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High uranium dose from the groundwater in a granitic terrain in the eastern part of Karnataka, India

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Abstract
Very high uranium concentrations of ~3000 μgL^{-1} or more have been found in groundwater held in the granitic aquifers of four villages in eastern Karnataka, India. The highest uranium concentration was 8649 μgL^{-1} (calculated 218.7 BqL^{-1}) and a maximum radon activity of 101.4 BqL^{-1}. The ingestion doses of uranium for males and females of all age groups are very much higher compared to the corresponding dose calculated for World Health Organization and Atomic Energy Regulatory Board recommended concentrations of 30 and 60 $\mu gL^{-1}$for drinking water. It is therefore recommended that alternative sources for drinking water need to be made to meet United Nations Sustainable Development Goals 3 and 6 to ensure good health from safe drinking water.

Keywords Eastern Karnataka · India · Groundwater · Ingestion dose · Uranium and radon

Introduction

The WHO 1958 [1] and Bureau of Indian Standards 1983 [2] provided guideline values for drinking water. Many contaminants such as fluoride, arsenic, mercury, chromium, and nitrate have been recognized to have a negative influence on human health. They were determined by the scientific community following the publication of standards. However, uranium in drinking water has not received much attention, probably because some uncertainties regarding the health effects on humans and animals still prevail. Epidemiological studies on humans in relation to uranium ingestion are scanty. Hence, even in the Fourth edition of the WHO publication of 2011[3] on drinking water quality, we see only arbitrary limits for uranium. There is a wide range of accepted levels of uranium in drinking water among different countries. WHO recommends 30 μgL^{-1}. In Japan, the permissible limit is as low as 2 μgL^{-1} uranium, whereas in Russia, it is as high as 1000 μgL^{-1} [4, 5]. In India, the Atomic Energy Regulatory Board (AERB) in 2004 recommended a limit of 60 $\mu g\ L^{-1}$ for drinking water [6].

Uranium in low concentrations is found in almost all naturally occurring surface water bodies, such as rivers, lakes and oceans. In naturally occurring groundwater, however, the uranium concentration can reach significant levels. In recent years, this has been recorded in groundwater in various countries worldwide, making uranium as one of the emerging contaminants. The source of uranium in groundwater is attributed to rock-water interactions controlled by hydrogeochemical conditions. Uranium, as a pollutant in groundwater used for drinking, attracted attention in Punjab early in the 1990s [7]. However, uranium contamination and its significance did not receive considerable attention until recently. CGWB [8] and Sahoo et al. [9] analyzed samples of ground and surface water on a countrywide basis. Coyte et al. [10] drew specific attention to this pollutant in parts of Rajasthan, Punjab-Haryana, Gujarat, Andhra Pradesh, Karnataka and Tamil Nadu. Srinivasan et al. [11] showed evidence of high uranium concentrations in the groundwater used for drinking from the bore wells in eastern Karnataka.

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Uranium dissolution in groundwater depends on its oxidation state and the pH of the water. Uranium occurs in the U^{4+}, U^{5+} and U^{6+} oxidation states, but the most stable form is U^{6+}, which is highly mobile compared to U^{4+}. U^{6+} ions, such as in UO_2^{2+}, form rapidly soluble complexes and are transported in groundwater [12]. The pH of water is the controlling factor in the speciation of uranium in water. The major species in water below pH 5 is UO_2^{2+}, between pH 5 and 7, it is UO_2OH^+ (hydrolysis complexes) and $(UO_2)_3(OH)_5^+$ (multinuclear hydroxide complexes), and above pH 7, the dominant species is $UO_2(OH)_3^-$ [13, 14]. Radium (Ra), one of the major daughter products of uranium (U) in the decay chain, produces radon (Rn), which is a noble gas. Out of several isotopes of radon, three isotopes of radon are widely known in nature, namely radon (^{222}Rn), thoron (^{220}Rn), and actinon (^{219}Rn). They are formed from radium (226), radium (224), and radium (223), having half-lives of 3.82 days, 55.8 s, and 3.98 s, respectively. Radon is one of the primary sources of ionizing radiation. ^{222}Rn, which has the longest half-life of 3.82 days, is considered to have relatively high human health risk compared to other isotopes of radon. ^{222}Rn largely contributes to the background radiation of the absorbed dose (55%) [15, 16]. Radon and uranium, which are present in water samples, can enter the human body via ingestion and inhalation. In drinking water, the dose by ingestion is higher than the dose by inhalation. It affects the kidney, lung, skin, and gastrointestinal tract and can circulate through the blood [17, 18].

In this paper, we present the results of the calculation of ingestion dose values from four villages in eastern Karnataka, where very high uranium concentrations are found in the groundwater (hosted in granitic aquifer) used for drinking and agricultural purposes. This can be considered as baseline values for further investigation as there is no other data available on the ingestion dose values from the area of study. Through this, we wish to draw the attention of health officials to initiate health surveys in and around such hot spots to identify the possible impact of drinking such water on human health.

