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Spatial Distribution of Natural and Artificial Radionuclides in Urban Soils and Bottom Sediments of Monchegorsk Lakes: Russia

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ABSTRACT

The article presents the results of a study of soils and bottom sediments of lakes in the area of Monchegorsk city. The purpose of the work is to identify patterns of distribution of natural and man-made radionuclides in urban soils and bottom sediments of lakes in Monchegorsk city. The specific activity values of radionuclides in urban soil samples were as follows: for technogenic ^{137}Cs, up to 31.3 Bq/kg; in soils in the zone of influence of the plant (in subflare areas), up to 63.4 Bq/kg. For natural radionuclides in urban soils, the values were as follows: ^{226}Ra – up to 14.2 Bq/kg; in soils in the zone of influence of the plant (in sub-flare areas) – up to 21.6 Bq/kg; ^{232}Th in urban soils – up to 1. The concentration of 8.3 Bq/kg was observed in soils in the zone of influence of the plant (in sub-flare areas), while the concentration of 17 Bq/kg was observed in soils in the same area. The concentration of 498 Bq/kg was observed in urban soils for ^{40}K, while the concentration of 317 Bq/kg was observed in sub-flare areas. In bottom sediments of lakes, the concentration of technogenic ^{137}Cs was found to be up to 45.8 Bq/kg, while the concentration of natural radionuclides, including ^{226}Ra (up to 62.6 Bq/kg), ^{232}Th (11 Bq/kg), and ^{40}K (268 Bq/kg), was also determined.

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INTRODUCTION

The most important sources of man-made radioactivity for the territory of Monchegorsk are: stratospheric fallout as a result of atmospheric nuclear tests, local fallout as a result of tests at the nuclear test site of the Novaya Zemlya archipelago and the accident at the Chernobyl nuclear power plant. Research in previous years (Kuzmenkova & Vorobyeva, 2015; Nikanov et al., 2019; Melentiev, 2021) did not determine increased values of artificial radioactivity in the soils of the Murmansk region. The specific activity of artificial ^{137}Cs in the upper soil layer varies from 3 to 60 Bq/kg (Vorobyeva et al., 2017). The Kola Peninsula is a place potentially dangerous for radionuclide contamination (Fig. 1A) as a result of transboundary transfer (Kuzmenkova & Vorobyeva, 2015; Nikanov et al., 2019; Melentiev, 2021). The average activities of artificial ^{90}Sr and ^{137}Cs in the bottom sediments of the Kola coast of the Barents Sea are 3.5 and 5.5 Bq·kg−1, respectively (Yakovlev et al., 2023). Peaceful thermonuclear explosions used to crush rocks were carried out in the central part of the Kola Peninsula in the Khibiny mountain range in 1972 and 1984. The specific activity of natural radionuclides ^{226}Ra, ^{232}Th in undisturbed soils of the Khibiny tundra was: in the swamp - from 7.03 to 71.06, and in the mountain tundra - from 15.17 to 27.75 Bq/kg (Nikanov et al., 2019). Since the overwhelming majority of the Arctic

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population lives in cities and there is insufficient data on the spatial distribution of specific radioactivity of urban soils and lake bottom sediments within cities, it seems necessary to study their composition as a component of the human environment. Among the natural radionuclides, we studied the activities of ^{226}Ra, ^{232}Th and ^{40}K, which are the main natural radioactive elements that enrich the acid igneous rocks of the Precambrian basement making up the territory of the Kola Peninsula (Melentiev, 2021).

Several anthropogenic sources such as nuclear energy, carbon combustion, radioactive waste dumping, mining and manufacturing have an impact on the distribution of radionuclides (Cevik et al., 2007; Ibraheem et al., 2018; Monged et al., 2020; Sotiropoulou & Florou, 2021; Jeelani et al., 2022b;Yakovlev et al., 2023).

Urban soils are formed both by natural soil transformation, with the participation of active artificial sedimentogenesis, and by artificial movement of natural soils onto substrates excavated during construction activities. For this reason, the origin of urbanised soils determines the subsequent nature of radionuclide migration and thus shapes the complex structure of soil contamination with natural and anthropogenic radionuclides.

In addition to the origin of the soil, the geochemical processes occurring in the soils of Arctic towns are strongly influenced by permafrost (Kriauciunas et al., 2018). Another impact that should not be overlooked is global warming, as predicted by the overwhelming majority of the international scientific community, which could drastically alter the existing spatial distribution of radionuclides in soils by releasing natural radionuclides preserved in perennial ice. Consequently, all these effects add to the complications of the already complex process of assessing the radiological condition of urbanized areas. Currently, Russia does not have any approved standards for the content of radionuclides in soils or, more importantly, a standard classification of urban soils (Aparin & Sukhacheva, 2015). In view of the above, and considering that the vast majority of the population of the Arctic live in cities (Fedorets et al., 2015; Antrop, 2004), and taking into account the significant contribution of soils to the formation of the effective dose of human exposure (Gablin et al., 2010), we believe that the few areal radioecological surveys conducted so far in the urbanized territories of Russia remain relevant and up-to-date. Furthermore, given the increased interest of contemporary researchers in urban ecology, it is very likely that over time an urban soil radioecological monitoring system will be implemented in more Russian cities.

The aim of the article is to identify patterns of distribution of natural and artificial radionuclides in urban soils and bottom sediments of lakes in Monchegorsk.

MATERIALS AND METHODS

Characteristics of the study area (Monchegorsk, Kola peninsula, Murmansk region, Russia)

A significant part of the city is geographically located in a flat area, at elevations of 120 to 130 m above sea level. The coastal region of the Nyudyavr lake has elevations of 126 to 129 m. Between the lakes Lumbolka, Nyudyavr, and Monche Guba (the central part of the city) pass through a watershed with a height of 10 to 150 m. The absolute surface elevations here range from 127 m to 180 m up the slope. The territory of the city occupies 36.5 km^2 (Dauwalter & Kashulin, 2016). Quaternary deposits are formed by glacial, fluvioglacial, glaciolacustrine, and postglacial formations. Areas with a artificial landscape include the industrial region of the Open Joint-Stock Company Severonickel Combine H-1. In the moraine section within Monchegorsk there are sandy loam; gravelly, heterogeneous, less often silty sands; loam with layers of silty sand; pebble and crushed stone formations. Modern lake sediments make up the low shores and bottoms of lakes: diatomites of the bottom of many lakes and on the eastern shore of the lake Nyudyavr (thickness from 1.5 to 12 m); lenses of loams and silts (thickness from 0.5 to 4 m); sands of narrow beaches (no more than 2 m wide); boulders, pebbles and sands of the coastal

