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ORIGINAL ARTICLE

Study of radiation dose due to ^{226}Ra, ^{222}Rn, and ^{210}Po in drinking water of Chamarajanagar district, Karnataka, India

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Abstract

Groundwater carries radioactive elements like ^{226}Ra, ^{222}Rn, and ^{210}Po during its flow beneath and above the land. When this water is used for drinking, cooking and other household purposes, the radioactive substances in the water may enter the human body and cause adverse health effects. This study was conducted to determine the distribution of ^{226}Ra, ^{222}Rn, and ^{210}Po in the groundwater samples of Chamarajanagar District, Karnataka, India. The activity of ^{222}Rn in 66 places was studied using the smart radon monitor. The activity of ^{226}Ra, and ^{210}Po was studied at 12 places using emanometry technique and radiochemical analysis, respectively. The activity of ^{222}Rn in groundwater samples varied from 0.94 ± 0.13 to 26.90 ± 3.53 Bq L^{-1} with an average of 4.44 ± 0.56 Bq L^{-1}. The activity of ^{226}Ra, and ^{210}Po varied from 2.18 ± 0.31 to 96.42 ± 16.55 mBq L^{-1} with an average of 31.38 ± 9.93 mBq L^{-1} and 0.72 ± 0.24 to 6.33 ± 0.88 mBq L^{-1} with an average of 2.86 ± 0.52 mBq L^{-1}, respectively. A good correlation between ^{226}Ra, ^{222}Rn, and ^{210}Po was observed, indicating that they might be of the same origin. The average ingestion dose due to ^{226}Ra, ^{222}Rn, and ^{210}Po were 6.41, 11.58, and 2.51 μSv y^{-1} respectively, which is less than the recommended effective dose of 100 μSv y^{-1} associated with the intake of radionuclide from drinking water by WHO.

Keywords Radionuclide · Radon · Emanometry · Scintillation detector · Ingestion dose

Introduction

Radiation is omnipresent, and all living beings are continuously exposed to it. Radiation dose due to naturally occurring radionuclide is higher than those provided by man-made radiation sources (WHO 2017). Uranium and its progeny are found in almost all types of rocks and soils, and as water flows through these soil and rocks, this uranium is transported into water. More than 99% of natural uranium is present as ^{238}U and 0.72% occurs as ^{235}U. The two main oxidation states of uranium that are found in natural water are the hexavalent (VI) form and the tetravalent (IV) form. The tetravalent U form is significantly less soluble in water than the hexavalent U form. In oxidizing conditions with pH (> 6), the dominant species is the uranyl ion (UO_2^{2+}). At higher pH levels, uranium forms highly soluble carbonate complexes, like UO_2CO_3, leading to a significant increase in dissolved uranium concentrations in water. In reducing conditions, uraninite (UO_2), which has limited solubility, becomes the dominant form, resulting in lower concentrations of aqueous uranium (Cumberland et al. 2016).

^{226}Ra, ^{222}Rn, and ^{210}Po, which are the daughter products of the ^{238}U radioactive decay series, have got importance because of their radiological effects when health issues are concerned. ^{226}Ra is known to be one of the most toxic long-lived radioactive elements in the environmental matrix (Sill 1987). The ^{226}Ra isotope has a longer half-life, and is chemically similar to calcium, as both are alkaline earth elements. ^{226}Ra can replace calcium in bone structure, thus increasing the internal radiation dose to the individuals (Iyengar 1990). Studies have shown that ingestion of ^{226}Ra can result in skeletal tumours and paranasal sinus carcinoma diseases (Rana et al. 2010). There are many studies on absorption of calcium and radium from the gastrointestinal tract of the rat

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and metabolism of radium and calcium in humans (Norris and Kisieleski 1948).

^{222}Rn, an alpha emitting radioactive noble gas with a half-life of 3.82 days, is the major contributor to radiation exposure among all natural radiation sources. ^{222}Rn in water is released to the dwellings and mixed with the indoor air, when used in household activities, which increases the inhalation dose apart from the ingestion dose (UNSCEAR 2000). The alpha particle emitted by radon and its progeny inhaled into the lungs can damage cellular DNA, which can eventually result in clinically evident lung cancer. A recent study of 66 countries on residential radon shows that 16.5% of lung cancer cases were attributable to residential radon exposure (Gaskin et al. 2018). In 1988, ^{222}Rn has been classified as a human carcinogen by the World Health Organization, and it is the key cause of lung cancer in non-smokers and the second cause in smokers (WHO 2009).

^{210}Po is another important natural radionuclide in the uranium decay series that causes internal dose. The half-life of ^{210}Po is 138.4 days which undergo alpha decay (5.3 MeV) to produce ^{206}Pb and delivers a significantly higher dose through ingestion. Therefore, ^{210}Po is classified as a Group 1 human carcinogen (IARC 2001). ^{210}Po is found in variable amounts in all types of natural water and has a high specific activity compared to that of ^{226}Ra and ^{238}U. About 7% of the natural internal radiation dose is due to ingestion of ^{210}Po alone and about 18% of the internal dose to the people is due to ingestion of ^{210}Po along with its precursor ^{210}Pb (Bulman et al. 1995; Clayton and Bradley 1995). When ingested, ^{210}Po is mainly absorbed into blood (ICRP 1979, 1993) and is predominantly transported to soft tissues. The most susceptible organs to ^{210}Po are the liver, spleen, bone marrow, kidneys, and skin (Leggett and Eckerman 2001). ^{210}Po is not filtered by the kidneys as it strongly binds to haemoglobin and plasma proteins, and hence, renal excretion of ^{210}Po is very slow compared to other radioactive elements (Thomas et al. 2001).

The estimation of radionuclide in drinking water and assessment of radiation dose to the population is important, particularly when the groundwater is used for drinking purpose and household activities. Bore wells are the only sources of drinking water in major parts of the study area; therefore, it is very essential to estimate the activity of radionuclide in groundwater to assess the radiation dose to the population of the Chamarajanagar district of Karnataka state, India. The concentration of radionuclide in groundwater is not the same in all the seasons of a year due to rainfall and agricultural practices. In the present investigation, the annual average activity of these radionuclides in groundwater sources of the Chamarajanagar district was carried out. Ingestion and inhalation dose to the residents was also estimated. This type of extensive and systematic work has not been carried out earlier in this region of study.

