

Evaluation of Radon (^{222}Rn) Concentration in Drinking Water and Its Radiological Health Implications in Hirehalli Industrial Area, Tumkur, Karnataka, India

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Abstract: Radon-222 (^{222}Rn) in groundwater is an important source of natural radiation exposure, particularly in regions underlain by crystalline rocks. This study investigates dissolved ^{222}Rn activity concentrations in drinking-water sources and the associated radiological exposure in the Hirehalli Industrial Area, Tumakuru, Karnataka, India. Water samples were collected from 15 representative locations and analysed using an emanometry technique coupled with a Lucas scintillation cell. The measured ^{222}Rn activity concentrations ranged from 10.91 to 36.71 Bq L⁻¹, with an arithmetic mean of 21.82 ± 6.88 Bq L⁻¹ and a geometric mean of 20.82 Bq L⁻¹. All measured concentrations were below the 100 Bq L⁻¹ parametric value specified in the European drinking-water framework, although 14 of the 15 locations exceeded 11.1 Bq L⁻¹, corresponding to 300 pCi L⁻¹ used in the U.S. Environmental Protection Agency's proposed radon-in-drinking-water rule. Annual effective doses due to inhalation of radon released from water and direct ingestion were estimated using UNSCEAR-based parameters. The inhalation dose ranged from 27.52 to 92.40 $\mu\text{Sv y}^{-1}$, whereas the ingestion dose ranged from 2.30 to 7.68 $\mu\text{Sv y}^{-1}$. The combined annual effective dose ranged from 29.83 to 100.85 $\mu\text{Sv y}^{-1}$, with a mean of 59.60 ± 18.89 $\mu\text{Sv y}^{-1}$. Inhalation accounted for approximately 92.2% of the mean total effective dose, indicating that radon transferred from water to indoor air is the dominant exposure pathway in the adopted assessment. The highest ^{222}Rn concentration and total dose were observed at location L11. Overall, the measured concentrations were below the 100 Bq L⁻¹ screening value considered in the European regulatory framework. Periodic monitoring, particularly at comparatively elevated locations, together with seasonal sampling and complementary measurements of ^{226}Ra , uranium, hydrochemical parameters and indoor-air radon, is recommended to improve assessment of radiological exposure and source attribution.

Keywords: Radon-222; drinking water; groundwater; Lucas scintillation cell; radiological assessment; annual effective dose; Hirehalli Industrial Area

1. Introduction

Natural background radiation is an inherent component of the environment and originates from cosmic and terrestrial sources. Naturally occurring radionuclides in rocks, soils, air and water contribute to human radiation exposure. Among these radionuclides, uranium-238 (^{238}U), thorium-232 (^{232}Th) and their decay products are particularly important because they can be mobilized from geological materials and transported through environmental pathways [1–3].

Radon-222 (^{222}Rn) is a radioactive, chemically inert noble gas produced by the decay of radium-226 (^{226}Ra) in the ^{238}U decay series. Owing to its gaseous nature and mobility, radon can migrate through pores and fractures and can occur in groundwater, particularly in regions underlain by uranium-bearing crystalline rocks. Dissolved radon in groundwater can contribute to radiation exposure through direct ingestion and through transfer from water to indoor air during domestic use [1–3].

The concentration of radon in groundwater is influenced by geological, hydrogeological and geochemical factors, including uranium content and mineralogical composition of host rocks, weathering, fracturing, permeability, groundwater residence time, recharge characteristics and

rock–water interaction. Groundwater circulating through weathered and fractured crystalline formations can enhance interaction with mineral surfaces and facilitate transport of uranium-series decay products into the aqueous phase. Consequently, radon measurements in groundwater provide useful information for assessing radiological exposure and water–rock interaction.

The radiological significance of radon is mainly associated with its short-lived progeny, which emit alpha particles and can produce localized irradiation following inhalation. Although indoor-air exposure is generally the dominant pathway, drinking water can also contribute to radiation dose through ingestion and through the release of dissolved radon into indoor air during domestic water use [1–3]. Assessment of radon in drinking-water sources is therefore relevant in regions where groundwater is widely used for domestic purposes.

