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Radon concentration measurement and effective dose assessment in drinking groundwater for the adult population in the surrounding area of a thermal power plant

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ABSTRACT

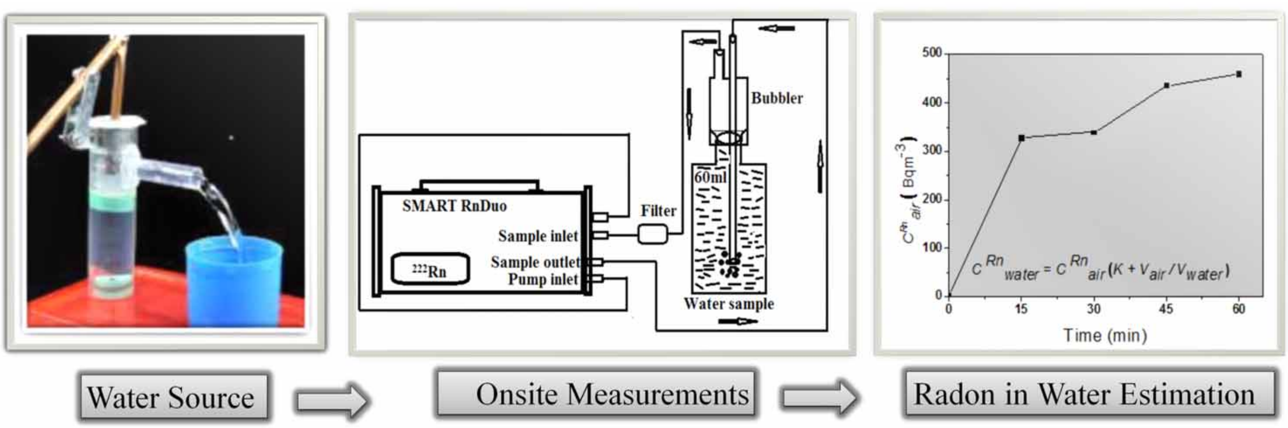
Radon in the household water collected from hand pumps is measured using a continuous radon monitor. Water samples are collected from 25 villages from the surrounding regions of the National Capital Power Cooperation (NTPC), Dadri. The radon concentration ranges from 17 ± 1 to 68 ± 3 Bql^{-1} with a mean value of 33 ± 13 Bql^{-1}. The measured radon concentration in all collected samples lies well within the limit of 100 Bql^{-1}as set by the World Health Organization (WHO). The mean values of the annual effective dose due to ingestion of radon and due to the inhalation of radon released from water are 84 ± 33 and 167 ± 65 μSvy^{-1}, respectively. In addition, the mean values of estimated total annual effective doses are found to be 167 ± 65 μSvy^{-1}. The mean value of total annual effective doses is found to be higher than the reference dose level of 100 μSvy^{-1} recommended by the WHO and the United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR). The mean values of effective doses per annum to the lungs and stomach are 9.9 ± 3.9 and 10.1 ± 3.9 μSv, respectively.

Key words: active method, annual effective doses, drinking water, radon

HIGHLIGHTS

- SMART Rn Duo: A Continuous radon monitor.
- Radon concentration present in the drinking groundwater is measured.
- The annual effective ingestion, inhalation, and total dose of radon are measured.
- Radon concentration is found to be below the recommended action level of 100 Bql^{-1} proposed by the EU and WHO.
- The mean value of total annual effective dose is found to be higher compared to the safe limit recommended by the WHO.

GRAPHICAL ABSTRACT



INTRODUCTION

Radon (^{222}Rn) is a naturally occurring radioactive gas in the decay chain ^{238}U. This gas is produced continuously and is commonly present in the pore space of rock and soil. A fraction of radon present in pore space is dissolved in groundwater depending upon the air–water partition coefficient. The consequences of radon in drinking water are twofold: (i) irradiation of stomach tissues and small intestine through ingestion and (ii) irradiation of lung tissues through inhalation. In terms of ingested radon, the radiation exposure is primarily due to radon gas itself (NRC 1999; Kendall & Smith 2002). The highest organ dose (>90%) from ingested radon is to the stomach (Kendall & Smith 2002). The US NAS (1999) assessed that the risk of stomach cancer caused by radon dissolved in drinking water is small compared to stomach cancer due to other causes. No definitive link between ingestion of drinking water containing radon with increased risk of stomach cancer (Auvinen *et al.* 2005) has been established. Still, worldwide efforts are ongoing to study the linear relationship between radon exposure and health risk due to the assumption of the Linear No Threshold (LNT) hypothesis in radiation risk assessment (WHO 2017). Based on the estimated risk to human health from the LNT model because of radiation protection, different radon levels have been introduced for radon in drinking water. In the European Union countries, the limit is between 100 and 1,000 Bql^{-1} (EURATOM 2013). Spanish legislation has set a limit of 500 Bql^{-1} (Gonzalez *et al*. 2018). In the United States, two different levels, a maximum contamination level of 11.1 Bql^{-1} and an alternative maximum contamination level of 148 Bql^{-1}, are given (EPA 1999). The World Health Organization (WHO) and the European Commission (EU) set the guidance level to 100 Bql^{-1} (EU 2001; WHO 2008). The WHO (2008) has recommended a reference dose level (RDL) of 0.1 mSv due to the annual intake of drinking water. The RDL of 0.1 mSv is equal to 10% of the dose limit for the intervention level recommended by the ICRP (1991) and the International Basic Safety Standards (IAEA 1996).