Study area

Chamarajanagar district lies between the latitudes 11° 40′ 58″ N and 12° 6′ 32″ N and longitudes 76° 24′ 14″ E and 77° 64′ 55″ E in the southern tip of Karnataka state, India. The geographical area is about 5,000 km^2 and has an average altitude of 662 m above sea level. 47.54% of the district's area is covered by dense forest. The topography is mountainous with north–south trending hill ranges of Indian Eastern Ghats.

The district has five taluks, viz., Chamarajanagar, Gundlupet, Hanur, Kollegal, and Yelandur (Fig. 1). This district is endowed with rich mineral resources, including both metallic and non-metallic minerals. The major mineral available is black granite. Gneiss rocks are found in the eastern parts of the district and granite rocks are found in most parts of Kollegal taluk. The southern part of this taluk is surrounded by M. M. Hills. The B. R. Hills in Yelandur taluk is mainly surrounded by gneiss rock. Granite compositions like granodiorite and tonalite rock types are found in Gundlupet and Hanur taluks (CGWB 2008). Borewells are the major sources of water supply for domestic, agriculture, and industries in the entire district. Groundwater which originates from granitic rocks that leach and dissolve radioisotopes may result in higher doses to the local population. The concentration of radionuclides on earth varies from region to region, which mainly depends on the type of soil and rocks in the study area. Therefore, the distribution of radioactive elements in the groundwater and its relation with geological features of the area is studied in the present investigation. The sampling locations are shown in Fig. 1.

Materials and methods

Concentration of ^{222}Rn in water samples

Water samples of about 500 mL were collected in airtight vials from different sampling stations throughout the district. The representative sample was collected after flushing out the stagnant water in the bore well for about 30 min. To minimize ^{222}Rn leakage and bubble formation during sample collection, the vials were filled by immersing them in the sample-filled container and closing the lids beneath the water (Rajesh et al. 2012; ASTM 1998). GPS coordinates of the location and sampling time were noted, and the samples were bought to the laboratory within 3–4 h after sampling. In remote areas, in situ measurements were conducted by taking all the required equipment to the spot.

The activity of ^{222}Rn in water samples was measured using the Smart Radon Monitor (SRM) (Figs. 2 and 3)