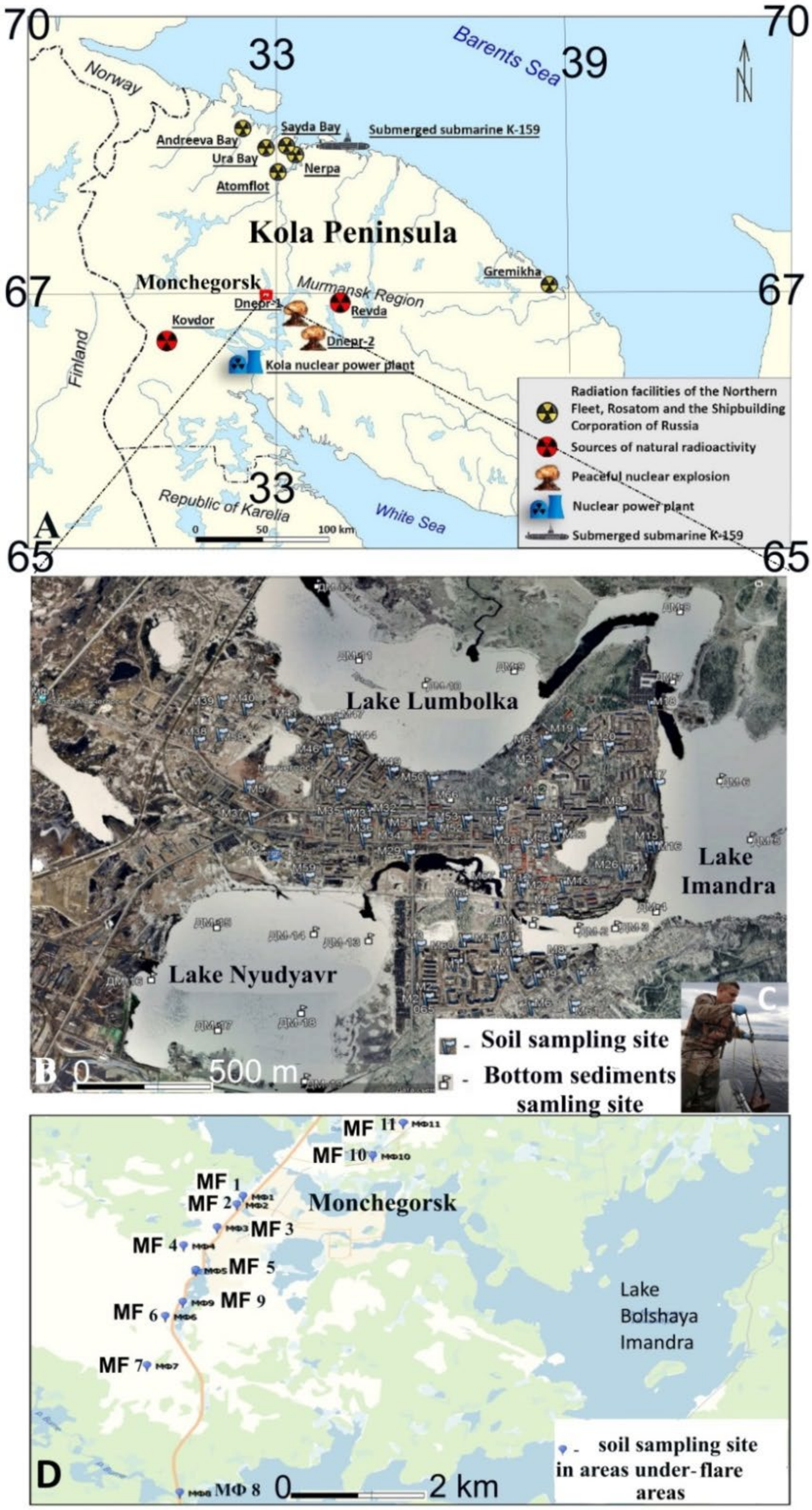

Fig. 1. The following images illustrates the locations of radiation-hazardous objects on the territory of the Kola Peninsula, Murmansk region, Russia (A), points of collection of soil samples and bottom sediments of lakes (B), sampling lake sediments with a bottom grab from a rubber boat (C) and soil samples in sub-flare areas (D) in Monchegorsk in 2018-2019 on a fragment of a Google space image.

ramparts of some lakes (up to 3 m) (Rules of land use and construction..., 2024). Lake Monche has a number of tributaries, with the river flowing out of the Moncha river and into the lake Lumbolka (Fig. 1). Lake Rogovaya Lambina is connected to Lake Monche by a channel, after which the latter flows into Lake Lumbolka via a smaller channel. Lake Nyudyavr is a shallow reservoir connected to the Monche Guba Bay by the Nyuduay channel. The shores of the lake are low-lying and swampy, with overgrown bushes (Motuzova et al., 2004).

Samples

During the summer, the authors conducted a study on the specific radioactivity of soils and bottom sediments of lakes in the territory of Monchegorsk (Murmansk region, Russia). The research is carried out in summer for logistical reasons. In winter, urban soils are subject to freezing, which makes their selection difficult. At the preliminary stage, regions were selected by the type of development, and sampling points for soil and bottom sediments of lakes were determined. A total of 58 samples were collected from across the city, including 14 sub-flare soil samples from outside the city limits. Additionally, 6 bottom samples were obtained in 2018 and 19 bottom samples were collected from lakes within the city in 2019 (Fig. 1). Bottom sediment samples were collected using a bottom grab from a boat (Fig. 1C).

Instruments

The soil samples were then dried in an oven at a temperature of 105°C. In order to determine the presence of radionuclides ^{137}Cs, ^{226}Ra, ^{232}Th and ^{40}K, a low-background semiconductor gamma spectrometer manufactured by ORTEC (USA) was employed. This instrument is based on a high-purity coaxial germanium detector GEM10P4–70 (HPGe) (USA), which is equipped with an SBS-75 pulse signal processor and Gamma-pro software (Ortec, 2008). The calibration and quality control of gamma spectrometric measurements are carried out using volumetric activity measurements, specifically Marinelli glasses (1 L). The gamma radiation spectrum exhibits a clear distinction between two peaks of total absorption, with the first occurring at 661 keV (^{137}Cs) and the second at 1460 keV (^{40}K). No other radionuclides are observed within the gamma radiation spectrum (Fig. 2).The minimum detectable activity at an exposure time of 12000 s in the Marinelli geometry for the GEM10P4–70 0 detector was 0.3 Bq for ^{226}Ra, 15.0 Bq for ^{40}K, 0.1 Bq for ^{137}Cs and 0.2 Bq for ^{232}Th.

Fractional composition

The fractional composition was determined using an AS200 sieving machine (Retsch, Germany) with a set of sieves ranging from 45 μm to 2 mm.

