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Effect of soil's porosity and moisture content on radon and thoron exhalation rates

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Abstract

We study the variation of radon mass exhalation rate (J_m) and thoron surface exhalation rate (J_s) with soil's porosity and moisture content using a scintillation based monitor-Smart RnDuo. Assessment were carried out in around 40 soil samples collected from four villages of East Khasi Hills district, Meghalaya, India. Results revealed that, both J_m and J_s shows no convincing trend of variation with porosity, while with respect to moisture content, a sporadic increase is observed in the values of J_m and J_s up to certain level, beyond which a decreasing trend is observed; accountable reasons are discussed in the manuscript.

Keywords Radon mass exhalation rate · Thoron surface exhalation rate · Smart RnDuo · Porosity · Moisture content

Introduction

The earth's crust is composed of minerals, organic matter, water, air and organism [1]. It has been well documented that these components especially soils and rocks always contain trace amounts of primordial radionuclides such as uranium (^{238}U) and thorium (^{232}Th), whose immediate daughters are the radium isotopes—^{226}Ra and ^{224}Ra, and which further decay into radon (^{222}Rn) and thoron (^{220}Rn) respectively. These gaseous elements are of utmost important when considered from geological as well as epidemiological perspectives because of their subterranean origin and their potential health hazards [2, 3]. Geologically, radon plays many roles including tracer, seismic precursor, exploratory tool for uranium and hydrocarbon deposition, geochemical signal for study of geological fault, etc. [4]. Epidemiologically their importance arises from the fact that radon, its isotopes and their decay products are major contributors (~ 50%) to the global annual effective dose from natural radiation to humans; the ensuing carcinogenicity due to exposure has also been established [5].

The radon and thoron concentrations in the atmosphere are sourced mainly from exhalations from the soil surface [6]. The creation of the radon and thoron atoms from their parent nuclides in the soil matrix is followed by the process of emanation from the source grain. The emanation process is strongly dependent on the nature of the soil like the size and texture of the grain, the distribution of radium atoms inside the grain, etc. [7]. On reaching the pore space in the soil matrix, these gaseous radionuclides get driven by either diffusion or advection finally leading to their exhalation from the soil surface. After being exhaled they mix with the atmosphere; they may also find their way into the indoor environment through different pathways and entries [8, 9]. The transport mechanism is largely influenced by the soil characteristics as well as the meteorological parameters of the area under consideration [10]; the former is given importance in the present study.

The present study is aimed at discussing the effects of soil characteristics such as porosity and moisture content on radon mass exhalation rate and thoron surface exhalation rate under controlled laboratory conditions. This exercise also characterises the radiogenic properties of the soil in the geologically and economically important district of East Khasi Hills of Meghalaya, India [11]. Comparison with other reported values is also undertaken, eventually

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providing a conclusion with supportive rationale based on the obtained results.

Geology of the study area

The study area includes four villages of East Khasi Hills District i.e. Mawsmai, Mawryngkneng, Pyndenglitha and Mawkdok (Fig. 1). These villages forms the periphery of the district. The district has a total geographical area of 2748 Sq. Kms and approximately lies between 25°07″ to 25°41″ N Lat. and 91°21″ to 92°09″ E Long. Falling within the Shillong Plateau, most places in the district are mainly composed of Precambrian rocks of gneissic composition. Geomorphologically, the district is characterized by denotational high and low hills with deep gorges. Surrounded by the Bangladesh plains in the southern part, these areas mainly constitute of alluvial soils that are localized in nature. Overall, the soil type is dependent on few primary factors like geology, climate and vegetation. Red loamy soil is also abundance in certain parts of the district which is a product of weathering of rocks like granites and gneisses which are relatively rich in clay forming minerals (Fig. 2). Typically, such soil type are rich in organic matter, nitrogen and acidic in nature. The northern part of the district is mainly composed of laterite soil; a result of weathering product of rocks like quartzite, schist, conglomerate etc., and such soils are rich in iron and aluminium [12].