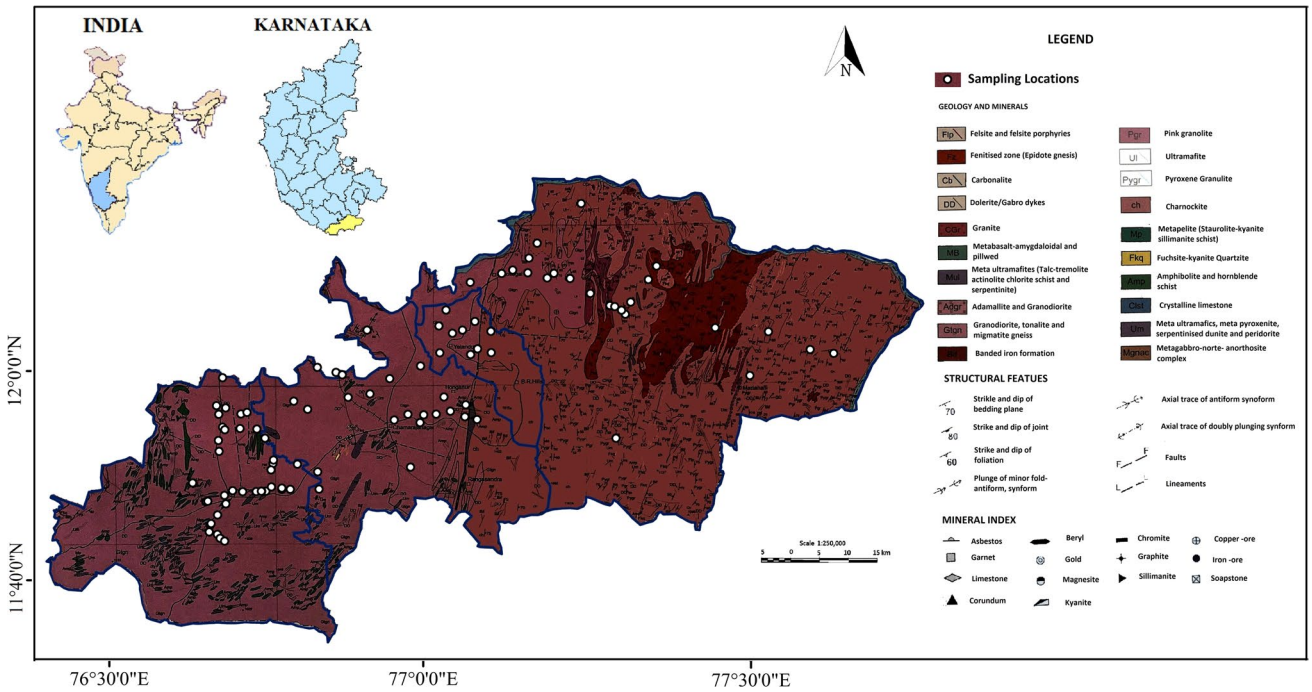

Fig. 1 The study area; Chamarajanagar district

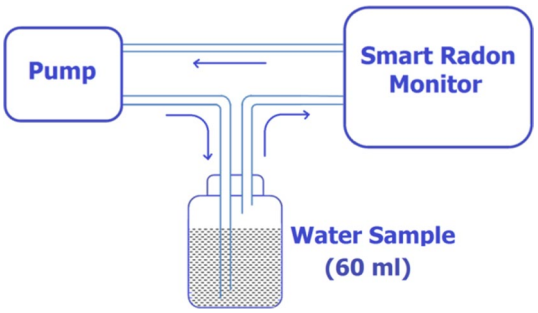

Fig. 2 Schematic representation of SRM

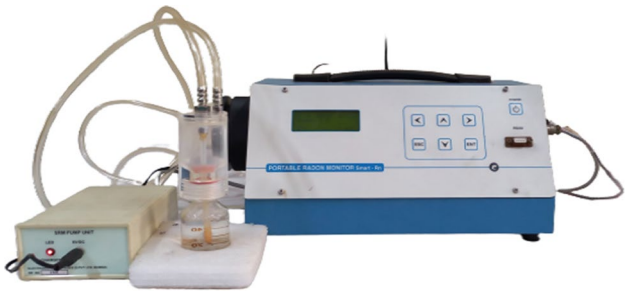

Fig. 3 Radon measurements in water samples

(Hidayath et al. 2022; Gaware et al. 2011). The samples were analysed by incorporating the standard protocol for the measurement of ^{222}Rn in drinking water samples (ASTM 1998). About 60 mL of sample was taken in the sampling holder. By bubbling air through the water, the dissolved ^{222}Rn in the water was transferred to the scintillation cell through a progeny filter for the elimination of ^{222}Rn and ^{220}Rn daughter products. The scintillation cell, which is coupled to a photomultiplier tube and counting electronics, will measure the ^{222}Rn concentration. Background counts due to the residual decay product of ^{222}Rn was eliminated using the indigenous smart algorithm of the microprocessor. The efficiency of the ZnS (Ag) scintillation cell used in the radon monitor is 74%. The SRM was calibrated regularly using a standard source. The minimum detection level of the SRM used for analysing radon concentration in water samples is 0.007 Bq L^{-1}. For confirmation, 10% of the samples were analysed at other national laboratories.

The concentration of ^{222}Rn in water samples was calculated using Eq. (1) (Raghavayya et al. 1980)

$$C_{Rn} = \frac{6.97 \times 10^{-2} \times (D - B)}{V \times E \times \left(1 - e^{-\lambda t}\right) \times e^{-\lambda T}}, \quad (1)$$

where C_{Rn} is the activity of ^{222}Rn in the water sample (Bq L^{-1}), D is the alpha counts (s^{-1}), B is the background counts (s^{-1}), V is the volume of the actual water sample taken for analysis (mL), E is the efficiency of the radon monitor, λ is the radioactive decay constant of ^{222}Rn, t is the time duration of counting (s), and T is the time delay after sample collection (s).

Estimation of radiation dose

The annual effective dose due to inhalation and ingestion from ^{222}Rn in water is calculated by UNSCEAR established parameters. The inhalation and ingestion dose due to ^{222}Rn in water are given by Eqs. (2) and (3), respectively (UNSCEAR 2000). The weighted average water consumption by the population of the district is considered to be 730 L y^{-1}, recommended by WHO, to estimate the ingestion dose (WHO 2017).

Inhalation dose due to ^{222}Rn in water

$$D_{inh} = C_{Rn} \times R_{aw} \times I \times F \times F_D, \quad (2)$$

where, D_{inh} is the annual effective inhalation dose (μSv y^{-1}), C_{Rn} is the activity concentration of ^{222}Rn in the water sample (Bq L^{-1}), R_{aw} is the ratio between the concentration of ^{222}Rn in the air to the concentration of ^{222}Rn in water (10^{-4}), I is the average time spent by an individual in indoor (7000 hy^{-1}), F is the equilibrium factor between ^{222}Rn and its progeny (0.4), and F_D is the dose conversion factor for ^{222}Rn exposure (9 nSv (Bq h m^{-3})$^{-1}$) (UNSCEAR 2000).

Ingestion dose due to ^{222}Rn in water

$$D_{ing} = C_{Rn} \times W \times E_{DC}, \quad (3)$$

where, D_{ing} is the effective ingestion dose (μSv y^{-1}), W is the weighted average water consumption (730 L y^{-1}), and E_{DC} is the dose coefficient for ^{222}Rn in water through ingestion (3.5 nSv Bq^{-1}) (UNSCEAR 2000).

Estimation of ^{226}Ra by emanometry method

Emanometry technique was employed to measure ^{226}Ra concentration in water (Raghavayya et al. 1980). For radium measurements in water, the locations were marked based on the results of radon measurements. In each taluk of Chamarajanagar district, 5–6 locations were identified and water samples of about 20 L were collected in pre-cleaned cans. The pH of samples and GPS coordinates of the locations were also noted.

The water sample was filtered and pre-concentrated by co-precipitation and evaporation methods for ^{226}Ra analysis. About 5 g of analytical grade manganese dioxide was added and stirred for an hour using a mechanical stirrer and kept for 2 h to settle down. The precipitate was heated to evaporate the water content and treated with 50 mL of concentrated hydrochloric acid. This solution was evaporated to near dryness and treated with 30 mL of concentrated nitric acid and heated to near dryness to evaporate organic materials. The solution was allowed to cool and then treated with 50 mL of 4 N HNO_3 and filtered using Whatman 42 filter paper (Hidayath et al. 2022; Raghavayya et al. 1980).

About 70 mL of pre-concentrated solution was transferred to the radon bubbler (Figs. 4 and 5). Using a vacuum pump, the air was sucked through the solution to purge dissolved ^{222}Rn. The solution-filled bubbler was kept undisturbed for 21 days (3–5 half-lives of ^{222}Rn) for ^{222}Rn build-up. An evacuated and background counted scintillation cell was connected to the bubbler through a swage connector. Air with dissolved ^{222}Rn gets sucked through the solution and fills the scintillation cell under the influence of the vacuum of the scintillation cell (Hidayath et al. 2022). The bubbling was made uniform and steady to have the complete transfer of ^{222}Rn. The cell was kept for about 3–4 h to have equilibrium between ^{222}Rn and its daughter products. The alpha activity in the scintillation cell was measured using a scintillation-based programmable alpha counting system for duration of 1000 s. The minimum detection level of this counting system is 1.12 mBq L^{-1}. The calibration of the programmable counting system was done using standard source regularly. The activity of ^{226}Ra in the water sample was calculated using Eq. (4) (Raghavayya et al. 1980)

$$C_{Ra} = \frac{6.97 \times 10^{-2} \times (D - B)}{V \times E \times e^{-\lambda T} \times \left(1 - e^{-\lambda t}\right) \times \left(1 - e^{-\lambda \tau}\right)}, \quad (4)$$

where C_{Ra} is the activity of ^{226}Ra in the water sample (mBq L^{-1}), D is the alpha counts (s^{-1}), B is the background alpha counts (s^{-1}), V is the volume of the water sample taken for

