Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Radon and Thoron Exhalation from Soil ground water and Non-Ground water Zones and Building Materials in Pune City

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Abstract:

Radon and thoron are naturally occurring radioactive gases released from soil and building materials, and they contribute significantly to indoor radiation exposure. The present study investigates the radon and thoron exhalation rates from soil samples collected from ground water (GW) and non-ground water (NGW) zones of Pune City, along with commonly used building materials. Measurements were carried out to understand how geological conditions and moisture availability influence the release of these gases. Results indicate that soil from GW zones generally shows higher exhalation rates compared to NGW zones, likely due to increased moisture content and enhanced radium mobility. Building materials also exhibited varying levels of radon and thoron release depending on their composition and origin. The findings highlight the importance of monitoring radon and thoron emissions in both soil and construction materials, as they play a key role in assessing environmental radiation risk and ensuring safer living conditions in urban areas like Pune

.**Keywords: Radon, Thoron, Ground water, Non-Ground water, Building materials.**

1.1 Introduction

The primary source of natural radioactivity, which is a fundamental aspect of the Earth's environment, is primordial radionuclides like uranium (238U), thorium (232Th), and potassium (40K), which are found in soil, rocks, groundwater, and construction materials. The background radiation dose that human populations receive is largely influenced by these radionuclides and the byproducts of their disintegration. As radioactive noble gases, radon (222Rn) and thoron (220Rn) are the most common ones that cause internal radiation exposure through breathing. (Amanjeet et al., 2017; Lamarsh, 1983; Sing et al., 2017; Sannappa et al. 2003; Ridvan et al.,2011; Ramola et al., 2008; Tzortzis et al., 2004; Chiozzi et al., 2002; Arafa, 2004).

The earth's crust and geological formations are the usual origins of the majority of natural resources used as building materials, including sand, soil, cement, bricks, and rocks. Naturally occurring radioactive materials (NORMs) are frequently present in these materials in different amounts. Regional geology, mineral composition, and geological processes all have a significant impact on the radionuclide content of building materials (Raste et al., 2018; Sharma et al., 2015; Semwal et al., 2018). The use of waste materials and industrial byproducts including fly ash, phosphogypsum, and slag in the building sector in recent decades may have increased radioactivity levels above natural background levels (Rafat, 2015).

Genetic damage and cancer are among the serious health concerns associated with prolonged exposure to low doses of ionizing radiation (UNSCEAR, 2000). The research of alpha-emitting radionuclides is especially relevant because, even though alpha radiation has a modest penetrating strength, it is roughly 1000 times more harmful to the body when ingested than gamma radiation (Ghosh et al., 2008). The need for systematic evaluation of natural radioactivity and radon/thoron release from soil and building materials is highlighted by the fact that people spend almost 85% of their time indoors, making them a constant and inevitable source of radiation exposure (Stoulos et al., 2003; Zikovsky et al., 1992).

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Received: 25th May, 2026; Revised: 6th June, 2026; Accepted: 8th June, 2026; Available Online: 29rd July, 2026

(DOI): 10.70102/AEJ.2026.18.2s.27

1.2 Radon and Thoron: Sources and Characteristics

With a half-life of 3.82 days, radon (222Rn) is a radioactive noble gas created during the uranium decay cycle by the decay of 226Ra. Radon can travel great distances from its source through groundwater, soil pores, and fractures before accessing the atmosphere or indoor spaces because of its comparatively prolonged half-life (Rawat et al., 1991). In contrast, Thoron (220Rn) has a substantially shorter half-life of 55.6 seconds and comes from the thorium decay chain via 224Ra. Because thoron migration is restricted to areas near its source, surface and near-surface soil properties have a significant impact on its exhalation (Nazaroff et al., 1988; Lara et al., 2015; UNSCAR, 2000).

After smoking, radon is the second most common cause of lung cancer. Inhaling radon and its short-lived byproducts has been definitively linked to an elevated risk of lung cancer (Darby et al., 2004). Also, sometimes it effects on the plants and animals present in that area (IH Attitalla., 2024). Although they have historically gotten less attention because of measurement issues, thorium and its offspring also contribute to radiation exposure, especially in areas with significant thorium content (Ramola, 2008; Che et al., 2010; Aswal, 2016; Bourai, 2016; Singh, 2016).

2.0 Methodology

2.1 Site and Sample Collection

The study was carried out in India's Pune City. After being divided into GW and NGW zones, eleven locations were chosen for soil sampling (Photo 1). 22 soil samples in all were taken from these sites. Samples of building materials were gathered from ongoing construction projects around the research region. Among the materials were brick, rock, sand, and cement. Ten samples in all—four cement samples, two brick samples, one rock sample, and three sand samples—were gathered in order to evaluate their role in indoor radon exposure and ambient radioactivity.

Measurements were carried out using the AQTEK Systems Smart RnDuo Portable Radon Monitor.

