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RESEARCH ARTICLE

The Radon-222 Field Parameters in the Floodplain and Above-Floodplain Terrace Soils of the Irtysh and Tobol Rivers

Gulsem Salimovna Alimova*, Alena Yur'evna Tokareva

Tobolsk complex scientific station of the Ural Branch of the Russian Academy of Sciences, 15 Academician Yury Osipov St., Tobolsk 626152

Study Area: Tobolsk, Russia
Coordinates: 58°12′N; 68°16′E

Key words: Radon flow density, Radon volumetric activity, Radon flow rate, Soil grain-size distribution

Abstract

For the first time, the updated data were obtained on the radon field parameters, namely, the radon flow density and radon volumetric activity in the soils of the floodplain and above-floodplain terraces of the Irtysh and Tobol rivers within the Tobolskiy, Vagayskiy and Yarkovskiy districts of the Tyumen region. The statistical analysis revealed a statistically significant quadratic dependence between the radon flow density from the earth's surface and the subsoil radon volumetric activity in the studied soils with the various grain-size distribution. This trend was determined in the summer during the data analysis of synchronous and space-aligned measurements of the radon field specified parameters in the soil. According to the grain-size distribution, the studied soils are specified by light (23%), medium-textured (25%), and heavy clay (27%) loams, less often by the sandy loams (14%) and sands (11%). The average radon flow density in the sands and sandy loams is 1.1 and 1.7 times lower, and in the light and medium-textured loams is 55% and 21% lower, respectively than in the heavy clay loams prevailing at a depth of 0.4–1 m. The most sensitive parameter of the radon field to the soil grain-size distribution for the combined spatiotemporal measurements is the ratio of the radon flow density from the earth's surface to the subsoil radon volumetric activity, that is, the radon transfer rate. It is confirmed by the works of other authors. A linear decrease in the radon flow rate from a depth of 1 m to the soil surface was revealed.

Introduction:

Radon-222 being an isotope of radon is a radioactive gas (alpha-emitter) with a half-life of 3.82 days. It is part of the uranium-238 decay chain. The radon radioactive precursor (radium-226) is available in the soils and rocks (Bollhöfer & Doering, 2018). The radon-222 field parameters, representing the potential radon hazard of soils, include the radon flow density (Q) from the earth's surface and the subsoil radon volumetric activity (CRn) (Bondarenko *et al*., 2009; Miklyaev *et al*., 2013). In Russia, the studies of the radon field parameters were launched intensively in the late 1990s - early 2000s in the large cities. Its main aim was the radiation survey during the building construction (Miklyaev *et al*., 2013). Both in Russia and abroad, the radon-222 field parameters are studied to identify the uranium deposits and areas with the possible earthquakes, as well as for radiation survey of the former uranium deposits (Matveev *et al.*, 1996; Ryzhakova, 2014; Bollhöfer & Doering, 2018; Nazarov *et al.*, 2018; Firstov *et al*., 2018). The study relevance of the radon field parameters is due to the fact that at present, the high correlation has been established between the radon-222 content in the air and pulmonary cancer in the human body (Clement *et al*., 2016: Yarmoshenko, 2017; Chunikhin *et al*., 2018, Ferri *et al*., 2018). 222Rn is classified as a carcinogenic substance (Darby *et al*., 2009). According to the International Commission on Radiological Protection (ICRP), the main radiation burden (> 50%) on the human body over a lifetime is provided mainly by natural radiating sources, in particular, due to exposure to radon-222 (Dorozhko, 2010).
The study of the radon-222 field parameters in the floodplain soils and above-floodplain terraces is of

**Corresponding Author: gulsem76@mail.ru*

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particular interest since there are often various settlements (villages, townships, settlements, cities) in such areas. The research article analysis over the past 10 years did not reveal information on the distribution of radon-222 in the floodplain soils above-floodplain terraces of the Irtysh and Tobol rivers. Distribution of radon-222 in the soils can be influenced by various external factors, such as meteorological conditions, physical and chemical properties of soils, including the grain-size distribution of soils (De Martino *et al.*, 1998; Chitra *et al.*, 2018; Yang *et al.*, 2019). This paper considers the influence of the most stable factor, namely the grain-size distribution of soils, on the radon field parameters. The aim of this work is to study the 222Rn radon field parameters in the floodplain and above-floodplain terrace soils of the Irtysh and Tobol rivers, considering the grain-size distribution of soils. In order to achieve this goal, the radon field parameters (CRn and Q) were determined, and the radon flow rate CRn/Q was calculated in the soils at a depth of 0 to 1 m within the boundaries of three administrative districts of the Tyumen region - Yarkovsky, Vagayskiy, and Tobolskiy.