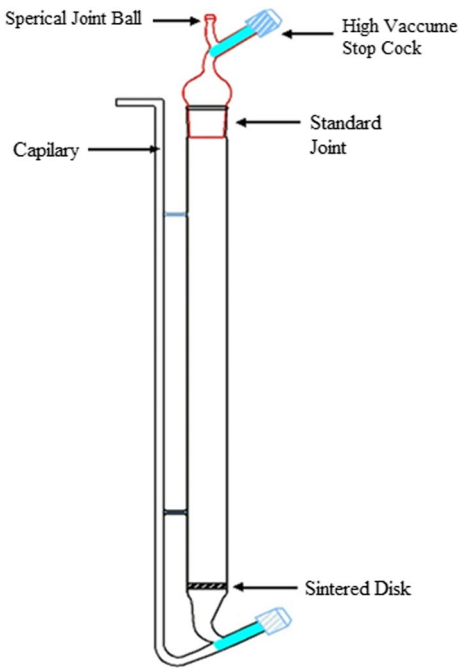

Fig. 4 Schematic representation of radon bubbler

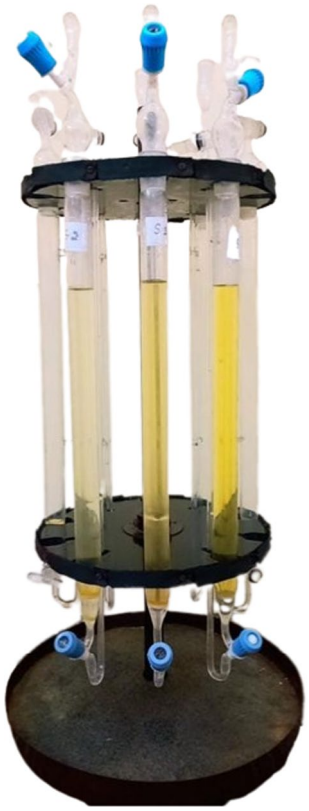

Fig. 5 Radon bubblers filled with pre-concentrated ^{226}Ra solution

processing (about 20 L), E is the efficiency of the programmable alpha counting system (74%), λ is the radioactive decay constant of ^{222}Rn (2.098×10^{-6} s^{-1}), T is the time delay after transferring the solution from radon bubbler to the scintillation cell (s), t is the time duration of alpha counting (s), and τ is radon build-up period in the bubbler (s).

Ingestion dose due to ^{226}Ra in water

Ingestion dose to the public due to the dissolved ^{226}Ra in drinking water was estimated using the method and dose coefficients described in the IAEA reports (IAEA 2011). The ingestion dose per annum is calculated using Eq. (5) (UNSCEAR 2000)

$$D_{Ra} = C_{Ra} \times W \times D_{CRa}, \quad (5)$$

where D_{Ra} is the ingestion dose due to ^{226}Ra in water (μSv y^{-1}), W is the weighted average water consumption by the population (730 L y^{-1}), and D_{CRa} is the dose conversion factor for dissolved ^{226}Ra in drinking water (2.8×10^{-7} Sv Bq^{-1}) (WHO 2017).

Measurement of ^{210}Po in water samples

Sampling

Water samples of about 10 to 20 L, collected from different regions of Chamarajanagar district, were analysed for the ^{210}Po activity by radiochemical analysis technique (Namitha et al. 2023). Water samples were collected in clean plastic cans and the pH of the sample was measured at each location. The water was filtered using Whatman 42 filter paper and is transferred to a clean tub. Hydrochloric acid was added to maintain the pH of the water to 2.0. Iron carrier (5 g) was added to the solution and stirred for an hour using a specially designed mechanical stirrer. Ammonia solution was slowly added until the pH of the solution increases to 9.0 to precipitate iron as iron (III) hydroxide in the solution. The solution was stirred steadily for 6 h and left undisturbed overnight to settle. The precipitate was dissolved using concentrated hydrogen peroxide to remove the organic content present in the solution. Hydrochloric acid was added to this solution, stirred using a magnetic stirrer, and evaporated to near dryness in the beaker. The total dryness was avoided to prevent loss of ^{210}Po due to volatilization and sorption onto the surface of the glass beaker. The residue was treated with 0.5 M hydrochloric acid, and to this solution, ascorbic acid was added to avoid interference of ferric ion deposition on the silver disc (Sharma et al. 2021; WHO 2011).

Sample processing

A background counted silver disc was immersed into the solution and stirred for 6 h by maintaining the temperature at 90 °C (Fig. 6). This process spontaneously deposits 99% of ^{210}Po on the polished silver disc. After agitating for 6 h, the silver disc was rinsed with double distilled water and ethanol and then dried. The silver disc was subjected to alpha counting and counts were recorded for 6000 s on both surfaces (Namitha et al. 2023; Makmur et al. 2020; Kavitha et al. 2017). Using this technique, the minimum polonium concentration that can be measured is 0.09 mBq L^{-1}. The activity concentration of ^{210}Po was calculated using Eq. (6)

$$C_{Po} = C \times \frac{100}{\varepsilon} \times \frac{100}{E_p} \times \frac{1000}{V}, \quad (6)$$

where C_{Po} is the activity of ^{210}Po (mBq L^{-1}), C is the background subtracted sample counts (s^{-1}), ε is the efficiency of the alpha counting system (17.65%), E_p is the efficiency of ^{210}Po deposition on a silver planchet (99%), and V is the volume of the water taken for processing (L).

Fig. 6 Experimental setup for the spontaneous deposition of ^{210}Po on a silver disc

Ingestion dose due to ^{210}Po in water

The effective dose due to activity of ^{210}Po in the ingested water per annum was calculated using Eq. (7) (Ahmed et al. 2018)

$$D_{Po} = C_{Po} \times W \times D_{CPo}, \quad (7)$$

where D_{Po} is the ingestion dose due to ^{210}Po in water (μSv y^{-1}), W is the weighted average of water consumption (730 L y^{-1}), and D_{CPo} is the dose conversion factor for ^{210}Po (1.2×10^{-6} Sv Bq^{-1}) (WHO 2017; ICRP 1996).

