Factors influencing radon transport in the soils of Moscow

Sakhayaan Gavriliev · Tatiana Petrova · Petr Miklyaev

Abstract
This article delves into the factors that may influence radon flux, such as soil properties and weather conditions, on the example of two experimental locations with different soil compositions, composed primarily of clay and sand, respectively. The experimental location with sandy soil was previously observed to have anomalously high radon flux levels. Radon monitoring was performed routinely, approximately at the same time of day and in parallel on both of these locations to exclude the influence of diurnal variations. The results show that radon transport in these locations differs in mechanism: Location with clay soil has diffusive radon transport, with an average radon flux density of \(37.4 \pm 24.9 \text{ mBq m}^{-2} \text{ s}^{-1}\) and a range of \(0.3–167.8 \text{ mBq m}^{-2} \text{ s}^{-1}\), while the location with sandy soil has convective radon transport with an average radon flux density of \(93.6 \pm 51.2 \text{ mBq m}^{-2} \text{ s}^{-1}\) and a range of \(9.8–302.2 \text{ mBq m}^{-2} \text{ s}^{-1}\). This corresponds to about 8.3% of RFD measurements on site with clay soils exceeding the national reference level of 80 mBq m\(^{-2}\) s\(^{-1}\) and 45.6% exceeding them on the site with sandy soils. Average radon flux density values were then compared to meteorological variables using Pearson correlation analysis with Student’s t-test. It was observed that radon flux density correlates the most with ambient air temperature both for diffusive and convective radon transport mechanisms, while a weaker inverse correlation is observed with atmospheric precipitation and wind speed for the diffusive mode of radon transport, but not for the convective. Radon activity concentration in soil air correlates with the radon flux density and air temperature in the case of convective radon transport, but does not correlate in the case of diffusive transport.

Keywords Radon · Convective radon transport · Diffusive radon transport · Weather · Soil · Monitoring data · Moscow · Correlation · Radon flux density · Radon activity concentration

Introduction

\(^{222}\text{Rn}\) is the decay product of \(^{226}\text{Ra}\), which is, in turn, a member of the \(^{238}\text{U}\) decay chain. It is the most common isotope of radon with a half-life of 3.8 d and is considered to be a bigger health hazard than any of the other isotopes of radon. On decay, it produces a plethora of other radioactive elements, of which the alpha-emitters such as \(^{218}\text{Po}\), \(^{214}\text{Po}\), and \(^{210}\text{Po}\) are the biggest health risk. Decay products of radon are electrically charged, and as such, they readily adsorb on aerosols and produce a significant effective dose when they decay further in the lungs. This is the reason why radon is regarded as a class-I carcinogen and is the second biggest cause of lung cancer after smoking, according to WHO (WHO, 2009). Additionally, radon-related lung cancer risk stacks with the lung cancer risk from smoking, making radon even more dangerous to smokers than to non-smokers (Darby et al. 2004).

Governments around the world set their radon limits and acceptable levels in accordance to International Commission on Radiological Protection (ICRP report 126 2014) guidelines. These guidelines set a maximum radon activity concentration of 300 Bq m\(^{-3}\) in dwellings or workplaces, which corresponds to an effective dose of 4 mSv y\(^{-1}\) and 14 mSv y\(^{-1}\) at work and home, respectively.

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Radon flux density (RFD) from the soil surface, content of 226Ra, and, to a lesser extent, radon activity concentration (RAC) in soil gas are routinely measured in Russian Federation in order to assess radiation safety of land lots before construction. However, some of these values may vary with changes in measurement conditions and cannot always be reliable. This is especially apparent due to the existence of radon anomalies, i.e., instances where radon flux density and soil gas radon concentration values are unusually high, that are sometimes observed in locations with otherwise low radon potential. The maximum allowed RFD levels are set in accordance with OSPORB-99/2010 guidelines (Federal Center of Hygiene and Epidemiology of Rospotrebnadzor Basic sanitary rules for radiation safety – OSPORB-99/2010), with 80 mBq m$^{-2}$ s$^{-1}$ and 250 mBq m$^{-2}$ s$^{-1}$ for civilian and industrial constructions, respectively. According to the guidelines, these RFD levels would limit the equivalent equilibrium concentration of radon (EECR) in the finished buildings to 100 Bq m$^{-3}$ or 300 Bq m$^{-3}$, respectively. These EECR values correspond to the RAC values of 300 Bq m$^{-3}$ and 1000 Bq m$^{-3}$ recommended by the ICRP for homes and workplaces.

