Paper

CONCENTRATIONS OF ^{226}Ra, ^{232}Th, AND ^{40}K IN THE SOILS OF BANGALORE REGION, INDIA

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Abstract—**Several soil samples of Bangalore region were analyzed for the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K by gamma ray spectrometry. The concentration of ^{226}Ra varied in the range 7.7–111.6 Bq kg^{-1} with a mean value of 26.2 Bq kg^{-1}, ^{232}Th in the range 16.7–98.7 Bq kg^{-1} with a mean of 53.1 Bq kg^{-1}, and that of ^{40}K in the range 151.8–1424.2 Bq kg^{-1} with a mean of 635.1 Bq kg^{-1}. The external gamma absorbed dose rates in air were also measured using a portable environmental radiation dosimeter, and the gamma dose rates were found to vary in the range 61.4–201.7 nGy h^{-1} with a mean of 117.2 nGy h^{-1}. These results along with the results of estimation of radium equivalent activity (Ra_{eq}), absorbed dose rate (D), annual effective dose rate, external hazard index (H_{ex}), internal hazard index (H_{in}), and representative level index (I_γ) are presented in this paper. The results are also compared with the literature values reported for other regions of India as well as worldwide average values and discussed.**

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Key words: dose assessment; dose equivalent, effective; dose, absorbed; gamma radiation

INTRODUCTION

THE PREVALENT background radiation level in the environment is largely due to natural sources of radiation. Natural sources include radiation from both extraterrestrial and terrestrial origins. The extraterrestrial radiation originates from outer space as primary cosmic rays. Terrestrial radiation originates mainly from the primordial radionuclides like ^{238}U, ^{232}Th, and ^{40}K that are present in the Earth ever since its formation. Apart from these natural sources, modern scientific and technological activities also contribute to the radiation level in the environment. It has been established that, out of the total radiation dose that the world population receives, about 96.1% is from natural sources and the remaining 3.9% is from man made sources (Chougankar et al. 2003).

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Bangalore is one of the major cities of India and is located in the southern part of Karnataka state. It is a fast growing city and host to many types of industries such as metallurgical, chemical, aircraft, leather, paper, sugar, glass and ceramics, textiles, etc. This city has received the attention of the world due to the establishment of major information technology and computing technology industries. In addition to these, a large number of granite quarries have been established recently and several thousands of people are engaged in quarrying activities. Rock crushing industries produce a lot of air pollution and water pollution through the emission of rock dust. In view of large scale industrialization, studies aimed at establishing the baseline data on radiation levels and radionuclides distribution in various environmental matrices of Bangalore region is important because such a study would help to assess, in the future, the impact of our scientific and technological activities on the environment.

Studies on radiation levels and radionuclides distribution in Bangalore region have not been carried out so far. In view of the large-scale industrialization, which can enhance the background radiation levels prevailing in the region, there was a need for a detailed study aimed at establishing the baseline data on background radiation levels in the environs of Bangalore. Therefore, we have initiated a study on the background radiation levels and distribution of radionuclides in different environmental matrices of Bangalore. This paper presents the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soils and the gamma absorbed dose rates to the general population of the region.

Geology of the study area

The Bangalore district extends between 12°15′ and 13°13′ N latitude and 77°3′ and 77°56′ E longitude with an average elevation of 900 m from the sea level. The study area includes Bangalore rural and urban districts with a population density of 322.86 persons km^{-2} and 2978.59 persons km^{-2} respectively (District Planning 1997). Geologically, the area belongs to peninsular

gneisses, younger and older granites, dolerite and amphibolite dykes, laterite, charnockite, and amphibolite and pelitic schist. The soils of the study area are highly porous and sandy in nature. Red loams, red gravelly loams, and red sandy loams are the predominant types of soils.

The climate is very agreeable and free from temperature extremes. It is classified as the seasonally dry savannah climate. There are two rainy seasons: one of the southwest monsoon (June–September) and the other of the northwest monsoon (October–November). The average rainfall in the study area is 793.6 mm per year. The season from December to February is the winter season of fine cool weather with little or no rainfall and from March to May is the summer season with low humidity. The dwellings in the study area are constructed with brick and mud, which are locally available. The population of Bangalore City is about 6.8 million.