Photo 1: AQTEK Systems Smart RnDuo Portable Radon Monitor

2.2 Experimental details

2.2.1 Measurement of exhalation rate of ^{222}Rn (Radon):

In the current study, the radon content and exhalation rate in soil and construction materials were measured using the active device AQTEK SMART RnDuo (Photo 1). A portable, commercially accessible device called the SMART RnDuo can identify alpha, 220, and 222Rn radiation in soil, construction materials, and the air. The SMART RnDuo instrument's fundamental function is to use ZnS:Ag scintillation to detect alpha particles. Additional information about the measurement procedures and acquisition strategy can be found elsewhere (Gaware et al. 2011). For the mass exhalation rate of 222Rn and concentration, samples of commonly used building materials (~ 1000 g) such as rock, soil, sand, and different types of cement are acquired from nearby markets, construction sites, and hardware stores. The sample is ground into a fine powder using a vibrating ball machine or a mortar and pestle. A finely ground object is put in the breathing chamber to test for radon. A closed accumulation chamber with a sample capacity of about 500 g is connected to the Smart RnDuo (Figure 1a). The chamber is composed of 8 cm high by 10 cm wide stainless-steel cylinders that are attached to a photomultiplier tube and a Lucas cell at the top. The SMART Duo was utilized in diffusion mode at 222Rn (if available in samples) to prevent 222Rn interruptions. After an hour, the compartment's 222Rn concentration was monitored and kept going until it reached saturation. Analysis was done on the alpha radiation concentration and 222Rn concentration data displayed against the amount of time that had passed. The accumulator chamber's radon growth over time is shown in Bq.m-³ (Aldenkamp et al., 1992).

$$C_{(t)} = \frac{J_m M}{V\lambda}(1-e^{-\lambda t}) + C_0 e^{-\lambda t} \quad -----(1)$$

Where $C_{(t)}$ is ^{222}Rn concentration (Bqm^{-3}) at time t Bqm^{-3}

$$J_m = {}^{222}Rn \ \ mass\ exhalation\ rate\ (Bq/Kg/h)$$

$$\lambda = effective\ decay\ const(h^{-1})$$

C_0 = ^{222}Rn concentration (Bqm^{-3}) present in the chamber volume at t=0

M = mass the dry sample (Kg)

V= Volume of accumulator chamber and scintillation cell volume (volume of detector + porous volume of sample +residual air volume of the mass exhalation chamber) (m^{-3})

The porous volume (Vp) can be estimated using the following equation

$$V_p = V_s - \frac{M}{\rho_g} \text{------(2)}$$

V_s is the sample volume in the mass exhalation chamber

ρ_g is the specific gravity of the sample, which can be taken as 2.7 gm/cc for clay type soil sample.

2.2.2 Radon mass exhalation rate can be calculated by the formula

$$J_m = \frac{BV}{M} \text{----(3)}$$

Where J_m=Radon (^{222}Rn) mass exhalation rate

B=Slop of the linear fit graph of radon concentration (Bqm^{-3}) vs. time (hr)

V=Effective volume, M=Total mass of the dry sample

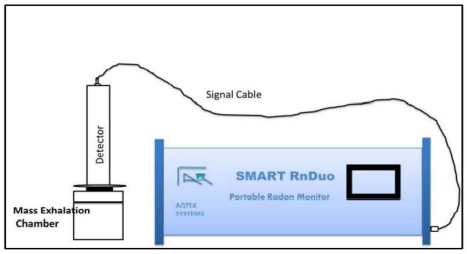

Figure 1 a): Set-up for radon mass exhalation rates measurement
(Diffusion mode) in soil samples

2.2.3 Thoron (^{220}Rn) surface exhalation rate:

A flow-mode sample that is attached to a pump inlet of the monitor is used in a program-based sampling procedure for 220Rn monitoring by SMART RnDuo. The 220Rn surface exhalation rate is measured using the flow mode sampling type. because 220Rn has a half-life of 55 seconds. Therefore, 220Rn decays in the soil chamber before it reaches the scintillation detector. To get all 220Rn into the scintillation detector, a pump is used with flow mode in this case. As seen in figure 5.1, the airflow pump connects the exhalation chamber to a scintillation 220Rn monitor, creating a closed-circuit loop. The measurement cycle lasts roughly fifteen minutes. In a 15-minute cycle, the sampling pump is run for 5 minutes to provide a measure of background and 220Rn, then for 5 minutes to guarantee that 220Rn decays almost completely, and finally for 5 minutes to count the background counts for that cycle. The equation provides the 220Rn surface exhalation rate at equilibrium.

$$J_s = \frac{C_{eq} V \lambda}{A} \text{\_\_\_\_\_(4)}$$

Where C_{eq} is equilibrium 220Rn concentration (Bqm^{-3})

λ is the 220Rn decay constant (0.0126s^{-1})

V is the sum of the residual volume of the mass exhalation chamber and the internal volume of the RnDuo detector and tubing volumes (m^3)

A is the surface area (m^2) of the sample emitting 220Rn.

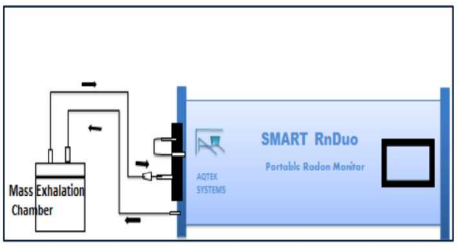

Figure 1.b) Set-up for thoron surface exhalation rate measurement (flow mode) in soil samples.