Soils in Moscow are generally comprised of sand and clay. According to survey data, radon flux density from the surface of the soil in Moscow varies from the soil type: Clay soils generally have higher levels of radon flux on the order of 40 mBq m$^{-2}$ s$^{-1}$, while sandy soils have lower levels of radon flux, averaging around 24 mBq m$^{-2}$ s$^{-1}$ (Miklyaev et al. 2013). These radon flux levels correlate well with radium content in the soil. However, surveys have also found that some locations have anomalously high radon flux densities that do not correlate at all with the soil radium content. These anomalies may cause extremely high levels of radon flux density, averaging several hundreds of mBq m$^{-2}$ s$^{-1}$ and reaching up to 4300 mBq m$^{-2}$ s$^{-1}$, while the radium content of the soil remains within the range characteristic of the soil type. Similar RFD levels are usually found at uranium tailings sites (Sahoo et al. 2010) and are uncharacteristic of the region since the locations in question do not have a history of uranium or rare earth metal production.

Measurements of RFD are generally performed once at about 20 points on a construction site (STC “NITON” 1993). These singular measurements may fail to reflect the real average yearly values of radon flux density due to the variability of weather, seasonal differences, and the possibility of convective radon transport.

Diffusive radon transport is the most commonly observed mode of radon transport and, as such, is used most often when estimating radon flux densities. Diffusive radon transport depends most on the diffusion coefficient of the given soil type and the water content of the soil. As an example of previously mentioned radon potential formulae, the formula used in the UNSCEAR report is a good tool to estimate potential radon flux on construction sites (UNSCEAR 2000).

$$J_D = C_{Ra} \lambda_{Ra} \rho_s (1 - \varepsilon) L$$

where $J_D$ is the radon flux density, Bq m$^{-2}$ s$^{-1}$; $C_{Ra}$ is the specific activity of 226Ra in soil, Bq kg$^{-1}$; $\lambda_{Ra}$ is the decay constant of 222Rn, s$^{-1}$; $f$ is the emanation coefficient, which is the fraction of radon, that escapes the volume of the soil particle; $\rho_s$ is the soil particle density, kg m$^{-3}$; $\varepsilon$ is the soil porosity; and $L$ is the diffusion length, m.

This formula is great for estimating radon flux densities and can be used for mapping radon hazard on a large scale. However, using it may rarely (in about 1% of land lots in Moscow (Miklyaev et al. 2013)) lead to an incorrect estimation of the radon hazard. Such mistakes can usually be attributed to the convective mode of radon transport. In this mode, radon is generated in a much larger layer of soil, and the transport of it is governed by the pressure differential (Nazaroff 1992).

A rough formula for estimating radon flux density $J_{Rn}$ taking into account both convective and diffusive mechanisms of radon transport is given by Yakovleva (2002)

$$J_{Rn} = D_e C_\infty \left[\frac{(\frac{v}{2D_e})^2}{2D_e} + \frac{\lambda}{D_e} + \frac{v}{2D_e}\right]$$

where $D_e$ is the effective coefficient of diffusion, m$^2$ s$^{-1}$; $C_\infty$ is the radon activity concentration in equilibrium with radium, Bq m$^{-3}$; $v$ is the velocity of the vertical convective transport, m/s; $\lambda$ is the 222Rn decay constant, s$^{-1}$.

This model can be used under the following assumptions: Firstly, the soil is approximated to be a uniform isotropic half-space; secondly, radon activity concentration in the atmosphere is assumed to equal zero; thirdly, radon is presumed to move only vertically, and finally, radon in the soil is assumed to be in radioactive equilibrium with radium.

Miklyaev et al. in papers (Miklyaev et al. 2020; Miklyaev et al. 2021) show how convective heat-driven transport occurs on an example of the mount Beshtau in Southern Russia. The mountain is rich in uranium minerals and was previously used as a uranium mining site. Some sites on and around the mountain were found to have anomalously high radon flux density levels which are not caused by the local diffusion of radon from radium-rich soil, and since the mountain is located on a fault line, convective radon transport was suspected.