Materials and methods:

The studies of the radon field parameters in soils were performed in the summer period - from June 25, 2018, to July 12, 2018, at 24 points of the Tobolskiy, Vagayskiy and Yarkovsky districts of the Tyumen region (Fig.-1). Dorozhko (2010) indicated that a relatively constant radon flow from the earth is observed only in the summer.

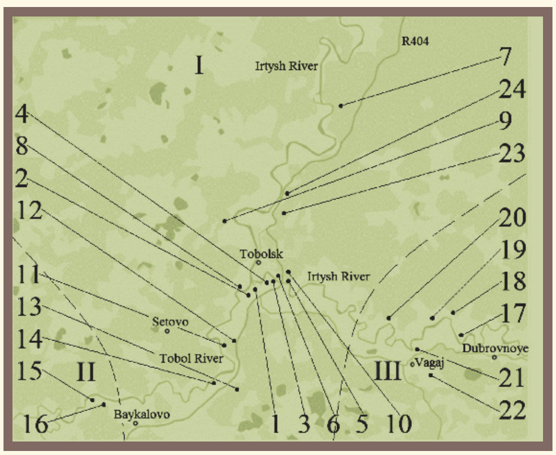

Figure-1: Schematic map of the measurement points for the subsoil radon volumetric activity and the radon flow density from the earth's surface in the floodplain and above-floodplain terrace soils of the Irtysh and Tobol rivers within the Tobolskiy (I) Vagayskiy (III) Yarkovskiy (II) districts of the Tyumen region:
1)58º07.134'N, 68º11.843'E; 2)58º07.2379'N, 68º12.8276'E;
3)58º09.779'N, 68º18.215'E; 4) 58º09.817' N, 68º17.284' E;
5)58º09.017' N, 68º22.717' E; 6)58º09.137' N, 68º21.557' E;
7)58º37.903' N, 68º34.823' E; 8)58º07.538' N, 68º08.362' E;
9)58º19.042' N, 68º07.017' E; 10)58º09.327 N, 68º22.855 E;
11)57º57.596' N, 68º04.299' E; 12)57º58.280' N, 68º08.210' E;
13)57º53.477' N, 68º07.235' E; 14)57º53.473' N, 68º01.633' E;
15)57º50.309' N, 67º28.547' E; 16)57º49.463' N, 67º28.794' E;
17)57º59.486' N, 69º16.445' E; 18)58º03.744 N, 69º12.551 E;
19)58º02.924' N, 69º07.701' E; 20)58º01.335' N, 68º56.814' E;
21)57º58.367' N, 68º59.936' E; 22)57º54.411' N, 68º01.920' E;
23)58º19.009' N, 68º20.264' E; 24)58º24.230' N, 68º22.109' E.

Both in Russia and abroad, the methodological basis for studying the radon field parameters (Q, C_{Rn}) represents its direct measurement using the verified measuring instruments - radiometers and radon survey measurement systems and using the computational method (Q/C_{Rn}) (Matveev *et al.*, 1996; Bondarenko *et al.*, 2009; Ryzhakova, 2014; Nazarov *et al.*, 2018; Noverques, *et al.*, 2019). The most informative depths for solving the radon control issues are the depths of up to 1 m (Yakovleva, 2013). The measurements of Q and C_{Rn} were performed simultaneously directly on the soil surface and in the pits with a depth of 0.2; 0.4; 0.6; 0.8; 1.0 m and a diameter of 0.3 m using a radon radiometer PPA-01M-03 and a radon survey measurement system "Camera-01" in the daytime under the stable weather conditions (air temperature of 23–26ºC, the atmospheric pressure of 760±7 mm Hg, air humidity of 42-76%, partly cloudy, without precipitation). The basic maximum relative measurement error in the entire measuring range of the instruments is ±30%. Three accumulation chambers with activated carbon were installed in order to determine Q at each point at each depth. The radon accumulation was performed for 3 hours. The use of accumulation chambers is a fairly reliable method for determining the radon flow density in the soils [Noverques, etc., 2019]. The total number of Q measurements in the soils is 447. The altitude and geographic coordinates of the studied points are determined by the GPSMAP 62s navigator. The grain-size distribution of the studied soils was determined in the field by the organoleptic method, its classification was made according to Vadyunina & Korchagina (1986). The soil sample density was determined using the standard method (Mamontov, 2017).