2.2.4: Alpha radiation (in air) measurement

The AQTEK SMART RnDuo detector was used to measure alpha radiation in the air over GW and NGW locations. After being positioned in the chosen location (over GW and NGW areas), the instrument was left to stabilize. Alpha particles released by radon and thoron progeny were recorded in the detection chamber, which was continually sampled with air. The average alpha activity concentration was calculated from the recorded data after measurements were made for a predetermined amount of time (only one to six minutes) under controlled circumstances.

3.1 Result and Discussion

3.1.1 Soil samples: The findings from soil samples taken from the study region are shown in this section. Graphical depictions of the measured radon and thoron concentrations and alpha activity levels are used to show how they vary geographically throughout the study area. As indicated in Table No. 2, the research area's findings have been compared to those of related studies conducted in other parts of India.

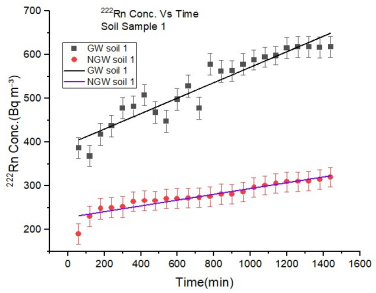

Figure 2: 222 Radon Conc. (Bq m^{-3}) in Soil sample of location1 Vs. Time (min)

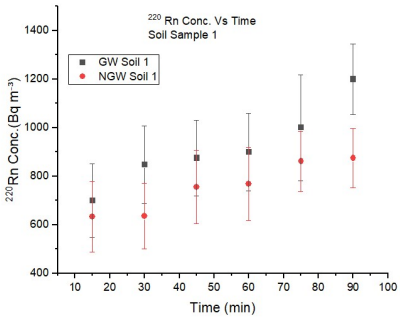

Figure 3: 220 Radon Conc. (Bq m^{-3}) in Soil sample of location1 Vs. Time (min)

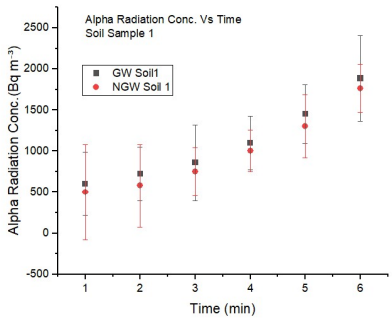

Figure 4: Alpha rad. Conc.(Bq m^{-3}) in Soil sample of location1 Vs. Time (min)

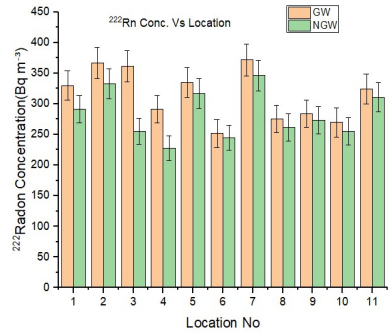

Figure 5: ^{222}Rn Conc. (Bq m^{-3}) Vs. Locations

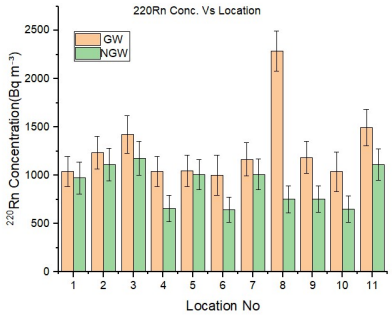

Figure 6: ^{220} Rn Conc. (Bq m^{-3}) Vs. Locations

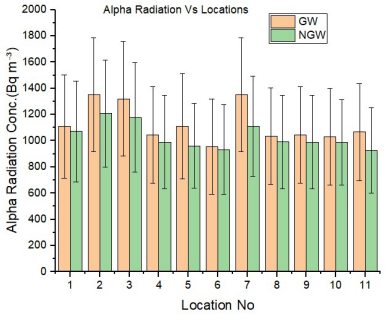

Figure 7: Alpha Radiation Conc. (Bq m^{-3}) Vs. Locations

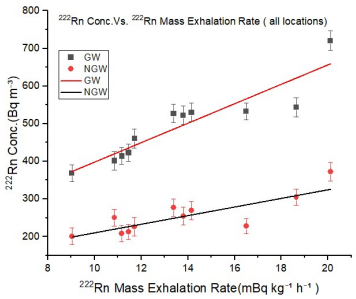

Figure 8: ^{222}Rn Conc. (Bq m^{-3}) Vs. 222Rn Mass Exhalation Rate (mBq kg^{-1} h^{-1}) in soil samples

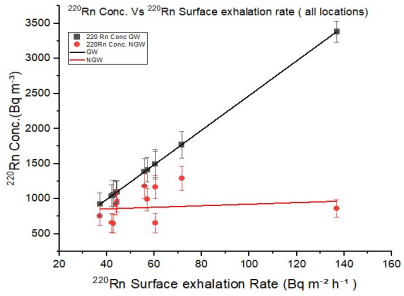

Figure 9: ^{220}Rn Conc. (Bq m^{-3}) Vs. 220Rn Surface Exhalation Rate (Bq m^{-2} h^{-1}) in soil samples.