Gamma survey

Automotive gamma spectrometric studies were conducted using a mobile scintillation gamma spectrometric complex RS-700 (Canada), which is equipped with a digital spectrometer with a resolution of 1024 channels. This enables the measurement of the total radioactivity of the area at a count rate per second. The measurements were taken at a height of 1.7 m above the ground. The spectrometer was placed in the trunk of a car. During the gamma spectrometric survey, 370 measurement points were processed. The georeferencing accuracy was ± 1-1.5 m (RS-700 mobile radiation monitoring system..., 2019).

Statistical processing

The statistical processing of the data included the calculation of the arithmetic mean, median, standard deviation, standard error of the mean, standard deviation for the sample, coefficient of variation, and p-value, which was performed using the StatSoft, Inc. software (2011). This was the STATISTICA (data analysis software system) (Afifi et al., 2004).

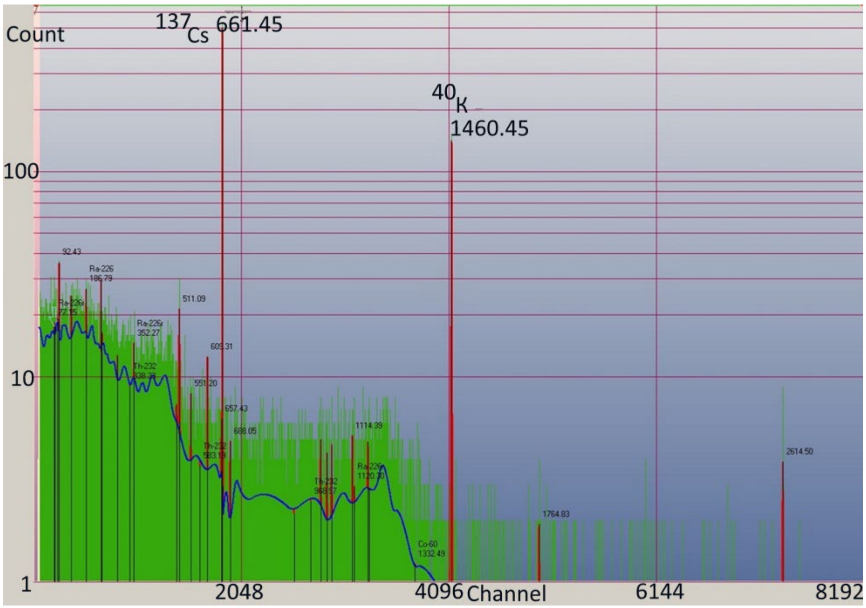

Fig.2. The following diagram illustrates the spectrum of the amplitude distribution of gamma radiation in soil sample m39 in Monchegorsk (Fig.1).

RESULTS AND DISCUSSION

The objective of this study is to determine the specific radioactivity of artificial and natural radionuclides in soils of city districts with different building types

In Monchegorsk, urbanquasizems, which are horizons of accumulation and biogenic transformation of organomineral and artificial material that were formed synlithogenically under the influence of human activity, have become a common feature of the urban landscape. These horizons contain a minimum of 10% anthropogenic inclusions (including debris). Replantozems have been observed to form on lawns in blocks with stone low- and high-rise buildings, a phenomenon also documented in neighbouring cities (Iglovsky et al., 2023a, b, c). A well-formed soil profile is observed under tree and shrub vegetation in park and forest areas (Kriauciunas et al., 2020). The soil sampling points, numbered 6, 7, 61, and 62, fall within the regions of development and placement of low-rise buildings. The multi-storey buildings, numbered 1-5, 8-16, 19, 23-28, 31-35, 43-45, and 48, are situated in different locations. 49, 51-53, 55, 56, 60, 68, 69; city center – 24, 25, 32, 35; retail facilities – 50, 57; healthcare institutions – 65; parks and squares – 17, 66; urban Forests and forest parks are located in the following areas: 20, 22, 23, 54. Sports facilities can be found in the following locations: 21. Industrial facilities can be found in the following areas: 16-18, 29, 38-41, 64, 67. Support objects can be found in the following areas: 36-38, 59 (Fig. 1, 2).

The maximum value of the specific activity of radionuclides in urban soil samples (58 samples) was ^{137}Cs – 31.3, ^{226}Ra – 14.2, ^{232}Th – 18.3, ^{40}K – 498 Bq/kg. The mean specific activity of ^{137}Cs, ^{226}Ra and ^{232}Th in the area affected by the Severonickel Combine H-1 industrial area was higher at a time when the specific activity of ^{40}K in urban soil samples was lower (Tables 1, 3).

As indicated in Table 2, the activity values of natural radionuclides are below the global mean (UNSCEAR 2000).

The established higher values of specific activity of ^{137}Cs are typical for the soils of parks, spruce-birch forest parks located along the Leningradskaya embankment (points 17 and 20) and in the southern part of the city in soils within the buildings of multi-storey panel buildings (point

Table 1. The specific activity of radionuclides in urban soil samples, expressed in Bq/kg.

Radionuclides	Specific activity of radionuclides					
	Urban soils			The soils in the region of influence of the Severonickel Combine H-1 industrial area (sampling points MF1-MF11 are marked in Figure 1D)		
	Minimum and maximum values	Average value and standard deviation	Number of samples above the lower limit of detection	Minimum and maximum values	Average value and standard deviation	Number of samples above the lower limit of detection
^{137}Cs	3.1-31.3	11.78±8.5	0	3.5-63.4	20.5±21.9	6.4
^{226}Ra	4.7-14.2	8.08±2.2;	0	5.1-21.6	6.2±7.2	4.4
^{232}Th	4.9-18.3	10.25±2.9	10.3	5.3-17.0	11.1±5.2	12.8
^{40}K	74.8-498	212.94±68.8	244	82.2-317	176±91	195

Table 2. Measured concentrations of ^{137}Cs, ^{226}Ra, ^{232}Th, and ^{40}K in sediment samples with the values reported for North Russia and various countries in the world.

