Applied Chemical Engineering (2024) Volume 7 Issue 2
doi: 10.59429/ace.v7i2.1865

ORIGINAL RESEARCH ARTICLES

Development of a methodology for radon pollution studies based on algorithms taking into account the influence of constant mountain-valley winds

Andrey A. Sokolov[1,*], Vladimir A. Fomenko[1], Maria A. Aksenova[1], Nikita V. Martyushev[2], Boris V. Malozyemov[3], Manshuk F. Kerimzhanova[4]

[1] *Department of Natural Sciences and Humanities, Southern Federal University, Branch of the Southern Federal University in Gelendzhik, st. Zastavnaya 10 A, 353461 Gelendzhik, Russia*

[2] *Department of Advanced Technologies, Tomsk Polytechnic University, 634050 Tomsk, Russia*

[3] *Department of Electrotechnical Complexes, Novosibirsk State Technical University, 20, Karla Marksa ave., 630073 Novosibirsk, Russia*

[4] *Department of Mechanical Engineering, Institute of Energy and Mechanical Engineering, Satbayev University, KZ-050000 Almaty, Republic of Kazakhstan*

*** Corresponding author:** Andrey A. Sokolov, anso@sfedu.ru

ABSTRACT

The article describes the development of a methodology for radon pollution studies based on algorithms that take into account the influence of constant mountain-valley winds. The solved problem of the study of radon emanations arising from the stress-strain state of rocks is an important step in the study of man-made bulk arrays on the environment and the assessment of radiation safety. Decommissioned tailings dumps eventually dry up and turn into hardening man-made bulk arrays, which negatively affect the surrounding ecosystems. The proposed methodology is implemented on the basis of the proposed algorithms for determining the optimal choice of measurement conditions, taking into account the influence of constant mountain-valley winds. As an approbation of the methodology, field studies were carried out, including measurements of the equivalent equilibrium volume activity of radon-222 at various points of the tailings dump. For this purpose, specialized methods and devices were used, which made it possible to determine the concentration of radon in the air and evaluate its emanations from the tailings dump. The data obtained were processed and analyzed using specialized software and algorithmic software, which allows for a detailed analysis and evaluation of the values.

Keywords: radon pollution; environmental safety; methodology; algorithm; mountain-valley winds

ARTICLE INFO

Received: 20 July 2023
Accepted: 20 November 2023
Available online: 13 March 2024

1. Introduction

Radon is one of the main sources of ionizing radiation for humans. A high concentration of radon in the air can lead to the development of radon hazard, which can become a serious threat to human health and life. Inhalation of radon and its daughter products can cause lung cancer, especially in smokers. In addition, radon can accumulate in buildings and become a source of radioactive radiation indoors. Improving the quality of human life includes not only improving physical and psychological well-being, but also protection from various types of pollution, including radon. Therefore, it is necessary to take measures to reduce the concentration of radon in the air and prevent its accumulation in buildings.

To reduce the concentration of radon, it is necessary to monitor the level of radon in the air, especially in mountainous areas, and take appropriate measures to eliminate the sources of its formation. This may include improving indoor ventilation, sealing cracks and crevices, using special sorbents and filters to purify the air.

It is also necessary to carry out information work among the population about the dangers of radon and methods of its reduction. It is important to pay attention to the education and prevention of radon hazard in mountainous areas, especially in tourist and recreational areas. It is possible to establish special signs and warning information for visitors about the presence of radon in the area. In addition, it is important to pay attention to the environmental aspects of the mining industry and take measures to reduce radon emissions into the environment. This may include the use of modern technologies and methods of ore enrichment, as well as monitoring of tailings and radon content in waste.

Thus, improving the quality of human life and protecting it from radiation pollution includes not only protection from ionizing radiation, but also taking measures to reduce the concentration of radon in the air and prevent its accumulation in buildings and the environment. First of all, it is necessary to monitor radon in places of potential danger, where there are stress-deformable sections of rocks and. in particular, decommissioned desiccated tailings dumps.

For preliminary studies, the North Caucasus was chosen, where the recultivated alluvial massif of the floodplain type of the Unalsky tailings dam (Republic of North Ossetia-Alania), located at an altitude of 1670 meters, was studied, and the hypothesis of the use of radon-222 field data to assess and characterize the stress-strain state of the tailings body and to justify further studies of factors, affecting the stability of the tailing dump during flooding, seismic, geodynamic and man-made impacts.