Surface and underground water samples contain natural radionuclides in various concentrations depending on their origin. Radon gets released into waters due to the decay of its parent nuclide ^{226}Ra contained in rock and soil. The amount of radon dissolved depends upon different factors such as radium content, radon emanation coefficient, air–water partition coefficient, and aquifer characteristics (Moreno *et al.* 2014). The groundwater generally has much higher concentrations of radon than surface water. In public water supplies derived from surface water, the mean radon concentration is usually less than 0.4 Bql^{-1} and its mean value is about 20 Bql^{-1} from groundwater sources (WHO 2008).

Various studies have been performed in different parts of India to measure the radon concentration in groundwater used for drinking purposes. In various states of India, the concentration of radon dissolved in groundwater ranged as follows: 0.87–6.73 Bql^{-1} in Himachal Pradesh (Singh *et al.* 2016), 0.4–74.37 Bql^{-1} in Jammu and Kashmir (Kumar *et al.* 2017a, 2017b, 2018; Kaur *et al.* 2019), 0.14–35 Bql^{-1} in Punjab (Kaur *et al.* 2017; Kumar *et al.* 2017c, 2019; Sharma *et al.* 2019, 2020; Pant *et al.* 2020), 0.60–57.35 Bql^{-1} in Haryana (Duggal *et al.* 2017; Panghal *et al.* 2017; Sharma *et al.* 2017a, 2017b; Singh *et al*. 2019), 0.50–861.5 Bql^{-1}in Rajasthan (Mittal *et al.* 2016a, 2016b; Duggal *et al.* 2020a, 2020b), 0.19–160.18 Bql^{-1}in Karnataka (Srinivasa *et al.* 2015, 2018, 2019; Rangaswamy *et al.* 2016; Niranjan *et al.* 2017; Reddy *et al.* 2017; Shilpa *et al.* 2017; Kaliprasad & Narayana 2018; Sannappa *et al.* 2020; Yashaswini *et al.* 2020), 0.12–28.20 Bql^{-1}in Kerala (Nandakumaran *et al.* 2016; Divya & Prakash 2019), 0.07–40.7 Bql^{-1}in Tamil Nadu (Singaraja *et al.* 2016), 1.04–10.02 Bql^{-1} in West Bengal (Krishna *et al.* 2015), 0.33–7.32 Bql^{-1} in Maharashtra (Raste *et al.* 2018), and 2–400 Bql^{-1} in Uttarakhand (Prasad *et al.* 2018). These available literature values show that the overall range in India varies from 0.07 to 861.5 Bql^{-1}. Singaraja *et al.* (2016) have reported the minimum value of 0.07 Bql^{-1} in the Tuticorin district in Tamil Nadu state. Duggal *et al.* (2020a, 2020b) have reported the maximum value of 861.5 Bql^{-1} in the Khandela region of the Khetri Copper Belt of Rajasthan.

Coal-fired power plants are the sources of fly ash, which contains naturally occurring radioactive elements such as ^{238}U, ^{232}Th, and their decay products and other toxic elements. Fly ash is generally stored at coal power plants or placed in landfills. Ash stored or deposited outdoors may eventually leach radioactive elements (^{238}U, ^{232}Th, and their decay products) and other toxic composites into underground water aquifers. This may lead to contamination of underground water used for drinking purposes and may cause internal exposure to the public. One of the important radionuclides in drinking water causing internal exposure is the dissolved radon gas which originates from the ^{238}U decay series. As per the WHO, internal exposure to radon is the second highest cause of lung cancer, next to smoking. In view of radiological importance of radon in drinking water, the present study was taken up to measure the concentration of dissolved radon in water and estimate the corresponding annual effective dose in water samples collected from hand pumps in the surrounding area of coal and natural gas-based power plant situated in the Gautam Buddha Nagar district, Uttar Pradesh, India. To the best of our information, the measured values for radon in drinking water and associated doses are the only data available for the studied region around the National Capital Power Cooperation (NTPC), Dadri. Some novelties of this study includes onsite measurements using a portable continuous radon monitoring system and a novel sampling technique to prevent loss of dissolved radon by aeration and air-contact, which is commonly faced by researchers.

MATERIALS AND METHODS

Study area

The area under study around the NTPC, Dadri power station, lies between 28.5568°–28.6419°N and 77.5476°–77.6521°E. This region comprises an aquifer system that forms a good repository of groundwater. These water repositories occur in granular zones constituted of fine to coarse and occasional gravel. Thick clay beds interlying with sand act as confining layers and separate the aquifers. Groundwater occurs in shallow aquifers down to the depth of 100 m below ground level under confined and semi-confined conditions and is safe for drinking. In the deeper zone, water becomes brackish to saline (Joshi 2008–2009). Figure 1 shows a map of the study region with sampling locations.

Sample collection and instrument details

Samples were collected from hand pumps in the month of February 2020 from 25 villages from the surrounding region of the NTPC in a leak-tight bottle made up of low-permeability material having a volume of 60 ml. Sufficient precaution was taken during sampling to minimize aeration and prevent loss of dissolved radon in water sample. Measurements were carried out at the site within 3 h of sample collection to minimize the loss of radon due to the radioactive decay process.