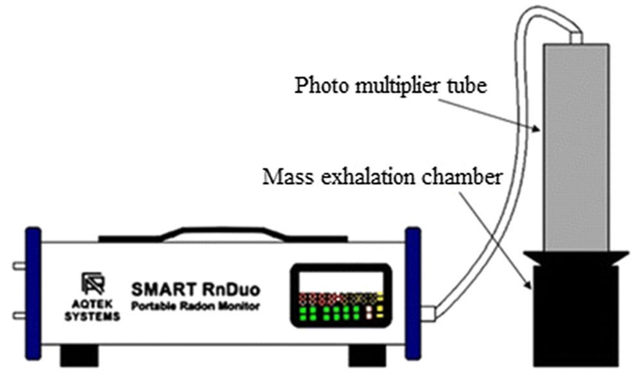

Fig. 2 Set-up for measurement of radon mass exhalation rate

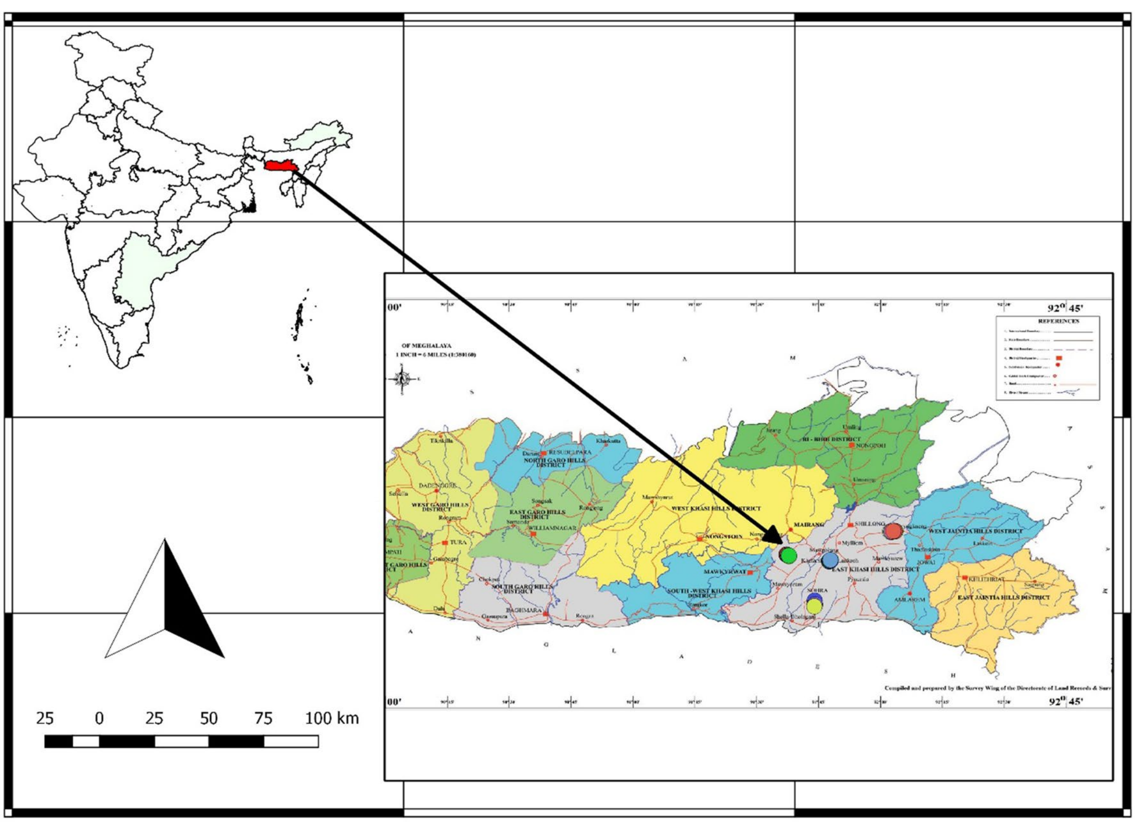

Fig. 1 Map showing the location of sampling sites

Materials and methods

Sampling procedure

During sampling, minimization of the possible effect of few meteorological parameters and variation of atmospheric pressure is achieved by considering samples from much deeper range, because surface soil may not serve the purpose, as most radionuclides present in it, sooner may be detached by water or wind [13]. The presence of fine loamy soil in the study region made the sampling simplistic [14]. Although it might have been preferable to measure the exhalation rate of the radionuclides in-situ, but due to logistical limitations, the measurement have been done ex-situ. In the present study, 10 soil samples were collected from each of the four studied villages of East Khasi Hills district, at a minimum depth of 30–40 cm to obtain an undisturbed or pure base soil. Neglecting gravels and pebbles, about 1.5 kg of soil samples were collected from each location, packed in a zip polythene bag and finally brought to the laboratory for processing.

