High uranium concentration in groundwater used for drinking in parts of eastern Karnataka, India

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The limits recommended by World Health Organization (WHO) and the Atomic Energy Regulatory Board (AERB) of India for uranium concentration in drinking water are 30 μg/l and 60 μg/l respectively. The present study on uranium concentration in groundwater used for drinking purposes in 73 villages of Karnataka, India, shows that in 57 villages uranium concentration is more than 30 μg/l, including 48 villages where it exceeds 60 μg/l. Thus in 78% and 66% of the villages studied, uranium concentration exceeds permissible limits given by WHO and AERB respectively. It is alarming to note that in one village each in Tumkur and Chitradurga districts, five in Kolar and seven in Chikkaballapura districts, uranium concentration is in thousands of micrograms per litre. None of the borewells from which water has been sampled is anywhere in the vicinity of nuclear facilities or urban waste disposal channels. Thus, the observed uranium contamination is considered to be geogenic. Previous geological studies have shown that the eastern portion of Karnataka is a part of the Neoarchean Eastern Dharwar Craton dominated by large ion lithophile element-rich K-feldspar granites and gneisses with higher abundance of radioactive elements (uranium and thorium) compared to the Mesoarchean tonalite–trondhjemite–gneisses and granitoids widely distributed in the Western Dharwar Craton.

Keywords: Dharwar Craton, geogenic contamination, groundwater, uranium.

DISSOLVED uranium (U) in drinking water is radio- and chemotoxic in the human body[1]. Studies carried out in Iowa and South Carolina, USA, and Bavaria, Germany, have shown that uranium-rich water could cause kidney and other types of cancer[2–4]. The World Health Organization (WHO) has set the guideline value of 30 μg/l for uranium in drinking water[5]. The Atomic Energy Regulatory Board (AERB) of India revised this limit to 60 μg/l for the country[6]. Groundwater used for drinking in several parts of India is known to have uranium content more than these permissible limits. In recent years, studies have reported uranium content in groundwater exceeding the limits given by WHO and AERB in several places in eastern Karnataka, although there are no nuclear installations or uranium mining areas anywhere in their vicinity[7–9]. These sites are also not adjacent to urban wastewater disposal channels, which could be carrying industrial and hospital wastewater. During studies on geogenic contaminants in groundwater in eastern Karnataka, since 2019, the Divecha Centre for Climate Change (DCCC), Indian Institute of Science (IISc), Bengaluru has noticed widespread contamination of groundwater with uranium in addition to fluoride and locally arsenic. The objective of the present study is to draw attention to the areas where DCCC has so far found high uranium content in groundwater used for drinking in eastern Karnataka. Most of the borewells having water with significant uranium contamination lie in the fluoride belt in eastern Karnataka (Figure 1)[10]. This necessitates evolving a holistic approach to address the problem of fluoride and uranium contamination together in the eastern districts of Karnataka. Since 2019, DCCC, at intervals, has been keeping the Department of Rural Water Supply, Government of Karnataka informed about this contamination.

Study area – Karnataka

Karnataka is the sixth largest state in India. Its area is 191,791 sq. km and the population is about 68.4 million (as of 2021). The state is divided into 30 districts. The province to the east of 76°30′ long., because of its distinct geological setting, is taken in this study as the eastern Karnataka province. This province has a spread of about 92,000 sq. km. A report on the climate change scenario in Karnataka by KSNDMC[11], based on 58 years of rainfall data between 1967 and 2017 has found that during the

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Anthropocene, rainfall had increased by 8% in the southern part of eastern Karnataka and decreased by 1% in the northern part. The average annual rainfall was estimated to be 650 mm. However, rainfall distribution has been uneven in space and time during the past two decades. The variation in southwest monsoon (the main contributor to the total rainfall in the state) has caused drought in the state. In the last two decades (2001–19), nearly 80% of the talukas (tehsils) have become drought-prone. A major portion of the drought-prone areas lies in the northern part of Karnataka. There is very low forest cover in the eastern part of the state (about 4.85% of the area). Eastern Karnataka has 15 administrative districts and a population of about 25 million, excluding the state capital Bengaluru (earlier Bangalore) and its suburbs. Most of this population is rural. Based on the dependency factor, 85% of the population, i.e. nearly 20 million people, directly depend on groundwater for drinking and agriculture. The Central Ground Water Board (CGWB), has estimated that in 2018–19, groundwater in nearly 25% of the area in the state was over-exploited[12]. In 12,930 sq. km, i.e. nearly 7% of the total area in Karnataka, groundwater has reached a critical level. Much of this overexploited portion of Karnataka lies in the eastern part of the state. Irrigation based on groundwater, irregular rainfall pattern, urban growth, increasing demand for groundwater after several droughts, have all led to a decline in the water table, especially in the eastern part of Karnataka. The CGWB report[12] also shows that relative to the decadal mean water level for the period 2007–16, water level in May 2017 had recorded a fall in 70% of observation wells[12].