Radon is one of the main sources of ionizing radiation affecting humans, basically all of its daughter decay products have a positive charge in relation to the earth. Radon, as an isotope, is designated in the special literature as 222Rn is a monatomic inert gas, 7.5 times heavier than air, with a half-life of about 4 days, well soluble in water, blood plasma, actively adsorbed on sorbents, for example activated carbon. The insidiousness of radon lies in the fact that its entire subsequent series are elementary positively charged ions or monatomic metals that actively interact with dust microparticles and aerosols in the air and are easily transported by wind over long distances. This explains its ability to “attract and stick” well to negatively charged bodies that have a physical connection with the “negative” earth. The products of radioactive decay of radon emitting alpha-beta particles and gamma rays ionize the air, causing various phenomena in nature. Such phenomena can be considered “blue glow” over faults during earthquakes, the presence of geopathogenic zones, malaise during summer calm, etc.[1–3].

The volume activity of 222Rn is measured in Bq/m^3, which roughly corresponds to the number of radioactive decays per cubic meter and varies in the atmosphere from 1 to 10 Bq/m^3 (on average 4 Bq/m^3), but this is not the case everywhere. In the North Caucasus, values of 200 or more Bq/m^3 were recorded in some places. Sometimes there are also “hurricane” values of radon volume activity of 60,000 Bq/m^3 or more in places of faults and geodynamic disturbances, for example, the North-Western Caucasus.

After recultivation of the surface and slope of the Unalsky tailing dump in 2018, covering it with a layer of a special mixture and soil, changes in the state of its bulk were noted, in particular water content, crack expansion, internal stresses and the associated increase in radon emissions.

Mountain-valley winds are constantly blowing in the studied area. And there is also a transfer of air masses caused by climatic conditions that violate the stability and adequacy of the measurement of radon emanations, introducing significant errors. In some cases, the magnitude of the measurement error of emanations caused by wind gusts is equal or almost equal to the magnitude of the measurements.

In this regard, the development of a methodology for radon pollution studies based on algorithms that take into account the influence of constant mountain-valley winds is an urgent task that solves the problem of the accuracy of measurements of radon emanations, and therefore increases the adequacy of the assessment of environmental safety of the region[4,5].

2. Purpose of research

To develop a methodology for radon pollution studies based on algorithms that take into account the influence of constant mountain-valley winds.

3. Object of research

As an example of the implementation of the proposed methodology, the Unal tailing dump located in the Alagir Gorge between the Transkam federal highway and the Ardon River was chosen. The banks of the river contain an abundance of loose moraine and gravitational material, and difficult weather conditions constantly create associated seismic and mudflow hazards. The basin of the Ardon River is composed of easily eroded limestones and organogenic sandstones, dark gray clays not calcareous with fine pebble conglomerates of various capacities. According to estimates of seismic hazard and maps of general seismic zoning, a significant part of the North Caucasus belongs to the 8- and 9-point zones, including part of the Alagir Gorge.

The recultivated tailings dump is located on the left bank slope of the river with slopes of 12–16 degrees in the zone of influence of the seismically active from the Late Jurassic-Early Cretaceous epoch to the present time of the Ardon fault with the well-known Ardon seismogenic node[6], as shown in **Figure 1**.

Figure 1. Location of the Unal tailings dump.

The lower eastern part of the tailings dump is completely shielded by an inclined concrete embankment up to 5 meters high, located directly at the edge of the river. In some places, the embankment is directly adjacent to the stream. The shore is separated from the berm by an embankment about 6 meters high and about 1000 meters long, while no fragments of erosion or leakage were found. No cracks were visually detected on the surface of the plowed mound layer. The northern curb is made in the form of a concrete dam with a vertical step from the road to the water's edge. Along the entire length of the tailings dump, the roadside is fenced with concrete structural elements. In the middle of the road there is a bridge under which a dry channel runs, which serves to partially drain flood waters from the slope adjacent to the road on the other side, as shown in **Figure 2**.

Figure 2. Dry channel near the tailings dump.

The channel continues all the way to the top and goes directly to the surface of the tailings dump. Currently, the main flood stream is discharged directly into the river through an uncut drainage channel located to the right of the bridge, along the roadbed, forming its own channel. The wall of the culvert is vertical, at a depth of about 2 meters and a width of up to 3 meters, parts of the tailings dump are clearly visible. In the section, fragments of backfill and reclamation layers of various thicknesses (from 0.1 meters to 1 meter) and structures, as well as various granulometric composition with varying shades of color between the layers are exposed. The tailings dump, located in the left-bank part of the floodplain of the Ardon River near the village of Nizhny Unal, contains about 2 million tons of crushed ore fragments. The surface was filled in to a thickness of about 2 meters, after which it was drained. The change in the internal structure of the tailings dump as a result of drying led to the accumulation of internal stresses in its array, an increase in fracturing and the opening of numerous vertical cracks. Measuring the radon flux density on the surface of the tailings pond is difficult due to constant gusty winds, which are often reversible and are probably the cause of increased purges in the tailings pond array. A preliminary study conducted in July 2022, measuring the equivalent equilibrium volume activity of radon in specially installed pits, revealed an increase in the radon content in the tailings. To carry out work related to the measurement of radon concentration in the Ardon River gorge, it is necessary to develop a special methodology based on the proposed algorithms that take into account the influence of wind and local climatic conditions[7,8].