MATERIALS AND METHODS

External gamma dose rate

The external gamma dose rates in air were measured in different locations of the study area (Fig. 1) using a portable Geiger-Mueller (GM) tube-based Environmental Radiation Dosimeter (model ER709, Nucleonix Systems Pvt. Ltd., Hyderabad, India). This dosimeter is exclusively designed to serve as a low-level survey meter. It was factory calibrated using a gamma survey instruments calibrator (model 773, AEA Technology, Carlsbad, CA 92010). The instrument is capable of measuring gamma dose rates in the range 0–10 mR h^{-1}. The accuracy and the sensitivity of the dosimeter are $\pm$15% and 1 μR h^{-1}, respectively. These features make this dosimeter an ideal choice for the measurement of gamma dose rates from environmental radiation and also for geological prospecting for radioactive minerals. Gamma absorbed dose rates were measured at a height of 1 m above the ground level (EML 1983) at sites that were open, undisturbed level ground surfaces free from sheltering, vegetation and away from public roads and buildings. The dose recorded by this instrument includes both terrestrial and cosmic ray components.

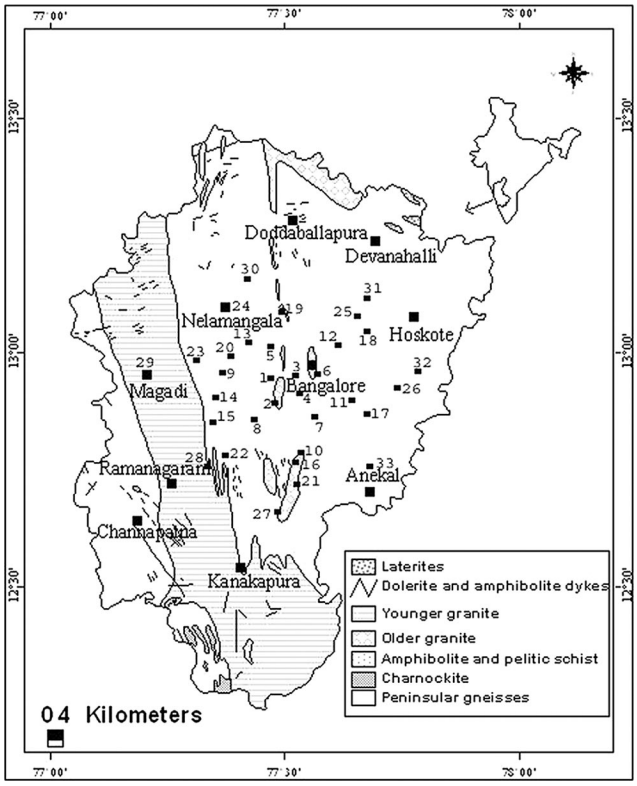

Fig. 1. Area covered under the study and its geological classification.

Soil sample collection and processing

Soil samples were collected from different locations (Fig. 1) at undisturbed sites. At each sampling station about 5 to 6 spots with an area of 0.5 m^2 were marked, each spot being separated from the others by at least 4 to 5 m. The top layer of soil (a few mm) which contains decayed vegetation and roots was removed. The soil was then dug up to a depth of 10 cm and about 1 to 2 kg of soil from each spot was collected. Finally, all the samples were mixed thoroughly and a composite sample of about 2 to 3 kg that is the representative of the location was collected in a polythene bag. The polythene bag was sealed, labeled and brought to the laboratory. Samples from all 33 sampling stations were collected for the present study.

In the laboratory, the samples were mixed thoroughly and extraneous materials like plant materials, roots, mat portions, pebbles, etc., were removed. Each sample was then oven dried at 110°C until a constant dry weight was obtained and then crushed and sieved through 100 meshes (IAEA 1989). The oven-dried soil sample was filled into a 300 mL polythene container and the lid was screwed tightly so as to avoid the escape of radon and thoron from the sample. The sample was stored for a period of about 30 d to allow radon to come into equilibrium with its progeny.

Activity determination

The concentrations of ^{226}Ra, ^{232}Th and ^{40}K were determined by gamma spectrometry employing a 41% relative efficiency n-type HPGe detector (Canberra Industries, 800 Research Park Way, Meriden, CT 06450, USA) available at University Science Instrumentation Centre, Mangalore University, India. The detector was enclosed in a graded lead shield (Model 747, Canberra). The detector was connected to a DSA-1000 (Digital Signal

Analyzer, which contains bias supply, analog to digital converter, and 16K multichannel analyzer) for data acquisition and the spectrum was analyzed by GENIE-2000 software. The energy and efficiency calibration of the detector were performed using International Atomic Energy Agency (IAEA) reference materials (RG-U, RG-Th, and RG-K). Both sample and standards were counted in the same type of containers so that the geometry configuration remained the same. Samples were counted for a period of 60,000 s. The concentration of ^{226}Ra was evaluated using the characteristic gamma ray lines of energy 609, 1,120, and 1,764 keV of its decay product ^{214}Bi; the concentration of ^{232}Th was measured using the 583, 911, and 2,614 keV gamma lines of its decay product ^{228}Ac; and that of ^{40}K from the 1,460 keV gamma line of this radionuclide (Karunakara et al. 2001).