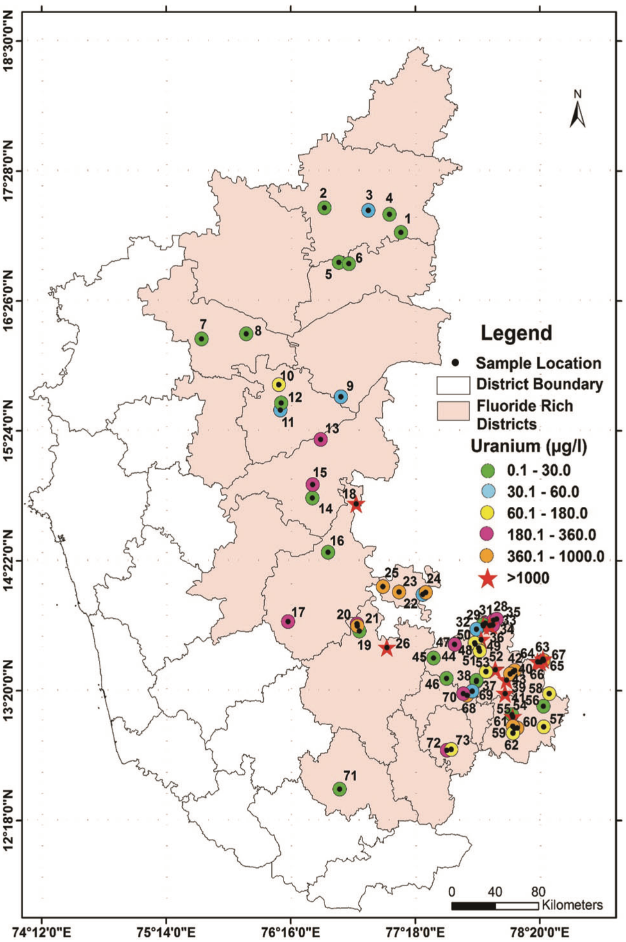

Figure 1. Map showing groundwater sampling sites along with the range of abundance of uranium with reference to the limits given by World Health Organization and Atomic Energy Regulatory Board of India. These uranium-rich groundwater sites are also found to occur in the fluoride endemic belt of eastern Karnataka, which is shown as a pink shaded area.

Geological and geomorphological setting of groundwater

Karnataka is in the southern Indian shield. It is composed of the Dharwar Craton, where Archean rocks older than 2500 Ma are exposed (Figure 2)[13]. The Dharwar Craton in the western part (west of 76.5°E long.), is dominantly composed of Meso- to Neoarchaean metamorphosed volcanic and sedimentary rocks (designated as the Dharwar Supergroup) overlying the Meso-Archean (older than 3000 Ma) tonalite–trondhjemite–granodiorite (TTG) gneisses and granitoids. They occur as schist belts amidst gneisses. In the eastern part of the state, Neoarchean (3000–2500 Ma), K-feldspar granitoid rocks (granodiorite and monzonite) with minor TTGs are dominant. Amidst them, there are narrow, linear schist belts of metamorphosed volcanic and sedimentary rocks of the Dharwar Supergroup.

These Archean rocks in Karnataka are exposed in an inclined cross-section of the earth's crust[14]. In the northern part, rocks of the greenschist facies crustal level are exposed. In the central and southern parts, rocks of amphibolite and granulite facies respectively are exposed. Regional gamma-ray spectrometric surveys have shown that there is a higher abundance of potassium (K), uranium (U) and thorium (Th) in the eastern part of the Dharwar Craton compared to the western part. It has been observed that while the granulite facies crustal level is depleted in K, U and Th, these elements are enriched in the amphibolite and greenschist facies levels. In the granites of greenschist facies crustal level, uranium is found to be higher than in amphibolite facies level (Figure 3)[15].

The Archean rocks mentioned above are overlain in the northern part of Karnataka in Belgaum, Bijapur (Vijayapura), Bagalkot, Yadgir and Gulbarga districts by sedimentary rocks of the Mesoproterozoic Kaladgi Group and the Neoproterozoic Bhima Group[13]. The principal sedimentary rocks in the Proterozoic sequences are sandstone, shale, magnesian and high-calcium carbonate rocks. Close to the base of the Proterozoic sedimentary sequences, there are uranium deposits formed by remobilization and concentration of uranium derived from the Neoarchean granitoids[16,17]. This further indicates that the late Archaean