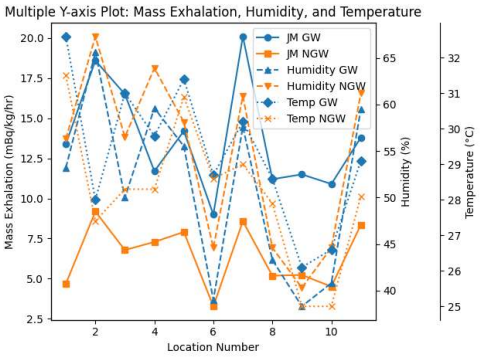

Figure 10: ^{222}Rn exhalation rate (mBq kg^{-1} h^{-1}), humidity (%), temperature 0C) in soil samples GW and NGW Vs. Location number.

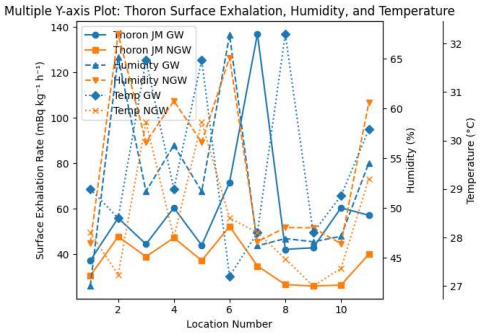

Figure 11: ^{222}Rn exhalation rate (mBq kg^{-1} h^{-1}), humidity (%), temperature 0C) in soil samples GW and NGW Vs. Location number.

3.1.2 Building Materials: The following results present the radon concentration and the mass exhalation rate of ^{222}Rn measured in building material samples collected from the study area.

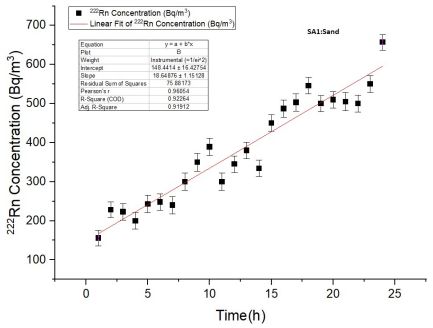

Figure 12: ^{222}Rn Conc. (Bq m^{-3}) Vs. time (hr) in sand material (SA1)

The following was the results and discussion for soil samples and building materials

For site 1**, Figure 2** shows how the 222Rn concentration (Bq m^{-3}) changes over time (minutes). The findings indicate that as measurement duration increases, the concentration of 222Rn gradually rises. Over GW areas, radon concentrations were consistently greater than those over NGW locations. At Location 1, as indicated in Table 1, the concentration of 222Rn was 526.9 ±24.2 Bq m^{-3} (from min 368 Bq m^{-3} to max 618 Bq m^{-3}) at 53.2% humidity and 32.6 °C. In contrast, the concentration was significantly lower over NGW soil at 276.8 ± 22.5 Bq m^{-3} (from min 190 Bq m^{-3} to maximum 320 Bq m^{-3}) at 56.3% humidity and 31.5 °C. With correlation coefficients of 0.9 for GW soil and 0.8 for NGW soil at location 1, the linear regression analysis shows a strong positive relationship between 222Rn concentration and time, suggesting a more noticeable buildup of radon in GW zones.

There was a substantial positive connection between radon concentration and time in both environments, as confirmed by the regression coefficients of 0.80 for GW and 0.88 for NGW when data from all locations were taken into account (Table number 1).

The change in 220Rn (thoron) concentration over time at Location 1 is shown in **Figure 3.** According to the results, the concentration of 220Rn rises with time, suggesting that emission and accumulation in the measuring environment are ongoing. Additionally, GW soils are found to have a consistently greater thoron concentration than NGW soils. The average 220Rn content at Location 1 was 755±138.2 Bq m^{-3} (min. 634 Bq m^{-3}-max. 875 Bq m^{-3}) over NGW soil and 920.5±165 Bq m^{-3} (min. 700 Bq m^{-3} to max. 1200 Bq m^{-3}) over GW soil. For GW and NGW, the equivalent climatic conditions were 42.16% humidity and 29.0 °C and 46.46% humidity and 28.1 °C, respectively (Table No 2).

The change in alpha radiation concentration (in air) over time at Location 1 is depicted in **Figure 4.** The findings demonstrate that alpha radiation rises with time, suggesting that the measurement environment experiences constant emission and buildup. Additionally, alpha radiation in the air is shown to be higher over GW locations than over NGW locations. The alpha radiation in the air at Location 1 was 981±383 and 1103±395 Bq m^{-3} (range: 601 Bq m^{-3}-1885 Bq m^{-3} over GW). Over NGW location, Bq m^{-3} (range: 500 Bq m^{-3}–1760 Bq/m3). For GW, the relevant climatic parameters were 31.5 °C and 57.4% humidity, whereas for NGW, the corresponding conditions were 30.6 °C and 59% humidity (Table No 3).

The variation in 222Rn concentration for GW and NGW soils across all sampling locations is shown in **Figure 5**. The findings show that the content of 222Rn in GW-influenced soils is significantly higher than in NGW areas.

With readings ranging from 368.8 ± 22.2 Bq m^{-3} to 720.0 ± 26.0 Bq m^{-3}, the average 222Rn concentration across all GW locations was 494.8 ± 24.1 Bq m^{-3}. The

related environmental factors revealed that temperatures ranged from 25.0 °C to 31.5 °C, with an average of 28.2 °C, while relative humidity levels ranged from 38.3% to 65.6%, with an average of 51.1%.