The minimum detectable concentrations of ^{226}Ra, ^{232}Th and ^{40}K at the 95% confidence level, for a counting period of 60,000 s and a sample weight of 300 g, were found to be 0.34 Bq kg^{-1}, 0.25 Bq kg^{-1}, and 0.92 Bq kg^{-1}, respectively.

RESULTS AND DISCUSSION

The results of soil radioactivity measurements are presented in Table 1. The range, mean, median and standard deviation of the entire study region are given in the bottom of the same table. The concentration of ^{226}Ra varied in the range of 7.7–111.6 Bq kg^{-1} with a mean value of 26.2 Bq kg^{-1}. The concentration of ^{232}Th varied in the range 16.7–98.7 Bq kg^{-1} with a mean value of 53.1 Bq kg^{-1} (column 4 of Table 1) and that of ^{40}K in the range 151.8–1,424.2 Bq kg^{-1} with a mean value of 635.1 Bq kg^{-1}. It may be noted that the concentrations of ^{226}Ra and ^{232}Th observed in Lalbagh and Katriguppe regions are significantly higher when compared to the other sampling stations.

Geologically, Lalbagh and Katriguppe exist on an older granitic base (Fig. 1). It is well known that granites contain high concentrations of uranium, thorium, and potassium (Ivanovich and Harmon 1982). The uranium and thorium are incorporated into the rocks in the crystallization of the last magmas and residual solutions, since their large ionic radii stop them from crystallizing out in the early silicates. This may be the reason for the higher ^{226}Ra and ^{232}Th concentrations observed in Lalbagh and Katriguppe. The higher concentrations of ^{40}K observed in some of the sampling stations such as Mallasandra, Harohalli, Lalbagh, etc., may be due to the high potassium content in the feldspars which form part of the granites (Carmichael 1989).

Table 1. Concentration of ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}).

Sl. No.	Location	^{226}Ra	^{232}Th	^{40}K
1.	Kannahalli	18.1 ± 0.6	62.2 ± 1.1	736.7 ± 12.1
2.	Kengeri	38.9 ± 0.6	87.7 ± 1.1	302.1 ± 5.9
3.	Mallathalli	23.7 ± 0.7	71.2 ± 1.2	361.8 ± 7.7
4.	Katriguppe	64.2 ± 1.3	98.7 ± 1.9	1139.1 ± 19.6
5.	Machohalli	17.7 ± 0.6	33.5 ± 0.9	441.9 ± 8.7
6.	Lalbagh	111.6 ± 1.2	95.4 ± 1.5	1262.1 ± 18.7
7.	Doddakallasandra	32.9 ± 0.7	33.5 ± 0.8	336.1 ± 7.1
8.	Kumbalagodu	9.3 ± 0.5	37.6 ± 0.9	559.7 ± 10.1
9.	Tavarekere	26.3 ± 0.7	76.3 ± 1.2	677.7 ± 11.7
10.	Bannerughatta	22.9 ± 0.7	59.6 ± 1.1	1291.7 ± 18.7
11.	Agara	23.9 ± 0.7	34.3 ± 0.9	197.3 ± 5.5
12.	Hebbal	45.9 ± 0.8	50.6 ± 1.1	350.8 ± 7.4
13.	Kambasandra	16.5 ± 0.6	36.1 ± 0.9	719.4 ± 11.7
14.	Beemanakuppe	12.9 ± 0.6	58.6 ± 1.1	452.9 ± 8.8
15.	Hejjala	17.1 ± 0.6	51.0 ± 0.9	653.6 ± 11.1
16.	Ragihalli	18.9 ± 0.6	69.5 ± 1.2	699.4 ± 11.7
17.	Kudlu	18.1 ± 0.5	44.6 ± 0.8	507.2 ± 8.3
18.	Kalkere	32.9 ± 0.9	92.4 ± 1.6	699.8 ± 12.9
19.	Tarabanahalli	20.2 ± 0.6	46.6 ± 0.9	393.9 ± 7.9
20.	Mallasandra	18.6 ± 0.7	29.5 ± 0.9	1424.2 ± 20.9
21.	Shivanahalli	27.4 ± 0.6	89.9 ± 1.1	1079.4 ± 15.2
22.	Bidadi	19.8 ± 0.5	41.5 ± 0.8	930.2 ± 13.3
23.	Mummenahalli	17.6 ± 0.5	47.4 ± 0.8	945.7 ± 13.7
24.	Nelamangala	31.3 ± 0.6	52.6 ± 0.9	303.1 ± 6.1
25.	Kannur	38.6 ± 0.6	65.8 ± 0.9	623.6 ± 9.9
26.	Varthur	10.5 ± 0.4	45.7 ± 0.7	166.5 ± 3.9
27.	Harohalli	13.2 ± 0.5	16.7 ± 0.6	454.3 ± 7.9
28.	Madapura	13.2 ± 0.5	22.5 ± 0.6	1390.2 ± 18.8
29.	Magadi	16.9 ± 0.6	57.5 ± 1.1	1073.0 ± 15.6
30.	Kukkanahalli	7.7 ± 0.4	21.1 ± 0.6	201.7 ± 4.6
31.	Baglur	39.4 ± 0.6	60.7 ± 0.9	151.8 ± 3.9
32.	Kadugodi	23.5 ± 0.5	33.9 ± 0.7	240.1 ± 5.0
33.	Morasur	12.9 ± 0.4	28.2 ± 0.6	194.9 ± 4.4
	Range	7.7–111.6	16.7–98.7	151.8–1424.2
	Median	19.8	50.6	559.7
	Mean	26.2	53.1	635.1
	SD	19.4	22.6	383.4