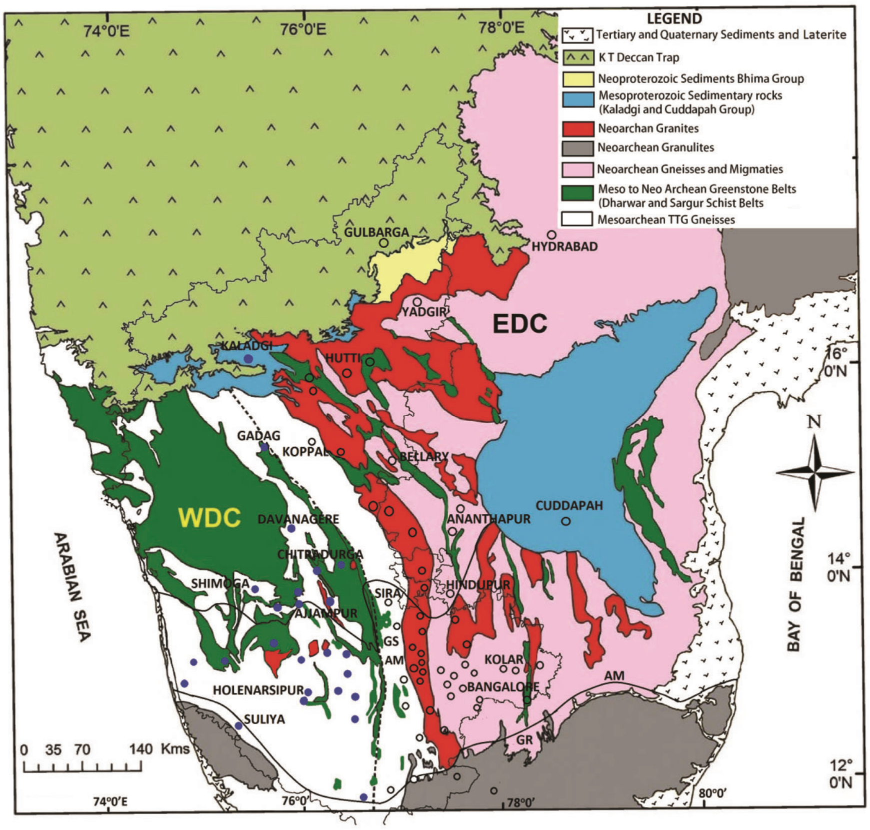

Figure 2. Geological map of the Dharwar Craton, southern India (modified from ref. 13) showing the Eastern and Western Dharwar Craton (EDC and WDC respectively). The map also shows boundaries between the greenschist (GS), amphibolite (AM) and granulite (GR) facies crustal levels. The sites where gamma-ray spectrometric measurements had been carried out earlier in the WDC are shown as blue dots and those in the EDC as open circles. The locations are as in ref. 13.

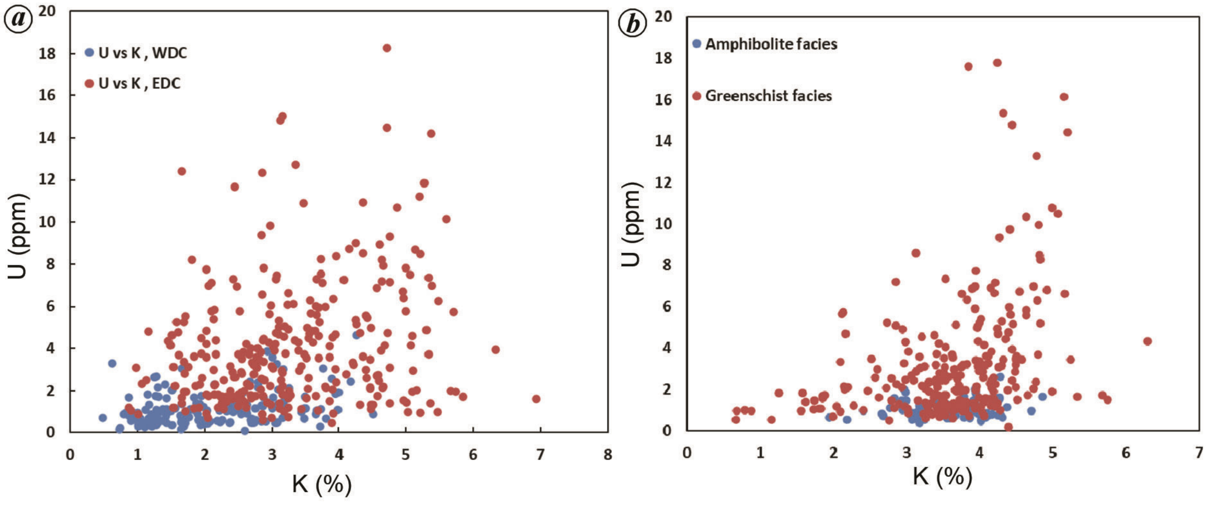

Figure 3. Abundance of uranium and potassium in (***a***) WDC and EDC gneisses and granitoids and (***b***) Neoarchean Closepet Granite at the amphibolite and greenschist facies crustal levels. Note that the EDC granites and gneisses have a higher abundance of uranium relative to those in the WDC. Higher concentration at greenschist facies crustal level relative to amphibolite facies crustal level can also be seen.

potash granitoids and gneisses are fertile granitoids in respect of their uranium content. In some parts of northern Karnataka, the Archean and Proterozoic rocks are covered over by ~66 Ma-old Deccan flood basalts.

All the above-mentioned rock formations constitute the hard rock terrain of Karnataka. Covering them in the coastal regions of the state are Tertiary and Quaternary sandstones, laterite and coastal sands. The hilly terrain to the east of the coastal tract – the Western Ghats – is the mountain belt that serves as the main water divide between the west coast and the Karnataka plateau to the east. The Karnataka plateau is divided into south interior and north interior parts. The major rivers of southern India originate in the Western Ghats and flow eastward through the Karnataka plateau to join the Arabian Sea. An EW, second-order water divide along Mangalore–Madras latitude separates the two major river basins of Karnataka, namely the Cauvery basin in the south and the Krishna basin in the north. The Western Ghats Mountains are adorned with forests and organic matter-rich forest soils. *In situ* red loam is the dominant soil in the eastern part of the state. Red loam has undergone further leaching giving rise to laterite in some sectors, as for example, in parts of Bengaluru, Kolar, Chikkaballapur and Hassan districts in south interior Karnataka and the Bidar district in north interior Karnataka. In the north interior part of the state, the Archean and Proterozoic rocks as well as red loam are covered by transported black cotton soils in the Krishna river valley. Red loam and laterite genesis is accompanied by a significant amount of oxidation in the eastern part of the state, especially where it is not covered by black cotton soils or Proterozoic sediments.