Region (Ref.)	Mean specific activity (Bq kg^{-1})			
	^{137}Cs	^{226}Ra	^{232}Th	^{40}K
Russia				
Delta of the Northern Dvina River (Kiselev et al., 2018)	4.5	9.5	11.3	328.9
Delta of the Pechora river (Yakovlev et al., 2021)	0.16	18.7	13.3	373.5
White Sea (Zykov & Druzhinin, 2012)	4.9	9.8	21.2	480.9
Barents Sea (Yakovlev & Puchkov., 2020)	2.9	13.6	20.8	438.9
This work	From 3.1 to 63.4	From 4.7 to 21.6	From 4.9 to 18.3	From 74.8 to 498
Various countries				
Port Sudan, Sudan (Sam et al., 1998)	-	11.05	10,36	325,00
Port of Patras, Greece	-	22.60	24.50	497.00
Mumbai Harbor, India	-	10.60	12.70	436,00
Karachi Harbor, Pakistan (Akram, et al., 2006)	-	23.90	23.60	527,00
Coast of Saudi Arabia (Al-trabulsy et al., 2011)	-	16.97	19.00	641,00
Red Sea Coast, Egypt (El Mamoney et al., 2004)	-	25.50	24.60	427,50
Mediterranean coast, Egypt	-	8.80	2.10	46.00
Inani Beach, Bangladesh (Ahmed et al., 2014)	-	15.14 ± 2.62–28.67 ± 3.09	24.39 ± 2.50–49.46 ± 3.58	362.00 ± 79.61–560.87 ± 81.40
Coast of Xiamen Island, China (Huang et al., 2015)	-	-	6.5–41.4	197.4–487.6
Caspian Sea Coast, Iran (Reza et al., 2009)	-	177.0	117.00	1085.00
Coast of Malaysia, South China (Mohammed et al., 2010)	-	45.90	73.30	-
Coastal areas of Kerala, India (Antony et al., 2019)	-	10.10	23.16	241.94
Karnaphuli and Halda rivers, Bangladesh (Islam Al Amin Md Sirajul et al., 2021)	-	23.74	37.22	445.09
World average (UNSCEAR... 2000)	-	35	30	400

1). As previously demonstrated by (Puhakainen et al., 2005), ^{137}Cs is capable of accumulating in litter. The activity values of ^{137}Cs were found to be up to 20 Bq/kg in the soils of the central and southern parts of the city, in areas of low- and high-rise residential buildings, business, public and commercial purposes. The following points were identified as having elevated levels of ^{137}Cs activity: 5, 6, 22, 24, 32, 33, 35, 40, 50, 54, 56, 60, 61. In other areas of the city, the specific activity of ^{137}Cs in soils was less than 10 Bq/kg.

The distribution of specific activity of natural radionuclides in the soils of functional regions of Monchegorsk is uniform (Fig. 3). The maximum values of specific activity ^{40}K were

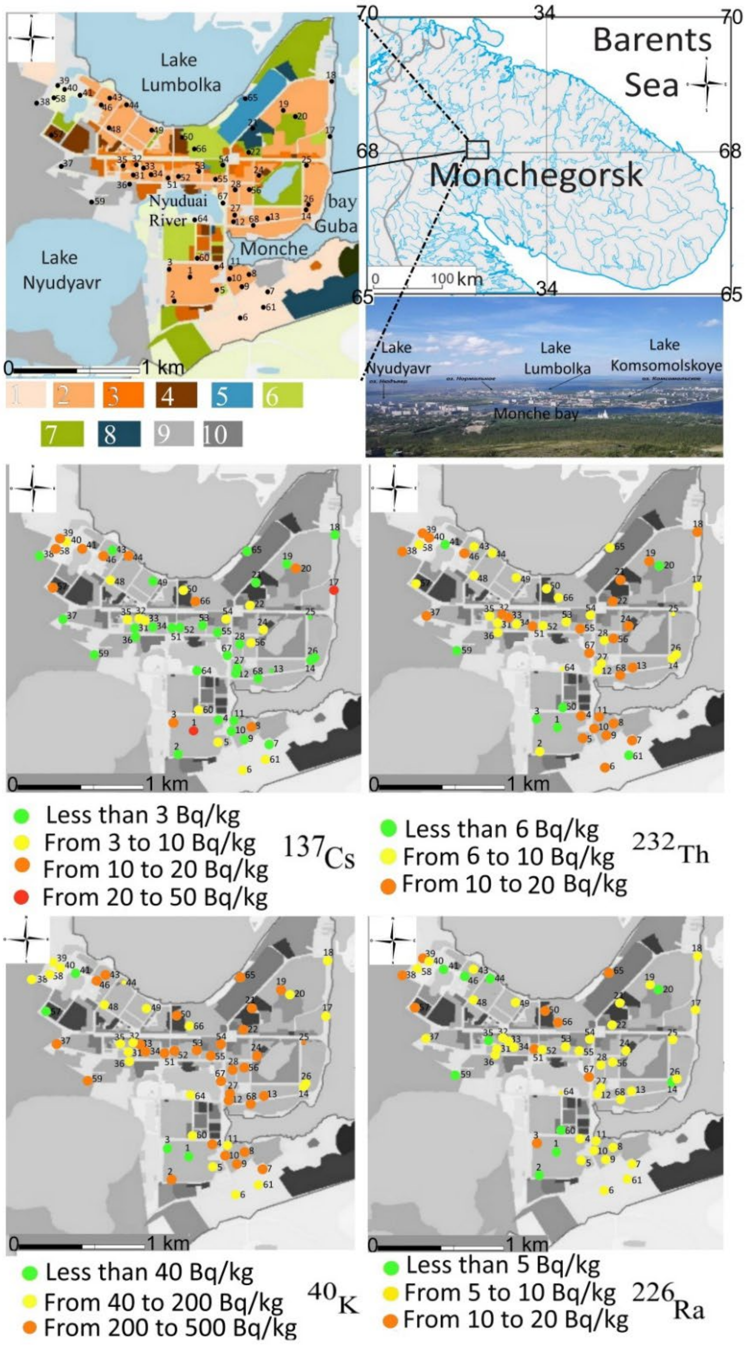

Fig. 3. The location of soil sampling points in Monchegorsk is shown on a fragment of the functional zoning map of the city territory (Rules of land use and construction..., 2024). Regions are indicated by numbers, as follows: 1 – low-rise residential buildings. 2 – multi-storey buildings .The third category comprises residential buildings in the city center. The fourth category encompasses retail locations and facilities. The fifth category includes the placement of healthcare institutions. The sixth category pertains to the parks and squares. The seventh category is urban forests and forest parks. The eighth category is sports facilities. The ninth category is industrial and communal services. The tenth category is the placement of engineering support facilities.

determined in soils of birch and willow forests near the intersection of Lenin Avenue and St. Komarov on the bank of the river Nyudai (point 67), where high values of the specific activity of ^{232}Th as well as ^{226}Ra were also noted.

The specific activity of ^{40}K was detected in soils of the western part of the city, in the industrial and communal region (38-40, 58), in soils built with low- and multi-story buildings in the center (points 31, 32, 35, 36), and in the eastern part near the lake Moncha-Guba (points 14, 17, 20, 26, 28). 6, 48, 49, 60, 64), the eastern part in the vicinity of Lake Moncha-Guba (points 14, 17, 20, 26, 28) and in the southern part of the city (points 5, 6, 11, 61). The specific activity of ^{40}K was found to be below 40 Bq/kg in soils near the lake (point 41) and the highway (point 57), as well as in the southwestern part of the city within a multi-storey panel building near the lake Nyudyavr (points 1, 3).