The range and mean values of ^{226}Ra, ^{232}Th, and ^{40}K concentrations observed for Bangalore region are compared with the values reported for other Indian environs, other parts of the world, and worldwide average values in Table 2. The region to which the values are reported in the literature and the geological classification are given in columns 4 and 5, respectively. It can be seen that the mean values of concentrations observed in the present study are comparable with the All India average (Kamath et al. 1996) and the world average values. It is interesting to note that the soil collected at Lalbagh (Table 1) showed a ^{226}Ra concentration of 111.6 Bq kg^{-1}, which is more than 3 times higher than the worldwide average value of 32 Bq kg^{-1} (UNSCEAR 2000) and also other regions of India (Karunakara et al. 2005).

In about 67% of the samples from Bangalore region the ^{232}Th concentrations were more than the world average of 40 Bq kg^{-1}. In five samples the concentrations were more than two-fold of that of the world average. In these five samples (Sl. Nos. 2, 4, 6, 18, and 21, Table 1), the concentration was around 90 Bq kg^{-1}. However, the mean

Table 2. Comparison of gamma concentration[a] of soil samples with other environments.

^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Region	Geology	Reference
7.7–111.6 (26.15)	16.7–98.7 (53.1)	151.8–1424.2 (635.2)	Bangalore	Peninsular gneiss, older granite dolerite, amphibolites, potassium feldspar	Present study
8.2–68.4 (30.6)	5.9–77.2 (38.2)	14.6–344.9 (152.2)	West Coast of India (Coastal Karnataka, Kaiga and Goa)	Predominantly lateritic, red to some extent	Karunakara et al. (2005)
10–200 (60)	3–60 (26)	40–800 (350)	Republic of Ireland	Granitic and carboniferous limestone areas	McAulay and Moran (1988)
13–165 (46)	7–204 (49)	48–1570 (650)	Spain	Granitic, sedimentary and shales	Baeza et al. (1992)
40.2–442 (112)	32.6–88.1 (71.5)	440–913 (672)	China[b]	Granitic bed	Yang et al. (2005)
82.32–166.99 (115)	151.91–275.63 (192)	1015.48–1484.93 (1207)	Turkey[b]	Young granitic and volcanic rocks are wide spread and show close spacial and temporal association	Merdanoglu and Altinsoy (2006)
21.48–48 (35)	22–59 (41)	303–945 (615)	Punjab province (Pakistan)	Sedimentary rocks	Tahir et al. (2005)
28.8–36.5 (32.9)	49.4–58.4 (53.6)	584.8–696.1 (647.4)	Bahawalpur division (Pakistan)	Clay mix with sand	Matiullah et al. (2004)
7.8–1520 (31)	17.5–158.3 (63)	43–766 (394)	All India average		Kamath et al. (1996)
8–160 (32)	4–130 (40)	100–700 (420)	World average		UNSCEAR (2000)

[a] Values given in the parenthesis are mean values.
[b] Soil samples collected from the surface of the weathering layer.

concentration of ^{232}Th (53.1 Bq kg^{-1}) was comparable to that of the All India and the world average values.