The role of thermal convection in radon transport has also been described in some other studies: For example, in the article (Lefebvre et al. 2019), the authors describe how soil gas containing radon flux reverses direction with changes in atmospheric temperature at a dump site in Germany. Similarly, in the study by Arvela H. and others (Arvela et al.
1994), it was found that radon concentrations in houses of Tampere that were built on an esker show extreme seasonal characteristics and show higher indoor radon concentrations in winter on the higher parts of the esker and higher indoor radon concentrations in summer on the sloped parts of the esker. This clearly shows how radon transport in the area can be driven by the local ambient air temperature.

Convective transport generally occurs when three conditions are met – Height difference and temperature gradient between the atmospheric and soil air must exist, and soil must be permeable. In this paper, measurements are performed on an experimental site at the base of a mountain. Maximum values of radon flux density, on the order of tens of Bq m$^{-2}$ s$^{-1}$, were observed in summer, with minimums in winter. The seasonal variance observed was most likely due to the reversal of the direction of the convective heat transport, which was caused by the change in ambient air temperature. During summer, cold, radon-rich air from inside the mountain sinks and is exhaled through fractures around the base of the mountain; meanwhile, during winter, the air inside the mountain is warmer than in the surrounding atmosphere; it floats up and is exhaled into the atmosphere through fractures around the peak of the mountain.

Weather influence on radon exhalation is well studied (Ferry et al. 2001; Yang et al. 2017; Schumann et al. 1992), and several main factors that affect radon exhalation are the water saturation of the soil and, sometimes, ambient air temperature. However, most of these studies were performed in climates different from normally cold and snowy Russian winters. The aim of this paper is to link variability in weather and soil types to radon flux density and activity concentration levels in the example of two experimental sites with a differing mechanism of radon transport in the conditions of the Moscow climate.

**Materials and methods**

This study measured radon activity concentration (RAC) in soil gas at a depth of 0.5 m and radon flux density (RFD) from soil surface during several time periods: Nov. 2018–Jan 2019, Apr 2019–May 2019, Nov 2019–Mar 2020, and Jan 2020–Oct 2021. Two experimental sites were chosen for the study: one on the territory of Lomonosov MSU Radiochemistry division (KR) and one on the territory of Neskuchny Garden (NS). The soils on these sites were primarily comprised of clay and sand, respectively. The experimental site Neskuchny Garden is located in Gorky Park on the steep right side of the valley of the Moskva River with an altitude of about 30 m measured from the water level and is about 400 m away from the river. This site was chosen for the experiment as it was previously reported to have

![Satellite map of southwestern Moscow with the locations of experimental sites. 1 – experimental site KR; 2 – experimental site NS](image-url)
anomalously high radon flux density levels averaging about 200–300 mBq m⁻² s⁻¹ and reaching 4300 mBq m⁻² s⁻¹ (Miklyaev et al. 2013). The experimental site on the territory of Lomonosov MSU was chosen as the most convenient place to take background measurements (Fig. 1).

Radon flux density measurements were performed using the open coal chamber method on 4–5 measurement points on each site (Fig. 1). The measurement points were cleared of any debris (such as leaves and snow), and the soil was loosened with a garden trowel before every measurement. The measurements were performed by installing a collection chamber with a set amount of activated charcoal in each spot and exposing them for 3–4 h. After the exposure, activated charcoal is transferred into an adsorption column for transport and temporary storage. Radon progeny is then allowed to build up for about 3 h in order for it to reach a secular equilibrium with 222Rn. After that, the measurements of radon activity in charcoal were carried out by means of a CAMERA-01 measurement complex. The counting chamber measures the beta-activity of radon progeny (²¹⁴Pb and ²¹⁴Bi). This method is described in (STC Niton 1993).

Radon activity concentration in the soil gas (RAC) was measured using the charcoal method. The values of RAC obtained by the charcoal method correspond to the moment of soil gas withdrawal. To do this, soil gas was collected from a probe driven into the ground of one of the experimental sites at a depth of 0.5 m. We could not penetrate deeper because the probe was halted on a pebble horizon located at a depth of 0.5 m. The soil gas samples with a volume of 1.05 l were pumped through an activated charcoal-filled absorption column using a 150-ml syringe (7 strokes at 150 ml). Proceeding measurements of radon activity in charcoal were performed using the 'CAMERA-01' measurement complex as described above.