Measurement of radon/thoron exhalation rate

A recently developed scintillation (ZnS: Ag) based monitor-Smart RnDuo [15], has been used for the assessment of radon/thoron exhalation rate. The monitor works on the principle of tracking number of alpha particles effused during decay process of sampled radon/thoron within the detector volume (153 cm^3). This monitor detects radioactivity range between 8 Bq m^{-3} and 10 MBq m^{-3} and has a sensitivity factor of 1.2 counts h^{-1} Bq m^{-3}.

For measurement of radon mass exhalation rate (J_m), diffusion mode sampling is preferred, where the detector probe is coupled directly to the accumulation chamber. Keeping the pump off, the measurement is carried out over a period of 24 h at a cycle of 1 h.

On completion of measurement cycle; radon build up as a function of elapsed time is retrieved and least square fitting is carried out using the model equation below [16].

$$C(t) = \left(\frac{Jm.M}{V}\right)t + C_0 \tag{1}$$

where $C\,(t)$ is the radon concentration (Bq m^{-3}) at time t, C_0 is the radon concentration (Bq m^{-3}) present in the chamber at time $t = 0$, M is the total mass (kg) of the sample, V is the effective volume (volume of the detector + porous volume of the sample + residual air volume of the mass exhalation chamber). The porous volume (V_p) of the sample can be estimated by the equation below.

$$V_p = V_s - \frac{M}{\rho_s} \tag{2}$$

where, V_s is the sample volume in the accumulation chamber, ρ_s is the specific gravity of sample which is taken as 2.7 gm/cc for typical clay soil sample [16]. With the information of sample mass M, detector effective volume V of the, J_m may be finally obtained from the fitted slope.

For measurement of thoron surface exhalation rate (J_s), the accumulation chamber containing the sample is connected to the detector probe via flexible cylindrical tubing having diameter 0.5 cm of preferably shorter length (Fig. 3), due to thoron shorter half-life. Before performing the measurement, the used scintillation cell is replaced with another background free scintillation cell to avoid possible errors. The device is then switch ON with Thoron mode being selected on the display screen.

The measurement cycle is set at 15 min. The sampling pump is on for the initial 5 min which gives the measure of background and thoron, then followed by a delay of 5 min to ensure complete decay of thoron. Finally, the last 5 min gives the background counts of the entire cycle. The rate of thoron activity in the loop is given by the equation below.

$$\frac{dC_t}{dt} = J_s A - C_t V_e \lambda \tag{3}$$

where, C_t is the thoron activity concentration (Bq m^{-3}) inside the accumulation chamber, J_s is the thoron surface exhalation rate (Bqm^{-2} h^{-1}), A is the surface area of the sample enclosed by the accumulator (m^2), V_e is the effective volume (m^3) which is the sum of; residual volume of chamber, volume of the detector and tubing volumes, $\lambda = 0.0126$ s^{-1} is the thoron decay constant. The thoron surface exhalation rate is estimated using the equation below [17].

$$J_s = \frac{C_{eq} V \lambda}{A} \tag{4}$$

where C_{eq} is the equilibrium thoron concentration in Bq m^{-3}.

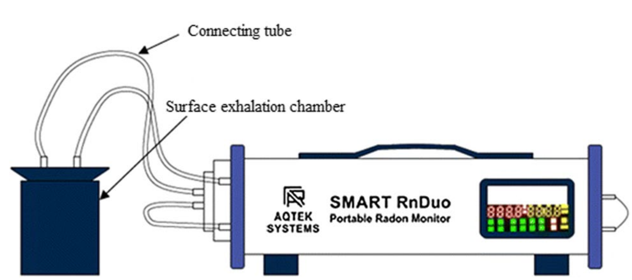

Fig. 3 Set-up for measurement of thoron surface exhalation rate

Estimation of moisture content

For estimation of moisture content in soil sample, gravimetric method is followed, where the moist soil sample is initially weighted, then it is dried in an oven for a period of about 24 h at a temperature of 100 ± 5 °C. When the drying time is over, the sample is taken out of the oven and weighed again. The percentage of moisture content (MC_s) in collected soil is calculated by the relation below [18]

$$MC_s = \frac{M_s - D_s}{D_s} \tag{5}$$

where M_s is the weight of moist soil, D_s is the weight of dry soil.

