study area. In general the drinking waters of Islamabad are safe.

4. Conclusions

In the current investigation, the concentrations of different radioactive-nuclides were analysed in water samples retrieved from tube wells in different sectors in the capital city of Islamabad, Pakistan.The employed hazard indices ($I(x)$, Ra_{eq}, H_{IN} and D_{IN}) in the water samples of the study area are within international ranges lower but are of low average values. E_{IN} is more low than the average concentration and also within the international range.The average $ELCR$ is 0.76×10^{-3}, which is lower than the global average value of 1.45×10^{-3}. Therefore, the radioactivity concentrations in water samples of Islamabad have a low chance of inducing cancer to the local inhabitants. These radioactive nuclides also do not seem to threat the surrounding areas. There are some sectors in Islamabad where radiation index values are slightly high, but that does not impose a threat as well. Hence, Islamabad can be considered as a less radiation prone city as far as drinking water is concerned.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

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