Groundwater in eastern Karnataka

Groundwater occurs dominantly under water table conditions in Karnataka and principally migrates through fractures in the hard rocks[18]. The water table has declined in many districts of eastern Karnataka, although rainfall has not uniformly decreased during the past three decades. While there is a decrease in rainfall in north interior Karnataka, an increasing trend has been observed in south interior Karnataka, as mentioned earlier. However, the water table has also recorded significant decline in south interior Karnataka because of urban growth, industrialization and agricultural activity in Bengaluru, Kolar, Tumkur and Chikkaballapura districts. Remote sensing studies have shown an 8.93% decrease in forest cover in the state during the period 2003–05 to 2011–13 (ref. 19). All these land use changes have lowered the water table promoting a greater degree of water–rock interaction, especially in eastern Karnataka.

Sampling and analytical methods

Groundwater samples were collected from borewells in 73 villages of 13 districts (Gulbarga, Yadgir, Bagalkot, Raichur, Koppal, Bellary, Chitradurga, Tumkur, Chikkaballapura, Kolar, Bengaluru Rural, Bengaluru Urban and Mandya). All the 13 districts lie in the fluoride endemic belt of Karnataka as inferred from the Department of Drinking Water and Sanitation, Government of India's Integrated Management Information System database on drinking water (Figure 1)[10]. The samples collected are all from borewells with energized submersible pumps, or those rarely fitted with hand pumps. All of them are actively supplying water for drinking purposes in the villages. They are not from abandoned wells or observation wells maintained by CGWB. The coordinates for the sampling sites were determined by hand-held Gramin GPS. Before collecting the water samples, static water in the borewells was flushed out by pumping for 3–5 min and then fresh groundwater flowing into the borewells was collected following standard protocols in pre-cleaned Borosil glass and HDPE bottles. Temperature, pH and electrical conductivity were measured at the site of sampling. The samples were transported and stored in the laboratory in an icebox until further use. The pH of water samples was determined again in the laboratory using an auto-titrator, and the accuracy of pH determined in the field was cross-checked and confirmed by measurements in the laboratory. Water samples were filtered using 0.22 μm mesh cellulose acetate membrane (millipore filters) to remove all the suspended particles. The filtrate was acidified with 2% dilute nitric acid to prevent biological activity and precipitation of metals. Uranium content in the water samples collected in the Borosil glass bottles was determined within 10 days from the date of collection of the samples at the CARER Laboratories of Mangalore University (a laboratory accredited by the AERB) using Quantalase LF-2a LED fluorimeter[20]. The excitation wavelength of the instrument is 405 nm and measurements were made at wavelengths >450 nm. The instrument can measure uranium concentration in water samples in the range 0.5–1000 μg/l, with an accuracy of 10% or 0.05 μg/l. Repeatability is better than 5%. A standard stock solution of ortho-phosphoric acid in ultra-pure water was used as fluorescence enhancing reagent – fluren – in the analysis. Because fluorescence yield varies for different complexes of uranium, fluren is added to the sample to convert all the uranium complexes into a single form having the same fluorescence. 6 ml of the sample with 10% fluren was taken in a cuvette made of ultra-low fluorescence fused silica and analysed for uranium in the fluorimeter. For samples in which uranium abundance exceeded 1000 μg/l, they were appropriately diluted to bring the concentration within the dynamic range of the instrument, and actual abundance was arrived at by correcting the determined value for the dilution factor.

Results

Table 1 shows the uranium abundances in groundwater from various localities in eastern Karnataka. The sample numbers are keyed to the sample locations shown in Figure 1. So far, uranium has been analysed in groundwater which is being supplied for drinking in 73 villages in eastern Karnataka.

It was observed that in 57 out of 73 villages, the uranium concentration in groundwater was more than 30 μg/l. In

Table 1. Uranium concentration in groundwater used for drinking in 73 villages of eastern Karnataka, India

District	Taluk	Village	ID of the sample** Location no (refer to Figure 1)	Well no.	Sample no.	Uranium (μg/l) with SD*
Gulbarga	Chitapur	Ramteerth	1	i	a	3
		Itga	2	i	a	4
		Taranhalli	3	i	a	17
		Chitapur	4	i	a	56
Yadgir	Shahapur	Ukkinhal	5	i	a	9
		Gogi	6	i	a	20
Bagalkote	Badami	Neerabudihal	7	i	a	23
	Bagalkote	Chowdapur	8	i	a	29
Raichur	Sindhnur	Hanchinhal	9	i	a	59
Koppal	Kushtagi	Nidsesi	10	i	a	134 ± 1
	Yelbarga	Bevoor	11	i	a	55 ± 1
				ii	a	56
		Katgihalli	12	i	a	20
Bellary	Hospete	Venkatapura (Near Hampi)	13	i	a	309 ± 6
	Kudligi	Kakkuppi	14	i	a	11
	Sandur	Jogikallu	15	i	a	187 ± 1
Chitradurga	Challakere	Khudapura	16	i	a	23
				i	b	21
	Hosdurga	Galirangainatty	17	i	a	345 ± 1
	Molakalmuru	Kadasiddapura (Ashoka Siddapura)	18	i	a	752 ± 9
				i	b	1047 ± 9
Tumkur	Sira	Maddakkanahalli	19	i	a	30 ± 1
				i	b	7
		Gomaranahalli	20	i	a	290 ± 5
				i	b	35 ± 1
		Kumbarahalli	21	i	a	537 ± 6
				i	b	80 ± 1
	Pavagada	Kodamadagu	22	i	a	40 ± 1
		Kariyammanapalya	23	i	a	104 ± 1
				i	b	46
				i	c	393 ± 1
				i	d	63 ± 1
Tumkur	Pavagada	Aralikunte	24	i	a	117 ± 1
				i	b	54 ± 1
				i	c	58 ± 6
				i	d	78 ± 1
		Kyathaganahalli	25	i	a	93 ± 1
				i	b	177 ± 1
				ii	a	527 ± 5
	Madhugiri	Badavanahalli	26	i	a	1575 ± 2
				ii	a	464 ± 4
Chikkaballapura	Bagepalli	Chancharayanapalli	27	i	a	39
				i	b	22
				i	c	16
				i	d	14 ± 1
				i	e	33
				ii	a	188 ± 1
				iii	a	28
				iv	a	190 ± 1
		D Kothapalli	28	i	a	209 ± 1
		Kothur	29	i	a	7
		Maddalakhane	30	i	a	1473 ± 4
				i	b	1945 ± 6
		G Maddepalli	31	i	a	>1000
				i	b	2755 ± 3
				i	c	3523 ± 3
				i	d	>5000
				i	e	>5000
		Pothepalli	32	i	a	35 ± 1