Results and discussion

The activity of ^{222}Rn in groundwater samples and the annual effective dose due to inhalation and ingestion of ^{222}Rn are shown in Table 1. The samples were collected at 66 villages/towns in Chamarajanagar district during 2020–2022 covering all the seasons of the year and the average values are presented in Table 1 for each location. ^{222}Rn concentration in water samples is due to the presence of radium isotopes in surrounding rocks and soils. Granodiorite, tonalite, and migmatic gneiss types of rocks are found in this region. During weathering of rocks, ^{226}Ra will be transported from rocks and collected in the soil. During the transport of groundwater through rocks and soil, ^{226}Ra gets dissolved in groundwater. ^{222}Rn concentration at different locations of the study area was found to vary from 0.94 ± 0.13 to 26.90 ± 3.53 Bq L^{-1} with an average of 4.44 ± 0.56 Bq L^{-1}. At all the locations, the average values of ^{222}Rn concentration were found to be below the suggested limit of 100 Bq L^{-1} by WHO (2011). Relatively higher concentrations of ^{222}Rn in water were observed at Manchahalli village (26.90 ± 3.53 Bq L^{-1}) of Gundlupet Taluk and Karinanjanapura village (19.20 ± 1.16 Bq L^{-1}) of Chamarajanagar taluk. The annual inhalation dose varies from 2.37 to 67.91 μSv y^{-1} with an average of 11.44 μSv y^{-1} and the annual ingestion dose varies from 2.40 to 68.86 μSv y^{-1} with an average of 11.60 μSv y^{-1}. The total annual effective dose due to inhalation and ingestion varies from 4.77 to 136.77 μSv y^{-1} with a geometric mean value of 15.96 μSv y^{-1}. The total effective dose lies below the recommended limit of 1 mSv y^{-1} by WHO (2011).

The statistical parameters like skewness and kurtosis were calculated to effectively explain the variation of ^{222}Rn concentration in water. A positive value of the skewness coefficient (2.69) suggests that the Gaussian distribution, which is moderately asymmetric, with the right tail longer than the left. The distribution is right-skewed. From the positive value of 11.94 for kurtosis coefficient, we deduce that the distribution is higher and narrower than the normal. ^{222}Rn concentrations in the 1st quartile, 2nd quartile, and 3rd quartile are 1.64, 2.61, and 5.96 Bq L^{-1}, respectively. The standard error of the mean is 0.56 and the coefficient of variation is 1.02.

The concentration of ^{226}Ra and ^{210}Po in borewell water samples and ingestion dose due to these radionuclides is shown in Table 2. The ^{226}Ra concentration in water samples varies from 2.18 ± 0.31 to 96.42 ± 12.85 mBq L^{-1} with an average of 31.38 ± 9.93 mBq L^{-1}. Higher concentrations were observed at Beguru (93.42 ± 12.85 mBq L^{-1}) and Terakanambi village (93.83 ± 11.53 mBq L^{-1}) of Gundlupet taluk due to granite rocks in the region, which is known to contain higher concentrations of radionuclides. Moreover, the depths of bore wells are more than 150 m below the ground level and effluents from industries in these regions may also be the cause for higher radioactive elements in groundwater. The lower concentrations are observed at villages of Yelandur taluk as this taluk is rich in surface water sources and the depths of bore wells are about 50 to 100 m below ground level. US-EPA has set the maximum contamination limit of 5 pCi L^{-1} (0.185 Bq L^{-1}) for ^{226}Ra in public water supplies (USEPA 2000), WHO has recommended 1 Bq L^{-1} for ^{226}Ra as a safe limit in drinking water (WHO 2017). The ingestion dose due to ^{226}Ra in water varied from 0.45 to 19.71 μSv y^{-1} with a geometric mean value of 3.67 μSv y^{-1}.These values are below the safe limits of 100 μSv y^{-1} recommended by WHO (2011). The total effective radiation dose due to inhalation of ^{222}Rn (Table 1) and ingestion of ^{226}Ra, ^{222}Rn, and ^{210}Po (Tables 1 and 2) in water varied from 6.40 to 162.02 μSv y^{-1} with an average value of 31.47 μSv y^{-1} is within the safe limits prescribed by WHO (100 μSv y^{-1}). The present investigation indicates that people in the study area are less prone to radiological hazards due to natural radionuclides in water.