RFD and RAC measurements were performed in parallel with a frequency of 2–3 times per week. To exclude the influence of daily fluctuations in the radon flux, measurements were performed routinely and at the same time of day (roughly 13:00–14:00 to 16:00–17:00). For the purposes of simplifying data, RFD values given in this paper are an average value for the experimental site on a given day unless specified otherwise.

The content of naturally occurring radionuclides in the soil and soil properties such as density and porosity were determined at both experimental sites. Ra-226 specific activity in soil was determined using HPGe gamma-spectrometer with Maestro software by taking the average of specific activity of ²¹⁴Bi and ²¹⁴Pb (Eγ = 609.3 keV, 295.2 keV, and 351.9 keV, respectively) after a period of 30 d in a sealed container. The containers were sealed using several layers of general-purpose LDPE plastic wrap. Content of ²³²Th and ⁴⁰K was determined using their specific gamma lines at 338.3 keV, 911.2 keV, and 968.9 keV for ²²⁸Ac (decay product of ²³²Th) and 1460.8 keV for ⁴⁰K.

### Table 1 Specific activities of naturally occurring radionuclides in the soil at the experimental sites

| Element | KR A²²⁶Ra (Bq kg⁻¹) | KR A²³²Th (Bq kg⁻¹) | KR A⁴⁰K (Bq kg⁻¹) |
|---------|---------------------|---------------------|-------------------|
| U [²³⁵U] | 2.0±0.2 | [23.72±2.40] | |
| Th [²³⁵Th] | 9.1±0.9 | [36.98±3.60] | 43.9±10.0 |
| K [⁴⁰K] | (2.1%) | [1107±98] | 1133±48 |
| NS U [²³⁵U] | 2.2±0.2 | [26.09±2.5] | |
| Th [²³²Th] | 4.1±0.3 | [16.64±1.80] | 16.6±4.8 |
| K [⁴⁰K] | (1.1%) | [580±49] | 573±15 |

### Table 2 Soil densities and porosity at the experimental sites

| Site | ρₛ, soil particle density, g cm⁻³ | ρₑ, density of dried bulk soil, g cm⁻³ | n, porosity |
|------|---------------------------------|-------------------------------------|------------|
| KR   | 2.71                            | 1.29±0.21                           | 0.52±0.09  |
| NS   | 2.68                            | 1.17±0.12                           | 0.56±0.05  |

### Table 3 Granulometric soil analysis results

| d, mm | %  | KR | NS |
|-------|----|----|----|
| 0.5+  | 2.05 | 5.34 | 3.35 |
| 0.25–0.5 | 5.95 | 41.84 | 18.56 |
| 0.1–0.25 | 9.55 | 19.42 | 34.90 |
| 0.05–0.1 | 14.94 | 13.53 | 15.33 |
| 0.01–0.05 | 10.46 | 8.12 | 8.12 |
| 0.005–0.01 | 5.41 | 8.12 | 5.41 |

### Table 4 Results of the element analysis of the soil

| Element | C, mcg kg⁻¹ (% weight) | A, Bq kg⁻¹ (calculated) | A, Bq kg⁻¹ (gamma-spec) |
|---------|------------------------|------------------------|------------------------|
| KR U [²³⁵U] | 2.0±0.2 | [23.72±2.40] | |
| Th [²³²Th] | 9.1±0.9 | [36.98±3.60] | 43.9±10.0 |
| K [⁴⁰K] | (2.1%) | [1107±98] | 1133±48 |
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| Th [²³²Th] | 4.1±0.3 | [16.64±1.80] | 16.6±4.8 |
| K [⁴⁰K] | (1.1%) | [580±49] | 573±15 |

Values in brackets represent specific activities calculated from the results of the elemental analysis.
Uranium content was determined using ICP-MS following an acidic breakdown of the soil sample. Thorium and potassium contents were also determined using ICP-MS and ICP-AES, respectively, in order to confirm the results of gamma-spectrometry.