(*Contd*)

Table 1. (*Contd*)

District	Taluk	Village	ID of the sample** Location no (refer to Figure 1)	Well no.	Sample no.	Uranium (μg/l) with SD*
		Sajjupalli	33	i	a	198 ± 1
		Sakavandlapalli	34	i	a	330 ± 1
		Thimmampalli	35	i	a	285 ± 1
				ii	a	2100 ± 3
				ii	b	3101 ± 5
		Yellampalli	36	i	a	903 ± 2
				ii	a	915 ± 2
				ii	b	>1000
	Chikkaballapura	Chalumenahalli	37	i	a	47
		Jathavara	38	i	a	15
				ii	a	2
	Chintamani	Chintamani	39	i	a	5267 ± 6
				ii	a	5913 ± 6
Chikkaballapura	Chintamani	Gudumarlahalli	40	i	a	416 ± 3
		Hirekattigenahalli	41	i	a	347 ± 1
				ii	a	>1000
				ii	b	769 ± 2
		Puligundlahalli	42	i	a	439 ± 3
		Siddepalli	43	i	a	456 ± 4
	Gauribidanur	Krishnarajapura Tanda	44	i	a	275 ± 5
		Mudugere	45	i	a	11
		Saganahalli	46	i	a	15
				ii	a	30
				iii	a	4
				iii	b	21
				iv	a	4
				v	a	5
				vi	a	12
		Subrayanahalli	47	i	a	250 ± 5
	Gudibande	Doddakurabarahalli	48	i	a	41
		Ganganahalli	49	i	a	43 ± 3
		Minchanahalli	50	i	a	176 ± 1
		Somenahalli	51	i	a	81 ± 1
	Sidlaghatta	Brahamanahalli	52	i	a	772 ± 6
				i	b	148 ± 2
				i	c	1236 ± 3
				i	d	1825 ± 4
				i	e	3218 ± 5
				iii	a	1107 ± 2
		Saddahalli	53	i	a	7
				i	b	3
				i	c	9
				i	d	10
				i	e	11
				ii	c	32
Kolar	Kolar	Antharagange	54	i	a	1
		Kondarajanahalli	55	i	a	943 ± 3
				i	b	770 ± 6
				i	c	1096 ± 3
				ii	a	300 ± 6
Kolar	Mulbagal	Kurudumale	56	i	a	21
		Honaganahalli	57	i	a	63
		Ganganahalli	58	i	a	178 ± 1
	Bangarapet	Ramanayakanhalli	59	i	a	31 ± 1
		Siddanahalli	60	i	a	391 ± 1
		Mageri	61	i	a	599 ± 6
	Malur	Thimmanaikanahalli Agrahara	62	i	a	61
	Srinivasapur	Chikkevaripalli	63	i	a	>1000
				i	b	308 ± 6

(*Contd*)

Table 1. (*Contd*)

District	Taluk	Village	ID of the sample** Location no (refer to Figure 1)	Well no.	Sample no.	Uranium (μg/l) with SD*
				i	c	2934 ± 3
				i	d	3838 ± 5
				i	e	5995 ± 7
				ii	a	921 ± 2
		Kadirampalli	64	i	a	>1000
				i	b	340 ± 1
				i	c	2227 ± 2
				i	d	2148 ± 2
				i	e	2986 ± 3
		Mudimadugu	65	i	a	516 ± 4
				ii	a	666 ± 6
		Banthonikatava	66	i	a	1141 ± 3
		Balthamari	67	i	a	3561 ± 1
Bengaluru rural	Devanahalli	Avathi	68	i	a	175 ± 1
				ii	a	942 ± 2
		Gudla Muddenahalli	69	i	a	56
		Kodagurki	70	i	a	356 ± 1
Bengaluru	Bengaluru	Gollahalli	71	i	a	9
				ii	a	61
				iii	a	310 ± 6
				iv	a	30 ± 1
		Gottigere	72	i	a	55 ± 1
				ii	a	62
Mandya	Nagamangala	Thirumalasagara Chathra	73	i	a	2

*The concentration and standard deviation (SD) values are rounded-off to the nearest whole number. No SD values are given for concentrations less than 10 μg/l. In case the concentration exceeded 1000 μg/l, the sample was diluted to bring the concentration within the dynamic range of the instrument.