Table 1 ^{222}Rn concentration in water and radiation dose to the public

Sl. no	Town/village	GPS coordinates (latitude and longitude)	No. of locations	^{222}Rn Conc (Bq L^{-1})	Inhalation dose (μSv y^{-1})	Ingestion dose	Total dose
Chamarajanagar taluk							
1	Bendaravadi	12.005011°N, 76.820099°E	4	3.01 ± 0.28	7.59	7.69	15.28
2	Bevinathalapura	11.848725°N, 76.966212°E	7	2.76 ± 0.23	6.96	7.05	14.01
3	Chamarajanagar	11.922479°N, 76.940477°E	10	3.76 ± 0.32	9.48	9.61	19.08
4	Chandakavadi	11.931780°N, 77.006369°E	4	1.42 ± 0.23	3.58	3.63	7.21
5	Heggotara	11.958140°N, 76.868298°E	9	6.06 ± 0.45	15.27	15.48	30.75
6	Hondarabalu	11.923523°N, 77.070360°E	3	2.17 ± 0.36	5.47	5.54	11.01
7	Jyothigowdanapura	11.946466°N, 77.052604°E	3	3.29 ± 0.42	8.29	8.41	16.70
8	Kagalavadi	11.958686°N, 77.018568°E	3	1.14 ± 0.20	2.87	2.91	5.79
9	Karinanjanapura	11.918605°N, 76.980993°E	6	19.20 ± 1.16	48.26	48.93	97.19
10	Kodimole	11.930793°N, 76.986703°E	3	2.03 ± 0.21	5.12	5.19	10.30
11	Mariyala	11.963691°N, 76.902510°E	4	1.68 ± 0.23	4.23	4.29	8.53
12	Muttige	11.997260°N, 76.849511°E	3	1.47 ± 0.21	3.70	3.76	7.46
13	Nagavalli	11.936424°N, 77.028375°E	9	2.41 ± 0.36	6.07	6.16	12.23
14	Nalluru	11.927711°N,77.051198°E	6	2.62 ± 0.33	6.60	6.69	13.30
15	Panyadahundi	11.993361°N, 76.859120°E	6	1.89 ± 0.18	4.76	4.83	9.59
16	Ramasamudra	11.931598°N, 76.962131°E	3	5.60 ± 1.25	14.11	14.31	28.42
17	Singanapura	12.007387°N, 76.981774°E	9	1.34 ± 0.31	3.38	3.42	6.80
18	Umatturu	12.063479°N, 76.898007°E	6	1.22 ± 0.27	3.07	3.12	6.19
Gundlupet taluk							
1	Begur	11.945174°N; 76.662027°E	9	11.65 ± 0.62	29.36	29.77	59.12
2	Chikkathuppur	11.810108°N; 76.703167°E	6	7.01 ± 0.86	17.67	17.91	35.58
3	Gundlupet	11.804419°N; 76.674734°E	3	5.96 ± 0.42	15.02	15.23	30.25
4	Guruvinapura	11.841529°N; 76.820529°E	7	4.94 ± 0.68	12.45	12.62	25.07
5	Hammirhosahalli	11.941680°N;76.676463°E	6	7.08 ± 0.78	17.84	18.09	35.93
6	Hangala	11.757876°N; 76.652039°E	4	8.54 ± 0.49	21.52	21.82	43.34
7	Hosapura	11.908601°N; 76.725251°E	6	4.52 ± 0.34	11.39	11.55	22.94
8	Hunasinapura	11.909236°N; 76.699098°E	9	1.35 ± 0.12	3.40	3.45	6.85
9	Kabbahalli	11.894175°N; 76.738237°E	9	8.40 ± 0.79	21.17	21.46	42.63
10	Kottalavadi	11.814218°N; 76.822762°E	9	9.03 ± 0.82	22.76	23.07	45.83
11	Kutluru	11.794594°N; 76.645640°E	4	7.96 ± 0.98	20.06	20.34	40.40
12	Madapattana	11.932081°N; 76.700461°E	6	15.80 ± 1.69	39.87	40.42	80.29
13	Manchahalli	11.988878°N; 76.671754°E	4	26.90 ± 3.53	67.91	68.86	136.77
14	Mukha halli	11.823960°N; 76.624823°E	6	7.70 ± 1.15	19.40	19.67	39.08
15	Shindanapura	11.811038°N; 76.739501°E	5	8.07 ± 1.31	20.34	20.62	40.96
16	Shyanadrahalli	11.853514°N; 76.788795°E	9	6.44 ± 0.87	16.23	16.45	32.68
17	Somahalli	11.934653°N; 76.710036°E	6	7.72 ± 0.98	19.45	19.72	39.18
18	Terakanambi	11.814017°N; 76.777810°E	6	10.10 ± 0.51	25.38	25.73	51.11
Kollegal taluk							
1	Chikkinduvadi	12.152495°N; 77.190741°E	6	1.68 ± 0.22	4.23	4.29	8.53
2	Haravanapura	12.145080°N; 77.180120°E	6	1.90 ± 0.18	4.79	4.85	9.64
3	Jinakanahalli	12.176420°N; 77.151823°E	8	1.34 ± 0.21	3.38	3.42	6.80
4	Kollegal	12.152088°N; 77.108924°E	10	1.64 ± 0.23	4.13	4.19	8.32
5	Kunthur	11.795329°N; 76.648674°E	6	1.10 ± 0.21	2.77	2.81	5.58
6	Madhuvanahalli	12.153203°N; 77.149715°E	8	1.62 ± 0.12	4.08	4.14	8.22
7	Palya	11.894061°N; 77.287890°E	6	2.76 ± 0.33	6.96	7.05	14.01
8	Siddaiahnapura	12.157650°N; 77.126091°E	8	1.68 ± 0.12	4.23	4.29	8.53
9	Singanallur	12.144270°N; 77.215924°E	6	2.41 ± 0.33	6.07	6.16	12.23
10	Teramballi	12.138295°N; 77.059713°E	10	3.75 ± 0.34	9.45	9.58	19.03

Table 1 (continued)

Sl. no	Town/village	GPS coordinates (latitude and longitude)	No. of locations	^{222}Rn Conc (Bq L^{-1})	Inhalation dose (μSv y^{-1})	Ingestion dose	Total dose
Yelandur taluk							
1	Alkere agrahara	12.061470°N; 77.092094°E	9	1.38 ± 0.22	3.48	3.53	7.00
2	Ambale	12.027861°N; 77.011822°E	6	2.14 ± 0.32	5.39	5.47	10.86
3	Gumballi	12.034068°N; 77.071020°E	8	2.60 ± 0.43	6.55	6.64	13.20
4	Honnuru	12.069980°N; 77.010633°E	9	5.14 ± 0.35	12.95	13.13	26.09
5	Kesturu	12.094971°N; 77.021667°E	8	1.62 ± 0.21	4.08	4.14	8.22
6	Maddur	12.076961°N; 77.066966°E	9	1.38 ± 0.22	3.48	3.53	7.00
7	Vadagere	12.028151°N; 77.092632°E	6	1.10 ± 0.19	2.77	2.81	5.58
8	Yelandur	12.058514°N, 77.031681°E	6	2.80 ± 0.29	7.06	7.15	14.21
9	Yeragamballi	12.025081°N; 77.060330°E	8	1.78 ± 0.22	4.49	4.55	9.03
10	Yeriyuru	12.063320°N; 77.047525°E	9	2.02 ± 0.18	5.09	5.16	10.25
Hanur taluk							
1	Bandalli	12.163919°N; 77.351414°E	3	0.94 ± 0.13	2.37	2.40	4.77
2	Bataguppa	12.107349°N; 77.310886°E	7	1.20 ± 0.16	3.02	3.07	6.09
3	Cowdalli	12.067181°N; 77.443322°E	6	5.43 ± 0.86	13.68	13.87	27.56
4	Hanur	12.088513°N; 77.302713°E	10	1.42 ± 0.21	3.58	3.63	7.21
5	Mahadeshwarabetta	12.032942°N; 77.592034°E	6	1.99 ± 0.32	5.01	5.08	10.10
6	Managalli	12.121031°N; 77.247730°E	3	4.07 ± 0.81	10.26	10.40	20.66
7	Mangala	11.992201°N; 77.497661°E	9	3.76 ± 0.44	9.48	9.61	19.08
8	Martalli	12.027077°N; 77.628988°E	4	2.39 ± 0.23	6.02	6.11	12.13
9	Nagamale	12.142780°N; 77.338641°E	3	2.38 ± 0.43	6.00	6.08	12.08
10	Talabetta	12.061069°N; 77.526649°E	3	5.58 ± 0.46	14.06	14.26	28.32
Minimum				0.94 ± 0.13	2.37	2.40	4.77
Maximum				26.90 ± 3.53	67.91	68.86	136.77
Average				4.44 ± 0.56	11.20	11.35	22.55
Geometric mean				3.15	7.93	8.04	15.96
Standard deviation				4.53	11.42	11.58	23.01