The statistical data processing was carried out in Excel using the regression analysis. The correlation ratio between Q and C_{Rn} was assessed using the multiple correlation coefficient R on the Chaddock scale, and the correlation ration between Q/C_{Rn} and the soil depth H was assessed using the Spearman's correlation coefficient r. The quality of the obtained regression equations was assessed using the determination coefficient R^2; its significance was verified using the Fisher's ratio test F for the critical level of statistical significance $P = 0.05$.

Results :

According to the grain-size distribution, the studied soils were specified by light, medium-textured, and heavy clay loams, less often by the sandy loams and sands: light loam (clay content of 15–30%) - 23%; medium-textured loam (clay content of 30–45%) - 25%; heavy clay loam (clay content of 40-60%) - 27%; sandy loam (clay content of 10–20%) - 14%; sands - 11%. The heavy clay loams in the studied soils prevail at a depth of 0.4–1 m (Table-1).

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Table-1: Grain-size distribution of soils at a depth from 0 to 1 m at the selected points (1–25) located in the floodplain and above-floodplain terraces of the Irtysh and Tobol rivers within the Tobolskiy, Vagayskiy & Yarkovskiy districts of the Tyumen region

No.	0 m	0.2 m	0.4 m	0.6 m	0.8 m	1 m
1	MTL	MTL	LL	S Loam*	S Loam*	S Loam*
2	MTL	MTL	MTL	HCL	HCL	S Loam*
3	LL	MTL	MTL	sand	HCL	HCL
4	MTL	S Loam*	HCL	HCL	HCL	HCL
5	LL	LL	LL	MTL	MTL	S Loam*
6	LL	LL	LL	LL	MTL	LL
7	LL	LL	LL	LL	S Loam*	S Loam*
8	S Loam*	S Loam*	S Loam*	MTL	HCL	HCL
9	LL	LL	MTL	MTL	S Loam*	S Loam*
10	LL	MTL	MTL	S Loam*	S Loam*	S Loam*
11	LL	MTL	HCL	HCL	HCL	HCL
12	LL	LL	sand	sand	sand	sand
13	LL	LL	LL	sand	sand	sand
14	MTL	MTL	HCL	HCL	HCL	HCL
15	LL	LL	HCL	HCL	HCL	HCL
16	LL	LL	LL	HCL	HCL	HCL
17	LL	MTL	MTL	S Loam*	MTL	MTL
18	S Loam*	S Loam*	HCL	HCL	HCL	HCL
19	LL	MTL	MTL	MTL	MTL	HCL
20	LL	MTL	MTL	MTL	MTL	HCL
21	LL	MTL	sand	MTL	HCL	HCL
22	LL	MTL	MTL	HCL	HCL	HCL
23	LL	S Loam*	sand	sand	MTL	MTL
24	sand	S Loam*	S Loam*	sand	sand	sand
25	LL	sand	HCL	HCL	HCL	HCL

Note: LL – light loam. MTL – medium-textured loam. HCL – heavy clay loam. S Loam* - Sandy loam

The sand-clay deposits differ in the average values of the volumetric activity C_{Rn}^{av}: the sandy loams have the lowest value of C_{Rn}^{av} that is 38.4% less than the CRnav of sand and approximately 1.1...1.8 times lower than the loams. The average radon flow density Q in the sands and sandy loams is 1.1 and 1.7 times less, and in the light and medium-textured loams, it is 55% and 21% lower, respectively, than in the heavy clay loams (Table-2).

Table-2: Measured and calculated average values of the subsoil radon volumetric activity C_{Rn}, radon flow density Q, and radon transfer rate Q/C_{Rn} for the sandy-clay soils of the floodplain and above-floodplain terraces of the Irtysh and Tobol rivers within the Tobolskiy, Vagayskiy & Yarkovskiy districts of the Tyumen region

Rock	C_{Rn}. kBq/m3	Q. MBq/(m² s)	$\frac{Q}{C_{Rn}}$.10 m/s
Sand	0.047-2.80/0.91	7460/154	146202/169
Sandy loam	0.011.37/0.56	17240/103	89200/154
Light loam	0.0392.55/0.64	7417/78	55201/150
Med.-tex. loam	0.0912.67/0.85	14498/136	90242/166
Heavy clay loam	0.0513.91/0.99	8729/173	84206/169

Note: the minimum and maximum values are indicated above the line. the average values are indicated below the line.