4. Materials and methods

The primary data on the object of research are as follows: the tailings dump has an oval shape, its length is 1000 m, width (maximum value) is 300 meters; area is 16 hectares; the volume of tailings accumulated since 1984 is about 3 million tons. The tails contain, in small quantities, the following ore minerals: sphalerite, galena, pyrite, pyrrhotite, chalcopyrite, arsenopyrite, bornite, marcasite and magnetite; non–metallic minerals - quartz, chlorite, siderite, calcite. According to the degree of danger, it is assigned to the 2–3 level of danger. After recultivation, backfilling of the upper part of the tailings dump with a 2.5-meter layer of soil, its surface was partially transformed into a local steppe territory with vegetation and inherent elements of the foothills of the Caucasus[9–11].

The inner body of the tailings dump with a capacity of alluvium up to 30 meters today is a mobile watered substance of a mixture of clays, sands and rock grinding products with the consistency of quicksand, starting from 9 meters along the section, the fact of erosion of the body of the tailings dump by rainfall with the formation of a pit with the exposure of a part of the body of the tailings dump has been established. It should be noted that additional dumping (recultivation) of the surface by soil led to a redistribution of the stress-strain state in the body of the tailings dump, and gradual drying led to a decrease in the water content of the internal volume and, as a consequence, the appearance of new stretch areas with increased fracturing and compression zones. An increase in fracturing leads to an increase in the magnitude of the fluxes of ascending gases. In areas of increased fracturing, the flow of ascending gases in relation to the compression zones will be greater. The radon migration of the resulting tailings body in the watered rocks is small, about 60 cm per day.

In the course of field research, the authors found sinkholes on the surface of the tailings dump, subsidence of the surface of more than 2 meters and local-extended ruptures, one of which is shown in **Figure 3** below.

Figure 3. One of the locally extended discontinuities.

Thus, by determining the amount of radon in the emanating tailings, it is possible to judge the state of the body of the tailings dump, which will further characterize the possible technogenic impact of the tailings dump on the environment, with subsequent assessment and prediction of the environmental damage caused.

The methodology developed by the authors includes several stages that are interconnected and represent a single set of measurements, including algorithms that take into account the influence of mountain-valley winds. The proposed method in the process of implementing exposure time exposure when measuring radon from a buried pit is passive, and in the process of performing further work when installing additional sensors and performing research on mobile measurement, the method is transformed into active.

4.1. The first stage

The first stage includes the selection of points for measurements taking into account the stress-strain state of the tailings body and the arrangement of special pits. The pits are carried out according to a proven method of arrangement, in which the device is provided to be buried to a depth of 0.3 meters and covered from above with a powder from the excavated soil. The measured values in the “pit” showed values of 380 Bq/m^3, repeated 460 Bq/m^3, with an acceptable MPC of 200 Bq/m^3. The radon radioactive gas detector RADON MR 107 was used for measurement, the technical characteristics of which are presented below in **Table 1**.

Table 1. Characteristics of the RADEX MR107 device.

Parameters	**Information**
Measuring range, Bk/m^3	from 1 to 100,000
The level of EROA for triggering the sound signal, Bk/m^3	from 1 to 100,000

Measurement duration, min	10, 20, 30, 60
Operating time from the built-in battery, h	120
Number of stored values in memory	10,000
Data transfer interface	microUSB, Bluetooth
Batteries	Built-in Li-Pol battery
Operating temperature range °C	from +10 to +35
Relative humidity of the air, %	no more than 90
Overall dimensions, mm	153 × 80 × 43
Weight, kg	0.27

As a result of the analysis of the results of intermediate studies, preliminary conclusions can be drawn that a seasonal pulsating mode of gas emanation should be expected due to unsteady equilibrium in the stress-deformable state of the body. Constant monitoring of the equivalent volume activity of radon in combination with additional measurement methods will allow us to develop an express method for assessing impact zones with abnormal pollution levels. Gradually, over a long period of time (years), the waterlogging zones will decrease, the pore space will be freed from water, fracturing will grow, the radon value will increase. The surface is subject to subsidence and deformation. In order to monitor the above factors, according to the researchers, it is necessary to equip specially equipped wells for monitoring the water level, assess the degree of danger of seismic impact on the tailings dump, and also investigate the seismic background of the body of the tailings dump with the help of seismic stations, since it is geographically located in the zone of possible nine-point earthquakes.

In order to determine the amount of shrinkage and determine the deformation of the surface, perform appropriate work using a global positioning system and other methods to visualize the results of research using geoinformation technologies[12,13].