The average 222Rn concentration in NGW locations, on the other hand, was much lower at 254.7 ± 22.5 Bq m^{-3}, with observed values ranging from 200.5 ± 19.7 Bq m^{-3} to 372.4 ± 24.8 Bq m^{-3}. While the temperature range (25.0 °C–31.5 °C) and average (28.2 °C) were similar to those recorded at GW locations, the average relative humidity at NGW sites was 54.4%, ranging between 40.3% and 67.3% (Table 1).

The variation in 220Rn (thoron) concentration across all research locations is shown in **Figure 6**. With values ranging from 920 ± 146 Bq m^{-3} to 3381 ± 20.2 Bq m^{-3}, the average 220Rn content throughout GW soils, taking into account all sites, was 1466.5 ± 177 Bq m^{-3}. The average temperature for these measures was 29.4 °C (range: 27.0–32.2 °C), while the average relative humidity was 52.34% (range: 42.16%–67.40%).

The average 220Rn concentration in NGW locations, on the other hand, was somewhat lower at 916 ± 149 Bq m^{-3}; observed values ranged from 643 ± 123 Bq m^{-3} to 1291 ± 174 Bq m^{-3}. At NGW sites, the average temperature was 28.3 °C (range: 27.0–30.38 °C), and the average relative humidity was 54.78% (range: 46.41%–67.48%) (Table 2).

The spatial fluctuation of the air's alpha radiation concentration at each of the places under study is shown in **Figure 7.** The findings unequivocally show that the air over GW areas has higher amounts of alpha radiation than the air over NGW locations. Alpha radiation concentrations in air at GW locations ranged from 1034.8±192.8 Bq m^{-3} to 1768.3 ± 435.7 Bq m^{-3}, with an average of 1240± 375.8 Bq m^{-3}. The average temperature for these readings was 31.0 °C (27.2–34.2 °C), while the average relative humidity was 56% (50–67.5%).

The average alpha radiation concentration at NGW locations, on the other hand, was relatively lower at 1022.9 ± 345.2 Bq m^{-3}, with values ranging from 836 ± 174 Bq m^{-3} to 1291 ± 418 Bq m^{-3}. Table 3 summarizes that the average temperature was slightly lower at 30.0 °C (27.5–32.9 °C) and the average relative humidity was slightly higher at NGW locations (58.3%, range: 51–67.5%). The correlation between 222Rn concentration and 222Rn mass exhalation rate for soils taken from GW and NGW sites within the study region is shown in Figure 8. The findings unequivocally show that GW soils have higher radon concentrations and exhalations than NGW soils.

As a result, the average 222Rn concentration over GW soils was 494.8 ± 24.1 Bq m^{-3}, with values ranging from 368.8 ± 22.2 to 720.0 ± 26.0 Bq m^{-3}. The average 222Rn mass exhalation rate over GW locations was 13.7 mBq kg^{-1} h^{-1}, with values ranging from 9.0 to 20.1 mBq kg^{-1} h^{-1}. On the other hand, NGW locations had an average 222Rn concentration of 254.7 ± 22.5 Bq/m3, which ranged between 200.5 ± 19.7 and 372.4 ± 24.8 Bq m^{-3}, and a much lower average 222Rn mass exhalation rate of 6.4 mBq kg^{-1} h^{-1}, with values ranging from 3.2 to 9.19 mBq kg^{-1} h^{-1} (Table 1).

Figure 9 shows the correlation between the surface exhalation rate of 220Rn and the concentration of 220Rn (thoron) at all sampling sites in the study region, which are divided into GW and NGW zones. The findings show a considerable difference between GW and NGW soils with respect to surface exhalation rates and thoron content.

With values ranging from 37.2 ± 5.9 to 136.9 ± 8.3 Bq m^{-2} h^{-1}, the mean surface exhalation rate of 220Rn at GW sites was 59.3 ± 7.1 Bq m^{-2} h^{-1}. Accordingly, the content of 220Rn in GW soils ranged from 920 ± 146 to 3381 ± 20.2 Bq m^{-3}, with an average of 1466.5 ± 177 Bq m^{-3}. These higher results show greater thoron release in groundwater-influenced soils, most likely as a result of increased soil wetness, humidity, porosity, and radionuclide mobility linked to subsurface water movement.

In contrast, NGW locations exhibited comparatively lower thoron levels. The average surface exhalation rate of ^{220}Rn was 37.1±6.0 Bq m^{-2} h^{-1} , with a range of 26.0±4.9 to 52.2±7.0 Bq m^{-2} h^{-1}, while the mean 220Rn concentration was 916±149 Bq m^{-3}, ranging from 643±123 to 1291±174 Bq m^{-3}. Unlike GW locations, NGW sites showed low and non-uniform distribution of surface exhalation rates (Table no 2).

A multiple Y-axis comparison of soil temperature, relative humidity, and radon mass exhalation rate (JM) over GW and NGW and locations is shown in **Figure 10.** At every sampling site, the mass exhalation rate is consistently higher at GW locations than NGW locations. The higher soil moisture content linked to GW presence, which promotes the emanation and transportation of radon from soil pores, is the cause of this improvement in exhalation over GW locations.