Results and discussions

The results of radon mass exhalation rate and thoron surface exhalation rate from 40 soil samples along with their respective mass densities are presented in Table 1. Overall, the value of radon mass exhalation rate vary from 1.3 ± 0.01 to 32.6 ± 1.4 mBq kg^{-1} h^{-1} with an average value of 11.6 ± 0.06 mBqkg^{-1} h^{-1}, and thoron surface exhalation vary from 2.2 ± 0.3 to 138 ± 2.8 mBq.m^{-2} h^{-1} with an average value of 24.1 ± 0.14 mBq m^{-2} h^{-1}. It is found that our results are much below the world average values of 57,600 mBq kg^{-1} h^{-1} for radon mass exhalation rate and 3600 Bq m^{-2} h^{-1} for thoron surface exhalation rate [19].

As seen from Fig. 4, highest mean values of both radon mass exhalation rate and thoron surface exhalation rate are observed in Pyndenglitha region, this may be due to abundance of potential radon/thoron emitters radionuclides in the soil of this region, while minimal values in the other three regions, suggest least content of potential radionuclides in the soil of those regions [2]. The plot also predicts asymmetrical distribution and dominance of left skewed pattern of radon/thoron exhalation rate data in all the four regions. Again, from the plot, it is seen that, the Inter Quartile Range (IQR) values of Pyndenglitha region for both radon and thoron exhalation rates are much higher, this suggest highest variability of measured parameters, while least IQR values have been observed in Mawryngkneng region, this suggest least variability of the measured parameters in this particular region.

Variation of radon mass and thoron surface exhalation rates with soil porosity

Figure 5a and b shows the variation of radon mass exhalation rate (J_m) and thoron surface exhalation rate (J_s) with soil porosity. It is observed that, both J_m and J_s shows no convincing trend of variation with porosity, in which initially it increases, saturate till some values of porosity and then it either increase or decrease. This pattern clearly violates the theoretical prediction, which states, exhalation rates favors high porous volume, this may be due to presence of resisting agent such as water/moisture in the pores, thereby inhibiting smooth transport of radon/thoron atom. Besides, absorption and adsorption phenomena in the soil matrix also play an important role as inhibitor [2, 3].

Effect of moisture content on radon mass and thoron surface exhalation rates

The scatter plot of variation of radon mass exhalation rate, J_m and thoron surface exhalation rate, J_s with moisture content is shown in Fig. 6a and b. The plot revealed that both J_m and J_s initially increase with increase in moisture content up to a certain value of 30%, this is because the capillary component of soil water enhances radon/thoron emanation from the grain containing radium by absorbing the recoil energy of the emanated atom. However, at higher value of moisture content, a decreasing trend is observed; this is because as the pore space is gradually filled with fluid; migration of emanated atom is obstructed. Besides, back diffusion process is also a responsible factor for observing lower exhalation rate value at higher moisture content [20, 21].

In order to know, whether the variation in radon/thoron exhalation rate is significant with change in moisture content, test statistics is applied. Results of the paired t-test are shown in Table 2. It is evident from the p values that, change in radon mass exhalation rate as a function of moisture content is significant at 95% confidence level, while change in thoron surface exhalation rate as a function of moisture content is not significant at 95% confidence level [22].

Comparative study

The present measurements of radon mass exhalation rate and thoron surface exhalation rate are compared with other researchers in Table 3, for a perspective on the expected range of values for exhalation. There could be number of reasons for the variation of exhalation rates reported for different regions including differences in methodology as well as soil morphology, lithology, geological and geographical condition [2]. Overall, our results are comparable with the reported values [23–28].

Table 1 Radon mass exhalation rate (J_m) and thoron surface exhalation rate (J_s) of 40 soil samples, together with their respective GPS values