4.2. The second stage

The second stage of the methodology is associated with a preliminary study of the mechanisms of migration of radon-containing soil gas by leakage from water-filled pore spaces and cracks, and diffusion through water-filled cracks, as well as environmental and social consequences considered in the researches of Sokolov et al.[14–16]. The gas permeability of the empty ore rocks composing the tail body should vary depending on the composition of the rocks, the stress-strain state of individual sections of the tail body. For a reliable interpretation of the results of observations, it is necessary to take into account the influence of this factor on gas permeability in each case. Calculations and experimental data show that the rate of radon transport through aquifers is 40–60 cm per day, which limits the outflow of radon from the space below the river level, with the exception of geological and seismological phenomena; in soils consisting of particles less than 0.5 mm in size, gas permeability increases with increasing water saturation. It decreases rapidly and is almost zero at a saturated humidity of 20–30%[17].

Studies have shown that with a particle humidity of up to 30%, air exchange between the soil and the atmosphere occurs through cracks and pore spaces. With a higher moisture content, gas exchange is significantly reduced. These features make it possible to control the stress state of gas permeability, and to carry out current operational control in natural conditions of the tailings storage facility[18].

With water absorption of more than 0.6% (or about 50% of open pores), “extreme” values of divergent ability are achieved, differing by more than 100% from the values of samples in dry conditions. According to Musa and Ahanonu[19], where the experiment is described, it is characterized by a certain decrease in divergent ability with water absorption above 1.5% (corresponding to more than 70% of open pores), while maintaining extreme values and under conditions favorable for radon migration (good permeability of sediments, the presence of a gradient in the medium necessary for gas migration). The depth of the divergence study does not exceed 10–12 m, since even under these conditions radon is formed at a depth of 10–12 m. This is due to the fact that radon formed at great depths will completely disintegrate before reaching the surface. Therefore, it can be argued that radon emission occurs mainly from the volume from the zero mark of the surface to the water level in the tailings pond. This is the most dynamic volume that characterizes the state of the tailings dump. Therefore, it is possible to normalize the results of actual measurements of radon-type volatile gases by the average value of radon emission. Thus, it is possible to observe zones of expansion, compression, dispersion, indirect subsidence, geodynamic and seismic effects of the geological environment on the internal volume of tailings. Regular observations allow us to assess the dynamics of these parameters, especially in the telemetry mode[20].

Seasonal pulsating modes of gas release are expected, due to the non-stationary equilibrium of the stress-strain state of the body. Over a long period of time (years), the additive zone decreases, and the pores are released by taps. In our methodology, gas permeability is a function of geodynamic stress rearrangements, seismic events, granulometric composition, porosity, fracturing, and the degree of soil moisture saturation. The porosity and fracturing of the soil also depend on the stress-strain state of the tail body. As a result, the gas permeability of dispersed rocks should depend on the stress-strain state of individual sections of the tailings. This is a physical prerequisite for assessing the condition of the tailing dump. However, for reliable interpretation of observations, it is necessary to take into account in each case the effect on gas permeability according to calculated and experimental data of radon transport through wet crushed stone and heavily watered bedrock, where radon transport slows down to a speed of 40–60 cm/day[21]. Seasonal humidification of the tailings dump as a result of precipitation changes the amount of divergence and the redistribution of forces and deformation vectors[22].

4.3. Third stage

As already noted above, the wind blows almost constantly in the area of the tailings dump. Therefore, it is not possible to carry out accurate measurements directly on the surface of the tailings dump. To solve the problem, an algorithm was developed for the optimal choice of location, time and measurement conditions, taking into account the influence of mountain-valley winds, presented in **Figure 4**.

The algorithm in the monitoring blocks and deterministic and probabilistic models takes into account seasonal changes in the surface runoff and mountain-valley wind fields were analyzed for the Unal tailings dam using hourly average data on wind speed and direction obtained from regional automatic stations. In the analysis, the wind vector (□, □) was calculated using the formulas:

$$u = U \times sin(W \times \pi/180) \tag{1}$$

$$v = U \times cos(W \times \pi/180) \tag{2}$$

where □ (m/s) and □ (m/s)—wind vector, □ (m/s)—wind speed values, □$(0^\circ - 360^\circ)$—wind direction values.

Interpolation of data for the wind field was carried out by the interpolation method based on mathematical modeling of atmospheric aerodynamics and the spread of pollutants over a complex underlying surface, where the behavior of atmospheric flows in mountain gorges is considered.

Obtaining an array of measurements and processing data is our goal, which implies in our future work the development of algorithms for determining the optimal choice of conditions for measuring radon and its daughter decay products, taking into account the influence of atmospheric flows of mountain-valley winds as shown in **Figure 5**. The algorithm allows using deterministic and probabilistic models to select the most optimal conditions for measuring the direction and the speed of mountain-valley winds, which will be described in more detail in subsequent articles.