At GW locations, relative humidity is somewhat greater than at NGW sites, suggesting more conducive moisture conditions that promote radioactive release. On the other hand, temperature differences between GW and NGW sites are still negligible, indicating that soil moisture regulates exhalation rates more so than temperature. The combined research demonstrates that the main elements influencing bulk exhalation behavior in the study location are groundwater effect and related humidity.

Figure 11: The numerous Y-axis graph shows how the temperature, humidity, and thoron surface exhalation rate (JM) vary for both GW and NGW locations

throughout eleven sampling sites. There is a noticeable difference between GW and NGW locales, with GW sites often showing higher rates of thoron exhalation than NGW sites. Higher soil moisture availability, which promotes radon/thoron transfer through pore spaces via diffusion and recoil mechanisms, is responsible for the improved exhalation at GW locations. increased humidity levels are also associated with comparatively increased thoron exhalation, suggesting that humidity has a beneficial effect on thoron emission, particularly in GW zones. By decreasing thoron loss across grain surfaces, moist soil conditions are known to improve emanation efficiency.

Temperature does not directly correlate with thoron exhalation and varies across the research area in a somewhat less noticeable manner. The minor increase in exhalation rates at moderate temperatures, however, raises the possibility that temperature has a secondary effect via affecting the rates at which soil gases diffuse. At some GW locations (e.g., Location 7), a significant peak in thoron exhalation suggests the combined influence of local lithology, soil structure, and moisture content rather than just meteorological factors. NGW sites, on the other hand, continuously exhibit lower exhalation rates, which is indicative of drier soil and less thoron mobility.

Overall, the graph shows that the presence of groundwater and the corresponding humidity are the main determinants of thoron surface exhalation, whereas temperature is a supporting but less important element. These findings are in line with past research on the behavior of radon and thoron in soil-gas in semi-humid tropical areas like Pune.

Figure 12 shows how the 222Rn concentration (Bq m^{-3}) changes over time (minutes) for sand samples taken from the research area's building site. The findings indicate that as measurement duration increases, the concentration of 222Rn gradually rises. At 42.99% humidity and 280°C, the average 222Rn concentration was found to be 381±21.3Bq m^{-3} (with a range of 156–657Bq m^{-3}).

As indicated in Table 5, all results were found to be within the bounds and methodological standards specified by international recommendations (IAEA/UNSCEAR) when compared to radon and thoron exhalation rates reported in analogous research from other parts of India.

The radon (222Rn) concentration and associated mass exhalation rates for ten samples of building materials (C1–C4, SA1–SA3, B1–B2, and R1) are summarized in Table 4. The reliability of the data is confirmed by the linear regression coefficients (0.741–0.948), which show a good to excellent linear association between exposure time and radon concentration build-up for all samples.

Between 257.04 ± 22.1 Bq m^{-3} (SA2) and 384.91 ± 19.9 Bq m^{-3} (R1), the observed concentrations of 222Rn fluctuate. Sample C4 exhibits the greatest radon concentration (375.5 ± 24.8 Bq m^{-3}) among the cement-based samples (C1–C4). This is consistent with its higher slope value (13.7 Bq /m3/h), indicating enhanced radon release as a result of material composition and porosity. Sand aggregate samples also show significant variation; SA1 has the highest slope (18.64 Bq/m3/h) and a high radon concentration (381 ± 21.3 Bq m^{-3}), suggesting stronger radon emission, which is probably caused by increased density and uranium content.

The range of the mass exhalation rate of 222Rn is 16.983 ± 1.17 mBq/kg/h (R1) to 4.820 ± 0.233 mBq/kg/h (SA2). There is a clear correlation between the production of radon and its release from the material matrix, as samples with steeper slopes typically exhibit higher mass exhalation rates. For example, SA2 and B1 have relatively lower values, while R1, SA1, and C4 have greater slopes and larger exhalation rates. Every result is determined to fall within the bounds and methodological standards outlined in international guidelines (IAEA/UNSCEAR).

4.1 Conclusion

In comparison to non-groundwater (NGW) zones, the current study consistently shows that groundwater (GW) zones have much greater levels of 222Rn and 220Rn concentrations in soil, their corresponding mass/surface exhalation rates, and alpha radiation in air. The main cause of this improvement, which is shown in all figures and places, is hydrogeological circumstances brought on by groundwater, which include higher soil moisture, porosity, pore connectivity, and improved mobility of radionuclides that contain uranium and thorium. The presence of groundwater dominates the regulation of radon and thoron formation, emanation, and movement in soils, as evidenced by the strong positive correlations seen between radon/thoron concentrations and their exhalation rates.However, this improvement is mostly controlled by higher relative humidity and soil wetness in GW regions, which raise the emanation coefficient by promoting diffusive transport across interconnected pore networks and easing recoil release from mineral grains. On the other hand, temperature primarily affects gas diffusion kinetics rather than radionuclide production, exhibits little regional fluctuation, and has a secondary effect. From the standpoint of radiological safety and habitability, areas above groundwater-bearing zones might not be intrinsically suitable for habitation without appropriate mitigation because high

levels of soil-gas radon and thoron can result in increased indoor accumulation, particularly in buildings with inadequate ventilation or when radon-emanating building materials are used. One known risk factor for lung cancer is prolonged exposure to high radon levels.The implementation of suitable radon control measures, such as adequate subsurface ventilation, radon-resistant construction techniques, the use of low-emission building materials, and routine indoor radon monitoring, is necessary before GW sites can be deemed suitable for habitation.