Sample code	Sample GPS coordinates	Density (Kg m^{-3})	J_m (mBq kg^{-1} h^{-1})	J_s (mBq m^{-2} h^{-1})
S_1	N-25°14′ 53.86″ E-91°43′ 58.93″	1231	9.4 ± 0.1	6.8 ± 0.6
S_2	N-25°14′ 56.12″ E-91°44′ 01.89″	1402	8.6 ± 0.5	10.1 ± 0.7
S_3	N-25°14′ 52.81″ E-91°43′ 56.98″	1295	8.1 ± 0.2	2.8 ± 0.4
S_4	N-25°15′ 55.91″ E-91°43′ 57.76″	1571	16.3 ± 0.8	6.6 ± 0.6
S_5	N-25°14′ 58.22″ E-91°43′ 57.26″	1346	9.3 ± 0.2	4.9 ± 0.5
S_6	N-25°14′ 57.73″ E-91°44′ 01.59″	1382	5.9 ± 0.06	5.3 ± 0.5
S_7	N-25°14′ 59.17″ E-91°43′ 58.95″	1350	1.3 ± 0.01	9.9 ± 0.7
S_8	N-25°15′ 01.34″ E-91°44′ 01.50″	1084	3.3 ± 0.7	9.4 ± 0.7
S_9	N-25°14′ 33.65″ E-91°43′ 52.02″	1342	9.4 ± 0.4	13 ± 0.8
S_{10}	N-25°14′ 30.77″ E-91°43′ 52.67″	1169	2.6 ± 0.3	3.5 ± 0.5
S_{11}	N-25°32′ 54.73″ E-92°02′ 32.11″	1224	7.2 ± 0.4	10.5 ± 0.7
S_{12}	N-25°32′ 50.82″ E-92°02′ 50.86″	1105	17.3 ± 0.6	16.7 ± 0.9
S_{13}	N-25°32′ 55.23″ E-92°02′ 46.95″	1338	8.9 ± 0.07	5.8 ± 0.5
S_{14}	N-25°32′ 57.72″ E-92°02′ 56.51″	1074	11.3 ± 0.6	7.3 ± 0.6
S_{15}	N-25°33′ 06.41″ E-92°03′ 30.47″	1536	5.4 ± 0.4	8.3 ± 0.7
S_{16}	N-25°33′ 05.22″ E-92°03′ 22.14″	1443	3.9 ± 0.04	18 ± 1
S_{17}	N-25°33′ 06.18″ E-92°03′ 32.31″	1566	8.9 ± 0.5	8.6 ± 0.6
S_{18}	N-25°33′ 02.66″ E-92°03′ 51.94″	1544	1.5 ± 0.02	9 ± 0.6
S_{19}	N-25°33′ 03.46″ E-92°03′ 40.66″	1151	1.9 ± 0.04	6.7 ± 1.1
S_{20}	N-25°33′ 03.92″ E-92°03′ 19.04″	1633	7.6 ± 0.4	7.2 ± 0.7
S_{21}	N-25°27′ 02.11″ E-91°37′ 29.95″	1133	20.4 ± 0.5	38.2 ± 1.3
S_{22}	N-25°27′ 17.83″ E-91°37′ 01.91″	1158	16.1 ± 0.4	102 ± 2.3
S_{23}	N-25°27′ 17.06″ E-91°37′ 00.77″	974	6.8 ± 0.4	100.5 ± 2
S_{24}	N-25°27′ 16.63″ E-91°37′ 04.64″	984	12.8 ± 0.2	114 ± 2.7
S_{25}	N-25°27′ 07.93″ E-91°37′ 15.49″	1123	22.9 ± 0.5	138 ± 2.8
S_{26}	N-25°27′ 04.58″ E-91°37′ 24.00″	1081	10.5 ± 0.4	44.2 ± 1.4
S_{27}	N-25°27′ 05.72″ E-91°37′ 22.75″	1017	23.8 ± 0.3	12.5 ± 0.8
S_{28}	N-25°27′ 02.63″ E-91°37′ 31.62″	1010	28.3 ± 0.2	108 ± 2
S_{29}	N-25°26′ 54.04″ E-91°37′ 37.37″	1020	21.4 ± 0.7	21.5 ± 1.2
S_{30}	N-25°27′ 01.50″ E-91°37′ 36.86″	1584	10.7 ± 0.09	41.2 ± 1.3
S_{31}	N-25°25′ 36.21″ E-91°47′ 30.48″	882	17.5 ± 0.2	4.5 ± 0.5
S_{32}	N-25°25′ 38.48″ E-91°47′ 30.94″	1126	15.4 ± 0.9	6.8 ± 0.6
S_{33}	N-25°25′ 41.93″ E-91°47′ 32.80″	955	9.4 ± 0.5	6.5 ± 0.5
S_{34}	N-25°25′ 42.34″ E-91°47′ 38.81″	1020	13 ± 0.8	11 ± 0.7
S_{35}	N-25°25′ 42.16″ E-91°47′ 41.50″	977	4.9 ± 0.4	7.9 ± 0.7
S_{36}	N-25°25′ 47.47″ E-91°47′ 48.01″	1091	11.1 ± 0.2	2.2 ± 0.3
S_{37}	N-25°25′ 49.16″ E-91°47′ 47.56″	1130	12.6 ± 0.6	7.5 ± 0.6
S_{38}	N-25°25′ 47.43″ E-91°47′ 49.55″	1362	5.8 ± 0.05	10.5 ± 0.7
S_{39}	N-25°25′ 53.29″ E-91°47′ 55.75″	1231	17.3 ± 0.9	6.1 ± 0.5
S_{40}	N-25°25′ 57.67″ E-91°47′ 49.39″	1064	32.6 ± 1.4	10.5 ± 0.7