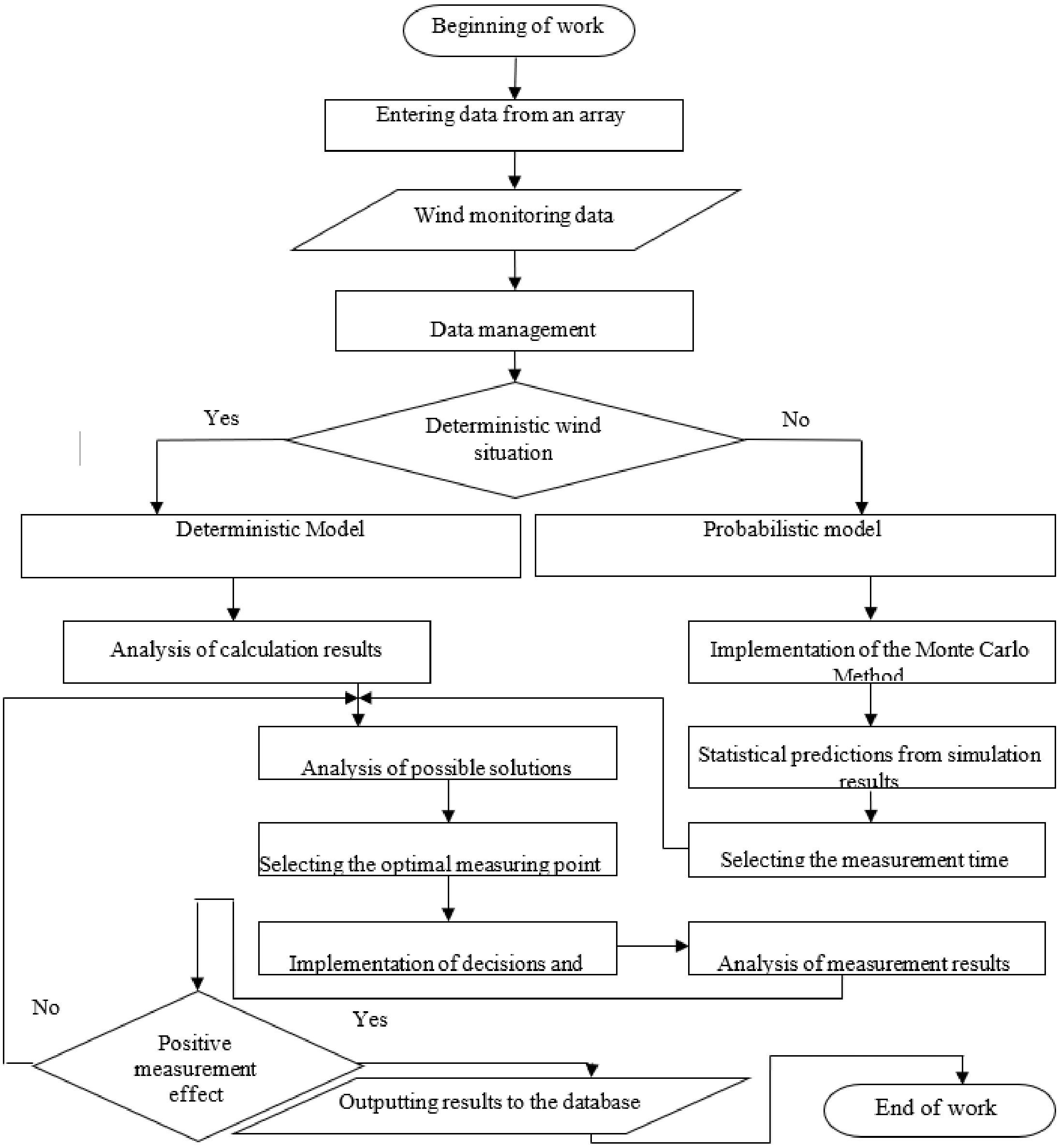
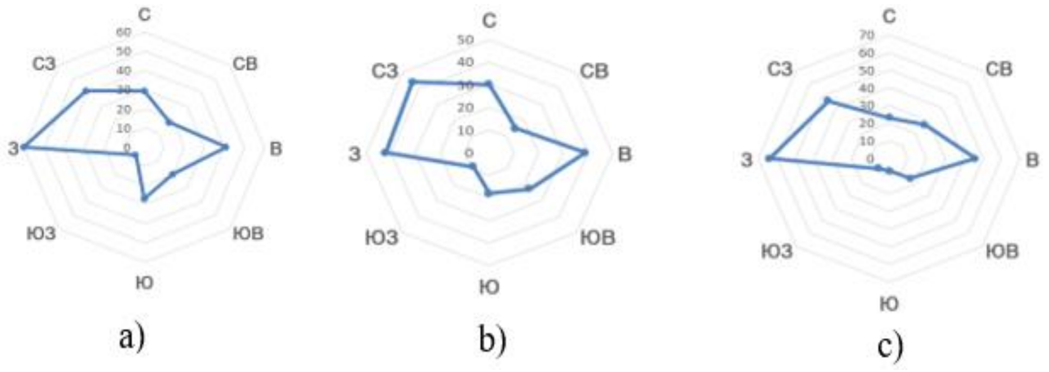


Figure 4. An algorithm for the methodology of measuring radon emanations taking into account the influence of winds.



a) b) c)

Figure 5. The significance of the distribution of wind directions for the summer months in the period 2015–2022. a) June; b) July; c) August.