About 64% of the samples showed higher ^{40}K concentrations when compared to the world average of 420 Bq kg^{-1} (UNSCEAR 2000), whereas the rest of the samples exhibited lower concentration. In some samples (Sl. Nos. 6, 10, 20, and 28, Table 1) the concentration of ^{40}K was more than three times higher than the world average. The mean concentration was also higher than the All India and world average values. As discussed earlier, the reason for the higher concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in some of the soil samples of the Bangalore region may be attributed to their granitic origin.

In Table 2, effort has also been made to compare the results of the present study with those reported for other regions with similar geology (West Coast of India, Republic of Ireland, Spain, China, and Turkey). It is known that the concentrations of primordial radionuclides vary from place to place depending upon the geology of the region (e.g., types of rocks, age of the rocks, extent of weathering, etc.). Hence, while making comparison of the concentrations reported for different parts of the world (Table 2), the geology of the region was considered as the criteria. As shown in Table 2, the geology of Bangalore region can be compared with the West Coast of India (covering Coastal Karnataka, Kaiga and Goa regions), the Republic of Ireland, Spain, China, and Turkey, as they have similar geology.

It is evident that the range and mean values of concentrations of ^{232}Th and ^{40}K observed in the present study are higher when compared to those of the West Coast of India (Karunakara et al. 2005) and Republic of Ireland (McAulay and Moran 1988). The mean concentration of ^{226}Ra compares with that of West Coast of India, but it is lower when compared to that reported for Republic of Ireland. The mean of ^{40}K for the Bangalore region is two and three times higher than that of the Republic of Ireland and West Coast of India, respectively. However, the mean and the range of concentration of all the three radionuclides in the soils of the Bangalore region compares well with that observed in Spain (Baeza et al. 1992). The mean values of ^{232}Th and ^{40}K concentrations observed in the present study also compare well with those of China (Yang et al. 2005), but they are very

much less than that reported for Turkey (Merdanoglu and Altinsoy 2006). The ^{226}Ra concentration reported for these two regions is almost four times higher than that observed in the present study. It may be noted that, upon comparison of the results of the present study with those of Punjab and Bahawalpur provinces of Pakistan (Tahir et al. 2005 and Matiullah et al. 2004, respectively), it is clear that the mean values of all three radionuclides are very much comparable.

Correlation studies

In order to find the extent of the existence of these radioactive nuclides together at a particular place, correlation studies were performed between the combinations of radionuclides such as ^{226}Ra and ^{232}Th, ^{232}Th and ^{40}K, and ^{226}Ra and ^{40}K and are shown in Figs. 2, 3, and 4, respectively. From the figures it is clear that no significant correlation is found between the last two combinations. But a significant (Fisher 1950) correlation ($R = 0.63$ for $n = 33$) is observed for the ^{226}Ra and ^{232}Th combination. The poor or insignificant correlation between ^{232}Th and ^{40}K and ^{226}Ra and ^{40}K indicates that individual results for any one of the radionuclide concentrations in each pair is not, therefore, a good predictor of individual values for the other.

Dose calculations

From the measured concentrations of ^{226}Ra, ^{232}Th and ^{40}K the absorbed dose rates in air were calculated using the following relation (UNSCEAR 1998):

$$D = [(0.427 \times A_{Ra}) + (0.666 \times A_{Th}) + (0.043 \times A_K)]\ \text{nGy h}^{-1}, \quad (1)$$

where A_{Ra}, A_{Th}, and A_K are the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, in Bq kg^{-1}. The absorbed dose rates thus calculated are presented in column 3 of Table 3 and are found to vary in the range 25.9–165.5 nGy h^{-1} with a mean value of 73.9 nGy h^{-1}. This is relatively higher when compared to the global average value of 55 nGy h^{-1} (UNSCEAR 1988).

As mentioned earlier, direct measurements of gamma absorbed dose rates were also performed at all the 33 locations using an environmental radiation dosimeter. The results are presented in column 4 of Table 3. The measured dose rates, which include the cosmic ray component, ranged from 61.4–201.7 nGy h^{-1} with a mean value of 117.2 nGy h^{-1}. The lowest and the highest values were observed, respectively, at Kukkanahalli and Lalbagh. The observed trend of variation in the external gamma dose rates in air can be directly correlated with the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K present in the respective locations. This has been confirmed by the