**a, b, c, d,… are the samples drawn in different months. i, ii, iii,… are the various borewell.

Table 2. Summary of the number of villages showing greater than 30, 60 and >1000 μg/l (very high) of uranium in groundwater in eastern Karnataka

District	Total no. of villages sampled	Uranium concentration (μg/l) >30	>60	>1000
Gulbarga	4	1		
Yadgir	2			
Bagalkot	2			
Raichur	1	1		
Koppal	3	2	1	
Bellary	3	2	2	
Chitradurga	3	2	2	1
Tumkur	8	7	6	1
Chikkaballapura	27	25	22	7
Kolar	14	12	11	5
Bangalore rural	3	3	2	
Bangalore	2	2	2	
Mandya	1			
Total	73	57	48	14

48 villages it exceeds 60 μg/l. Thus in 78% and 66% of the villages, uranium concentration exceeded the permissible limits given by WHO and AERB respectively.

It is alarming to note that in one village each in Tumkur and Chitradurga districts, five in Kolar and seven in Chikkaballapura district, uranium concentration was in the range of thousands of micrograms per litre (Table 2).

We examine below the district-wise uranium abundance data.

Gulburga

Sampling in Gulburga district was from wells at Ramteerth, Itga, Taranhalli and Chitapur villages. These are located in the carbonate rocks of the Bhima Group or in the granite area adjacent to the carbonate rocks. Near Chitapur, the Bhima Group limestone (called Shahabad limestone) is being exploited for a cement plant. The CGWB[8] reported uranium values greater than 30 μg/l (34.1 μg/l) from an observation well near Chitapur[8]. We sampled water from the borewell which is supplying water for drinking purposes to the Chitapur village. The sample confirmed that there is uranium abundance higher than the threshold given by WHO and it is almost close to the limit given by AERB. The borewell at Chitapur is within the Bhima Group limestone.

At Ramteerth, the main uranium-bearing mineral is collophane. In spite of uranium mineralization here, no high values of the element were observed in groundwater.

Yadgir

We sampled the groundwater in Yadgir district, as these are locales where the Atomic Minerals Directorate had explored for uranium and reported uranium mineralization in phosphatic limestones at Ukkinhal and in high-silica non-phosphatic limestones at Gogi[17]. Similar to Ramteerth, uranium at Ukkinhal was in the form of collophane. Hydrothermal uranium occurs in the reduced state as coffinite or uraninite at Gogi[21]. Although Gogi and Ukkinhal Tanda villages lie in the mineralized belt, it is interesting to note that uranium abundance in groundwater at these places was well within permissible limits given by WHO and AERB. Manoj *et al.*[22] also did not record high values of uranium at Gogi, but found greater than 30 μg/l uranium in groundwater in granite areas 15–20 km south of Gogi close to the Krishna River.

Bagalkote

In the Mesoproterozoic Kaladgi Group and bordering Neoarchean potash granitoid rocks, uranium mineralization has been discovered in recent years by Chaki *et al.*[16]. Also, there are reports of high-fluoride groundwater in limestone near Neerabudihal and granite near Chowdapur[10]. We sampled groundwater from the wells supplying water for drinking purposes from these latter villages. Water from both the localities had uranium within permissible limits.

Raichur

CGWB reported uranium abundance of 35.66 μg/l from an observation well at Hanchinhal, Sindhanur taluk[8]. The village uses water from a well fitted with a hand pump for drinking purposes. The water sample collected from this well is found to have 59.3 μg/l uranium. While our finding confirms the inference of uranium contamination reported by CGWB, it shows that the water being used has a much higher concentration of uranium, almost equivalent to the threshold given by AERB.

Koppal

Pink potash feldspar granite of Koppal and associated syenites are known to cause fluoride contamination in groundwater. Nidsesi village with high fluoride contamination has attracted the attention of the Public Health Department in recent years. We have analysed from this setting water samples from three villages – Nidsesi in Kushtgi taluk and Bevoor and Katagihalli in Yelburga taluk, where the wells had yielded fluoride-rich waters, to see if the water is also contaminated with uranium. While the sample from Nidsesi was found to have 134 μg/l uranium which is more than twice the limit prescribed by AERB, the Bevoor sample showed abundance higher than the limit prescribed by WHO. Corrective steps to find alternative sources of freshwater from the surface are in progress at Nidsesi.

Bellary

The CGWB[8] reported uranium content in groundwater to be higher than the WHO prescribed limits at Venkatapura in Hospet taluk and Kakkuppi and Jogikallu in Sandur taluk[8]. Our results confirm high uranium in the Venkatapura drinking water well (308 μg/l). We observed uranium content three times higher than the AERB limit of 60 μg/l at Jogikallu. There was no evidence of uranium contamination in the drinking water borewell at Kakkuppi.

Chitradurga

Groundwater samples were collected from three villages in Chitradurga district. Two samples were from Khudapura village in Challakere taluk. This borewell is in the Challakere campus of IISc. The groundwater in this well recorded 21–23 μg/l uranium concentration and therefore is considered safe. The well is located in a large mafic body in the migmatite zone to the east of the Chitradurga greenstone belt. By contrast, the wells located in Galirangainatty and Kadasiddapura are amidst K-feldspar-rich granite zones (Hosdurga and Closepet Granite respectively). These are discharging water with high uranium in the range of hundreds of micrograms per litre.