In the process of working in the algorithms, both deterministic and probabilistic mathematical models were analyzed, taking into account the data obtained from the instrument for online measurements. The algorithm takes into account the situation in which the wind direction should be typical for the month of work in order to exclude changes in aerosol dispersion concentrations. Such a parameter as wind speed should be within 5–10 m/s, which corresponds to moderate wind strength (4–5 points on the conditional 12-point Beaufort scale). Firstly, such a condition for wind speed was chosen for comfortable research, and secondly, to minimize interference associated with the spread of other aerosol and dusty substances.

4.4. Fourth stage

At this stage, directly related to measurements, the selection of devices that meet the climatic conditions for measurements is carried out[23–25]. In our case, this is a radon radioactive gas detector RADEX MR 107, designed for the initial detection of radon emissions. After determining the points, the measurement is started using a professional device “Alfarad + R”, the characteristics of which are given in **Table 2** below.

Table 2. Characteristics of the device “Alfarad+R”.

Parameters	Information
Measuring range of radon-222 volumetric activity in the air, Bk/m^3	from 1 to 2.0 × 10^6
The limit of permissible basic relative error in air samples	± 20%
Volumetric flow rate of the microblower, l/min	1.0 ± 0.2
The level of the volume activity measurement unit’s own background, Bk/m^3	not more than 0.3

4.5. Stage five

This stage of the methodology is devoted to the results of preliminary studies, which allowed us to formulate the necessary assumptions under which measurements of radon emanations are most accurate and adequate.

1) Sampling sites are not subject to significant seasonal disturbances.
2) The natural and climatic conditions in the studied canyon, especially the amount of precipitation, should not change abnormally before sampling.
3) Sampling should preferably be carried out in autumn on fallen leaves in depressions where the post-dump movement is limited.

It should also be noted that dust particles transferred earlier from unexplored tailings dumps significantly increased the concentration of geochemical pollutants throughout the gorge, including other radon compounds, which complicates the task.

5. Discussion of research results

The results of measurements obtained by the proposed method based on the developed algorithm are shown in **Figure 6** and in **Table 3**.

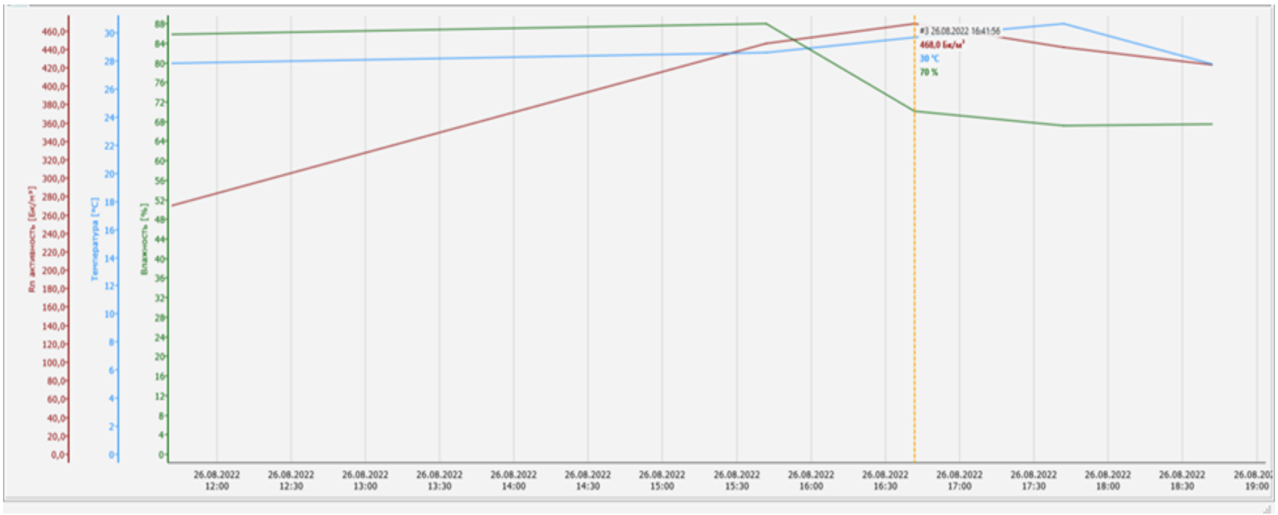


Figure 6. Graph of the measured values of the equivalent equilibrium volume activity of radon.