Soil porosity was then determined by comparing the volumetric density of dry soil and the density of soil particles according to formula (3):

$$\pi = \frac{\rho_s - \rho_c}{\rho_s}$$  \hspace{1cm} (3)

where \(\pi\) is the porosity; \(\rho_s\) is the soil particle density, g/cm³; and \(\rho_c\) is the bulk dry soil density, g/cm³. Soil particle density was assumed to equal 2.71 g/cm³ and 2.68 g/cm³ for clay and sandy soils of sites KR and NS, respectively.

In addition to soil porosity, granulometric soil composition analysis was also performed using a pipette method (Trofimov and Korolev 1993), which is based on the difference in speed of sedimentation of differently sized soil particles.

Weather data used in this paper was provided by the weather archive website rp5.ru (Raspisaniye Pogodi Ltd 2022) that uses data obtained from the Balchug meteorological observatory in the center of Moscow.

### Results and discussion

After a period of 30 days, gamma-spectroscopy of the sealed soil samples was performed. This period was necessary to allow ²²²Rn and its progeny – ²¹⁴Pb and ²¹⁴Bi, to reach secular equilibrium with ²²⁶Ra. The specific activity of ²²⁶Ra was then calculated using the following formula:

### Table 5 Relevant soil property values

|               | KR       | NS       |
|---------------|----------|----------|
| \(C_{\text{Ra}}\), Bq kg\(^{-1}\) | 32.4 ± 3.6 | 21.5 ± 1.2 |
| \(f\)         | 0.35     | 0.20     |
| \(\rho_s\), kg m\(^{-3}\) | 2710     | 2680     |
| \(\varepsilon\) | 0.52 ± 0.08 | 0.56 ± 0.04 |
| \(D_e\), m² s\(^{-1}\) | \(3 \times 10^{-6}\) | \(3 \times 10^{-6}\) |
| \(L_m\)       | 1.19     | 1.19     |

### Table 6 Radon flux density and soil radon activity concentration at the experimental sites

| Experimental site | Number of measurements | Mean \(\text{RFD}, \text{mBq m}^{-2} \text{s}^{-1}\) | Geometric mean | Standard deviation | Range |
|-------------------|------------------------|------------------------------------------------|----------------|-------------------|-------|
| KR (loam)         | 151                    | 37.4 ± 24.9                                    | 25.8           | 30.7              | 0.3–167.8 |
| NS (sandy)        | 136                    | 93.6 ± 51.2                                    | 72.6           | 66.3              | 9.8–302.2 |

| Experimental site | Number of measurements | Mean \(\text{RAC}, \text{kBq m}^{-3}\) | Geometric mean | Standard deviation | Range |
|-------------------|------------------------|--------------------------------------|----------------|-------------------|-------|
| KR                | 37                     | 13.7 ± 1.5                           | 13.4           | 2.6               | 7.2–23.7 |
| NS                | 106                    | 26.3 ± 2.7                           | 20.1           | 11.7              | 5.0–82.8 |

![RFD monitoring results at the site KR](Fig.2)
The results of the elemental analysis were compared to the results of gamma-spectrometry using average natural radionuclide content ($^{235}$U at 0.7200% for uranium and $^{40}$K at 0.0117% for potassium).

It is generally known that clay soils generally contain more naturally occurring radioactive elements such as $^{40}$K, $^{226}$Ra, and $^{232}$Th compared to sandy soils, which can be seen from the results of gamma and elemental analyses. Results of the soil granulometric analysis prove that soils on the sites KR and NS can be classified as clay and sandy soils, respectively, according to the Kachinsky classification (Tables 1, 2, 3, and 4).

Using a formula given in a UNSCEAR 2000 report (UNSCEAR 2000) and obtained soil data, theoretical average radon flux density in the case of a diffusive radon transport mechanism was calculated for both experimental sites.

$$J_D = C_{Ra} \lambda_{RD} \rho_s (1 - \varepsilon) L$$

Clarification for this formula was given earlier (1).
Values such as emanation coefficients $f$ and diffusion coefficient $D_e$ can be found using the following formulas:

To find the emanation coefficient, a radium-containing sample of known activity is placed into an enclosed volume, and after the radium-radon equilibrium is established, the radon activity of the entire volume is measured (Kovler et al. 2005):

$$f = \frac{A_{Rn}}{A_{Ra}}$$

where $A_{Rn}$ is the equilibrium radon activity in an enclosed volume of air, Bq; $A_{Ra}$ is the activity of $^{226}$Ra in the sample, Bq.