Study area

The present study is confined to Chikkaballapura and Kolar districts of Karnataka. Chikkaballapura district covers an area of 4244 Sq. km. It has 1515 villages and 1.25 million people [19]. Kolar district spread over 4012 Sq. km. area has 2092 villages with 1.53 million people [20]. People in the Chikkaballapura and Kolar districts are mainly dependent on agriculture. As there are no perennial rivers in these districts, people of these districts are mainly dependent on groundwater for drinking purposes.

Geological setting of the study area

The investigated area forms a part of the Meso/Neo Archaean Eastern Dharwar craton in South India (Fig. 1) [21]. The terrain is dominantly composed of 3000–2500 Ma granodioritic gneisses (the Peninsular gneiss) with relicts of greenstone belts (e.g., the Kolar greenstone belt). The gneiss and greenstone belts are intruded by 2500–2550 Ma K-feldspar-bearing porphyritic or homogeneous monzonites (equivalents of Closepet Granite) [22]. Generally, the low-lying areas are occupied by the Peninsular Gneiss, while the K-feldspar metacystic granites constitute hilly terrains. The greenstone belt is composed of greenschist-facies to low-grade amphibolite-facies metamorphosed basalts of dominantly tholeiitic and minor komatiitic composition [23]. These rocks are associated with sulfide facies banded iron formation and felsic volcanic rocks of rhyodacitic composition designated as Champion gneiss, which occurs bordering the Kolar greenstone belt in the east. Champion gneiss is essentially a sericite gneiss of granodioritic composition. Tourmaline is abundant as an accessory mineral in Champion gneiss. Both the Champion gneiss and greenstones are intruded by pegmatites and gold-bearing quartz carbonate veins. Detailed petrology/mineralogy of the four areas discussed in the paper is specifically not available. However, recently Nandy et al., 2019 have described this aspect in the eastern geotectonic continuity of the studied area near T Sundapalle [24].

The gneisses and granitoids carry both K-feldspar and sodic plagioclase. Biotite mica and hornblende are the essential accessory minerals. Sphene, monazite (?) and, in places, tourmaline are widely distributed as accessory minerals (Fig. 2). Epidote is a common alteration product. Radiation cracks around sphene and monazite and pleochroic haloes around sphene occurring as inclusions in biotite are common. Pegmatites are potash feldspar rich. They also carry biotite, sphene, and tourmaline as accessory minerals. All these rock formations are intruded by 2367 Ma and 1862 Ma Proterozoic mafic (dolerite) dyke rocks [25]. Structural analysis of T Sundapalle, an area which lies in the eastern geotectonic continuity of the studied area has been described by Goswami et al., 2019 [26].

The oxidative weathering of all the aforementioned rock formations results in red loam, which is sometimes further leached of silica to produce laterite. Regional gamma-ray spectrometric investigations have revealed that the gneisses and granitoids of the eastern Dharwar Craton have larger abundances of potassium (K), uranium (U), and thorium (Th) compared to the western part [11, 27].

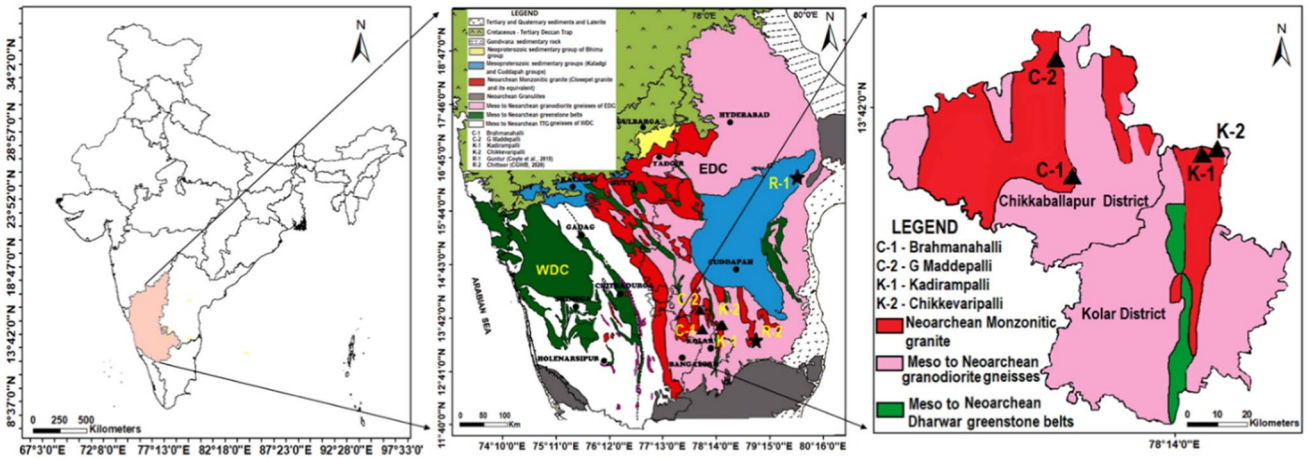

Fig. 1 Geological map of the study region: **a** Key map of study area, **b** Geological map of the Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) showing the sample locations of the study area (C-1, C-2, K-1 and K-2) along with sample locations given by Coyte et al. (2018) [10] (R-1: Guntur) and of CGWB (2020) [8] (R-2: Chittoor); **c** sample locations in Chikkaballapur and Kolar Districts