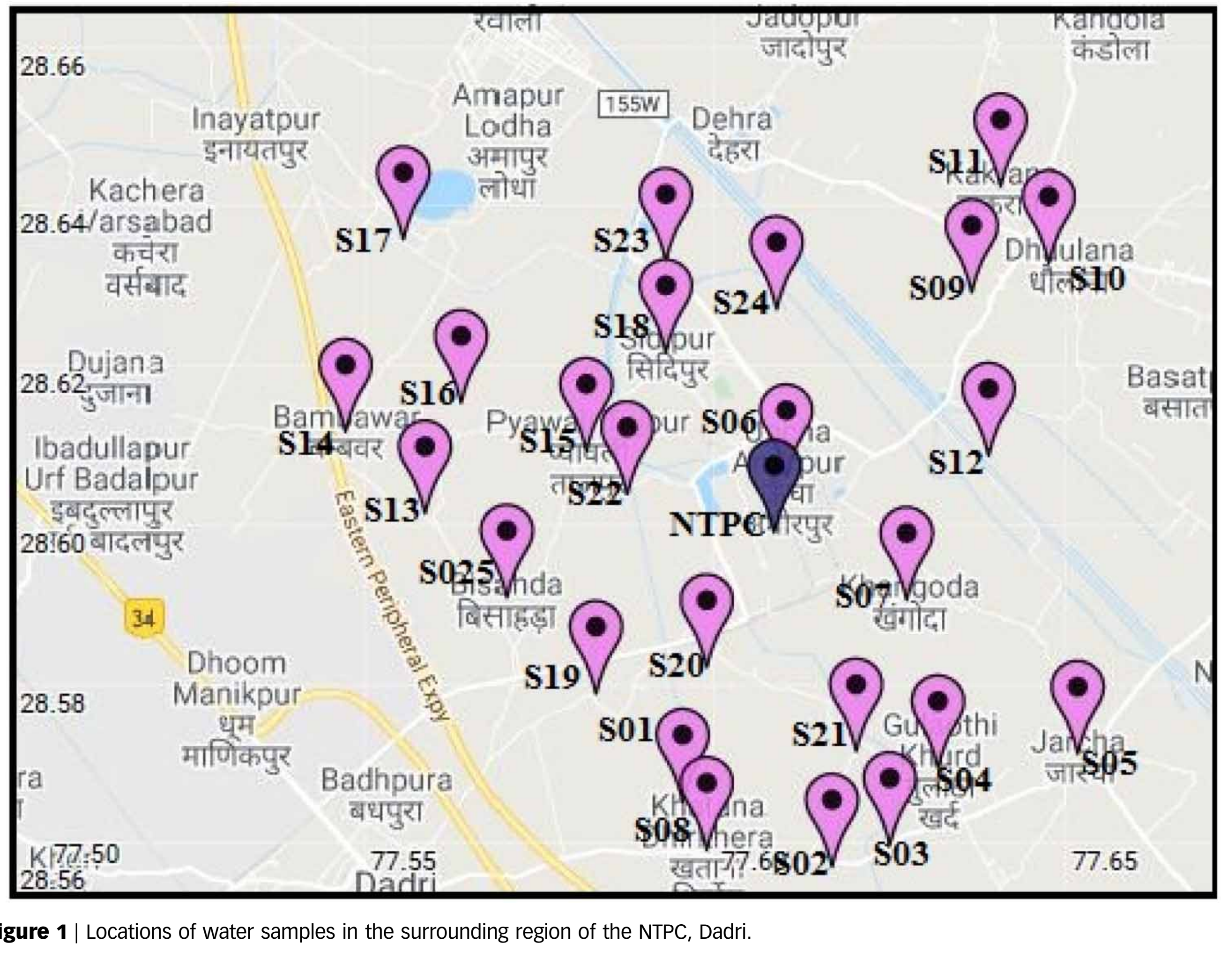


Figure 1 | Locations of water samples in the surrounding region of the NTPC, Dadri.

A continuous activity monitor (SMART RnDuo), developed and calibrated by the Bhabha Atomic Research Centre, Mumbai (Gaware *et al.* 2011), was used to measure radon in water samples because of its very high sensitivity per unit activity concentration of radon (~1.2 cph/Bq m^{-3}) and less dilution due to low-detector volume (1.53×10^{-4} m^3). A scintillation technique is employed to detect alpha particles of sampled radon and its progeny formed inside the detector volume. Alpha counts obtained in each interval get converted into the radon concentration through a novel in-built algorithm in the micro-controller. The measured values are always free from the effects of humidity and trace gases because this device does not have any interference from charge-neutralizing species (such as humidity, CO_2, CH_4, etc.).

The sampling bottle is attached to the SMART RnDuo monitor through a bubbler and tubes. Figure 2 shows a schematic of the experimental setup for measuring radon in the water. A fast mode with a counting interval time of 15 min and a pump on time of 5 min per interval is employed. The measurement was continued to about 1 h for obtaining converge reading of radon concentration in water sample.

Mathematical formalism

The radon concentration in water, C_{water}^{Rn}, is obtained from the experimentally measured radon concentration, C_{air}^{Rn} by the following formula:

$$C_{water}^{Rn} = C_{air}^{Rn}\left[K + \frac{V_{air}}{V_{water}}\right] \quad (1)$$

where K (~0.25) is the partition coefficient between the two media (air and water). V_{air} and V_{water} denote volume of setup occupied with air and water, respectively. In this present setup, dependence on K is minimized by maximizing the ratio V_{air}/V_{water} ~10.

Uncertainty error in the measurements of radon concentration in water (ΔC_{water}^{Rn}) is calculated by using the following relation:

$$\Delta C_{water}^{Rn} = \Delta C_{air}^{Rn}\left(\frac{V_{air}}{V_{water}}\right) \quad (2)$$

where ΔC_{air}^{Rn} is the average measurement error reported by the equipment.