Soils of birch and willow forests near the intersection of Lenin Avenue and St. Komarov on the bank of the Nyudai River (point 67), on the station highway (points 1, 38), near the private wooden sector (point 39), panel buildings in the vicinity of the morgue (point 65), the maximum value of the specific activity of ^{226}Ra in the soils was noted. This was observed at the registry office, the central park (points 50, 66), and at the intersection of the street Nyudovskaya and Novoprologennaya in the area of low-rise buildings (point 51). In the remainder of the city, the specific activity of ^{226}Ra in soils was found to be less than 10 Bq/kg.

The specific activity of ^{232}Th and ^{226}Ra is found to be at its maximum in the soils of birch and willow forests located in the vicinity of the intersection of Lenin Avenue and St. Komarov, situated on the banks of the Nyudai River (point 67). This is also the case in the industrial and communal region (point 39), as well as in the area of low-rise brick buildings (point 33) and in the vicinity of multi-storey panel buildings (point 4). The values below 6 Bq/kg were recorded in the soils of park and forested areas located along the Leningradskaya embankment (points 17, 20) and in samples of peat deposits near the nameless lake (point 41) and Lake Nyudyavr (point 59).

The specific radioactivity of artificial and natural radionuclides in lake bottom sediments is the subject of this study

The distribution of the maximum values of the specific activity of natural radionuclides in the bottom sediments of lakes is as follows: 62.6 Bq/kg for ^{226}Ra in Lake Lumbolka, 4.5 Bq/kg for ^{232}Th, and 247.7 Bq/kg for ^{40}K in bottom sediments, which is comparable to soils (Fig. 4).

The mean specific activity of ^{137}Cs in soils in the vicinity of multi-storey panel buildings was 11.74 Bq/kg, within the industrial and communal sphere (15.44 Bq/kg), and in the vicinity of low-rise buildings. The mean activity concentration of ^{137}Cs in the soil was 4.55 Bq/kg in areas of business, public and commercial development, 7.58 Bq/kg in the area of engineering support facilities, and less than 3 Bq/kg (Fig. 5).

The mean specific activity of ^{137}Cs in the bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and the river Nuduai was found to be 16.94 Bq/kg (Fig. 6).

The concentration of ^{226}Ra in Lake Nyudyavr was found to be 32.9 Bq/kg, while that of ^{232}Th was less than 5 Bq/kg. The concentration of ^{40}K in the same lake was 268 Bq/kg. In Lake Komsomolskoye, the concentration of ^{226}Ra was found to be 5 Bq/kg. The concentration of ^{226}Ra was 0.8 Bq/kg, while that of ^{232}Th was less than 6.5 Bq/kg. The concentration of ^{40}K was 231.4 Bq/kg. In the Nyuduai river, the concentration of ^{226}Ra was 6.7 Bq/kg, while that of ^{232}Th was 9. The concentration of 1 Bq/kg, ^{40}K – 151.5 Bq/kg, in the lake Imandra was observed, along with ^{226}Ra – 25 Bq/kg, for ^{232}Th – 7.3 Bq/kg, ^{40}K – 265 Bq/kg.

The distribution of average values of the specific activity of natural radionuclides in lake bottom sediments revealed that the concentration of ^{226}Ra was 21.81 Bq/kg, which is approximately 2.3 times higher than that observed in soils. Conversely, the concentration of ^{232}Th was 10.22 Bq/kg, which is almost 1.15 times lower than that observed in soils.

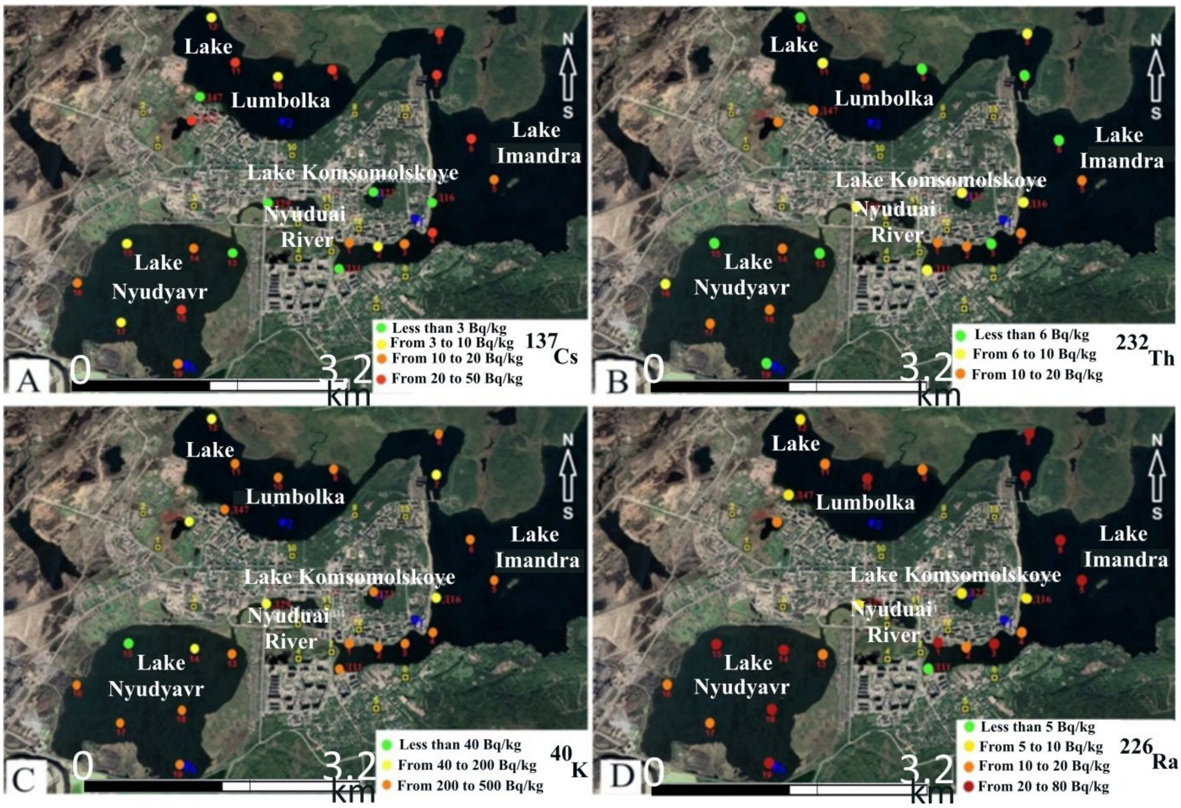

Fig. 4. The spatial distribution of specific activity of ^{137}Cs (A), as well as that of natural radionuclides in bottom sediments of lakes of the city of Monchegorsk (Bq/kg) which presented in Figures (^{232}Th (B), ^{40}K (C) and ^{226}Ra (D)).