On the other hand, under comparable circumstances, NGW locations—which exhibit lower and more variable radon/thoron levels primarily determined by local soil characteristics—generally provide a lower natural radiological risk and are more advantageous for residential building.

Overall, the results highlight the need for thorough radon risk assessment and mitigation planning prior to residential use in groundwater-rich places, and the importance of hydrogeological conditions as a criterion for land-use planning, housing development, and environmental radiation protection.Table No-1: Shows result table of 222Rn concentration, mass exhalation rate with humidity and temperature over study area

		222Rn (Radon)												Humidity (%)		Temp (0C)	
Sr. No	Sample code	Slop (Bq/m³/h)		Linear Regression Coeff.(R)		Density (kg/m3)		^{222}Rn Conc. (Bq/m3)		Mass Exhalation J_M(mBq/kg/hr)		GW	NGW	GW	NGW
		GW	NGW	GW	NGW	GW	NGW	GW	NGW	GW	NGW						
1	S1	10.63	4.02	0.9	0.885	2227.13	2227.13	526.9±244.2	276.8±22.5	13.4	4.68	53.2	56.3	32.6	31.5
2	S2	13.5	8.37	0.79	0.872	23644.	23644.	5443.7	3043.5	18.6	9.19	65.6	67.3	28.0	27.4
3	S3	12.77	5.97	0.742	0.811	22866.56	22866.56	5333.0±222.5	227.4±19.7	16.5	6.78	50.0	56.5	31.0	28.3
4	S4	10.05	5.79	0.724	0.869	20611.45	20611.45	4600.7±25.7	225.7±24.6	11.7	7.29	59.6	63.9	29.8	28.3
5	S5	11.24	6.9	0.813	0.755	22622.86	22622.86	529.7±24.5	269.4±24	14.2	7.91	55.5	58.1	31.4	30.9
6	S6	9.01	2.29	0.823	0.741	18116.32	18116.32	368.0±22.5	200.5±22.1	9.0	3.27	39.0	44.6	28.7	28.6
7	S7	14.04	8.56	0.8	0.867	2589.44	2589.44	720.3±26.0	372.4±24.8	20.1	8.58	57.6	60.9	30.2	29.0
8	S8	9.84	3.8	0.731	0.828	19033.79	19033.79	4133.9±2	208.2±2	11.2	5.18	43.3	44.6	28.6	27.9

								2.2	2.1							
9	S9	9.99	3.97	0.897	0.945	1970.92	1970.92	423.1±23.2	212.2±20.1	11.5	5.23	38.3	40.3	26.1	25.0
10	S10	9.89	3.26	0.771	0.943	18880.48	18880.48	401.3±24.2	250.0±22.1	10.9	4.5	40.8	44.6	26.6	25.0
11	S11	11.19	6.78	0.762	0.767	2105.19	2105.19	522.5±24.1	254.5±23.9	13.8	8.36	59.5	61.2	29.1	28.1
	Avg.	**11.10**	**5.443**	**0.800**	**0.884**	**2133.55**	**2133.55**	**494.8±24.1**	**254.7±22.5**	**13.7**	**6.4**	**51.1**	**54.4**	**29.3**	**28.2**
	Min.	**9.01**	**2.29**	**0.072**	**0.074**	**1816.32**	**1816.32**	**368.0±22.2**	**200.5±19.7**	**9.0**	**3.27**	**38.3**	**40.3**	**26.1**	**25.0**
	Max.	**14.04**	**8.56**	**0.900**	**0.995**	**2589.44**	**2589.44**	**720.3±26**	**372.4±24**	**20.1**	**9.19**	**65.6**	**67.3**	**32.6**	**31.5**

Table No-2: Shows result table of 220Rn concentration, surface exhalation rate with humidity and temperature over study area

Sr. No	Sample code	220Rn (Thoron)							
		^{220}Rn Conc. (Bq/m3)		Surface exhalation (Bq/m2/s)		Humidity %	Temp (0c)	Humidity %	Temp (0c)
		GW	NGW	GW	NGW	GW	GW	NGW	NGW
1	S1	920.5±165.0	755±138.2	37.2±6.6	30.5±5.5	42.16	29	46.46	28.1
2	S2	1382.1±192.8	1178.3±174.7	55.9±7.8	47.7±7	65.16	28.4	67.48	27.23
3	S3	1097.5±161.2	962.6±153.5	44.4±6.5	38.9±6.2	51.66	31.66	56.6	30.38
4	S4	1493.3±187.0	1165.8±162.3	60.4±7.5	47.2±6.5	56.30	29.00	60.75	28
5	S5	1085.5±161.2	920.8±153.5	43.9±6.5	37.2±6.2	51.66	31.66	56.6	30.38
6	S6	1768.3±192.8	1291±174.7	71.6±7.8	52.2±7.0	67.40	27.2	65.1	28.4
7	S7	3381±146.0	861±123	136.9±5.9	34.8±4.9	46.2	28.1	46.6	28.1
8	S8	1039.8±158.2	657.1±133.5	42.1±6.4	26.6±5.4	46.92	32.2	48.03	27.56
9	S9	1057.6±207.2	643.3±131	42.8±8.3	26.0±.5.3	46.60	28.1	48	27
10	S10	1492.8±207.2	653.3±137.2	60.4±8.3	26.4±5.5	47.15	28.86	46.41	27.36