The concentrations of ^{210}Po in groundwater ranged between 0.72 ± 0.24 and 6.33 ± 0.88 mBq L^{-1} with an average of 2.86 ± 0.52 mBq L^{-1}. Higher concentration is observed at Beguru (6.33 ± 0.88 mBq L^{-1}) and Terakanambi (5.21 ± 0.63 mBq L^{-1}) village of Gundlupet taluk. The higher concentration of ^{210}Po is attributed to higher concentration of radionuclide in the surrounding granite and phosphatic rocks. The European Union and World Health Organization recommend 100 mBq L^{-1} as safe limit for ^{210}Po in drinking water (WHO 2011). ^{210}Po activity concentration in Chamarajanagar district is within safe limits. The ingestion dose varies from 0.63 to 5.55 μSv y^{-1} with an average value of 2.51 μSv y^{-1}. These values are below the recommended value of 10 μSv y^{-1} by WHO (1993) and 1 mSv y^{-1} by ICRP (2008).

The results are useful in identifying the relationship between ^{222}Rn, ^{226}Ra, and ^{210}Po concentrations in water samples. Figure 7 shows a scatter plot of ^{226}Ra versus ^{222}Rn concentration, and ^{210}Po versus ^{222}Rn concentration in water samples. The linear regression of ^{226}Ra versus ^{222}Rn shows a Pearson's r value of 0.84, and the linear regression of ^{210}Po versus ^{222}Rn concentration shows a Pearson's r value of 0.83. Both ^{226}Ra and ^{210}Po concentration show a positive correlation between the ^{222}Rn concentration. The linear regression of ^{210}Po versus ^{226}Ra concentration is shown in Fig. 8. Because ^{210}Po is a decay product of ^{226}Ra, a good correlation was observed between these two radionuclides, with Pearson's r value of 0.86. This finding will also indicate that ^{210}Po and ^{226}Ra might be of same origin.

The activity of ^{226}Ra, ^{222}Rn, and ^{210}Po reported across the world is shown in Table 3. These radionuclides show a wide range of variation from place to place. Nguyen and Jakub (2021) have reported the highest concentration of ^{226}Ra in Poland thermal water samples (Nguyen and Jakub 2021). These locations contain Devonian limestone and this formation is covered by impermeable shale and variegated sandstone. The authors have suggested that the water could be

Table 2 ^{226}Ra and ^{210}Po concentration in bore well water samples and ingestion dose

Sl. no	Sampling area	Concentration mBq L^{-1}		Ingestion dose μSv y^{-1}		
		^{226}Ra	^{210}Po	^{226}Ra	^{210}Po	Total
1	Ramasamudra	15.93 ± 3.82	2.87 ± 0.35	3.26	2.51	5.77
2	Panyadahundi	12.98 ± 0.76	1.18 ± 0.27	2.65	1.03	3.69
3	Bevinathalapura	19.49 ± 1.12	3.65 ± 0.51	3.98	3.41	7.39
4	Gundlupet	68.91 ± 7.40	4.10 ± 0.63	14.09	3.59	17.68
5	Terakanambi	93.83 ± 11.53	5.21 ± 0.63	19.18	4.56	23.74
6	Beguru	96.42 ± 12.85	6.33 ± 0.88	19.71	5.55	25.25
7	Hanur	10.63 ± 2.49	1.46 ± 0.29	2.17	1.28	3.45
8	Bataguppe	6.07 ± 0.73	0.72 ± 0.24	1.24	0.63	1.87
9	Kollegal	7.14 ± 0.94	1.36 ± 0.17	1.46	1.19	2.65
10	Teramballi	16.59 ± 1.89	3.89 ± 0.52	3.39	3.41	6.80
11	Yelandur	2.18 ± 0.31	1.35 ± 0.28	0.45	1.18	1.63
12	Honnuru	26.34 ± 2.75	1.98 ± 0.21	5.38	1.73	7.12
	Minimum	2.18 ± 0.31	0.72 ± 0.24	0.45	0.63	1.63
	Maximum	96.42 ± 12.85	6.33 ± 0.88	19.71	5.55	25.25
	Average	31.38 ± 9.93	2.86 ± 0.52	6.41	2.51	8.92
	Geometric mean	17.93	2.34	3.67	2.05	6.02
	Standard deviation	34.39	1.81	7.03	1.58	8.43

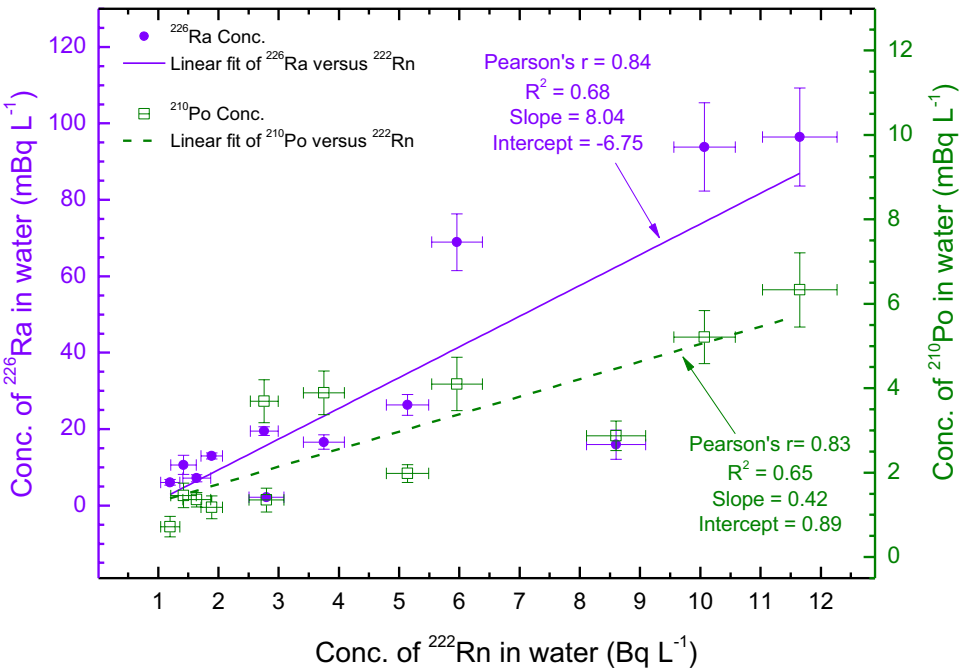

Fig. 7 Linear regression of ^{226}Ra concentration with ^{222}Rn concentration and ^{210}Po concentration with ^{222}Rn concentration in groundwater

isolated from infiltration and mixed with dehydrated water from the impermeable shale (Nguyen and Jakub 2021). The higher ^{222}Rn concentration in Polish thermal water is because of the granite aquifer in this area. They have observed a strong radioactive disequilibrium between radium and radon. Walencik-Lata et al. have observed higher ^{222}Rn concentration at Ladek-Zdroj Spa in Poland and this was attributed to a huge dislocation zone and an increased radon exhalation rate from