Mawsmai (S_1–S_{10}), Mawryngkneng (S_{11}–S_{20}), Pyndenglitha (S_{21}–S_{30}), Mawkdok (S_{31}–S_{40})

The uncertainty in the reported values are standard deviation

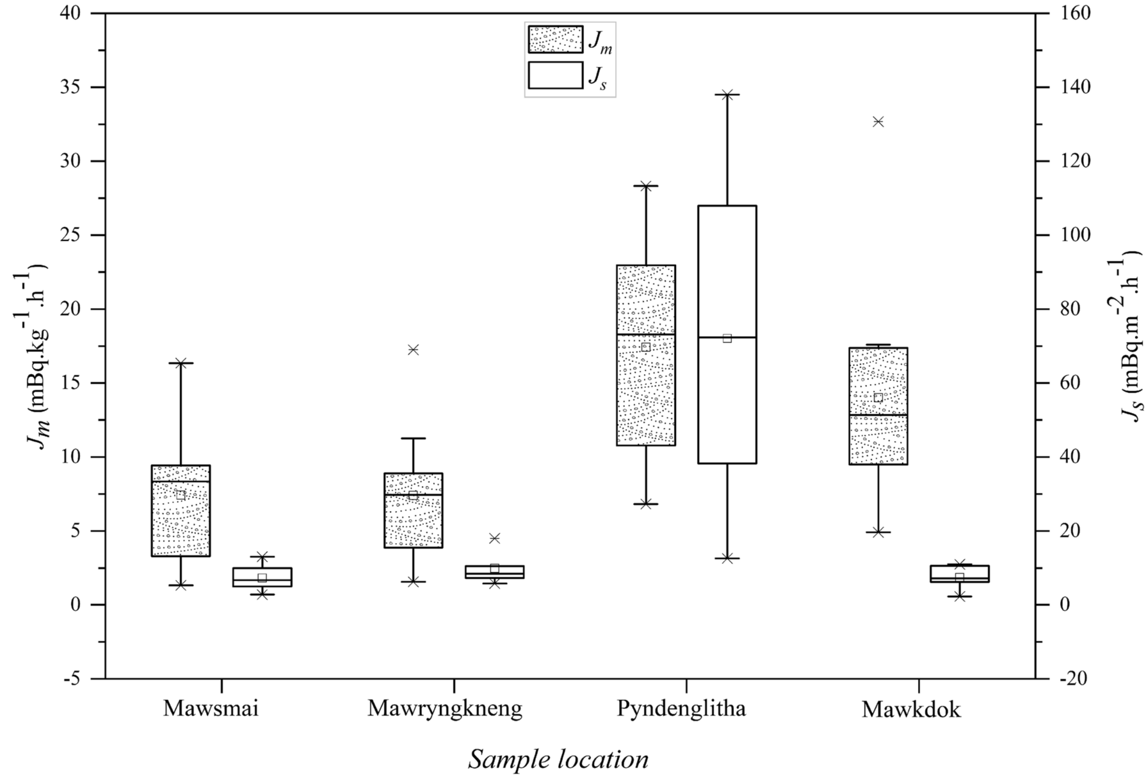

Fig. 4 Box-whisker plot of radon mass exhalation rate (J_m) and thoron surface exhalation rate (J_s) in different locations of the study area