Karnataka contains extensive Precambrian crystalline formations associated with the Dharwar Craton, including granitic, gneissic and other metamorphic rocks. Tumakuru District forms part of this crystalline geological environment, where groundwater commonly occurs in weathered and fractured hard-rock formations. These conditions provide a suitable setting for investigating naturally occurring radionuclides in groundwater, while

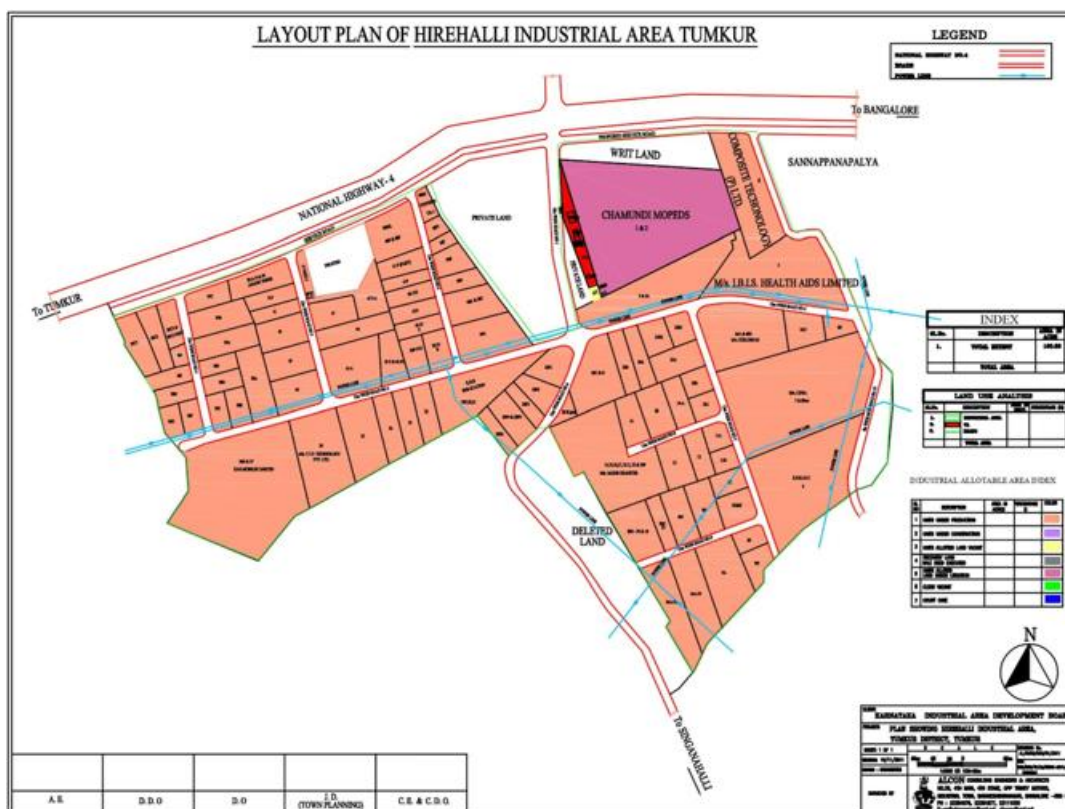
variations in lithology, mineral composition, fracture characteristics, groundwater movement and recharge may produce spatial differences in radon concentration.

Hirehalli Industrial Area in Tumakuru District is an established industrial and manufacturing region along the Bengaluru–Tumakuru corridor. The area includes electrical and electronic equipment manufacturing, automobile and automobile-component production, machinery and machine-component manufacturing, metal fabrication, precision engineering and general engineering activities. Groundwater is used for domestic and industrial purposes in the area and surrounding settlements, making its radiological quality an important environmental consideration. However, site-specific information on radon concentrations in drinking water from Hirehalli Industrial Area is limited.

The present study therefore aims to determine the activity concentration of dissolved ^{222}Rn in drinking-water sources at representative locations in the Hirehalli Industrial Area and to estimate the associated annual effective doses through inhalation and ingestion pathways. The study also evaluates the spatial variation of radon concentrations and discusses the implications for radiological monitoring.

Study area

Hirehalli Industrial Area is located in Tumakuru District, Karnataka, India, along the Bengaluru–Tumakuru corridor. The area is connected by major road and railway networks and supports a range of industrial activities, including electrical and electronic equipment manufacturing, automobile and automobile-component production, machinery and machine-component manufacturing, metal fabrication, precision engineering and general engineering.



The regional geological setting belongs to the Precambrian crystalline terrain of the Dharwar Craton. The geological framework is characterized predominantly by crystalline basement rocks, including granites and gneisses, together with granodioritic, tonalitic, amphibolitic, migmatitic, metabasic and schistose units. Weathering, jointing and fracturing strongly influence groundwater occurrence, recharge and movement in this hard-rock terrain. These geological characteristics are relevant to naturally occurring radionuclides because granitic and gneissic rocks may contain uranium- and thorium-bearing minerals [1,10].