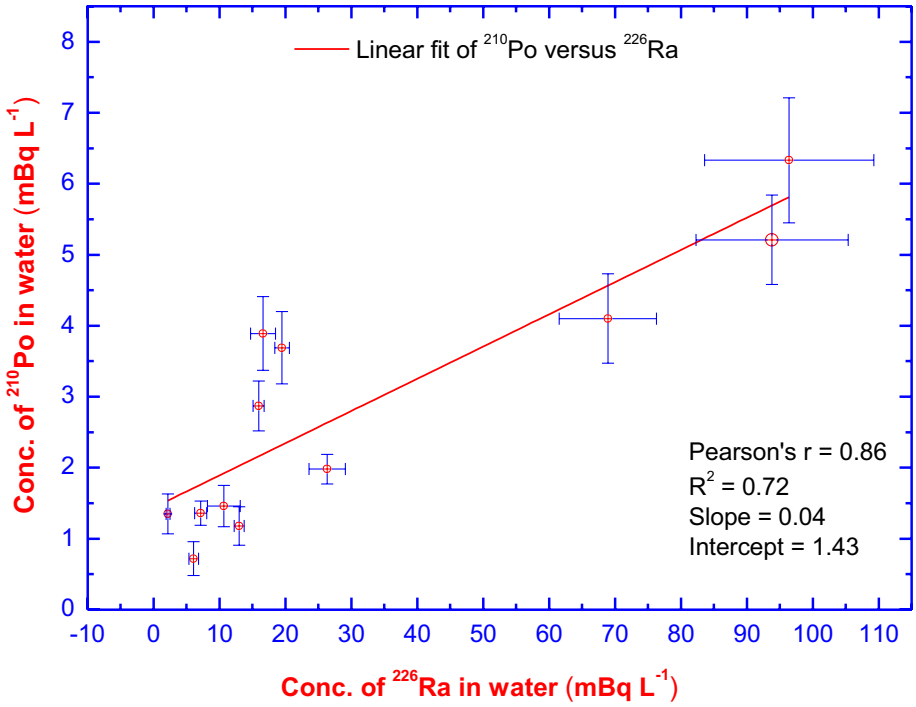

Fig. 8 Linear regression of ^{210}Po concentration with ^{226}Ra concentration in groundwater

weathered rocks (Walencik-Lata et al. 2016). Higher ^{210}Po concentration is reported in Switzerland (Zehringer 2019). The ^{226}Ra and ^{222}Rn concentrations of the present investigation at Chamarajanagar district of India are low compared to the literature values and the activity of ^{210}Po is in the comparable range.

Conclusion

Radionuclides in drinking water are a public health concern due to their chemical and radiological toxicities. The estimated concentrations of ^{226}Ra, ^{222}Rn, and ^{210}Po in the drinking water samples of Chamarajanagar district

Table 3 Concentration of radionuclides in water from different regions of the world

Sl. no	Geographical region	Source	Activity concentration			References
			^{226}Ra (mBq L^{-1})	^{222}Rn (Bq L^{-1})	^{210}Po (mBq L^{-1})	
1	Algeria	Mineral water	12–46	2.6–14	–	Amrani (2002)
2	Austria	Drinking water	< 0.3–110.6	1.46–644	–	Wallner and Steininger (2007)
3	Belgium	Drinking water	< 2–340	–	< 0.1–3.5	Vasile et al. (2016)
4	Illinois	Groundwater	74–1850	1.48–37	–	Gilkeson and Cowart (2020)
5	India	River water	9.09–55.07	–	0.86 –4.49	Kavitha et al. (2017)
6	India	Drinking water	15.6–68.9	37–245	–	Hidayath et al. (2022)
7	Italy	Mineral water	< 10–52.50	–	< 0.4–21.01	Desideri et al. (2007)
8	Japan	Mineral water	0.85–13	–	1–4.9	Kinahan et al. (2020)
9	New Jersey	Groundwater	22–833	2.63–588.3	–	Szabo and Otto (1991)
10	North Vietnam	Thermal waters	< 5–3430	–	0.56–8.26	Chau et al. 2022
11	Poland	Spa Water and Mineral water	10–1060	5–1171	–	Walencik-Lata et al. (2016)
12	Poland	Thermal water	21–66,000	< 0.2–148	–	Nguyen and Jakub (2021)
13	South-eastern Pennsylvania	Groundwater	3.7–1150	3.18–906.5	–	Cecil et al. 2020
14	Switzerland	Mineral water	2–1400	0.4–4.4	10–230	Zehringer 2019
15	Present study	Drinking water	2.18–96.42	0.94–26.90	0.72–6.33	
	Acceptable values	Drinking water	1000	100	100	WHO (2011)

are well below the guideline values prescribed by various regulatory agencies like WHO, USEPA, and UNSCEAR. The average ingestion dose due to ^{226}Ra, ^{222}Rn, and ^{210}Po is 6.41 μSv y^{-1}, 9.74 μSv y^{-1}, and 2.51 μSv y^{-1}, respectively. A good correlation between ^{226}Ra and ^{222}Rn; ^{210}Po and ^{222}Rn; ^{226}Ra and ^{210}Po radionuclide is observed with a Pearson's r coefficient of 0.84, 0.83, and 0.86, respectively, indicating that they might be of the same origin.

The total effective radiation dose due to inhalation of ^{222}Rn and ingestion of ^{226}Ra, ^{222}Rn, and ^{210}Po in water varied from 6.40 to 00.02162.02 μSv y^{-1} with an average value of 31.47 μSv y^{-1} is within the safe limits prescribed by WHO (100 μSv y^{-1}). The present investigation indicates that people of the study area are less prone to radiological hazards due to natural radionuclide in water.

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