The following formula determines the diffusion coefficient by measuring radon activity concentration in the material at two different depths using a strong radon source, such as a uranium ore powder (Chauhan et al. 2008).

$$D = \lambda \left( \frac{X_2 - X_1}{\ln \left( \frac{A_1}{A_2} \right)} \right)^2$$

where $X_1$ and $X_2$ are the distances to the source of radon, m; $A_1$ and $A_2$ are the radon activity concentrations.

However, calculation of the emanation coefficient using the given formula would ideally require taking a sample of the soil several times over the course of a year, with precautions being taken in order not to draw out the moisture out of the soil sample, which would make the measurement process much more complex. Calculating the diffusion coefficient would similarly require creating a controlled environment and withdrawing several samples, as well as handling a highly radioactive powder. Therefore, fixed values taken from a literary source for the corresponding soil type were used instead (Nazaroff 1992).

According to the UNSCEAR formula, experimental site KR would have an average radon flux density of 46.8 mBq m$^{-2}$ s$^{-1}$ and NS would have 12.7 mBq m$^{-2}$ s$^{-1}$. Experimental site KR was found to have an average radon flux value of $37.4 \pm 24.9$ mBq m$^{-2}$ s$^{-1}$. This value is close to the estimated value for the site of 46.8 mBq m$^{-2}$ s$^{-1}$, which confirms that radon transport on the site KR is diffusive. On the site NS, however, the monitoring results differ greatly from the estimations: The average radon flux value for site NS equals $93.6 \pm 51.2$ mBq m$^{-2}$ s$^{-1}$, while the estimated radon flux value equals 12.7 mBq m$^{-2}$ s$^{-1}$. Additionally, RFD values on the site NS varied widely, from almost no radon flux up to 808 mBq m$^{-2}$ s$^{-1}$ on one of the measurement points. This suggests that most of the time, radon flux on the site NS cannot be attributed to radium-poor layers of top soil and instead has to be generated in a much larger layer of soil and carried out of it by the action of convection (Tables 5 and 6).

By solving Eq. (5) for $L$ and inserting the resulting equation into Eq. (6), diffusion coefficient $D_e$ can be calculated.
using the known value of average radon flux density. A diffusion coefficient of $3.4 \pm 0.9 \times 10^{-6}$ m$^2$ s$^{-1}$ was found for the site KR. For the site NS using the same formula results in a diffusion coefficient of $3.4 \times 10^{-6}$ m$^2$ s$^{-1}$. This adds to the evidence that radon transport on site NS is driven mainly by convection, rather than diffusion.

Using the previously described formula for diffusive-convective radon transport (4), convection speed was estimated for the site NS using the same formula results in a diffusion coefficient of $3.4 \times 10^{-6}$ m$^2$ s$^{-1}$. This adds to the evidence that radon transport on site NS is driven mainly by convection, rather than diffusion.

The results of theoretical RFD estimations and RFD monitoring show that radon transport on site KR can be adequately described using a diffusive radon transport model, while radon transport on site NS must be described using a diffusive-convective model.

RFD monitoring results for both experimental sites are presented in Figs. 2 and 3.

Strong variations in RFD can easily be seen on the graph, which suggests a strong influence that external factors such as weather. Seasons also seem to affect radon transport – During winter months, average RFD values tend to be much lower than in summer and autumn months, especially during the exceedingly warm winter of 2019–2020 with an average ambient air temperature of $-1.0$ °C compared to the average ambient air temperature during the winter of 2018–2019 of $-4.6$ °C. Early-to-mid spring also usually causes dips in radon flux due to the saturation of soil with water due to snow melt. Early spring also makes measurements difficult due to an ice crust forming on the surface of the soil, which is why some of the spring data is missing from the graphs.

RAC monitoring results for both experimental sites are presented in Figs. 4 and 5.

RAC values on the site KR vary with a much smaller amplitude than those on the site NS, with an arithmetic mean of 13700 and a standard deviation of 2600 Bq m$^{-3}$, compared to an AM of 26,300 and an SD of 11,800 Bq m$^{-3}$, respectively. This can be attributed to a much lower permeability of clay soils when compared to that of sandy soils. However, it must be noted that a much lower number of measurements was performed at the site KR due to the availability of probes and blocking of the probe with mud and water during the spring measurement period.