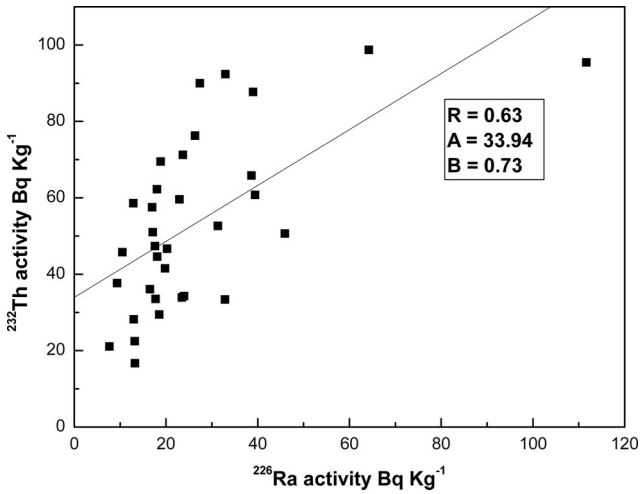

Fig. 2. Correlation between radium and thorium in soil.

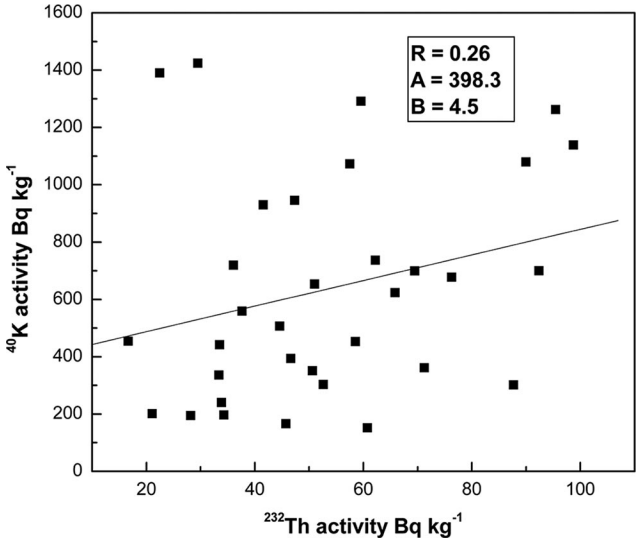

Fig. 3. Correlation between thorium and potassium in soil.

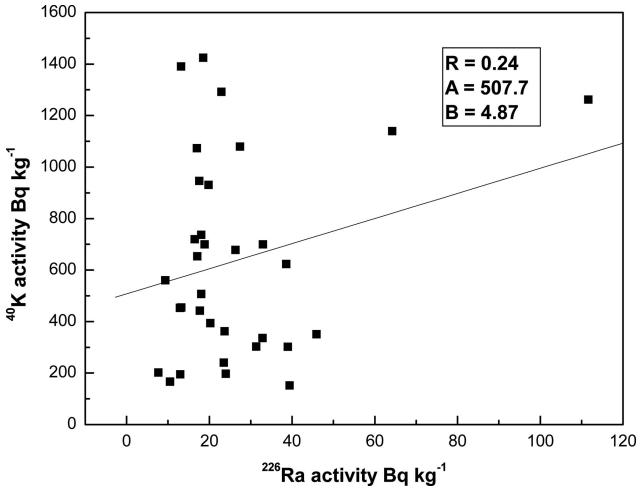

Fig. 4. Correlation between radium and potassium in soil.

Table 3. Dose calculations for the study area.