The dependence of nearby settlements on groundwater and the presence of extensive industrial activity make Hirehalli an appropriate location for an environmental radiological investigation. Spatial differences in groundwater flow, recharge, water–rock interaction and lithology may contribute to variations in dissolved radon activity.

2. Materials and Methods

2.1 Sampling and radon measurement

Drinking-water samples were collected from representative locations within the Hirehalli Industrial Area. The final dataset comprised 15 sampling locations (L1–L15), with four replicate measurements used to obtain representative concentrations at each location. Approximately 500 mL of water was collected in airtight polyethylene bottles, with care taken to minimize headspace and air bubbles. Samples were immediately sealed, labelled and transported to the laboratory and analysed within 24 h to minimize radon loss through radioactive decay [4,5].

Radon was extracted by an emanometry procedure using a PSI-RBS-1 radon bubbler coupled to a Lucas scintillation cell and photomultiplier-tube alpha-counting system.

Approximately 70 mL of water was introduced into the bubbler, and air was circulated through the sample to transfer dissolved radon into an evacuated Lucas cell. The cell was then sealed and allowed to approach equilibrium with the short-lived radon progeny for approximately 3 h before counting. Alpha counts were recorded for 17 min and corrected for background. The activity concentration was calculated using the calibrated Lucas-cell/emanometry relationship [4,5].

2.2 Determination of ^{222}Rn activity concentration

The activity concentration of ^{222}Rn in water was calculated from the measured alpha counts using the following emanometry expression:

$$C_{\text{Rn,w}} = [6.97 \times 10^2 \times N] / [E \times V \times (1 - e^{-\lambda T'}) \times e^{-\lambda T}]$$

where $C_{\text{Rn,w}}$ is the ^{222}Rn activity concentration in water (Bq L^{-1}), N is the net count rate after background correction, E is the counting efficiency of the Lucas scintillation cell (0.74), V is the water volume in the bubbler (L), λ is the decay constant of ^{222}Rn ($2.098 \times 10^{-6} \text{ s}^{-1}$), T' is the ingrowth/equilibration time in the Lucas cell, and T is the elapsed time between sample collection and measurement. The adopted approach follows established emanometry procedures for radon determination in water [4,5].

2.3 Estimation of annual effective dose

Annual effective doses associated with radon released from drinking water were estimated for the inhalation and ingestion pathways using the parameter set adopted from UNSCEAR-based calculations [1,6].

$$E_{\text{inh}} = C_w \times R_{\text{aw}} \times F \times O \times \text{DCF}$$

where E_{inh} is the annual effective inhalation dose ($\mu\text{Sv y}^{-1}$), C_w is the ^{222}Rn concentration in water (Bq L^{-1}), R_{aw} is the air-to-water transfer ratio (10^{-4}), F is the equilibrium factor between radon and its progeny (0.4), O is the annual indoor occupancy time (7000 h y^{-1}), and DCF is the dose conversion factor for radon exposure ($9 \text{ nSv [Bq h m}^{-3}\text{]}^{-1}$) [1,6].

$$E_{\text{ing}} = C_w \times V_w \times \text{DCF}_{\text{ing}}$$

where E_{ing} is the annual effective ingestion dose ($\mu\text{Sv y}^{-1}$), C_w is the ^{222}Rn concentration in water (Bq L^{-1}), V_w is the weighted annual direct tap-water consumption (60 L y^{-1}), and DCF_{ing} is the effective dose coefficient for ingestion of ^{222}Rn (3.5 nSv Bq^{-1}) [6,7]. The 60 L y^{-1} value represents direct consumption of tap water in the adopted radon-in-water assessment rather than total daily water intake [1,6].

$$E_{\text{total}} = E_{\text{inh}} + E_{\text{ing}}$$

For the tissue-weighted contributions reported in the manuscript, a tissue weighting factor of $w_T = 0.12$ was applied to the corresponding pathway effective dose [8]. These values are presented as tissue-weighted contributions and are not interpreted as equivalent organ doses.

$$ET = w_T \times E_{\text{pathway}}$$

3. Results and Discussion

3.1 Spatial distribution of ^{222}Rn

The measured activity concentrations of dissolved ^{222}Rn at the 15 sampling locations showed appreciable spatial variability. Concentrations ranged from 10.91 Bq L^{-1} at L5 to 36.71 Bq L^{-1} at L11, with an arithmetic mean of $21.82 \pm 6.88 \text{ Bq L}^{-1}$ and a geometric mean of 20.82 Bq L^{-1} . All measured concentrations were below 100 Bq L^{-1} , the parametric value specified for radon in water under the European drinking-water framework [9]. However, 14 of the 15 locations (93.3%) were above 11.1 Bq L^{-1} , corresponding to 300 pCi L^{-1} used in the U.S. Environmental Protection Agency's 1999 proposed radon-in-drinking-water rule [10]. This comparison should be interpreted cautiously because the U.S. value was a proposed regulatory level rather than a universal international health-based guideline.