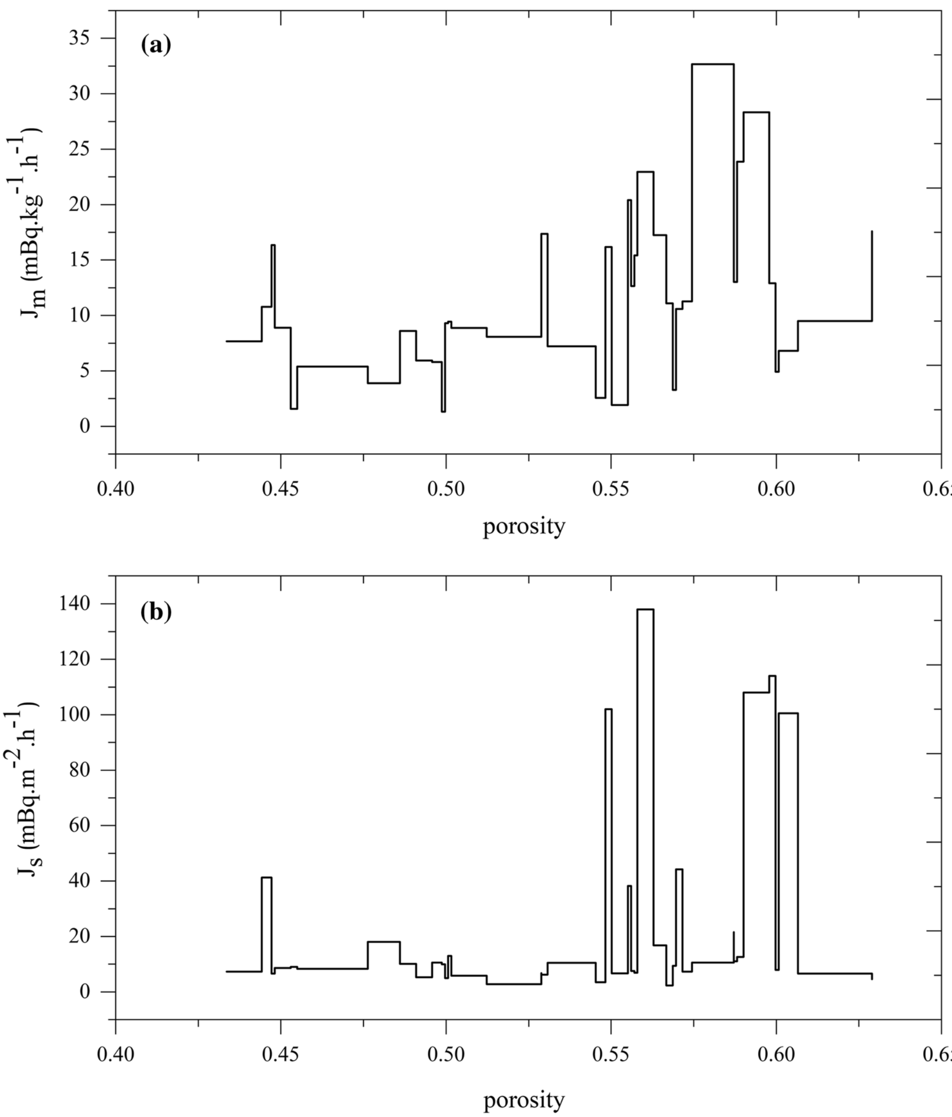

Fig. 5 Variation of **a** radon mass exhalation rate (J_m) and **b** thoron surface exhalation rate (J_s) with soil porosity

Fig. 6 Scatter plot showing variation of **a** radon mass exhalation rate (J_m) and **b** thoron surface exhalation rate (J_s) with moisture content