One-sided Pearson correlation analysis was performed on RFD and RAC monitoring data to find correlations with meteorological data. Meteorological factors that were compared to monitoring data were ambient air temperature, wind speed at an altitude of 15 m, and precipitation in the previous 48 h measured in mm. These correlations are presented in Table 7. Correlations in italics indicate that the correlation was found to exist for a $p = 0.95$ and a given $n$.

With $p = 0.999$, correlations between RFD and ambient air temperature were found on both experimental sites: on the site KR, $n = 151$, $R = 0.4527$; on the site NS, $n = 136$, $R = 0.5049$. This falls in line with some of the previous research on the topic (Stranden et al. 1984; Iskandar et al. 2004) and can be explained by both an increase in the diffusion coefficient, which drives the increase in radon flux on site KR, which is defined by diffusion, and an increase in the strength of convection, which is the main driving force behind radon exhalation on site NS (Figs. 6 and 7).

Correlations between RFD and RAC were found with $p = 0.999$ for site NG, $n = 106$, $R = 0.5621$ and with $p = 0.95$, $n = 27$, and $R = 0.3365$ for site NG (Figs. 8 and 9). These correlations show the difference between convective and diffusive radon transport. At the site KR with a diffusive mechanism, RFD and RAC correlate negatively because any factor that causes enhanced exhalation of radon from

### Table 7: Radon correlations for the experimental sites and all measured weather data

| Exp. site | Correlation       | $n$ | $R^2$ | $R$  | $t$-coefficient |
|----------|-------------------|-----|-------|------|-----------------|
| KR       | RFD-T             | 151 | 0.2049 | 0.4527 | 6.20 |
|          | RFD-wind speed    | 151 | 0.0013 | -0.0336 | 0.41 |
|          | RFD-precip. 48 h  | 151 | 0.0004 | 0.0200 | 0.24 |
|          | RFD-precip. 48 h  |     |        |        |     |
|          | warm              | 70  | 0.0834 | -0.2887 | 2.49 |
|          | cold              | 81  | 0.0008 | 0.0279 | 0.25 |
|          | RFD-atm. pressure | 151 | 0.0103 | 0.1014 | 1.24 |
|          | RAC-T             | 37  | 0.0075 | -0.0867 | 0.52 |
|          | RAC-wind speed    | 37  | 0.0228 | 0.1511 | 0.90 |
|          | RAC-RFD           | 27  | 0.1132 | -0.3365 | 1.79 |
|          | RFD KR-NS         | 73  | 0.3491 | 0.5909 | 6.17 |
| NS       | RFD-T             | 136 | 0.2548 | 0.5049 | 6.77 |
|          | RFD-wind speed    | 136 | 0.0255 | -0.1596 | 1.87 |
|          | RFD-precip. 48 h  | 136 | 0.0276 | -0.1661 | 1.95 |
|          | RFD-precip. 48 h  |     |        |        |     |
|          | warm              | 73  | 0.0651 | -0.2551 | 2.22 |
|          | cold              | 63  | 0.0467 | -0.2160 | 1.73 |
|          | RFD-atm. pressure | 136 | 0.0012 | 0.0347 | 0.40 |
|          | RAC-T             | 106 | 0.5531 | 0.7437 | 11.35 |
|          | RAC-RAC           | 106 | 0.0017 | 0.0412 | 0.42 |
|          | RAC-precip. 48 h  | 106 | 0.0091 | 0.0956 | 0.98 |
|          | RAC-precip. 48 h  |     |        |        |     |
|          | warm              | 60  | 0.0007 | 0.0268 | 0.20 |
|          | RAC-precip. 48 h  |     |        |        |     |
|          | cold              | 46  | 0.0055 | -0.0744 | 0.49 |
|          | RAC-RAC           | 106 | 0.3160 | 0.5621 | 6.93 |
|          | RAC-atm. pressure | 106 | 0.0012 | -0.0619 | 0.63 |
the surface of the soil will also deplete the soil of its air, which contains radon. Contrarily, on site NG, convective movement of soil gas causes the values of RAC and RFD to be linked, as radon-rich soil gas moves through the RAC measurement area and enters the atmosphere through the lower part of the experimental site, particularly during the summer months.