11	S11	1412.3 ±173.2	989.3± 158.5	57.1± 7.0	40.0 ±6.4	54.53	30.23	60.61	29.21
	Avg.	**1466.5 ±177.4**	**916.1± 149**	**59.3± 7.1**	**37.1 ±6**	**52.34**	**29.4**	**54.78**	**28.30**
	Min.	**920 ±146**	**643.3± 123**	**37.2± 5.9**	**26.0 ±4.9**	**42.16**	**27.2**	**46.41**	**27**
	Max.	**3381±207.2**	**1291±174.7**	**136.9 ±8.3**	**52.2 ±7**	**67.4**	**32.2**	**67.48**	**30.38**

Table No-3: Shows result table of alpha radiation concentration, with humidity and temperature over study area

Location No		GW				NGW			
	Sample code	Alpha Concentration (Bq/m3)	sigma	Humidity (%)	Temp(0c)	Alpha Concentration (Bq/m3)	sigma	Humidity (%)	Temp (0c)
1	S1	1103.0	395.7	57.4	31.5	981.5	383.7	59.0	30.6
2	S2	1211.3	435.7	55.0	30.1	1061.8	418.5	60.7	29.3
3	S3	1181.5	369.5	53.7	33.4	917.2	357.2	54.9	32.9
4	S4	1376.7	434.7	64.7	28.4	1184.7	408.5	67.5	27.5
5	S5	1236.2	399.7	52.1	31.8	836.0	323.3	56.5	30.6
6	S6	1768.3	19	67.5	27.2	1291.0	17	65.2	28.4
			2.8				4.7		
7	S7	1474.3	4344.8	56.2	29.3	1105.8	383.7	61.2	28.0
8	S8	1034.8	369.5	53.7	34.2	990.8	357.2	54.9	32.9
9	S9	1077.2	362.0	50.0	34.0	1050.0	339.0	51.0	32.0
10	S10	1091.7	369.5	53.0	34.2	925.8	325.7	54.9	32.9
11	S11	1087.5	369.5	53.0	34.2	907.5	325.7	54.9	32.9
	Avg.	**1240.2**	**375.8**	**56.0**	**31.7**	**1022.9**	**345.2**	**58.3**	**30.7**
	Min.	**1034.8**	**192.8**	**50.0**	**27.2**	**836.0**	**174.7**	**51.0**	**27.5**
	Max.	**1768.3**	**435.7**	**67.5**	**34.2**	**1291.0**	**418.5**	**67.5**	**32.9**

Table no 4: Results of radon concentration and mass exhalation rates in building material samples collected from the study area.

Sr No	Sample Code	Slop (Bq/m3/h)	Linear Regression Coeff.	Density kg/m3	222Rn Concentration Bq/m3	22Rn Mass Exhalation Rate (mBq/kg/hr
1	C1	9.96	0.938	2507	294.45±21.7	9.644±0.54
2	C2	10.08	0.837	2227	307.7±20.1	11.456±0.94
3	C3	10.39	0.845	2188	279.33±22.4	12.090±0.94

4	C4	13.7	0.811	2227	375.5±24.8	15.570 ±1.40
5	SA 1	18.64	0.922	2779	381±21.3	15.607 ±1.15
6	SA 2	3.48	0.91	1912	257.04± 22.1	4.820± 0.233
7	SA 3	8.18	0.817	2685	268.66± 19.7	7.212± 0.82
8	B1	5.58	0.741	1813	290.5±22.1	6.725± 0.70
9	B2	6.76	0.851	2227	292.87± 22.5	7.683± 0.66
10	R1	15.9	0.948	2255	384.91± 19.9	16.983 ±1.17
C: cement material, R: Rock SA Sand, B: bricks						

Table no-5: Comparison radon/thoron exhalation rate with other, related research from other areas

Sr. No.	Place	Radon Mass Exhalation rate (mBq Kg $^{-1}$ h^{-1})	Thoron Surface Exhalation Rate (Bq m^{-2} S^{-1})
	Tarn Taran	23 ± 5	1531 ± 1503
	Amritsar	20 ± 7	664 ± 237
	Jammu and Kashmir	8 ± 1 to 62± 3	295 ± 3628
	Shiwalik Himalayas of J&K	7 ± 48	123 ± 2606
	Aravali hills	23 ± 50 with Average 35	-
	Unna Hamirpur Himachal Pradesh	39 to 91 with Average 60	-
	Cauvery river Sediments	45 to 433	-
	Faridabad, Hariyana	12 ± 1 to 62 ±4 with Average 31±12	
	Kalpakkam, Tamilnadu	-	942 to 7720
	Hanumangarh District	11.56±0.062 to 62.03 ±3.49 with average of 34.60±1.37	3.09 ± 0.39 to 9.56± 0.62 with average of 6.44±0.62

5.Authorship: All authors contributed equally to the study, analysis, and manuscript preparation and approved the final version.

6.Conflict of Interest: The authors declare no conflict of interest.

7. Funding: This research received no external funding.

8.0. References:

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