The calculated values of the mean square deviation s for two radon field parameters, CRn and Q, differ in s for Q/CRn by an order or more. Probably the most sensitive specification of the radon field to the grain-size distribution of soils is the ratio of the radon flow density from the earth's surface to the subsoil radon volumetric activity for the combined spatiotemporal measurements (Table-3). The results obtained are consistent with the data presented in the paper by (Bondarenko *et al.*, 2009).

Table-3: Mean square deviations

Rock	$\sigma(C_{Rn})$ kBq/m³	% of average	$\sigma(Q)$ Mbq/(m²s)	% of average	$\sigma(Q/C_{Rn})$ (m/s) 10^{-6}	% of average
Sand	±0.81	89	±132	86	±18	11
Sandy loam	±0.42	75	±78	76	±38	25
Light loam	±0.76	119	±87	112	±47	31
Med.-tex loam	±0.63	74	±103	76	±34	20
Heavy clay loam	±0.91	91	±163	94	±38	22

A linear reduction in the radon transfer rate from a depth of 1 m to the soil surface was noted (Fig.-2). The correlation equation for Q/C_{Rn} and depth H (m) is as follows: $Q/C_{Rn} = 90.23\,H + 141.02$, r = 0.94.

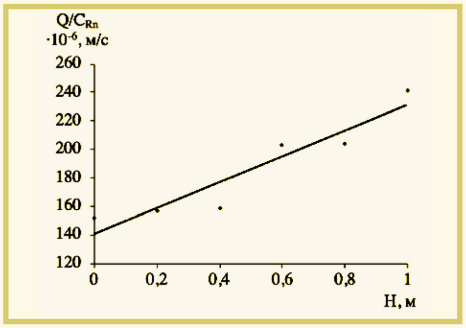

Figure-2: Correlation dependence between the average radon transfer rate (Q/C_{Rn}) and the depth (H) of measurements of the radon field parameters (Q, C_{Rn}) in the sandy-clay soils

As a result of the regression analysis, the statistically significant equations of the quadratic dependence between the subsoil radon volumetric activity and the radon flow density from the earth's surface in the soils with a various grain-size distribution of the floodplain and floodplain terraces of the Irtysh and Tobol rivers were obtained (Table-4).

Table-4.Regressional dependences of the radon flow density (Q) on its volumetric activity (C_{Rn}) in the soils with the various grain-size distribution of the floodplains and above-floodplain terraces of the Irtysh and Tobol rivers within the Tobolskiy, Vagayskiy and Yarkovskiy districts of the Tyumen region

Grain-size	Regression equation	R	R²
Sand	$Q = -10.47 \cdot C_{Rn}2 + 190.79 \cdot C_{Rn} - 4.16$	0.99	0.99
Sandy loam	$Q = 3.89 \cdot C_{Rn}2 + 189.33 \cdot C_{Rn} - 14.07$	0.98	0.97
Light loam	$Q = -45.01 \cdot C_{Rn}2 + 200.91 \cdot C_{Rn} - 5.21$	0.82	0.70
Med-text loam	$Q = -40.33 \cdot C_{Rn}2 + 240.26 \cdot C_{Rn} - 22.90$	0.87	0.76
Heavy clay loam	$Q = 9.59 \cdot C_{Rn}2 + 119.62 \cdot C_{Rn} + 64.164$	0.98	0.96

Note: R – multiple correlation coefficient, R² – determination coefficient

Discussion:

The points 1, 3, 8, 11, 14, 15, 17, 21, 24 were located on the territory of modern Upper Quaternary alluvial deposits of the floodplain and the first above-floodplain terrace of the Tobolskiy mainland and the Middle Irtysh plain. The points 5, 6, 7, 10, 18, 19, 20, 23 were located on the Lower-Middle Quaternary alluvial deposits of the Tobolskiy mainland. The points 2, 4, 9, 12, 13, 22 were located on the Upper Quaternary lacustrine-alluvial deposits of the second above-floodplain terrace of the Middle Irtysh plain. Point 16 was located on the Upper Quaternary lacustrine-alluvial deposits of the third above-floodplain terrace. Thus, the area under study is located in the southern taiga zone, the terrain of which is represented by the Quaternary deposits of low lacustrine-alluvial terraces of different ages. The Quaternary glacial clays refer to the clays that are the most radioactive after the Jurassic clays that accumulate the natural radioactive substances being a potential source of radon release (Dorozhko, 2010).