It needs to be pointed out that the RAC monitoring data for site KR was only taken during a single season – winter.
2018–2019, making results non-representative for other seasons of the year.

A strong correlation between RAC and ambient air temperature was also found ($n = 106$, $p = 0.999$) on the site NS (Fig. 10), but not on the site KR: $R = 0.7437$ for site NS, $R = -0.0867$ for the site KR. This seems to be caused by the difference in radon transport mechanisms, as discussed previously.

A very weak inverse correlation between RFD and wind speed can be observed for site NS with $p = 0.95$, ...
\[ n = 136, \text{ and } R = -0.1596, \text{ but not for site KR. This may suggest that wind speed may affect radon flux only if the mechanism behind radon flux is convective. No correlations between atmospheric pressure and radon variables were observed.}

Weak inverse correlations were also observed for RFD and the amount of precipitation in the last 48 h for both sites. To exclude winter data, which was done to exclude snow as a source of precipitation, the year was arbitrarily separated into two parts, one of which corresponded to cold months, with primarily negative ambient air temperatures (November–March inclusively), and the other representing warm months with primarily positive air temperatures (April–October inclusively). For site KR, this weak inverse correlation only occurred in “summer” months with \( p = 0.95, n = 70, \text{ and } R = -0.2887, \) while at site NS correlation was observable throughout the year: \( p = 0.95, n = 73, \text{ and } R = -0.2551 \) for warm months and \( p = 0.95, n = 63, \text{ and } R = -0.2160 \) for cold months (\( p = 0.95, n = 136, \text{ and } R = -0.1661, \) for both halves of the year).

Variations of seasons themselves must also be considered for a correct conclusion. The winter period of measurements in 2019–2020 was unusually warm with an average ambient air temperature of \(-1.0 \degree C\) and an average RFD at the site KR of 14 mBq m\(^{-2}\) s\(^{-1}\), while the same period in 2018–2019 was much colder with an average ambient air temperature of \(-4.6 \degree C\) and an average RFD at the site KR of 52 mBq m\(^{-2}\) s\(^{-1}\). The higher temperatures during the winter of 2019–2020 might have caused the topsoil to be saturated with water most of the time, lowering average RFD values.

\[ \text{Fig. 10 RAC and ambient air temperature chart for the site NS} \]

**Conclusions**

Monitoring of radon flux density and activity concentration on two specified experimental sites was carried out over the course of several years. Statistical analysis of the obtained data was carried out. Results show that the two experimental sites have different mechanisms of radon transport and, as such, are affected by external factors, such as variations in weather differently. Site KR has diffusive radon transport, and the radon flux there correlates with ambient air temperature primarily, with a weaker inverse correlation with precipitation (and as such, soil moisture content) during warm months. Radon transport on the site NS is convective and correlates the most with ambient air temperature, but unlike on the site KR, it also correlates with other weather factors such as wind speed and precipitation (ergo, soil moisture) during both summer and winter. While the negative correlation with precipitation is expected, a decrease in radon flow with an increase in wind speed is definitely surprising and may be due to a small data set. Atmospheric pressure was not found to correlate with radon flux or soil air concentration on either of the experimental sites. Radon activity concentration in soil air correlates with radon flux density differently based on the radon transport mechanism on the site: On site KR with a diffusive mode of radon transport, it correlates inversely, while on site NS with a convective mode of radon transport, it correlates directly and correlates with ambient air temperature in addition to correlating with radon flux density. This all means that the most important weather variable in predicting radon...
flux density from the surface of the soil is ambient air temperature. Precipitation is the second biggest weather factor observed, affecting diffusive radon transport mode more than the convective during warmer months, but less during winter. The convective mode of radon transport responds to changes in weather much more intensely than the diffusive mode, being affected by precipitation even during the cold months and reacting to wind speed, which can be explained by the fact that convection is driven by the weather, and by air temperature primarily.

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Author contribution Sakhayaan Gavriliev carried out the experiment and wrote the manuscript with support from Tatiana Petrova and Petr Miklyaev. Tatiana Petrova supervised the project. Tatiana Petrova and Petr Miklyaev provided the equipment for the project.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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