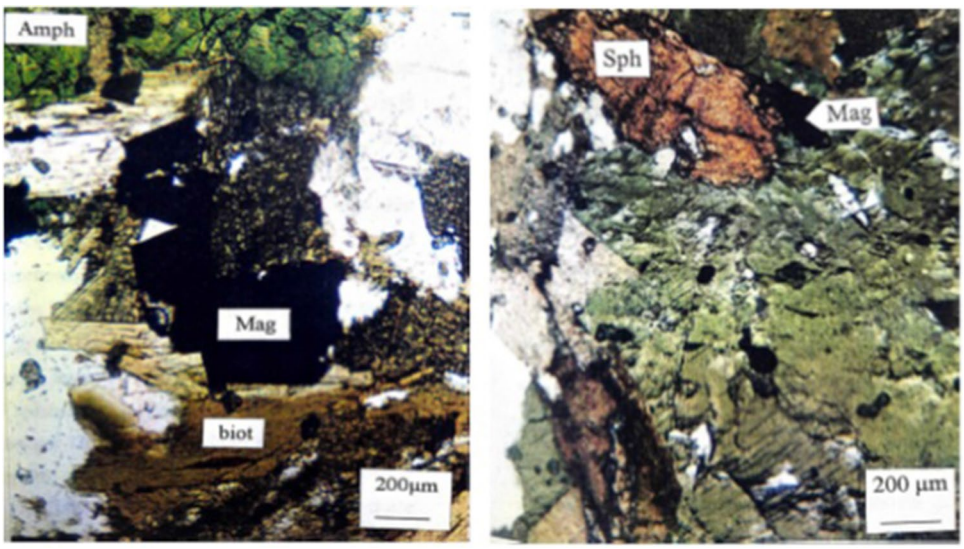

Fig. 2 Photomicrographs of radioactive minerals in granitoids and gneisses showing Sphene (Sph), Amphibole (Amph) and Biotite (Biot)

Methodology of sample collection and analysis

A total of 146 groundwater samples from 73 villages in different parts of eastern Karnataka were analyzed for uranium and other dissolved elements, such as fluoride and arsenic. The samples from Kadirampalli and Chikkevaripalli in Kolar district and Brahmanahalli and G. Madepalli villages in Chikkaballapura district are taken for detailed study in this work, as they have consistently shown higher uranium concentrations compared to other samples during both the post-monsoon (December) and dry seasons (February).

Samples were collected in pre-sterilized glass bottles that were rinsed three to four times with the water that was sampled. While collecting, care was taken to avoid static water in the borewells by pumping it out for not less than 5 min before sampling. The uranium content in the samples was analyzed using LED fluorimeter, model LF-2A, following the procedure described in Srinivasan et al. [11]. The ^{226}Ra present in the sample was coprecipitated with MnO_2, and the activity concentration was determined by HPGe gamma spectrometry [28–32] after allowing the buildup of radioactive equilibrium with its progenies (^{214}Pb and ^{214}Bi). The weighted mean activity of the daughter products ^{214}Pb and ^{214}Bi was used to infer the ^{226}Ra activity [33, 34]. Radon in water was analyzed by emanometry using radon bubbler as explained by Raghavayya et al. [35] in the field and also at the Physics laboratory, University of Mysore. Analysis of radionuclides except radon was carried out at the CARER, Mangalore University in the lab approved by the Department of Atomic Energy (DAE).

Computation of uranium and radon ingestion dose

The amount of water consumed by individuals varies according to age group, as well as their profession. This division is done because the dose is proportional to the quantity of water consumed by the individual. The village population is considered separately for males and females. Uranium and radon enter the human body in two ways: by ingestion and by inhalation (via breathing during drinking or bathing). Since the inhalation dose during drinking by the individual is negligible, in this study, it is not considered further for dose calculation. Uranium and radon ingestion doses from drinking water are calculated using Eqs. (1) and (2), respectively.

$$\begin{aligned}\text{Uranium Ingestion Dose } (\mu Sv/y) = &\text{Uranium activity}(Bq/L)\\ &\times \text{Water intake}(L/\text{day}) \times \text{Time (day}/y)\\ &\times \text{conversion fcator}(Sv/Bq) \times 10^6(\mu Sv/Sv)\end{aligned} \quad (1)$$

$$\begin{aligned}\text{Radon Ingestion Dose}(\mu Sv/y) = &\text{Radon activity}(Bq/L)\\ &\times \text{Water intake } (L/\text{day}) \times \text{Time (day}/y)\\ &\times \text{conversion fcator}(Sv/Bq) \times 10^6(\mu Sv/Sv)\end{aligned} \quad (2)$$

Dose values were computed following the dose conversion factors that are given in the IAEA report [36] for different age groups. Annual radon dose values were computed based on water intake and dose conversion factors for adults as given in the report by United Nation Scientific Committee on the Effect of Atomic Radiations (UNSCEAR) [37]. Total lifetime effective uranium and radon dose values were also computed for different age groups using the average lifespan of males (67.7 years) and females (70.8 years) as given by the RBI [38]. The major assumption in all the above estimates is that a person for whom the dose is valid lived in the same village during his lifetime and consumed raw water without undergoing RO or any other treatment process.