The observed spatial variability is plausibly associated with local hydrogeological conditions. Hirehalli is underlain by crystalline rocks in which weathering, jointing, fracturing and water-rock interaction can influence the mobilization and transport of uranium-series radionuclides. Similar spatial variability has been reported in other groundwater systems in Karnataka and has been related to local lithology and hydrogeological conditions [11]. Because ^{226}Ra and uranium were not measured in the same water samples in the present study, the geological interpretation should be regarded as a plausible mechanism rather than demonstrated source attribution.

3.2 Dose assessment and pathway distribution

Radiation exposure from radon in drinking water was evaluated through two pathways: inhalation of radon released from water during domestic use and direct ingestion of water. The annual effective inhalation dose ranged from $27.52 \mu\text{Sv y}^{-1}$ at L5 to $92.40 \mu\text{Sv y}^{-1}$ at L11, with a mean of $54.97 \pm 17.32 \mu\text{Sv y}^{-1}$. Inhalation accounted for approximately 92.2% of the mean total effective dose. The corresponding lung tissue-weighted contribution ranged from 3.30 to $11.06 \mu\text{Sv y}^{-1}$, with a mean of $6.60 \pm 2.07 \mu\text{Sv y}^{-1}$.

The annual effective ingestion dose ranged from $2.30 \mu\text{Sv y}^{-1}$ at L5 to $7.68 \mu\text{Sv y}^{-1}$ at L11, with a mean of $4.58 \pm 1.45 \mu\text{Sv y}^{-1}$. The corresponding stomach tissue-weighted contribution ranged from 0.37 to $0.91 \mu\text{Sv y}^{-1}$, with a mean of $0.58 \pm 0.14 \mu\text{Sv y}^{-1}$. These results indicate that inhalation of radon released from water during domestic use is the dominant exposure pathway in the adopted assessment, consistent with the general observation that transfer of radon from water to indoor air can contribute more to dose than direct ingestion [2,3,7].

The combined annual effective dose ranged from $29.83 \mu\text{Sv y}^{-1}$ at L5 to $100.85 \mu\text{Sv y}^{-1}$ at L11, with a mean of $59.60 \pm 18.89 \mu\text{Sv y}^{-1}$. The highest total dose occurred at L11, which also had the highest measured radon concentration. The approximately linear relationship between concentration and

calculated dose indicates that spatial differences in radon activity are the primary driver of dose variation in the present dataset.

Table 1: Summary statistics of ^{222}Rn activity concentration and associated annual effective doses

Parameter / exposure pathway	Minimum	Maximum	Arithmetic mean $\pm$ SD	Geometric mean
^{222}Rn activity (Bq L^{-1})	10.91	36.71	21.82 ± 6.88	20.82
Inhalation dose ($\mu\text{Sv y}^{-1}$)	27.52	92.40	54.97 ± 17.32	52.43
Lung tissue-weighted contribution ($\mu\text{Sv y}^{-1}$)	3.30	11.06	6.60 ± 2.07	6.30
Ingestion dose ($\mu\text{Sv y}^{-1}$)	2.30	7.68	4.58 ± 1.45	4.37
Stomach tissue-weighted contribution ($\mu\text{Sv y}^{-1}$)	0.37	0.91	0.58 ± 0.14	0.56
Total effective dose ($\mu\text{Sv y}^{-1}$)	29.83	100.85	59.60 ± 18.89	56.82

3.3 Radiological significance and monitoring implications

All 15 radon concentrations were below 100 Bq L^{-1} , the parametric value specified in the European framework for radon in water intended for human consumption [9]. At the same time, 14 locations exceeded 11.1 Bq L^{-1} , the value equivalent to 300 pCi L^{-1} used in the U.S. Environmental Protection Agency's 1999 proposed rule [10]. The coexistence of different reference values illustrates that radon-in-water screening criteria are jurisdiction-specific and should not be treated as interchangeable health thresholds. WHO guidance emphasizes that radon in drinking water is generally a smaller source of exposure than indoor-air radon and recommends that screening approaches be linked to national radon reference levels and local conditions [2,3].