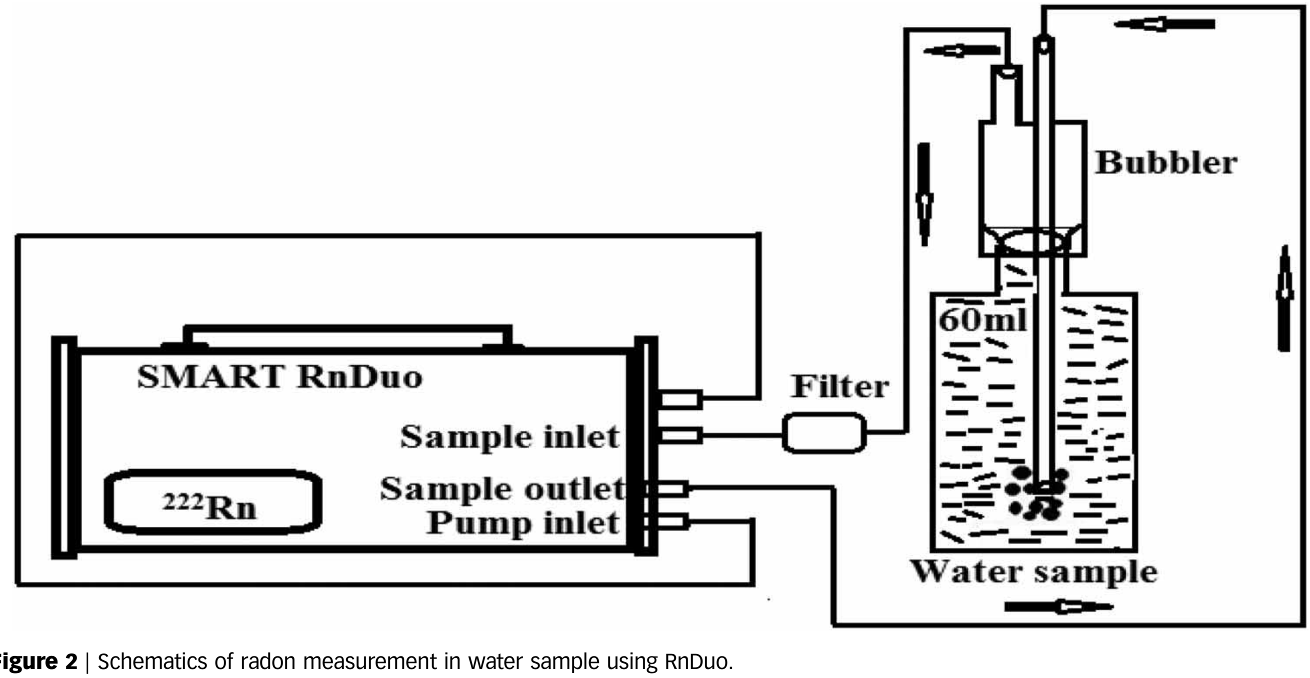


Figure 2 | Schematics of radon measurement in water sample using RnDuo.

The annual effective inhalation dose because of inbreathing of waterborne radon is estimated by using the following relation:

$$D_{inh.}(\mu\text{Sv}) = C^{Rn}_{water}(\text{Bql}^{-1}) \times 10^{-4} \times 0.4 \times 7000\,\text{h} \times 9\,\text{nSvBq}^{-1}\text{h}^{-1}\text{m}^{3} \quad (3)$$

where 10^{-4} is the ratio of radon in the air to water, 0.4 is the equilibrium factor between radon and its daughters, 7,000 h is the average indoor occupancy time per individual per year, and 9 $\text{nSvBq}^{-1}\,\text{h}^{-1}\,\text{m}^{3}$ is the dose conversion factor for inhalation of radon (ICRP 1993; UNSCEAR 2000).

The annual effective ingestion dose because of intake of radon-containing water is obtained by the following formula:

$$D_{ing.}(\mu\text{Sv}) = C^{Rn}_{water}(\text{Bql}^{-1}) \times 730 \times 3.5\,\text{nSvBq}^{-1} \times 10^{-3} \quad (4)$$

where 730 l is the annual water intake for adults (>17 y) population (WHO 2008) and 3.5 nSvBq^{-1} is the radon ingesting dose conversion factor for adults (UNSCEAR 2000).

For evaluating the annual effective dose for lungs (D_{lungs}) and stomach ($D_{stomach}$), the following formula is used:

$$D_{lungs,\ stomach}\ (\mu\text{Sv}^{-1}) = W_T \times D_{inh.,\,ing.} \quad (5)$$

where W_T (=0.12) is the tissue weighting factor for lungs and stomach (ICRP 1991).

RESULTS AND DISCUSSION

Table 1 shows the radon concentration in drinking water samples, annual effective inhalation, ingestion, total dose, dose to lungs and stomach for the adult population living in the study area around the NTPC, Dadri.

Radon concentration in water samples

The experimentally observed radon concentration in the water samples varies from 17 ± 1 to 68 ± 3 Bql^{-1}. The arithmetic mean with one standard deviation is found to be 33 ± 13 Bql^{-1}.

Seventeen locations out of 25 have radon concentrations lower than the upper limit (40 Bql^{-1}) recommended by the UNSCEAR (2008) in water for human consumption. Furthermore, all the samples have radon concentration much below the recommended action level of 100 Bql^{-1} proposed by the EU and the WHO (EU 2001; WHO 2008) and is also lower than the alternative maximum contamination level (AMCL) of 148 Bql^{-1} suggested by the Environmental Protection Agency (EPA) in the United States (EPA 1999).