Results

The lowest and highest concentrations of uranium in water samples from the four selected villages are shown in Table 1. Samples from Kolar district, K-1 and K-2, show uranium concentration levels ranging from 1000 to 2986 μgL^{-1} and 921 to 5995 μgL^{-1}, respectively. Similarly, samples from Chikkaballapura district, C-1 and C-2 show the lowest and highest uranium concentration levels of 772 to 3561 μgL^{-1} and 1000 to 8649 μgL^{-1}, respectively. The lowest uranium concentrations for both districts are in the month of December, while the maximum concentrations are in the month of February. December is considered as the beginning of the post- monsoon period, while February is regarded as the dryest part of the year in the study area.

Tables 2 and 3 give the maximum and minimum doses that individuals of different age groups can receive per year from the consumption of ground water in the four different villages.

Table 4 gives the corresponding dose for different age groups calculated based on the concentration level recommended as safe by the WHO and AERB, which are 30 and 60 μgL^{-1}, respectively. Dose values for infants vary from 1816.5 to 2352.9 $\mu Sv.y^{-1}$ at the minimum uranium concentration and 7025.2 to 20,350.5 $\mu Sv.y^{-1}$ at the maximum uranium concentration. The dose value computed for children up to 3 years of age varies from 1111.3 to 1439.4 $\mu Sv.y^{-1}$ at the minimum uranium concentration and 4297.7 to 12,449.7 $\mu Sv.y^{-1}$ at the maximum uranium concentration.

Table 1 Uranium concentrations in the studied water samples

District	Name of Village	Sample code	Number of samples (n)	Lowest concentration level		Highest concentration level	
				Month of sampling	Uranium concentration (μgL^{-1})	Month of sampling	Uranium concentration (μgL^{-1})
Kolar	Kadirampalli	K-1	4	December	1000	February	2985.7
	Chikkevaripalli	K-2	4	December	921	February	5995.2
Chikkaballapura	Brahmanahalli	C-1	4	December	772	February	3561.3
	G. Madepalli	C-2	5	December	1000	February	8649

Table 2 Uranium ingestion dose for different age groups through drinking water at minimum uranium concentration levels

Sample code	Activity concentration of uranium μgL^{-1} (BqL^{-1})	Age-dependent uranium ingestion dose ($\mu Sv.y^{-1}$)											Total lifetime dose (mSv)	
		Infants	Children		Males			Females			Pregnancy	Lactation	Male	Female
		0–1	1–3	4–8	9–13	14–18	Adults	9–13	14–18	Adults	14–50	14–50	67.7 [38]	70.8 [38]
K-1	1000 (25.3)	2352.9	1439.4	1254.9	1505.9	2040.1	1536.3	1317.6	1421.9	1121.1	1245.7	1577.9	105.6	84.4
K-2	921 (23.3)	2167.1	1325.7	1155.8	1386.9	1879	1415	1213.6	1309.6	1032.5	1147.3	1453.2	97.3	77.7
C-1	772 (19.5)	1816.5	1111.3	968.8	1162.5	1575	1186	1017.2	1097.7	865.5	961.7	1218.1	81.5	65.2
C-2	1000 (25.3)	2352.9	1439.4	1254.9	1505.9	2040.1	1536.3	1317.6	1421.9	1121.1	1245.7	1577.9	105.6	84.4

Table 3 Uranium ingestion dose for different age groups via drinking water at maximum uranium concentration levels

Sample code	Activity concentration of uranium μgL^{-1} (BqL^{-1})	Age-dependent uranium ingestion dose ($\mu Sv.y^{-1}$)											Total lifetime dose (mSv)	
		Infants	Children		Males			Females			Pregnancy	Lactation	Male	Female
		0–1	1–3	4–8	9–13	14–18	Adults	9–13	14–18	Adults	14–50	14–50	67.7 [38]	70.8 [38]
K-1	2985.7 (75.5)	7025.2	4297.7	3746.8	4496.1	6091.2	4587	3934.1	4245.4	3347.3	3719.2	4711	315.3	252
K-2	5995.2 (151.6)	14,106.3	8629.7	7523.4	9028	12,231	9210.6	7899.5	8524.6	6721.2	7468.1	9459.5	633	506
C-1	3561.3 (90)	8379.5	5126.3	4469.1	5362.9	7265.5	5471.3	4692.5	5063.9	3992.6	4436.2	5619.2	376	300.6
C-2	8649 (218.6)	20,350.5	12,449.7	10,853.6	13,024.3	17,645.1	13,287.7	11,396.3	12,298.1	9696.4	10,773.8	13,646.8	913.3	730