Table 3. Measurement result.

Points sampling	Exposition (h/min)	Radioactivity (bq/m^3)	Temperature (°C)	Humidity (%)
1	4:00	393	25.3	82
2	4:00	443	26.7	76
3	4:00	452	27.2	72
4	4:00	428	28.9	70
5	4:00	456	26.5	71

As a result of the implementation of a number of research activities to assess the geoecological stability of tailings with the use of seismic and GPS satellite equipment, including justification of the points of laying control wells for monitoring radon emanations. Special algorithms have obtained a number of data on radon 222 emanations. According to the data, it is possible to further assess the threat to the environmental safety of the region, which makes a certain contribution to the development of express methods for diagnosing the level of pollution of anomalous zones and risk assessment for adjacent environments using the latest geophysical, geochemical and geostatic methods.

After the fact of the presence of elevated radon concentrations was established as a result of field studies, further measurements were carried out using a professional device “ALFARAD + R”, which confirmed the data obtained using RADEX MR107.

In the future, based on the proposed methodology, the authors plan to develop the structure of a geo-economic monitoring system to assess the impact of anomalous zones, such as tailings dump on environmental quality and public health, as well as the structure of a system for diagnosing radon emanation pollution of the studied territories to assess the state of similar anomalous zones of technogenic pollution and their impact on adjacent environments using spatial modeling methods.

The proposed methodology for radon pollution studies based on algorithms that take into account the influence of constant mountain-valley winds can also be used to monitor other alluvial and bulk man-made massifs formed as a result of mining and processing plants located in various regions of the Russian Federation.

6. Conclusion

In conclusion, the authors formulate the following:

The proposed methodology allows for accurate measurements by minimizing the influence of mountain-valley winds on experimental studies, provided that all five stages are consistently implemented and taking into account these assumptions.

The need to take into account gas permeability indicated in the second stage of the methodology should be taken into account simultaneously with the moisture permeability of rocks, since in our opinion the ability of moisture to seasonally penetrate into the pore space of the rock can prevent the free release of radon, and then, increasing at times during drainage, radon concentrations can be dangerous, because the amount of enameling increases confidently when the tailings body is drained.

The problem of normalization of the negative impact of radon emanations should be investigated additionally during repeated expeditions for possible identification of technogenic effects of radon fields on the environment and society.

Author contributions

Conceptualization, AAS and VAF; methodology, VAF; software, BVM; validation, MAA and MFK; formal analysis, AAS; investigation, NVM; resources, MFK; data curation, MAA; writing—original draft preparation, VAF; writing—review and editing, VAF; visualization, BVM; supervision, AAS; project administration, AAS; funding acquisition, NVM. All authors have read and agreed to the published version of the manuscript.

Funding

The research was carried out at the Southern Federal University at the expense of the Russian Science Foundation (project no. RNF/23-37-GL, no. 23-77-00015).

Data availability statement

The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no conflict of interest.