Sl. No.	Location	Absorbed dose (nGy h^{-1})		Ra_{eq}	I_γ	Effective dose	H_{ex}	H_{in}
		Calculated	Measured	(Bq kg^{-1})		(μ Sv y^{-1})		
1.	Kannahalli	80.8	122.8	163.8	1.2	99.19	0.44	0.49
2.	Kengeri	88.0	114	187.7	1.3	108.03	0.51	0.61
3.	Mallathalli	73.1	114	153.4	1.1	89.70	0.41	0.48
4.	Katriguppe	142.2	175.4	293.1	2.2	174.45	0.79	0.97
5.	Machohalli	48.9	105.3	99.7	0.78	59.99	0.27	0.32
6.	Lalbagh	165.5	201.7	345.3	2.5	203.09	0.93	1.2
7.	Doddakallasandra	50.7	105.2	106.5	0.8	62.23	0.29	0.38
8.	Kumbalagodu	53.1	114	106.3	0.81	65.18	0.29	0.31
9.	Tavarekere	91.2	114	187.6	1.4	111.89	0.51	0.58
10.	Bannerughatta	105	175.4	207.6	1.6	128.87	0.56	0.62
11.	Agara	41.6	70.2	88.2	0.6	50.99	0.24	0.3
12.	Hebbal	68.4	131.6	145.3	1.05	83.95	0.4	0.52
13.	Kambasandra	61.9	140.2	123.5	0.95	76.07	0.33	0.38
14.	Beemanakuppe	63.9	105.3	131.5	0.97	78.51	0.36	0.39
15.	Hejjala	69.4	105.3	140.4	1.06	85.15	0.38	0.43
16.	Ragihalli	84.4	114	172.5	1.29	103.56	0.47	0.52
17.	Kudlu	59.2	114	120.9	0.9	72.67	0.33	0.38
18.	Kalkere	105.7	140.3	218.9	1.61	129.67	0.59	0.68
19.	Tarabanahalli	56.7	70.2	117.3	0.86	69.52	0.32	0.37
20.	Mallasandra	88.8	131.6	170.4	1.37	108.95	0.46	0.51
21.	Shivanahalli	118.1	149.1	239.2	1.80	144.85	0.65	0.72
22.	Bidadi	76.1	122.8	150.5	1.17	93.42	0.41	0.46
23.	Mummenahalli	79.7	122.8	158.1	1.22	97.82	0.43	0.48
24.	Nelamangala	61.5	87.7	129.9	0.94	75.43	0.35	0.44
25.	Kannur	87.2	122.8	180.8	1.33	106.94	0.49	0.6
26.	Varthur	42.1	70.9	88.4	0.64	51.67	0.24	0.27
27.	Harohalli	36.3	87.7	72.1	0.56	44.53	0.19	0.23
28.	Madapura	80.7	96.5	152.4	1.24	98.60	0.41	0.45
29.	Magadi	91.7	140.3	181.8	1.4	112.52	0.49	0.54
30.	Kukkanahalli	25.9	61.4	53.4	0.39	31.89	0.14	0.17
31.	Baglur	63.8	149.1	137.8	0.97	78.31	0.37	0.48
32.	Kadugodi	42.9	105.3	94.4	0.66	52.66	0.24	0.31
33.	Morasur	32.7	87.7	68.3	0.5	40.10	0.18	0.22
	Range	25.9–165.5	61.4–201.7	53.4–345.3	0.39–2.5	31.9–203.1	0.14–0.93	0.17–1.2
	Median	69.5	114	145.3	1.06	85.2	0.4	0.46
	Mean	73.9	117.2	151.1	1.13	90.6	0.41	0.48
	SD	30.4	31.4	62.1	0.46	37.3	0.17	0.21

regression analysis of measured dose rates with respect to the computed dose from the knowledge of concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Fig. 5). The correlation coefficient was found to be 0.85 with an intercept of 52.4 nGy h^{-1} in the y-axis. The value of intercept gives the contribution from the cosmic ray intensity.

The absorbed dose rate in air observed in the study area is compared with the values reported for other environments in Table 4. The mean value of the absorbed dose rate observed in Bangalore region (117.2 nGy h^{-1}) is slightly higher when compared to the Indian national average values of 80.7 nGy h^{-1} and 88.5 nGy h^{-1} reported by Mishra and Sadasivan (1971) and Nambi et al. (1987), respectively. It is two times higher than that of the world average value (UNSCEAR 1993). The absorbed dose rate observed in the present study is also almost two times than that of Spain (Baeza et al. 1994), but is very much less than that of Turkey (Merdanoglu and Altinsoy 2006).

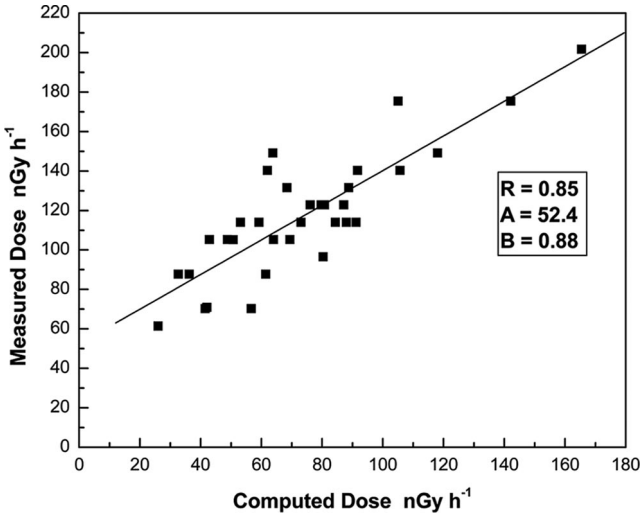

Fig. 5. Correlation between computed and measured gamma absorbed dose rates.

Table 4. Comparison of (measured) external gamma absorbed dose rate in air (nGy h^{-1}) with other environments.