Table 4 Calculated dose values of uranium ingestion dose considering compared against limits given by WHO (30 µgL^{-1}) and AERB (60 µgL^{-1}) for different age groups

Sample code	Activity concentration of uranium µgL^{-1} (BqL^{-1})	Age-dependent uranium ingestion dose (µSv.y^{-1})									Total lifetime dose (mSv)	
		Infants	Children		Males			Females			Male	Female
		0–1	1–3	4–8	9–13	14–18	Adults	9–13	14–18	Adults	Pregnancy	Lactation	67.7 [38]	70.8 [38]
											14–50	14–50		
WHO	30 (0.8)	70.6	43.2	37.6	45.2	61.2	46.1	39.5	42.7	33.6	37.4	47.3	3.2	2.5
AERB	60 (1.5)	141.2	86.4	75.3	90.4	122.4	92.2	79.1	85.3	67.3	74.7	94.7	6.3	5.1

Similarly, for children in the 4–8 year age group, the minimum and maximum uranium concentrations vary from 968.8 to 1254.9 µSv.y^{-1} and 3746.8 to 10,853.6 µSv.y^{-1}, respectively. Males are considered under three age groups, viz., 9–13, 14–18 and 18 to 67.7 years, and females are considered under 9–13, 14–18, and 18 to 70.8 years. The average life span for males and females is according to the RBI [38]. Pregnant and lactating women between 14 and 50 years are considered separately.

Figure 3 shows the multiplicand of annual dose values for both high and low uranium concentration levels in relation to estimated annual dose values that correspond to the upper limits for consumption given by the WHO and AERB. Even the minimum value at the lowest uranium concentration level in the water of the four villages under study is seen to be an order of magnitude higher. At higher uranium levels, the multiplicand annual dose values increase greatly. Lifetime ingested dose levels are also computed using the average lifespan reported for the region, which are 67.7 years for males and 70.8 years for females. Taking the annual dose for the minimum uranium concentration, the lifetime dose value works out to 81.5 and 65.2 mSv for males and females, respectively, which are lower than 100 mSv. However, if one considers the maximum uranium concentration level, the lifetime dose works out to 913.3 mSv (for males) and 730 mSv (for females). The Health Physics Society [39] states that "Considerable uncertainties remain for stochastic effects of radiation exposure between 100 mSv and 1,000 mSv, depending upon the population exposed, the rate of exposure, the organs and tissues affected, and other variables". The ground truth of the dose in the study areas generally lies between these limits. At this stage, it is difficult to calculate the dose value for the lifetime.

Other radionuclides

As it is clear that the uranium level in groundwater in the study region is anomalously high, the samples with the highest concentration of uranium were examined for ^{226}Ra activity by gamma spectrometry, as explained in the section, and the results are presented in Table 5. As radon contributes to nearly 55% of the radiation received through inhalation, analyzing radon in these water samples was important. Table 6 gives the radon levels and estimated annual dose. The radon level varies from 49.9 to 101.4 BqL^{-1} with respective annual doses of 172.1 to 349.8 µSv.y^{-1}. The health risk increases manifold by consuming such water.

The World Health Organization (WHO) has suggested that if the radon content in drinking water exceeds 100 BqL^{-1}, corrective action needs to be taken [3]. The Indian government, which controls drinking water quality, has yet to suggest a safe level of radon in drinking water for public supply.