Annual effective inhalation, ingestion, total effective dose, and dose to the body organs

The annual effective inhalation dose for the adult population around the NTPC varies from 42 ± 3 to 172 ± 7 μSv with an average value of 83 ± 32 μSv. The effective ingestion dose ranges from 43 ± 3 to 174 ± 7 μSv with an average value of 84 ± 33 μSv (Table 1). The contribution of inhalation dose due to waterborne radon and ingestion dose due to intake of water containing radon is almost equal in each study location around the plant.

The total annual effective dose, a sum of the inhalation and ingestion dose, varies from 85 ± 5 to 346 ± 10 μSv with an average value of 167 ± 65 μSv (Table 1). In six locations of 25, the total annual effective dose received by the adult population is below the safe value (100 μSv) recommended by the WHO (WHO 2008, 2017), whereas in the rest of the locations it is higher than the safe value.

Table 1 also presents the effective dose per annum to the lungs due to inhaled air having radon released from water and the stomach due to ingestion of radon-containing water. The effective dose per annum to the lungs ranges from 5.0 ± 0.4 to 20.6 ± 0.8 μSv with an average value of 9.9 ± 3.9 μSv. The effective dose per annum to the abdomen due to ingestion ranges from 5.1 ± 0.4 to 20.9 ± 0.8 μSv with a mean value of 10.1 ± 3.9 μSv.

CONCLUSIONS

The radon concentration is minimum (17 ± 1 Bql^{-1}) in the Rajatpur village and maximum (68 ± 3 Bql^{-1}) in the Hasanpur Lodha village. The observed maximum value of radon concentration dissolved in water is about 31.5% lower than the

Table 1 | Results of measured radon concentration in water samples collected from hand pump around the NTPC, Dadri and estimated annual effective doses

		Sample location			Annual effective dose (μSvy^{-1})			Annual effective dose to body organs (μSv)	
Sample code	Village	Latitude	Longitude	Radon concentration (Bql^{-1})	Inhalation	Ingestion	Total	D_{lungs}	$D_{stomach}$
S01	Dadupur Khatana	28.5649	77.5956	42±2	63±4	64±4	126±6	7.5±0.5	7.6±0.5
S02	Dhanibas	28.5568	77.6170	30±2	106±5	107±5	213±7	12.7±0.6	12.9±0.6
S03	Uplarasi	28.5593	77.6253	17±1	75±4	76±4	152±6	9.1±0.5	9.2±0.5
S04	Gulaothi Khurd	28.5689	77.6321	42±2	43±3	43±3	86±5	5.1±0.4	5.2±0.4
S05	Jarcha	28.5708	77.6521	48±2	105±5	106±5	211±7	12.6±0.6	12.8±0.6
S06	Unch Amirpur	28.6057	77.6106	34±2	121±5	123±5	244±8	14.5±0.6	14.7±0.7
S07	Khangoda	28.5901	77.6278	43±2	86±4	87±4	173±6	10.3±0.5	10.5±0.5
S08	Khatana Dhirkhera	28.5587	77.5991	24±2	109±5	110±5	219±7	13.1±0.6	13.2±0.6
S09	Daulatpur Dhikri	28.6287	77.6371	18±1	60±4	61±4	122±6	7.2±0.5	7.3±0.5
S10	Dhaulana	28.6324	77.6479	19±1	44±3	45±4	90±5	5.3±0.4	5.4±0.4
S11	Kakarana	28.6419	77.6410	31±2	47±3	48±4	95±5	5.7±0.4	5.7±0.4
S12	Saulana	28.6084	77.6392	41±2	78±4	79±5	158±6	9.4±0.5	9.5±0.5
S13	Iradatpur	28.6009	77.5590	18±1	103±5	104±5	207±7	12.3±0.6	12.5±0.6
S14	Bambawar	28.6114	77.5476	17±1	46±3	47±3	93±5	5.5±0.4	5.6±0.4
S15	Pyawali Tajpur	28.6088	77.5820	53±2	42±3	43±3	85±5	5.0±0.4	5.1±0.4
S16	Akilpur Jagir	28.6150	77.5640	68±3	134±6	136±6	270±8	16.1±0.7	16.3±0.7
S17	Hasanpur Lodha	28.6354	77.5559	34±2	172±7	174±7	346±10	20.6±0.8	20.9±0.8
S18	Sidipur	28.6214	77.5934	32±2	85±5	86±5	171±7	10.2±0.6	10.4±0.6
S19	Ranoli	28.5783	77.5834	43±2	81±4	82±4	163±6	9.7±0.5	9.8±0.5
S20	Salarpur Kalan	28.5817	77.5991	35±2	107±5	109±5	216±7	12.9±0.6	13.0±0.6
S21	Muthiyani	28.5711	77.6203	21±1	88±5	90±5	178±7	10.6±0.6	10.7±0.6
S22	Rasoolpur Dasana	28.6036	77.5877	20±1	53±4	54±4	107±5	6.4±0.4	6.5±0.4
S23	Chauna	28.6328	77.5934	37±2	49±4	50±4	99±5	5.9±0.4	6.0±0.4
S24	Tatarpur	28.6267	77.6089	32±2	92±5	93±5	186±7	11.1±0.6	11.2±0.6
S25	Bisahada	28.5905	77.5705	25±2	81±4	82±4	163±6	9.7±0.5	9.8±0.5
Minimum				17±1	42±3	43±3	85±5	5.0±0.4	5.1±0.4
Maximum				68±3	172±7	174±7	346±10	20.6±0.8	20.9±0.8
Average±SD				33±13	83±32	84±33	167±65	9.9±3.9	10.1±3.9

SD, standard deviation.

recommended safe value of 100 Bql^{-1} by the EU (2001) and WHO (2008). Furthermore, the measured values in all the locations are well below the alternative maximum contamination level (148 Bql^{-1}) suggested by the EPA (1999). Our measured values are also in the range (0.07–861.5 Bql^{-1}) reported by various researchers in different parts of India. Therefore, it appears that the measured radon level in water is mainly from the geological attributes of the study region.