The calculated total doses are relatively low in absolute terms; however, the comparatively elevated concentrations at L7 and L11 justify periodic follow-up measurements,

particularly where groundwater is used continuously for domestic purposes. Where waterborne radon is confirmed to be elevated, mitigation can include aeration or granular activated-carbon treatment, while adequate indoor ventilation can reduce accumulation of radon released during water use [2,3].

The present assessment is based on a limited number of sampling locations and a single monitoring period. Additional seasonal measurements would therefore improve evaluation of temporal variability. A further limitation is that ^{226}Ra , uranium, water chemistry and indoor-air radon were not simultaneously quantified. Consequently, the mechanisms responsible for site-to-site differences cannot be established solely from the present dataset. Future investigations should integrate groundwater chemistry, hydrogeological parameters, ^{226}Ra /uranium measurements and indoor-air radon monitoring to strengthen source attribution and refine dose assessment.

Table 2: Location-wise ^{222}Rn activity concentration and calculated annual effective dose components

Location	^{222}Rn (Bq L^{-1})	Inhalation ($\mu\text{Sv y}^{-1}$)	Lung contribution ($\mu\text{Sv y}^{-1}$)	Ingestion ($\mu\text{Sv y}^{-1}$)	Stomach contribution ($\mu\text{Sv y}^{-1}$)	Total ($\mu\text{Sv y}^{-1}$)
L1	20.17	50.84	6.10	4.24	0.52	55.06
L2	25.36	63.95	7.67	5.33	0.65	69.27
L3	26.44	66.42	7.97	5.55	0.74	71.96
L4	18.74	47.20	5.67	3.94	0.55	51.13
L5	10.91	27.52	3.30	2.30	0.45	29.83
L6	11.74	29.17	3.62	2.43	0.37	31.60
L7	33.60	84.61	10.17	7.09	0.79	91.70
L8	17.87	45.35	5.43	3.77	0.46	49.13
L9	20.72	52.21	6.25	4.36	0.53	56.55
L10	22.58	57.09	6.84	4.77	0.58	61.86
L11	36.71	92.40	11.06	7.68	0.91	100.85
L12	19.79	49.80	5.97	4.16	0.53	53.95
L13	23.17	58.51	7.02	4.89	0.63	63.38
L14	20.94	52.60	6.31	4.38	0.52	56.98
L15	18.56	46.88	5.62	3.92	0.46	50.77
Maximum	36.71	92.40	11.06	7.68	0.91	100.85
Minimum	10.91	27.52	3.30	2.30	0.37	29.83
Average	21.82	54.97	6.60	4.58	0.58	59.60
Geometric mean	20.82	52.43	6.30	4.37	0.56	56.82
SD	6.88	17.32	2.07	1.45	0.14	18.89

4. Conclusions

The present study assessed dissolved ^{222}Rn in drinking-water sources from the Hirehalli Industrial Area, Tumakuru, Karnataka, using a Lucas scintillation-cell emanometry method. Radon activity concentrations at 15 locations ranged from 10.91 to 36.71 Bq L^{-1} , with an arithmetic mean of $21.82 \pm 6.88 \text{ Bq L}^{-1}$. All measured concentrations were

below the 100 Bq L^{-1} parametric value specified in the European drinking-water framework, although 14 of the 15 locations exceeded 11.1 Bq L^{-1} , corresponding to the 300 pCi L^{-1} level used in the U.S. EPA's proposed radon-in-drinking-water rule.

The estimated annual effective dose ranged from 29.83 to $100.85 \mu\text{Sv y}^{-1}$, with a mean of $59.60 \pm 18.89 \mu\text{Sv y}^{-1}$.

Approximately 92.2% of the mean total effective dose was associated with inhalation of radon released from water, while the contribution from direct ingestion was substantially smaller. The highest ^{222}Rn concentration and total calculated dose occurred at L11, followed by comparatively elevated values at L7.

Overall, the measured concentrations do not indicate values above the 100 Bq L^{-1} screening value considered in the European regulatory framework. Nevertheless, periodic monitoring is warranted at comparatively elevated locations, particularly where groundwater is used for domestic purposes. Seasonal sampling combined with measurements of ^{226}Ra , uranium, hydrochemical parameters and indoor-air radon would help clarify the controls on radon occurrence, improve source attribution and refine the assessment of radiological exposure.

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