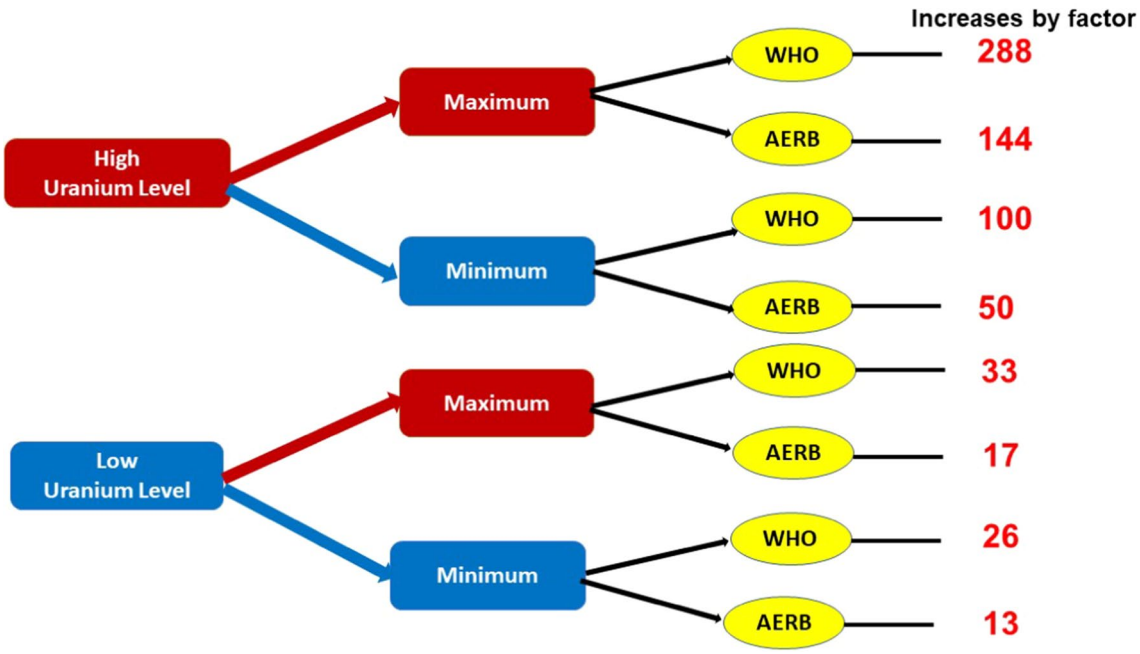

Fig. 3 Variation in the ingested uranium dose in comparison to the computed ingested dose of the WHO and AERB limits

Table 5 Concentrations of radionuclides in the studied water samples

Sample code	^{226}Ra activity (derived from the weighted mean of the daughter products) (BqL^{-1})
K-1	0.5 ± 0.01
K-2	0.8 ± 0.01
C-3	1.1 ± 0.01
C-4	3.3 ± 0.04

Table 6 Radon ingestion dose via drinking water

Sample code	Activity concentration of radon (BqL^{-1})	Radon ingestion dose($\mu Sv.y^{-1}$)
K-1	67.9	234.2
K-2	81.07	279.6
C-1	49.9	172.1
C-2	101.4	349.8

Discussion

As there are no nuclear installations (nuclear power reactors, nuclear fuel industries, nuclear fuel reprocessing units) in the studied villages or their surroundings, nor there are any other anthropogenic activities leading to uranium pollution, the observed radionuclide concentration in the groundwater in these villages is considered to be geogenic. Although no discrete primary or secondary uranium mineral phases have been identified in thin sections, minerals such as sphene, biotite and, to some extent, amphibole can accommodate uranium ions. These tetravalent uranium ions during weathering are oxidized and converted to hexavalent ions by water−rock interactions. Hexavalent uranium is more mobile and is released into groundwater. The variation in uranium concentration in the groundwater is attributable to the fluctuations in the groundwater table in different seasons. The observed lower levels of concentration in the samples collected during December can be attributed to the dilution caused by the increased percolation of rainwater immediately following the cessation of the northeast monsoon and the increased flow of water through fractures in the bed rock, the conditions that do not permit a longer water−rock interaction period. The higher concentration of uranium in the water samples collected in February long after the cessation of the monsoon during the beginning of the dry season can be the result of a reduced infiltration rate and flow in the fractures and lowering of the water table due to increased withdrawal of groundwater. The latter conditions allow a longer water−rock interaction period, promoting a greater degree of uranium leaching.

UNSCEAR [40] presented a global overview of uranium analysis data from Finland, Sweden, Norway, Poland, Spain, Switzerland, France, Greece, Canada, USA, Brazil, Morocco, Ethiopia, Egypt, Ghana, Fujian Province, Iran, Jordan, Bangladesh, Japan, and India. According to the

UNSCEAR report [40], out of 65,132 groundwater samples, the highest uranium concentration level was 7780 μgL^{-1} in the groundwater at Connecticut, USA. In India, there are reports on high uranium concentrations in drinking water samples, as published by Coyte et al. [10], CGWB [8], Sahoo et al. [9] and Srinivasan et al. [11]. Coyte et al. [10] analyzed 324 samples and reviewed 4769 sample analyses of the then available results. The highest concentration of uranium of 2074.8 μgL^{-1} was reported in the groundwater located in the Neoproterozoic quartz arenite from Guntur area in Andhra Pradesh (R-1 in Fig. 1b). The Central Ground Water Board (CGWB) [8], from a nationwide survey of 14,377 water samples, found the highest concentration value of 2876 μgL^{-1} in the groundwater near Damalcheruvu in Chittoor District in Andhra Pradesh (R-2 in Fig. 1b). Sahoo et al. [9], based on a similar survey, reported 4918 μgL^{-1} as the highest concentration out of 55,554 samples. However, they did not give the location of the sample. A glance at the geological map of the Dharwar craton shows that Chittoor and Guntur are also part of the Eastern Dharwar craton, where potassium feldspar-bearing granodiorites and monzonites that are enriched in large ion lithophile elements, including radioactive elements, dominate (Fig. 1b). Hydrogeochemical survey of 73 villages in the eastern Dharwar carton revealed 14 villages having more than 1000 $\mu gL^{-1}$of uranium [11]. Very high values are recorded in the potassium feldspar-rich monzonite and granodiorite terrain of Chikkaballapura and Kolar districts of Karnataka. The highest uranium concentration is recorded at G. Madepalli, Bagepalli taluk of Chikkaballapura district (C-2 in Fig. 1c). Based on these data sets, it appears that the uranium concentration of 8649 μgL^{-1} observed in the groundwater at G. Madepalli is probably the highest value documented.