The diffusional movement rate of any gas depends on the soil density (Mamontov, 2017). In the heavy clay loams, it will be less than in the sandy loams and light loams (from 882 to 1200 kg/m3), since the soil density is higher and ranges from 1042 to 1459 kg/m^3. Radon-222 is a part of the soil atmosphere. In the loams, the free air is isolated in the pores by the water plugs, and the diffusion rate through the aqueous medium is several orders lower than in the gaseous medium. The entrapped air accounts for more than 12% of the pore space of the total loam volume. Another factor affecting the radon-222 concentration in the loams is the gas adsorption on the clay particle surface due to an increase in soil dispersion (Mamontov, 2017).

The maximum value of the radon flow density was found at a soil depth of 1 m at the measurement point No. 22, namely, 729 mBq/(m^2s). The measurement point is a floodplain at the confluence of the Irtysh and Vagai rivers at a distance of 5 km from the Vagai village, Tyumen region, the altitude is 143 m. Rather high values of Q were also found at the measurement point No. 3 at a depth of 0.6 m - 387 mBq/(m^2s), and at a depth of 0.8 m - 559 mBq/(m^2s). This is the floodplain of the left bank of the Irtysh river near the Isenevskaya village, Tobolskiy district, the altitude is 138 m. The similar increased values of Q were observed at the point No.12 that is the coastal zone of the Tobol river at a distance of 2 km from the Bolshaya Blinnikova village in the Tobolskiy district, at a depth of 0.6 m - 460 mBq/(m^2s), and at a depth of 0.8 m - 358 mBq/(m^2s), the altitude is 139 m. It is possible that the important role is played by the suspended loads of the rivers that annually fall on the floodplain during the flood seasons, containing the contaminants, including the radionuclides of the uranium-238 decay chain.

The higher areas under study, namely, the points No. 5 and No. 7, located at an altitude of 328 and 189 m, also shown high Q values - 498 mBq/(m^2s) at a depth of 0.8 m (No. 5) and 499 mBq/(m^2s) at a depth of 1 m (No. 7). The measurement point No. 5 was a high terrace (mixed forest) on the right bank of the Irtysh river near the highway bridge in the Tobolskiy district, and No. 7 was a pine forest on the slope near the Nadtsy village in the Tobolskiy district.

The average radon flow rates (Q/C_{Rn}) in all grain-size soil fractions (sands, sandy loams and loams) almost do not vary, the difference is no more than 11% (Table-2).

The quadratic dependences between the subsoil radon volumetric activity and the radon flow density from the earth's surface can be explained by a sufficient increase in the radon flow rate Q/C_{Rn} when the Reynolds number is 1 or more. In this case, the ratio between the radon flow rate and the pressure gradient in the medium deviates from the linear form of Darcy's law as a result of the inertial quadratic flow resistance. The occurrence of non-linear dependency between these radon field parameters is also typical for the rock formation - schists (Bondarenko *et al*., 2009).

Conclusion:

The grain-size distributions of the soils under study include the light (23%), medium-textured (25%) and heavy clay (27%) loams, less often the sandy loams (14%) and sands (11%). The average radon flow density in the sands and sandy loams is 1.1 and 1.7 times lower, and in the light and medium-textured loams is 55% and 21% lower, respectively than in the heavy clay loams prevailing at a depth of 0.4–1 m.

The quadratic dependence has been established between the radon flow density from the earth's surface and the subsoil radon volumetric activity in the sandy-clay soils of the floodplains and above-floodplain terraces of the Irtysh and Tobol rivers within the Tobolskiy, Vagayskiy and Yarkovskiy districts of the Tyumen region.

The most sensitive parameter of the radon field to the soil grain-size distribution for the combined spatiotemporal measurements is the ratio of the radon flow density from the earth's surface to the subsoil radon volumetric activity, that is, the radon transfer rate. It is confirmed by the works of other authors. A linear decrease in the radon flow rate from a depth of 1 m to the soil surface was revealed. There is a linear decrease in the radon flow rate from a depth of 1 m to the soil surface.

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