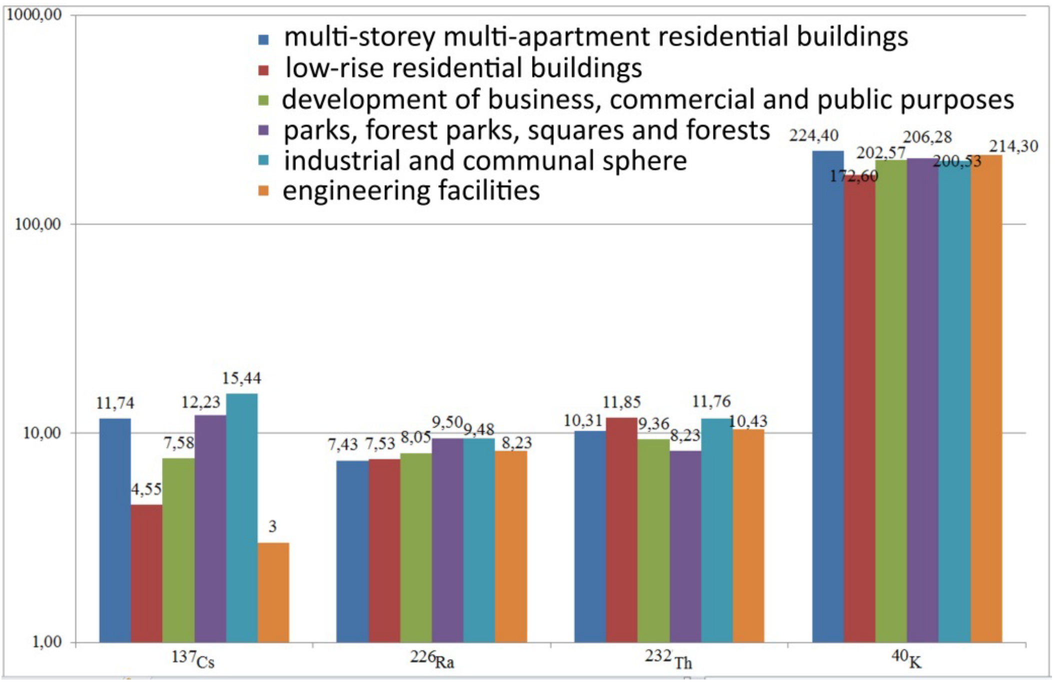

Fig. 5. The average specific activity of ^{137}Cs and natural radionuclides (Bq/kg) in soils of functional regions of Monchegorsk is presented in the following chart. The values are color -coded to indicate the type of building in the functional regions. The logarithmic scale is used.

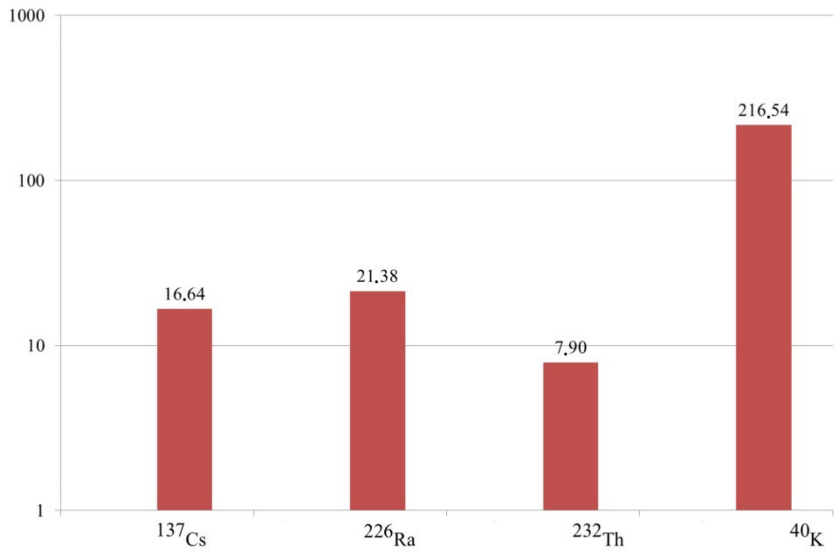

Fig. 6. The average specific activity of ^{137}Cs and natural radionuclides (Bq/kg) in the bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra, river Nyuduay, and Monchegorsk (N=25) was determined using a logarithmic scale.

The distribution of ^{40}K – 220.75 Bq/kg in lake bottom sediments is comparable to that observed in soils. Table 3 presents statistical indicators of changes in the specific activity of radionuclides in soils and bottom sediments of lakes in Monchegorsk.

The standard deviation allows for the estimation of the extent to which values from a set may differ from the average value. Thus, for ^{137}Cs, this deviation is less than the average value, for ^{226}Ra and ^{232}Th it is almost two times less, and for ^{40}K it is almost three times less than the average value. The summation of ^{137}Cs was found to be heterogeneous (73%), whereas that of other natural radionuclides was homogeneous (33% or less). For the bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and the Nyuduai river, the standard deviation of ^{226}Ra is 1.6 times less than the average value, while that of ^{137}Cs is 1.4 times less, ^{232}Th is 2 times less, and ^{40}K is almost 4.7 times less. The summation of ^{137}Cs, ^{226}Ra and ^{232}Th was found to be heterogeneous (94%, 62% and 50%, respectively), whereas that of other natural radionuclides was homogeneous (33% or less) (Table 3).

A correlation analysis was conducted to investigate the relationship between the specific activity of radionuclides and the fractional composition of soil

A correlation analysis of the specific activity of radionuclides and the fractional composition of the soil (Table 4) revealed a correlation with a high level of statistical significance (taking into account the p-value) between ^{226}Ra and ^{137}Cs.

Correlation analysis of specific activity of radionuclides and sand content: (1-2 mm), (500 μm - 1 mm), (250-500 μm), (125-250 μm) and silt fraction: The correlation between ^{232}Th and the 1 mm fraction in bottom sediments of lakes (Table 5) was found to be of a high level of statistical significance (taking into account the p-value), while a strong correlation was also noted between ^{226}Ra and the <45 μm fraction.

It should be noted that the gradients of connection strength are indicated by color, from red (representing a minimum value) to green (representing a maximum value). The correlation coefficient values are highlighted in bold to indicate critical values. The p-value represents the lowest value of the significance level.

Fractional composition of soils and bottom sediments of the lakes of Monchegorsk

The principal component of the soil samples was constituted by fractions of fine sand with

Table 3. The present study presents statistical indicators of changes in the specific activity of radionuclides in soils and bottom sediments of lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and the river Nyuduay.