References

1. Abojassim AA, Al-Gasaly HH, Al-Temimie FA, AlAarajy MA. Study of time measured factor on measuring radon concentrations in groundwater. International Journal of Theoretical and Applied Sciences, 2015. 21(1): 16–21. doi: 10.15863/TAS.2015.01.21.3
2. Aimbetova IO, Kuzmin A, Myrkheyeva DN, et al. An effect of hydrothermal synthesis time on the specific capacitance of vanadium pentoxide. International Journal of Energy for a Clean Environment, 2023, 24(2): 15–26. doi: 10.1615/InterJEnerCleanEnv.2022043086
3. Akar U, Gurler O, Kahraman A, et al. Measurements of radium levels in bottled natural spring water of Marmara region (Turkey). Romanian Journal of Physics, 2012. 57(7-8): 1204–1210.
4. Banerji S, Mitra D. Geographical information system-based groundwater quality index assessment of northern part of Kolkata, India for drinking purpose. Geocarto International. 2018, 34(9): 943–958. doi: 10.1080/10106049.2018.1451922
5. Bosikov II, Martyushev NV, Klyuev RV, et al. Modeling and Complex Analysis of the Topology Parameters of Ventilation Networks When Ensuring Fire Safety While Developing Coal and Gas Deposits. Fire. 2023, 6(3): 95. doi: 10.3390/fire6030095
6. Cazala C, Andrès C, Decossas JL, et al. Impact of uranium mines water treatment on uranium and radium behaviour. Uranium, Mining and Hydrogeology. Published online 2008: 829–838. doi: 10.1007/978-3-540-87746-2_109
7. Choubey VM, Bartarya SK, Ramola RC. Radon in groundwater of eastern Doon valley, Outer Himalaya. Radiation Measurements. 2003, 36(1-6): 401–405. doi: 10.1016/s1350-4487(03)00160-4
8. Idriss H, Salih I, Sam AK. Study of radon in ground water and physicochemical parameters in Khartoum state. Journal of Radioanalytical and Nuclear Chemistry. 2011, 290(2): 333–338. doi: 10.1007/s10967-011-1295-4
9. Inácio M, Soares S, Almeida P. Radon concentration assessment in water sources of public drinking of Covilhã's county, Portugal. Journal of Radiation Research and Applied Sciences. 2017, 10(2): 135–139. doi: 10.1016/j.jrras.2017.02.002
10. Fomenko VA, Sokolov AA, Miroshnikov AS, et al. Advancement of geoecological monitoring of radon emanations from out-of-service tailings dumps in mineral mining and processing industry. MIAB. Mining Inf. Anal. Bull. 2023; 6: 139-152. doi: 10.25018/0236 1493 20236_0 139
11. Kaliprasad CS, Narayana Y. Distribution of natural radionuclides and radon concentration in the riverine environs of Cauvery, South India. Journal of Water and Health. 2018, 16(3): 476–486. doi: 10.2166/wh.2018.242
12. Keramati H, Ghorbani R, Fakhri Y, et al. Radon 222 in drinking water resources of Iran: A systematic review, meta-analysis and probabilistic risk assessment (Monte Carlo simulation). Food and Chemical Toxicology. 2018, 115: 460–469. doi: 10.1016/j.fct.2018.03.042
13. Kondratyev YI, Sokolova OA, Aimbetova IO, Galachieva SV. Electrochemical metal leaching with added surfactant under the influence of infra-low-frequency current. Sustainable Development of Mountain Territories, 2021, 13(4): 591–598. doi: 10.21177/1998-4502-2021-13-4-591-598
14. Kumaritov AM, Sokolova EA, Sokolov AA. Geo-information system of ecological monitoring in inner-city industrial areas. Gornyi Zhurnal. Published online February 26, 2016: 94–96. doi: 10.17580/gzh.2016.02.18
15. Mansour HH, per Khdar S, Abdulla HY, et al. Measurement of indoor radon levels in Erbil capital by using solid state nuclear track detectors. Radiation Measurements. 2005, 40(2-6): 544–547. doi: 10.1016/j.radmeas.2005.06.033
16. Mittal S, Rani A, Mehra R. Estimation of radon concentration in soil and groundwater samples of Northern Rajasthan, India. Journal of Radiation Research and Applied Sciences. 2016, 9(2): 125–130. doi: 10.1016/j.jrras.2015.10.006

17. Moshchenko DI, Kolesnikov SI, Kuzina AA, et al. Mining information and analytical bulletin. 2023. 104–116. doi: 10.25018/0236_1493_2023_51_0_104
18. Müller JD, Bastkowski F, Sander B, et al. Metrology for pH Measurements in Brackish Waters—Part 1: Extending Electrochemical pHT Measurements of TRIS Buffers to Salinities 5–20. Frontiers in Marine Science. 2018, 5. doi: 10.3389/fmars.2018.00176
19. Musa J, Ahanonu J. Quality Assessment of Shallow Groundwater in Some Selected Agrarian Communities in Patigi Local Government Area, Nigeria. International Journal of Basic and Applied Science. 2013, 1(3): 548–563. doi: 10.17142/ijbas-2012.1.3.10
20. Ahmed Najam L. Radon Emanation from Drinking Water Samples of Nineveh Province (IRAQ). American Journal of Modern Physics. 2014, 3(6): 257. doi: 10.11648/j.ajmp.20140306.20
21. Nnaji JC, Igwe OU, Onyedim KM, et al. Radioisotope and Metal Concentrations in Borehole Water Samples of Umuahia and Umudike, Nigeria. Journal of Applied Sciences and Environmental Management. 2019, 23(7): 1403. doi: 10.4314/jasem.v23i7.32
22. Ramola RC, Choubey VM, Negi MS, et al. Radon occurrence in soil–gas and groundwater around an active landslide. Radiation Measurements. 2008, 43(1): 98–101. doi: 10.1016/j.radmeas.2007.05.054
23. Reddy KU, Ningappa C, Sannappa J, et al. Concentration of radon and physicochemical parameters in ground water around Kolar Gold Fields, Karnataka State, India. Journal of Radioanalytical and Nuclear Chemistry. 2017, 314(2): 907–915. doi: 10.1007/s10967-017-5492-7
24. Shabanov MV, Marichev MS, Minkina TM, et al. Changes in the ecological and geochemical state of bottom sediments in the area of copper pyrite deposits (on the example of Karabash copper deposits). Mining Information and Analytical Bulletin. 2023. 117–134. doi: 10.25018/0236_1493_2023 51_0_117
25. Shuttleworth AB. Ground gases in urban environments–Sources and solutions urban pollution. Science and Management, 2018. 69–89. doi: 10.1002/ 9781119260493.ch6