The mean value of the total annual effective dose due to inhalation of waterborne radon and ingestion of water is 167 μSv (0.17 mSv). This value is about 66.8% higher than the recommended RDL of 0.1 mSv from the possible total radioactive contamination of the annual drinking water consumption (WHO 2008). However, this value is only 17% of the intervention exemption level (1 mSv) recommended by the ICRP (1991). In view of this, it can be concluded that water collected from hand pumps for drinking purposes around the NTPC is safe as far as the radiological dose is concerned.

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AUTHORS' CONTRIBUTION

P.K. carried out field measurements. A.A. has prepared tables and figures. M.K. drafted the article and supervised the research and measurements. B.K.S. reviewed and edited the manuscript.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competition for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Auvinen, A., Salonen, L., Pekkanen, J., Pukkala, E., Ilus, T. & Kurttio, P. 2005 Radon and other natural radionuclides in drinking water and risk of stomach cancer: a case-cohort study in Finland. *Int. J. Cancer* **114**, 109–113. https://doi.org/10.1002/ijc.20680.

Divya, P. V. & Prakash, V. 2019 Investigation on radon concentration in drinking water to assess the whole-body dose and excess lifetime cancer risk along with coastal Kerala, India. *J. Radioanal. Nucl. Chem.* https://doi.org/10.1007/s10967-019-0658-5.

Duggal, V., Sharma, S. & Mehra, R. 2017 Radon levels in drinking water of Fatehabad district of Haryana, India. *Appl. Radiat. Isot.* **23**, 36–40. https://doi.org/10.1016/j.apradiso.2017.02.028.

Duggal, V., Sharma, S. & Mehra, R. 2020a Risk assessment of radon in drinking water in Khetri Copper Belt of Rajasthan, India. *Chemosphere* **239**, 124782. https://doi.org/10.1016/j.chemosphere.2019.124782.

Duggal, V., Sharma, S., Srivastava, A. K. & Mehra, R. 2020b Measurement of radon concentration in drinking water in Bhiwani district of Haryana. *J. Geol. Soc. India* **91**, 700–703. https://doi.org/10.1007/s12594-018-0926-6.

EPA 1999 Health risk reduction and cost analysis for radon in drinking water. *Fed. Regist.* **64** (38), 9559. Washington, DC.

EU (European Commission) 2001 Recommendation on the protection of the public against exposure to radon in drinking water supplies. *Off. J. Eur. Communities* **344**, 85–88.

EURATOM 2013 *Council Directive 2013/51/Euratom of 22 October 2013 Laying Down Requirements for the Protection of the Health of the General Public with Regard to Radioactive Substances in Water Indented for Human Consumption*.

Gaware, J. J., Sahoo, B. K., Sapra, B. K. & Mayya, Y. S. 2011 *BARC News Letter's*, Vol. 318, pp. 45–51.

Gonzalez, S. C., Gomez, D. R., Merino, I. F., Lopez, L. Q., Carreras, N. B., Castell, M. T. V., Villanueva, J. L. G. & Fernandez, C. S. 2018 A simple national intercomparison of radon in water. *Radiat. Prot. Dosim.* **181** (4), 343–349. https://doi.org/10.1093/rpd/ncy033.

IAEA (International Atomic Energy Agency) 1996 *International Basic Safety Standards for the Protection Against Ionizing Radiation and the Safety of Radiation Sources*. International Atomic Energy Agency, Vienna, Austria.

ICRP (International Commission on Radiological Protection) 1991 *1990 Recommendations. Annals of the ICRP. ICRP Publication 60*, Vol. 21, No. 1–3. Pergamon Press, Oxford.

ICRP (International Commission on Radiological Protection) 1993 *Protection Against Radon-222 at Home and Work. ICRP Publication 65. Annals of the ICRP*, Vol. 23, No. 2, Pergamon Press, Oxford. pp. 1–39.

Joshi, B. C. 2008–2009 Available from: https://cgwb.gov.in/DistrictProfile/UP/GB%2520Ngar.pdf (accessed 12 May 2021).

Kaliprasad, C. S. & Narayana, Y. 2018 Distribution of natural radionuclides and radon concentration in the riverine environs of Cauvery, South India. *J. Water Health* **16** (3), 476–486. https://doi.org/10.2166/wh.2018.242.

Kaur, M., Tripathi, P., Choudary, I., Mehra, R. & Kumar, A. 2017 Assessment of annual effective dose due to inhalation and ingestion of radon in water samples from some regions of Punjab, India. *Int. J. Pure Appl. Phys.* **13** (2), 193–200.

Kaur, M., Kumar, A., Mehra, R. & Mishra, R. 2019 Age-dependent ingestion and inhalation dose due to intake of uranium and radon in water samples of Shiwalik Himalayas of Jammu and Kashmir, India. *Environ. Monit. Assess.* **191**, 224. https://doi.org/10.1007/s10661-019-7361-z.

Kendall, G. M. & Smith, T. J. 2002 Doses to organs and tissues from radon and its decay products. *J. Radiol. Prot.* **22** (4), 389–406. https://doi.org/10.1088/0952-4746/22/4/304.