Conclusion

The observed uranium concentration in the groundwater is exclusively from natural sources, as there are no nuclear installations in the study area. The tetravalent uranium in the host rock has undergone oxidation during oxidative weathering characteristic of the region, and the hexavalent uranium produced could be leached into the groundwater system by water−rock interactions. K feldspar-rich Neoarchean granitoids (granodiorites and monzonites) that have high levels of uranium, following the above weathering reaction, have been able to release anomalous concentrations of uranium in groundwater, such as 2985.7 to 8649 $\mu g\ L^{-1}$. The lifetime dose values ranging from 315.3 to 913.3 mSv for males and 252 to 730 mSv for females, as calculated in this paper, are very high (by an order of magnitude) in comparison to the threshold values given by the WHO and AERB as safe. Interestingly, G. Madepalli recorded 8649 μgL^{-1} of U, which is the highest value recorded.

To understand the effects of dissolved uranium in drinking water on human health, health surveys in these areas are recommended. Since uranium is both radiotoxic and chemotoxic, the study region is an appropriate ground for conducting such medical research. Analyzing the radioactive concentration of fruits and vegetables cultivated in these places using groundwater is another suggestion for follow-up studies. The need of the hour in the area is to explore alternate sources of water for drinking water supply, such as tapping available surface water, roof water harvesting, etc. This is socially and ethically essential to meet the Sustainable Development Goals 3 and 6 of the United Nations.

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Declarations

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

Ethical approval All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or nonfinancial interest in the subject matter or materials discussed in this manuscript.

References

1. World Health Organization (1963) International standards for drinking-water
2. Indian Standard Specification for Drinking Water (1983) IS: 10500
3. World Health Organization (2011) Guidelines for drinking-water quality. WHO Chron 38(4):1–178
4. World Health Organization (2012) Uranium in drinking water. Background document for development of WHO guidelines for drinking-water quality. WHO, Geneva, pp 1–21
5. Sahoo SK, Jha VN, Patra AC, Jha SK, Kulkarni MS (2020) Scientific background and methodology adopted on derivation of regulatory limit for uranium in drinking water–a global perspective. Environ Adv 2:100020
6. AERB (2004) Limits on uranium in drinking water, atomic energy regulatory board of India, Mumbai, AERB/VC/16/2004/80/373
7. Virk HS (1997) Uranium and radon surveys in western Himalaya. Curr Sci 73(6):536–538
8. Central Ground Water Board (CGWB) report (2020) Uranium occurrence in shallow aquifers in India. http://cgwb.gov.in/WQ/URANIUM_REPORT_2019-20.pdf
9. Sahoo SK, Jha SK, Jha VN, Patra AC, Kulkarni MS (2021) Survey of uranium in drinking water sources in India: interim observations. Curr Sci 120(9):1482–1490