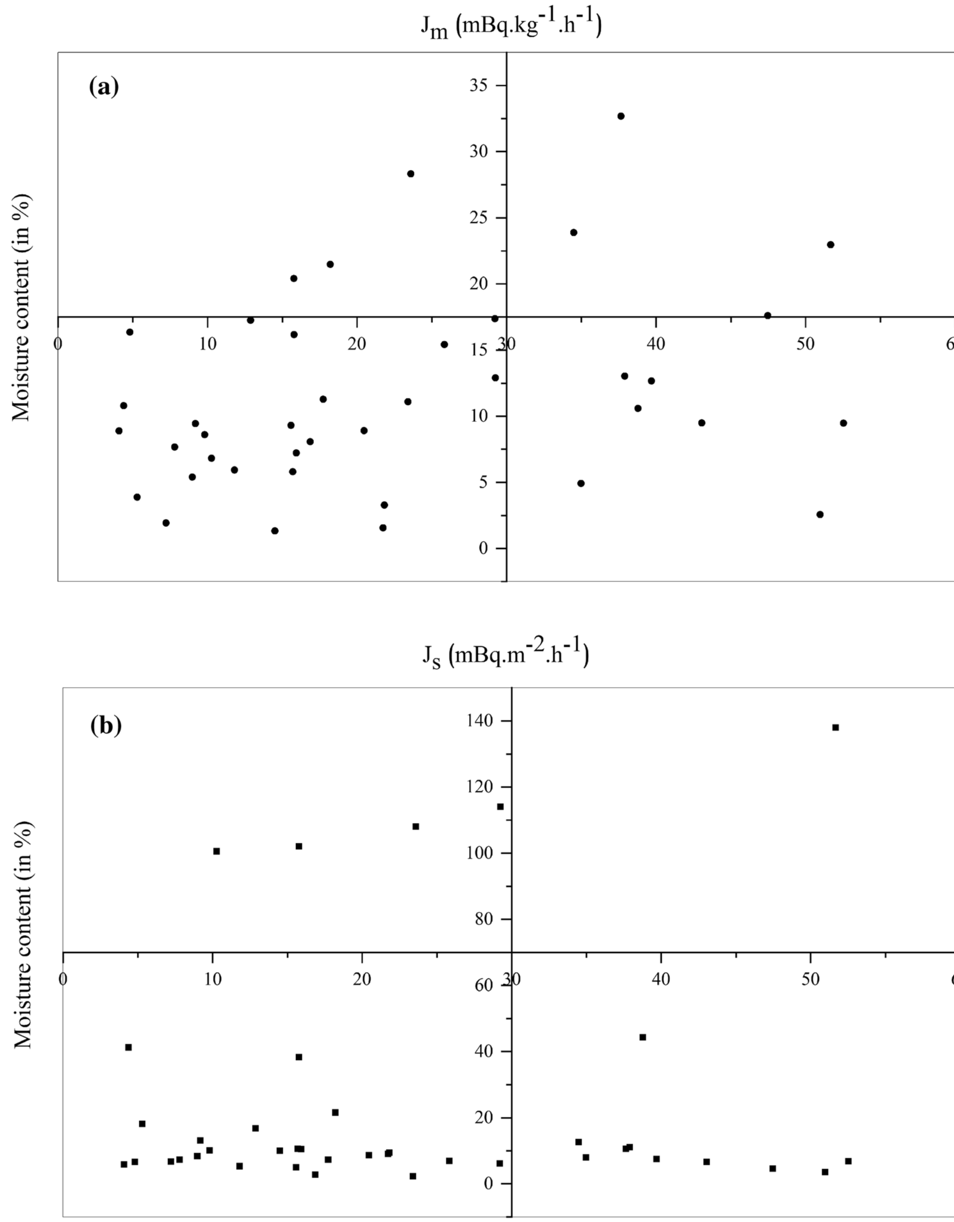

Table 2 Statistical analysis of the significant/in-significant change in radon/thoron exhalation rate with moisture content using paired t-test

Moisture content	Test statistics	p value for J_m	p value for J_s	Remarks
I (0–18)% II (18–53)%	Paired t-test	0.03	0.65	All values below 0.05 are significant

Table 3 Comparison of the present data of radon mass exhalation and thoron surface exhalation rate with other regions in the country

Regions	Radon mass exhalation rate (mBq kg^{-1} h^{-1})	Thoron surface exhalation rate (mBq m^{-2} h^{-1})	References
Faridabad, Southern Haryana*	31 ± 12	5846 ± 1424	[23]
Siwalik Himalaya, Jammu & Kashmir*	14 ± 4	537 ± 157	[24]
Northern Rajasthan	15.5	52	[25]
Hamirpur, Himachal Pradesh*	31.5	38	[26]
Garhwal Himalaya	0.195	–	[27]
Chikkaballapur, Karnataka*	143 ± 6	$10{,}443 \pm 5669$	[28]
East Khasi Hills, Meghalaya*	11.6 ± 0.06	24.1 ± 0.14	Present study

*Similar instrument/methodology

Conclusion

Radon mass exhalation rate and thoron surface exhalation rate have been assessed in 40 soil samples of East Khasi Hills district of Meghalaya, India. Based on the obtained results, the following conclusion are made:-

a. In majority of the soil samples, both radon and thoron exhale with a much lower rate in comparison to the world average value [19], and hence would pose no significant threat to the inhabitant of the study region.
b. No convincing trend was observed in the variation of radon and thoron exhalation rates with respect to soil porosity.
c. It is found that radon and thoron exhalation rate increases with increase in moisture content up to a certain level, beyond which a decreasing trend is observed.
d. Based on the paired t-test result, change in radon mass exhalation rate as a function of moisture content is significant at 95% confidence level, but showed no significance in the case of thoron surface exhalation rate.

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