Krishna, G., Rao, M. S., Kumar, C. P. & Semwal, P. 2015 Radon concentration in groundwater of east coast of West Bengal, India. *J. Radioanal. Nucl. Chem.* **303**, 2221–2225. https:/doi.org/10.1007/s10967-014-3808-4.

Kumar, A., Kaur, M., Mehra, R., Sharma, D. K. & Mishra, R. 2017a Comparative study of radon concentration with two techniques and elemental analysis in drinking water samples of the Jammu District, Jammu and Kashmir, India. *Health Phys.* **113** (4), 271–281. https://doi.org/ 10.1097/HP.0000000000000644.

Kumar, A., Narang, S., Mehra, R. & Singh, S. 2017b Assessment of radon concentration and heavy metal contamination in groundwater samples from some areas of Fazilka district, Punjab, India. *Indoor Built Environ.* **26** (3), 368–374. https://doi.org/10.1177/1420326X15591639.

Kumar, A., Vij, R., Sarin, A. & Kanwar, P. 2017c Radon and Uranium concentration in drinking water sources along the fault line passing through Reasi district, Lesser Himalayas of Jammu and Kashmir state, India. *Hum. Ecol. Risk Assess.* https://doi.org/10.1080/10807039.2017.1336426.

Kumar, A., Sharma, S., Mehra, R., Kanwar, P., Mishra, R. & Kaur, I. 2018 Assessment of radon concentration and heavy metal contamination in groundwater of Udhampur district, Jammu and Kashmir, India. *Environ. Geochem. Health* **40** (2), 815–831. https://doi.org/10.1007/s10653-017-0027-2.

Kumar, M., Kaushal, A., Sahoo, B. K., Sarin, A., Mehra, R., Jakhu, R., Bhalla, A. & Sharma, N. 2019 Measurement of uranium and radon concentration in drinking water samples and assessment of ingestion dose to local population in Jalandhar district of Punjab, India. *Indoor Built Environ* **28** (5), 611–618. https://doi.org/10.1177/1420326X17703773.

Mittal, S., Rani, A. & Mehra, R. 2016a Estimation of radon concentration in soil and groundwater samples of Northern Rajasthan, India. *J. Radiat. Res. Appl. Sci.* **9** (2), 125–130. https://doi.org/10.1016/j.jrras.2015.10.006.

Mittal, S., Rani, A. & Mehra, R. 2016b Radon levels in drinking water and soil samples of Jodhpur and Nagaur districts of Rajasthan, India. *Appl. Radiat. Isot.* **13**, 53–59. https://doi.org/10.1016/j.apradiso.2016.04.017.

Moreno, V., Bach, J., Baixeras, C. & Font, L. 2014 Radon levels in groundwater and natural radioactivity in soils of the volcanic region of La Garrotxa, Spain. *J. Environ. Radioact.* **128**, 1–8. https://dx.doi.org/10.1016/j.jenvrad.2013.10.021.

Nandakumaran, P., Vinayachandran, N., AnithaShyam, T. S., Jose, B., Sreehari, S. M. S. & Santhana, S. M. 2016 Radon in groundwater in parts of coastal tracts of southern Kerala, India. *J. Radioanal. Nucl. Chem.* **308**, 99–104. https://doi.org/10.1007/s10967-015-4272-5.

Niranjan, R. S., Ningappa, C., Yashaswini, T., Chamaraja, N. A., Rangaswamy, D. R. & Sannappa, J. 2017 Study of radon in drinking water around Hemavathi river basin, Karnataka State, India. *J. Radioanal. Nucl. Chem.* **314**, 321–331. https://doi.org/10.1007/s10967-017-5432-6.

NRC (National Research Council) 1999 *Committee on Risk Assessment of Exposure to Radon in Drinking Water*. National Academy Press (US), Washington DC.

Panghal, A., Kumar, A., Kumar, S., Singh, J., Sharma, S., Singh, P., Mehra, R. & Bajwa, B. S. 2017 Radiation dose-dependent risk on individuals due to ingestion of uranium and radon concentration in drinking water samples of four districts of Haryana, India. *Radiat. Eff. Defects Solids* **172** (5–6), 441–455. https://doi.org/10.1080/10420150.2017.1336762.

Pant, D., Keesari, T., Rishi, M., Sharma, D. A., Thakur, N., Singh, G., Sangwan, P., Jaryal, A., Sinha, U. K. & Tripathi, R. 2020 Spatiotemporal distribution of dissolved radon in uranium impacted aquifers of southwest Punjab. *J. Radioanal. Nucl. Chem.* **323**, 1237–1249. https://doi.org/10.1007/s10967-019-06656-w.

Prasad, M., Anil, K. G., Sahoo, B. K. & Ramola, R. C. 2018 A comprehensive study of radon levels and associated radiation dose in Himalayan groundwater. *Acta Geophys.* **66**, 1223–1231. https://doi.org/10.1007/s11600-018-0135-0.

Rangaswamy, D. R., Srinivasa, E., Srilatha, M. C. & Sannappa, J. 2016 Measurement of radon concentration in drinking water of Shimoga district, Karnataka, India. *J. Radioanal. Nucl. Chem.* **307**, 907–916. https://doi.org/10.1007/s10967-015-4216-0.

Raste, P. M., Sahoo, B. K., Gaware, J. J., Sharma, A., Waikar, M. R., Shaikh, A. A. & Sonkawade, R. G. 2018 Assessment of radon in soil and water in different regions of Kolhapur district, Maharashtra, India. *Radiat. Prot. Dosim.* **181** (4), 382–387. https://doi.org/10.1093/rpd/ncy039.