Present work	Literature value	Region	Reference
61.4–201.7 (117.2)	80.7	All India average	Mishra and Sadasivan (1971)
	88.5	All India average	Nambi et al. (1987)
	87	Switzerland	Herbst (1964)
	94 (24–270)	Germany	Ohlsen (1971)
	49 (50–100)	Japan	Abe et al. (1980)
	73 (20–1100)	Norway	Stranden (1977)
	66.1 (42–87)	Kaiga	Karunakara et al. (2001)
	56 (28–120)	World average	UNSCEAR (1993)
	64 (36–101)	Goa	Avadhani et al. (2001)
	56.6 (9–230)	Spain	Baeza et al. (1994)
	253 (205–337)	Turkey	Merdanoglu and Altinsoy (2006)

The measured concentrations of ^{226}Ra, ^{232}Th, and ^{40}K are expressed by a single entity, which takes in to account the radiation hazard called radium equivalent activity, Ra_{eq} (Tahir et al. 2005). This provides a useful guideline in regulating the safety standards on radiation protection for the general public. The Ra_{eq} has been calculated on the assumption that 370 Bq kg^{-1} of ^{226}Ra, 259 Bq kg^{-1} of ^{232}Th, and 4,810 Bq kg^{-1} of ^{40}K produce the same gamma dose rate (Beretka and Mathew 1985). The use of materials whose Ra_{eq} exceeds 370 Bq kg^{-1} is discouraged to avoid radiation hazards (Beretka and Mathew 1985). The annual effective dose for a Ra_{eq} of 370 Bq kg^{-1} corresponds to the dose limit of 1 mSv for the general population (Tahir et al. 2005). In the present work, the Ra_{eq} was calculated using the equation given by Tahir et al. (2005) and the values are presented in column 5 of Table 3. The Ra_{eq} varied in the range 53.4–345.3 Bq kg^{-1} with a mean value of 151.1 Bq kg^{-1}, which is well within the permissible limit of 370 Bq kg^{-1}.

Another radiation hazard index, called the representative level index I_γ, was also calculated using the formula given by NEA–OECD (1979), and is presented in column 6 of Table 3. The I_γ values varied in the range 0.39–2.5 with a mean value of 1.13.

The annual effective dose to the population of Bangalore region was estimated from the measured radionuclide concentrations using the dose conversion coefficient of 0.7 Sv Gy^{-1} and an outdoor occupancy factor of 0.2 as outlined in UNSCEAR (2000). The annual effective dose rates thus calculated are presented in column 7 of Table 3 and varied from 31.9 μSv y^{-1} to 203.1 μSv y^{-1} with a mean value of 90.6 μSv y^{-1}. The mean value of annual effective dose obtained in the present study is lower when compared to the worldwide average value of 0.46 mSv y^{-1} reported by UNSCEAR (1993, 2000) for normal background regions.

The external hazard index (H_{ex}) due to natural gamma radiation was calculated using the relation given by Yang et al. (2005), and the values are shown in column 8 of Table 3. The H_{ex} value in the study area ranged from 0.14 to 0.93 with a mean of 0.4. There is also a radiation hazard threat to respiratory organs due to the ^{222}Rn, decay product of ^{226}Ra, and its short-lived decay products. To account for this the maximum permissible concentration for radium must be reduced to half of the normal limit (Beretka and Mathew 1985). Considering this limit, the internal hazard index (H_{in}) was calculated and is found to range from 0.17–1.2 with a mean value of 0.48, which is shown in column 9 of Table 3. From the table it can be seen that Kukkanahalli and Lalbagh are found to have the lowest and highest values of both H_{ex} and H_{in} among the locations of the study area.

CONCLUSION

The study has established data on radiation dose to the population and radionuclide concentration in the soils of Bangalore region. The study showed that the overall mean values of ^{226}Ra, ^{232}Th, and ^{40}K concentrations in entire region covered under this study were comparable to that reported for other environs of India and the world. The mean concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the soils of Bangalore environment were 26.2 Bq kg^{-1}, 53.1 Bq kg^{-1}, and 635.1 Bq kg^{-1}, respectively, and were comparable with the worldwide findings. Some of the places showed higher concentrations of these radionuclides because of the presence of granites in the region, which are known to contain higher concentrations of ^{226}Ra and ^{232}Th. The higher concentration of ^{40}K is due to feldspars, which form part of the granites. The gamma absorbed dose rates, radium equivalent activity, annual effective dose to the general population, and the external and internal hazard indices observed for Bangalore region are comparable to other normal background regions of India as well as the world.

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