The following statistical parameters are presented for analysis:	^{137}Cs	^{226}Ra	^{232}Th	^{40}K
Urban soils				
Samples / n	58	58	58	58
Maximum	31.3	14.2	18.3	498.0
Minimum	3.1	4.7	4.9	74.8
The following table presents the standard deviation of the data set	8.65	2.25	2.98	69.53
Coefficient of variation	73%	28%	29%	33%
The bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and the river Nyuduay were analysed.				
Samples / n	25	25	25	25
Maximum	45.80	62.60	23.50	268.00
Minimum	4.10	4.30	2.80	127.00
The following table presents the standard deviation of the data set	11.79	13.62	5.09	46.42
Coefficient of variation	70%	62%	50%	21%

Table 4. A correlation matrix was constructed to examine the relationship between the specific activity of radionuclides and the content of soil skeleton particles (2 mm), as well as the fractions of soil fine earth (less than 1 mm) in the soils.

	2 mm	1 mm	500 µm	250 µm	100 µm	45 µm	<45 µm	^{137}Cs	^{226}Ra	^{232}Th	^{40}K
2 mm	1										
p-value	-										
1 mm	0.11	1									
p-value	0.40	-									
500 µm	0.00	0.68	1								
p-value	0.98	0.00	-								
250 µm	-0.33	-0.35	0.15	1							
p-value	0.01	0.01	0.28	-							
100 µm	-0.65	-0.65	-0.54	0.19	1						
p-value	0.00	0.00	0.00	0.17	-						
45 µm	-0.39	-0.23	-0.60	-0.48	0.40	1					
p-value	0.00	0.09	0.00	0.00	0.00	-					
<45 µm	0.02	-0.18	-0.55	-0.66	0.12	0.77	1				
p-value	0.87	0.18	0.00	0.00	0.39	0.00	-				
^{137}Cs	0.15	-0.02	0.19	0.20	-0.18	-0.26	-0.19	1			
p-value	0.48	0.94	0.36	0.34	0.40	0.21	0.35	-			
^{226}Ra	-0.06	-0.17	-0.12	-0.03	0.14	0.23	0.02	0.70	1		
p-value	0.69	0.24	0.41	0.83	0.35	0.11	0.88	**0.00**	-		
^{232}Th	0.12	-0.02	0.10	0.02	-0.10	-0.12	-0.05	-0.19	0.19	1	
p-value	0.41	0.91	0.48	0.88	0.50	0.41	0.74	0.44	0.19	-	
^{40}K	0.00	-0.01	-0.18	-0.33	0.11	0.26	0.31	-0.43	-0.02	0.17	1
p-value	0.99	0.92	0.19	**0.02**	0.42	0.06	**0.02**	**0.05**	0.89	0.24	-

dimensions of 100 and 250 microns, which collectively accounted for 27 and 24% of the total sample, respectively. The minimum proportion was represented by the fraction of fine clay to medium-grained silt (pelite), with a size of <45 µm, which constituted 5% of the sample (Fig. 7). The granulometric composition of urban soils was analyzed, and it was found that they are mainly represented by fine earth fractions with sizes of 100, 250 and 500 microns. Sand particles predominate (42%), with a significant gravel content (19%). The bottom sediments of lakes are dominated by fractions of fine and medium-grained sand, with 100 µm (27%) and 250 µm (21%) being the most prevalent (Blott & Pye, 2001; Valentine, 2019). The fractions

Table 5. A correlation matrix was constructed to examine the relationship between the specific activity of radionuclides and the content of sand. The sand content was categorised into six groups: very coarse (1-2 mm), coarse (500 µm - 1 mm), medium (250-500 µm), fine (125-250 µm) and silt (pelites): very coarse (45 µm) and medium (<45 µm) to fine clay* in sediments of lakes.

	2 mm	1 m	500 µm	250 µm	100 µm	45 µm	<45 µm	^{137}Cs	^{226}Ra	^{232}Th	^{40}K
2 mm	1										
p-value	-										
1 mm	0.54	1									
p-value	0	-									
500 µm	0.06	0.14	1								
p-value	0.76	0.49	-								
250 µm	-0.19	-0.28	0.37	1							
p-value	0.35	0.15	0.06	-							
100 µm	-0.41	-0.50	-0.67	-0.04	1						
p-value	0.03	0.01	0.00	0.83	-						
45 µm	-0.54	-0.26	-0.14	-0.41	-0.07	1					
p-value	0.00	0.19	0.49	0.03	0.74	-					
<45 µm	-0.40	-0.27	0.12	-0.29	-0.28	0.58	1				
p-value	0.04	0.17	0.54	0.14	0.16	0.00	-				
^{137}Cs	-0.07	-0.09	0.01	-0.23	-0.16	0.38	0.33	1			
p-value	0.76	0.68	0.96	0.30	0.47	0.08	0.13	-			
^{226}Ra	-0.31	-0.12	0.09	-0.17	-0.19	0.48	0.52	0.43	1		
p-value	0.14	0.57	0.68	0.41	0.37	**0.02**	**0.01**	**0.04**	-		
^{232}Th	0.09	0.62	-0.07	-0.25	-0.22	0.15	-0.21	-0.32	0.28	1	
p-value	0.69	**0.00**	0.75	0.27	0.33	0.51	0.36	0.20	0.23		
^{40}K	-0.29	-0.09	-0.39	-0.54	0.37	0.36	0.24	-0.14	-0.01	0.02	1
p-value	0.17	0.66	0.06	**0.01**	0.08	0.09	0.25	0.56	0.95	0.94	0.17

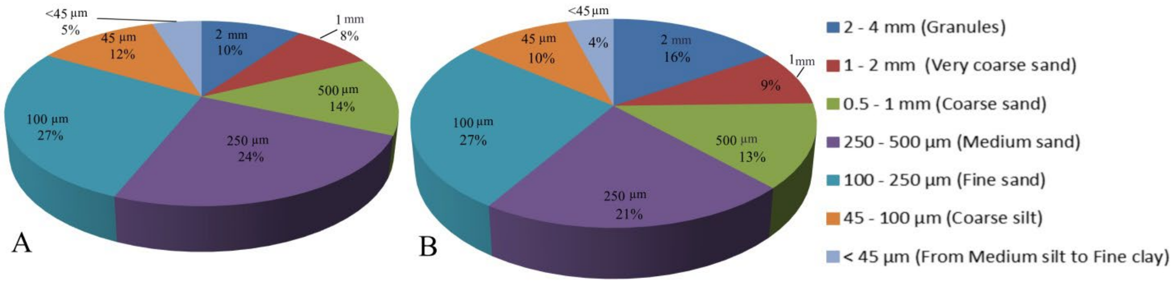

Fig. 7. The ratio of the fractional composition of soils (A) and bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and river Nyuduay (B) of Monchegorsk (%).