Reddy, U. K., Ningappa, C., Sannappa, J., Rangaswamy, D. R. & Srinivasa, E. 2017 Concentration of radon and physicochemical parameters in groundwater around Kolar fields, Karnataka state, India. *J. Radioanal. Nucl. Chem.* **314**, 907–915. https://doi.org/10.1007/s10967-017-5492-7.

Sannappa, J., Suresh, S., Rangaswamy, D. R. & Srinivasa, E. 2020 Estimation of ambient gamma radiation dose and drinking water radon concentration in coastal taluks of Uttara Kannada district, Karnataka. *J. Radioanal. Nucl. Chem.* **323**, 1459–1466. https://doi.org/10.1007/s10967-019-06812-2.

Sharma, S., Duggal, V., Srivastava, A. K. & Mehra, R. 2017a Assessment of radiation dose from exposure to radon in drinking water from Western Haryana, India. *Int. J. Environ. Res.* **11**, 141–147. https://doi.org/10.1007/s41742-017-0015-5.

Sharma, S., Duggal, V., Srivastava, A. K., Mehra, R. & Rani, A. 2017b Radon concentration in groundwater and associated effective dose assessment in Western Haryana, India. *Int. J. Innovative Res. Sci. Eng. Technol.* **3** (3), 69–78.

Sharma, S., Kumar, A., Mehra, R. & Kaur, R. 2019 Ingestion and inhalation dose to intake of radon in drinking water samples of Amritsar Province, Punjab, India. *Radiat. Prot. Dosim.* **187** (2), 230–242. https://doi.org/10.1093/rpd/ncz157.

Sharma, D. A., Keesari, T., Rishi, M., Thakur, N., Pant, D., Mohokar, H. V., Jaryal, A., Kamble, S. N. & Sinha, U. K. 2020 Radiological and hydrological implications of dissolved radon in alluvial aquifers of western India. *J. Radioanal. Nucl. Chem.* **323**, 1257–1267. https://doi.org/10.1007/s10967-019-06619-1.

Shilpa, G. M., Anandaram, B. N. & Mohankumari, T. L. 2017 Measurement of ^{222}rn concentration in drinking water in the environs of Thirthahalli taluk, Karnataka, India. *J. Radiat. Res. Appl. Sci.* **10** (3), 262–268. https://doi.org/10.1016/j.jrras.2017.05.007.

Singaraja, C., Chidambaram, S., Jacob, N., Selvam, S., Johnsonbabu, G. & Anandhan, P. 2016 Radon levels in groundwater in the Tuticorin district of Tamil Nadu, South India. *J. Radioanal. Nucl. Chem.* **307**, 1165–1173. https://doi.org/10.1007/s10967-015-4312-1.

Singh, P., Singh, P., Sahoo, B. K. & Bajwa, B. S. 2016 A study on uranium and radon levels in drinking water sources of a mineralized zone of Himachal Pradesh, India. *J. Radioanal. Nucl. Chem.* **309**, 541–549. https://doi.org/10.1007/s10967-015-4629-9.

Singh, B., Kant, K., Garg, M., Singh, A., Sahoo, B. K. & Sapra, B. K. 2019 A comparative study of radon levels in underground and surface water samples of Faridabad district of Southern Haryana, India. *J. Radioanal. Nucl. Chem.* **319**, 907–916. https://doi.org/10.1007/s10967-018-6384-1.

Srinivasa, E., Rangaswamy, D. R. & Sannappa, J. 2015 Determination of radon activity concentration in drinking water and evaluation of the annual effective dose in Hassan district, Karnataka state, India. *J. Radioanal. Nucl. Chem.* **305**, 665–673. https://doi.org/10.1007/s10967-015-4034-4.

Srinivasa, E., Rangaswamy, D. R., Suresh, S., Reddy, K. U. & Sannappa, J. 2018 Measurement of ambient gamma radiation levels and radon concentration in drinking water of Koppa and Narasimharajapura taluks of Chikmagalur district, Karnataka, India. *Radiat. Prot. Environ.* **41** (1), 20–25. https://doi.org/10.4103/rpe.RPE_15_18.

Srinivasa, E., Rangaswamy, D. R. & Sannappa, J. 2019 Measurement of radon concentration and evaluation of total dose in drinking water of Chikmagalur city, Karnataka. *J. Geol. Soc. India* **94**, 100–104. https://doi.org/10.1007/s12594-019-1273-y.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000 *Sources and Effects Ionizing Radiation, Report to General Assembly with Scientific Annexes, Annex B, Exposure From Natural Sources of Radiation*. United Nations, New York.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2008 *Sources and Effects Ionizing Radiation, Exposure From Natural Sources of Radiation. Report to General Assembly with Scientific Annexes*, Vol. 1. United Nations, New York.

US NAS (the United States, National Academy of Sciences) 1999 *Risk Assessment of Radon in Drinking Water, Committee on Risk Assessment of Exposure to Radon in Drinking Water*. National Academy Press, Washington DC.

WHO (World Health Organization) 2008 *Guidelines for Drinking-Water Quality, the Third Edition Incorporating the First and Second Addenda, Vol. 1 Recommendations*, 3rd edn. World Health Organization, Geneva, Switzerland.

WHO (World Health Organization) 2017 *Guidelines for Drinking-Water Quality, the Fourth Edition Incorporating the First Addenda*. World Health Organization, Geneva, Switzerland.

Yashaswini, T., Ningappa, C., Niranjan, R. S. & Sannappa, J. 2020 Radon concentration level in ground and drinking water around Kabini river basin, Karnataka. *J. Geol. Sco. India* **95**, 273–278. https://doi.org/10.1007/s12594-020-1425-0.

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