Tumkur

Groundwater samples were collected from nine villages. Seven of these villages were found to have groundwater with uranium concentration above 30 μg/l. Of these, six villages, viz. Kyathaganahalli, Kumbarahalli, Kariyammanapalya, Gomardhanahalli, Badavanahalli and Aralikunte had groundwater with uranium content greater than 60 μg/l. Among all the groundwater samples analysed from Tumkur district, the sample from Badavanahalli in Madhugiri taluk had uranium-concentration in thousands of micrograms per litre.

Chikkaballapura

High uranium values have been reported from several wells in Chikkaballapura district[7,9]. The CGWB reported 201 μg/l uranium in groundwater in Chintamani[19]. We have measured uranium in groundwater that is supplied for drinking in 27 villages in all the 6 taluks of this district (Table 1). Except for Kothuru in Bagepalli taluk, Jathavaara in Chikkaballapura taluk, Saganahalli in Gauribidanur taluk and Sadahalli in Shidlaghatta taluk, in 25 other villages of the district, groundwater had uranium higher than permissible limits of 30 or 60 μg/l. In 4 of these 25 villages, namely Bommaiyyagaripalli and Pothepalli of Bagepalli taluk, Chalumenahalli of Chikkaballapur taluk and Doddakurubarahalli of Gudibanda taluk, uranium content was higher than the WHO prescribed limit of 30 μg/l, but lower than the limit prescribed by AERB. In 22 other villages, it was found to exceed the limit set by AERB as well. In seven villages, namely Brahamanahalli, Hirekattigenahalli, Maddalakhane, Maddepalli, Thimmampalli, Yellampalli and Chintamani, uranium was high, exceeding 1000 μg/l. It is important to note that Chintamani is dependent on groundwater for drinking. The well supplying water to a large part of the town has a very high uranium content (more than 5000 μg/l). All these wells are in the potassic granodiorite belts of Nandi, Gudibanda, Bagepalli and Chintamani.

Kolar

The CGWB reported high uranium in water samples from Kurudumale and Anagondanahalli of Mulbagal taluk[8]. While at Kurudumale it recorded just about 30 μg/l, at Anagondanahalli it recorded more than 60 μg/l of uranium. Most villages in Kolar district are dependent on groundwater for drinking. Similar to Chikkaballapur district, Kolar district is also known as a fluorosis-endemic area. Therefore, we carried out studies in more villages in Kolar district. We report here uranium content in groundwater which is being supplied for drinking in 14 villages in Kolar district. Among these, 12 villages had water with uranium concentration >30 μg/l. In 11 out of these 12 villages, uranium concentration was more than 60 μg/l. Almost all the samples which we collected in Srinivasapura taluk had very high abundance of uranium. Groundwater in Kadirampalli, Chikkevaripalli, Balthamari and Banthonikatava had uranium concentration in thousands of micrograms per litre. Water from the Chikkevaripalli borewell had the highest uranium abundance among all the samples collected by us so far. The lateritized granitoids bordering the Kolar greenstone belt constitute the aquifers in the Srinivasapura taluk.

Bengaluru Rural and Urban

Hunse *et al.*[23] had reported high radon content from some localities in the Bengaluru urban and rural belt. The CGWB reported uranium above the threshold given by WHO and AERB from observation wells at Kodagurki and Avathi of Bengaluru rural and Gollahalli and Gottigere of Bengaluru urban districts[8]. Bengaluru is located on the Peninsular Gneiss dominantly made up of granodioritic gneisses and migmatites. A late tectonic to post-tectonic, fine-grained, K-feldspar granitoid invades the gneisses in the south-central part of the district. The gneisses and granitoids are known for monazite, sphene and zircon among accessory minerals, which have been used for radiometric dating. We sampled the drinking water being supplied to Avathi village and from Gudla Muddenahalli and Kodagurki. All the three villages belong to Devanahalli taluk, Bangalore rural district. The Avathi samples showed high uranium varying from 174 to 942 μg/l, while the Kodagurki sample had 356 μg/l uranium, confirming the observations of CGWB[8]. A sample from Gudla Muddenahalli also had uranium more than the WHO prescribed limit. Sampling was undertaken at Gollahalli and Gottigere in Bengaluru urban district. These wells are in a granite area amidst Peninsular Gneiss. In both areas, uranium >30 μg/l was noted and at Gollahalli, repeat sampling showed that it varied from 9 to 310 μg/l throughout the year.

Mandya

The CGWB reported uranium exceeding 30 μg/l from Thirumalasagara Chatra of Nagamangala taluk[8]. This area falls in the Western Dharwar Craton (WDC), which is generally known to be less radioactive than the Eastern Dharwar Craton (EDC). However, near Pandavapura and south of Melukote, close to Thirumalasagara Chatra, K-feldspar-rich granites are found to occur. While the CGWB noted 40.38 μg/l uranium in its observation well[8], the drinking water supply well here yielded very low uranium content of 2 μg/l, as could be expected in wells located in TTGs of WDC.

Variation in uranium content in groundwater throughout the year

Repeat sampling was done in four localities in Chikkaballapur and Kolar districts to confirm the very high values of uranium that had been observed. The samples were collected between July and February. Repeated analysis from all the four localities confirmed a high abundance of uranium in groundwater. In addition, it showed that the samples collected during January and February had much higher uranium content than those collected during July (Figure 4). Variation through the year is being studied to understand the pre- and post-monsoon compositional changes.