10. Coyte RM, Jain RC, Srivastava SK, Sharma KC, Khalil A, Ma L, Vengosh A (2018) Large-scale uranium contamination of groundwater resources in India. Environ Sci Technol Lett 5(6):341–347
11. Srinivasan R, Pandit SA, Karunakara N, Deepak Salim K, Sudeep Kumara M, Kumar R, Khatei G, Ramkumar KD (2021) High uranium concentration in groundwater used for drinking in parts of eastern Karnataka. India Curr Sci 121(11):1459
12. Markich SJ (2002) Uranium speciation and bioavailability in aquatic systems: an overview. Sci World J 2:707–729. https://doi.org/10.1100/tsw.2002.130
13. Kimura T, Serrano GJ, Nakayama S, Takahashi K, Takeishi H (1992) Speciation of uranium in aqueous solutions and in precipitates by photoacoustic spectroscopy. Radiochim Acta 58(1):173–178
14. Deshmukh P, Sar SK, Jindal MK, Ray T (2023) Magnetite based green bio composite for uranium exclusion from aqueous solution. J Radioanal Nucl Chem 332:297–310
15. Haynes WM (Ed) (2014) Section 4–properties of the elements and inorganic compounds, CRC Handbook of chemistry and physics (95th edn). CRC Press, Boca Raton.https://doi.org/10.1201/b17118
16. Degu Belete G, Alemu Anteneh Y (2021) General overview of radon studies in health hazard perspectives. J Oncol. https://doi.org/10.1155/2021/6659795
17. Agency for Toxic Substances and Disease Registry (ATSDR) (2013) Toxicological profile for uranium. U.S. Department of Health and Human Services, Public Health Service, Atlanta
18. Sanjon EP, Maier A, Hinrichs A, Kraft G, Drossel B, Fournier C (2019) A combined experimental and theoretical study of radon solubility in fat and water. Sci Rep 9(1):10768. https://doi.org/10.1038/s41598-019-47236-y
19. Chikkballapur district profile (2023) https://chikkaballapur.nic.in/en/demography/. Access on 5th April 2023
20. Kolar district profile (2023) https://kolar.nic.in/en/demography/. Access on 5th April 2023
21. Ramakrishnan M, Vaidyanadhan R (2008) Geology of India. Geological Society of India Publications, vol 1, p 557
22. Moyen JF, Martin H, Jayananda M, Auvray B (2003) Late archean granites: a typology based on Dharwar craton (India). Precabrian Res 127:103–123
23. Krogstad EJ, Hanson GN, Rajamani V (1991) U-Pb ages of zircon and sphene for two gneiss terranes adjacent to the Kolar Schist Belt, South India: evidence for separate crustal evolution histories. J Geol 99(6):801–815
24. Nandy J, Dey S, Heilimo E (2019) Neoarchaean magmatism through arc and lithosphere melting: evidence from eastern Dharwar Craton. Geol J 54(5):3148–3166. https://doi.org/10.1002/gj.3498
25. Sarma SD, Parashuramulu V, Santosh M, Nagaraju E, Ramesh Babu N (2020) Pb–Pb baddeleyite ages of mafic dyke swarms from the Dharwar Craton: implications for Paleoproterozoic LIPs and diamond potential of mantle keel. Geosci Front 11(6):2127–2139. https://doi.org/10.1016/j.gsf.2020.05.014
26. Goswami S, Maurya VK, Tiwari RP, Swain S, Verma MB (2019) Structural analysis of T. Sundupalle greenstone belt and surrounding granitoids, Andhra Pradesh, India. Arab J Geosci 12:1–18. https://doi.org/10.1007/s12517-019-4793-2
27. Kumar P. Senthil (2001) Radioelemental distribution in the Dharwar craton, south India: Implications for the evolution of the upper continental crust and heat generation in the craton (Ph. D. thesis, Osmania Univ., Hyderabad, India, p 218)
28. International Atomic Energy Agency (2010) Analytical methodology for the determination of radium isotopes in environmental samples. IAEA
29. Karunakara N, Yashodhara I, Sudeep Kumara K, Tripathi RM, Sanjeev MN, Sonal K, Chougaonkar MP (2014) Assessment of ambient gamma dose rate around a prospective uranium mining area of South India–a comparative study of dose by direct methods and by soil radioactivity. J Results Phys 4:20–27
30. Al-Azmi D, Sudeep Kumara MP, Mohan NK (2019) Gamma dose rates in the high background radiation area of Mangalore region, Results. Radiat Prot Dosim 184(3–4):290–293
31. Mohan MP, D'souza RS, Nayak SR, Kamath SS, Shetty T, Kumara KS, Karunakara N (2018) A study of temporal variations of ^{7}Be and ^{210}Pb concentrations and their correlations with rainfall and other parameters in the South West Coast of India. J Environ Radioact 192:194–207
32. Mohan MP, D'Souza RS, Nayak SR, Kamath SS, Shetty T, Kumara KS, Karunakara N (2019) Influence of rainfall on atmospheric deposition fluxes of ^{7}Be and ^{210}Pb in Mangaluru (Mangalore) at the Southwest Coast of India. Atmos Environ 202:281–295
33. Yashodhara I, Karunakara N, SudeepKumar K, Murthy R, Tripathi RM (2011) Radiation levels and radionuclide distributions in soils of the gogi region, a proposed uranium mining region in north Karnataka. Radiat Prot Environ 34(4):267
34. Yashodhara I, Sudeep Kumara K, Tripathi RM, Karunakara N (2012) Activity concentrations of ^{226}Ra and ^{238}U in water samples and estimation of radiation dose around the proposed uranium mining region in Gogi. In: 19th national symposium on radiation physics (NSRP-19), pp 525–528
35. Raghavayya M, Iyengar MAR, Markose PM (1980) Estimation of Radium-226 by emanometry. Bull Radiat Prot 3:11–14
36. IAEA Safety Standards (2011) Radiation protection and safety of radiation sources: international basic safety standards, p 471
37. UNSCEAR (United Nation Scientific Committee on the effect of Atomic Radiations) (2000) Ionizing radiation. Sources and biological effects report to the general assembly with scientific annexes. New York, United Nations, p 659
38. Reserve Bank of India (RBI) (2020) https://rbi.org.in/Scripts/PublicationsView.aspx?id=20000
39. Radiation Risk in Perspective (2019) Position statement of the heath physics society. https://hps.org/documents/radiationrisk.pdf
40. UNSCEAR (United Nation Scientific Committee on the effect of Atomic Radiations) (2016) Sources, effects and risks of ionizing radiation. New York, United Nations p 512. https://www.unscear.org/docs/publications/2016/UNSCEAR_2016_Report-CORR.pdf