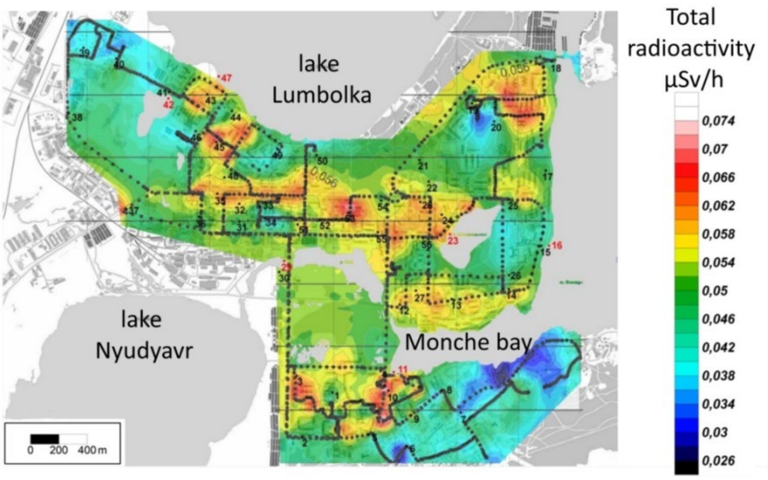

Fig. 8. Gamma survey of the city territory was conducted using a mobile gamma spectrometer RS-700. The gamma radiation dose rate, in microsieverts per hour (µSv/h), is represented by the dotted line, which also indicates the locations of automobile routes for gamma radiation dose rate measurements.

of coarse-grained sand (2-1 mm) occupy 25% of the total volume, while the medium-grained sand (250-500 µm) accounts for 34% (Fig. 7). The silt fraction (45-100 µm) is 37%, as noted in (Myasnikova & Potakhin, 2021).

A comprehensive examination of the region, conducted in accordance with the principles of a gamma survey

As part of the research conducted in Monchegorsk, a gamma survey of the area was carried out utilizing a mobile gamma spectrometer RS-700 (RS-700 mobile radiation monitoring system…, 2019) (Fig. 8). Within the city, three local regions of gamma radiation can be distinguished (from 0.056 to 0.074 µSv/h) (Fig. 7), which, however, does not exceed the average values for Russia (from 0.04 to 0.20 µSv/h) (Chubirko et al., 2019). The results of the evaluation of the radiation background show that the equivalent dose rate of gamma radiation in the city of Monchegorsk is from 0.056 to 0.074 µSv/h and it does not exceed the permissible value (0.3 µSv / h). The western border of one of these regions is located in the area of construction of panel multi-storey buildings. This is in the area of the street 10th Guards Division and School Division. Furthermore, the central region extends along Metallurgov Ave. and Komsomolskaya st. to the intersection with Nyudovskaya st. The northeastern region of gamma radiation values is confined to a block with panel multi-storey buildings in the area of Leningradskaya emb. and st. Kirov. The southern region of values is confined to panel multi-storey buildings in the area of the street Gruzovoy and Moroshkova and south of Lenin Ave. Furthermore, two regions of gamma radiation can be distinguished in the eastern part of the city, with lower values (µSv/h) observed in the vicinity of five-story panel buildings on Bredov Street and other metallurgists.

An increase in gamma radiation values in Monchegorsk is typical of areas with brick buildings constructed between the 1970s and 1980s and in areas with small architectural forms built using granite. In other areas of the city, the total gamma activity values were below 0.05 μSv/h, while in the southeastern (Holy Ascension Cathedral) and northwestern parts of the city, the values were below 0.03 μSv/h (Fig. 7).

CONCLUSIONS

The conducted studies allow us to draw the following conclusions.

The initial data gathered on the specific activity of ^{137}Cs and other naturally occurring radionuclides (^{232}Th, ^{226}Ra, ^{40}K) in the soils of Monchegorsk do not exceed the maximum permissible concentrations characteristic of the study area.

The maximum value of the specific activity of ^{137}Cs in urban areas in soils within the industrial and communal sphere is 31.3 Bq/kg. The mean value of the specific activity of ^{137}Cs in soils in the vicinity of multi-storey panel buildings is 11.74 Bq/kg, while in industrial and communal areas it is 15.44 Bq/kg. In low-rise buildings, the specific activity of ^{137}Cs is 4.55 Bq/kg; in business, public and commercial buildings, it is 7.58 Bq/kg; and in engineering support objects, it is less than 3 Bq/kg. The mean values of the specific activity of natural radionuclides in the soils of functional regions of Monchegorsk are consistent, with a comparable distribution observed for ^{232}Th (11.85 Bq/kg) in soils proximate to low-rise buildings and ^{226}Ra (9.5 Bq/kg) in soils of forest parks. The mean specific activity values of ^{137}Cs, ^{226}Ra and ^{232}Th in the area of influence of the Severonickel Combine H-1 site near of the flare were higher than those observed in the city.

The gamma survey of the territory of Monchegorsk did not identify any anomalies in the background radiation levels. The dose rate of gamma radiation in the city is below 0.074 μSv/hour, which is lower than the values observed in Russia (ranging from 0.04 to 0.20 μSv/hour). It is typical for areas with brick buildings constructed during the 1970s and 1980s as well as areas with small architectural forms built using granite, to exhibit elevated values. The results of the evaluation of the radiation background show that the equivalent dose rate of gamma radiation in the city of Monchegorsk is from 0.056 to 0.074 μSv/h and it does not exceed the permissible value (0.3 μSv/h).

The main component of the analyzed soil samples consisted of fine earth fractions measuring sizes of 100 and 250 μm (27% and 24% respectively). The smallest amount was represented by fractions measuring less than 45 μm (5%). The sediments at the bottom sediments of lakes are mainly composed of fine and medium-grained sand fractions measuring 100 and 250 microns (27% and 21% respectively), with a size of 2-1 mm (25%), 250-500 microns (34%), and the silt fraction (45-100 microns) accounting for 37%.

The analysis of radioactivity and the fractional composition of the soil revealed a statistically significant correlation (taking into account the p-value) between ^{226}Ra and ^{137}Cs. Moreover, the specific activity of radionuclides and the content of the sand and silt fraction in the lake bottom sediments were subjected to analysis, which revealed a correlation with a high level of statistical significance between ^{232}Th and the 1 mm fraction. A similarly robust correlation was identified between ^{226}Ra and the 45 μm fraction.

The maximum values of ^{137}Cs activity in the bottom sediments of the lakes Lumbolka, Nyudyavr, Komsomolskoye, Imandra and the river Nuduai were 45.8 Bq/kg, with an average of 16.94 Bq/kg. The distribution of average activity values of natural radionuclides in bottom sediments revealed that ^{226}Ra exhibited an average of 21.81 Bq/kg, which is approximately twofold higher than that observed in soils. Conversely, the average concentration of ^{232}Th in the lake bottom sediments was 10.22 Bq/kg, which is approximately 1.5 times lower than that observed in soils. The distribution of ^{40}K in lake bottom sediments is comparable to that observed in soils.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

DATA AVAILABILITY STATEMENT

Data sharing does not apply to this article, as no datasets were generated or analyzed during the current study.

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