Discussion and conclusion

Groundwater in Karnataka occurs under water table conditions and mainly circulates in the fractures of the saturated zone. Therefore, the soil–water and rock–water interactions play a major role in determining the chemical composition of water. Regional gamma-ray spectrometric

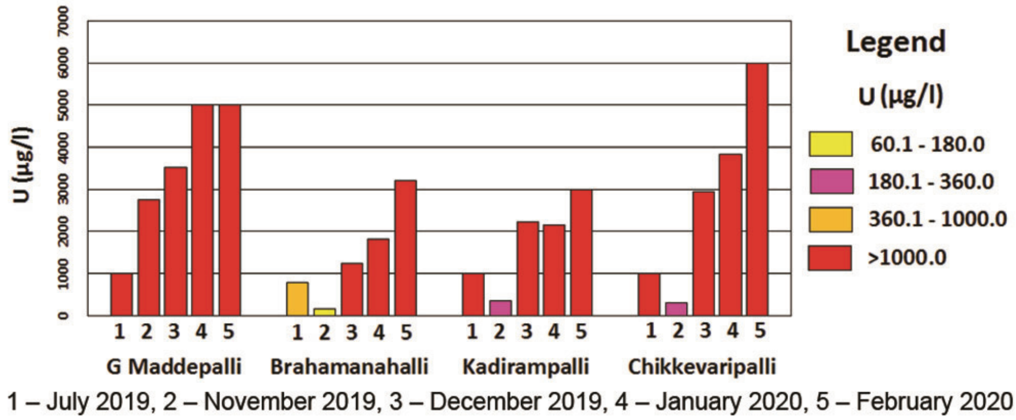

Figure 4. Variation in uranium content in four selected villages between July 2019 and February 2020.

studies indicate a higher abundance of uranium in gneisses and granitoids of EDC compared to those in WDC. Further, the soils in the eastern part of Karnataka being red loam with laterite at places, indicate a higher degree of oxidation during weathering. Oxidation of uranous to uranyl ion $(UO_2)^{+2}$ is promoted by such a weathering process[24]. As uranyl phases are soluble in circulating groundwater, the process leads to a higher concentration of dissolved uranium in groundwater. Such a process may play an important role in producing uranium-rich groundwater in eastern Karnataka.

There is evidence that the water table is going down in many parts of eastern Karnataka[12]. Oxidative weathering in the deeper levels is facilitated by this decline in groundwater level. It also provides for extended time of soil/rock–water interactions that lead to the release of more uranium to the circulating water. Detailed study of uranous and uranyl mineral phases in soils and rocks by X-ray diffraction and electron probe micro analyser is planned for further understanding the process of dissolution of uranium in circulating groundwater.

Uranium-rich groundwater spread over a wide area in eastern Karnataka is unrelated to any nuclear facility or discharge of wastewater from urban centres. There are no nuclear power/research reactors, uranium processing/fuel fabrication and enrichment plants in the study area. Even at Gogi, where uranium deposit was discovered by the Atomic Minerals Directorate, there is no uranium mining and related mine waste disposal. This indicates that uranium contamination is geogenic rather than anthropogenic.

The absence of high uranium abundance in groundwater in uranium mineralized belts at Ukkinhal and Gogi in Yadgir district and Ramteerth in Gulburga district is interesting. At Gogi uranium is still in the form of unoxidized uraninite and coffinite, whereas at Ukkinhal and Ramteerth it is in the form of collophane. Occurrence of these mineral phases indicates that oxidation has not significantly affected the uranium mineralized zones in these localities, preventing the release of uranium to groundwater on any significant scale. Also, a major part of the ore zone lies well below the zone of saturation (aquifer depth).

Although in this study we have not examined the relationship between elevated levels of uranium in drinking water and health effects, one cannot discount that health effects can arise especially in areas where uranium abundance is an order of magnitude higher than the prescribed limits. There is a need to undertake epidemiological studies in such areas to establish the toxic effects of uranium and the lowest observable adverse effect level.

In most of the sites which we have examined for uranium contamination in groundwater, it is found that the water also carries high fluoride content. Groundwater in most of the villages in eastern Karnataka is being treated by RO systems installed by the Department of Rural Water Supply and Sanitation, Government of Karnataka, to address the problem of fluorosis. It is known that RO units generally recover only one-fourth the quantity of water treated. The discharged wastewater going out into the environment has higher concentrations of pollutant ions. The groundwater resources in eastern Karnataka are already said to have reached critical levels in several sectors and wastage of water from RO units is not a sustainable approach for water resource development. Conjunctive use of surface water and groundwater, adoption of water harvesting techniques, production of water from condensation of atmospheric humidity need to be considered for resolving the issue of supply of hygienic water to the villages.

Although DCCC has so far studied uranium contamination in groundwater in 73 villages, it must be admitted that this does not include all the villages which may be utilizing the uranium-rich water for drinking in Karnataka. This pilot study, however, is representative enough to draw attention to this major contaminant problem which may be of importance for public health in the eastern part of Karnataka in particular and EDC in general. The adjacent states of Andhra, Telangana and Tamil Nadu have similar geological setting as the EDC of Karnataka. While DCCC will continue carrying out such regional reconnaissance evaluation, it will focus on intervention measures in a few selected villages where very high uranium, or uranium and fluoride contamination has been recognized so far.

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