Arctic Environmental Research

Arctic Environmental Research 18(1): 3–13
UDC 504.064
DOI 10.17238/issn2541-8416.2018.18.1.3

Research Article

Assessment of radioactivity of environmental components in the Kostomuksha State Nature Reserve

GP Kiselev[1,†], EYu Yakovlev[1], SV Druzhinin[1], IM Kiseleva[1], AV Bazhenov[1], VM Bykov[2]

1 *Federal Centre for Integrated Arctic Research named after N.P. Laverov, Russian Academy of Sciences (Arkhangelsk, Russian Federation)*
2 *Northern (Arctic) Federal University named after M.V. Lomonosov (Arkhangelsk, Russian Federation)*
† *Deceased*

Corresponding author: *Evgeniy Yakovlev* (yakovlev_eu@inbox.ru)

Academic editor: *Marsel Gubaidullin* ♦ **Received** 5 February 2018 ♦ **Accepted** 20 February 2018 ♦ **Published** 30 March 2018

Citation: Kiselev GP, Yakovlev EYu, Druzhinin SV, Kiseleva IM, Bazhenov AV, Bykov VM (2018) Assessment of radioactivity of environmental components in the Kostomuksha State Nature Reserve. Arctic Environmental Research 18(1): 3–13. https://doi.org/10.17238/issn2541-8416.2018.18.1.3

Abstract

The radiological state of the land and water areas constantly attracts public interest. Specially protected natural reservations deserve special attention when it comes to studying radiological conditions. This study presents findings of radioecological investigations conducted in the Kostomuksha State Nature Reserve in 2012 – 2015. The Kostomuksha Mining Company, which is developing the Kostomuksha iron ore deposit was identified as a potentially hazardous facility that might affect the radioecological situation in the naturel reserve, since production of iron ores at the deposit involves extraction to the ground surface of acid rocks characterised by a naturally high content of radioactive elements (granitic gneiss). Furthermore, several sources of radioactive radon gas have been identified within the reserve boundaries. The study included investigation of natural and anthropogenic radioactivity in the environmental components of the nature reserve and adjacent territories, including soil, plants, bottom sediments, ambient air and natural waters. It was found that development of the Kostomuksha iron ore deposit and operations of the mining and processing plant do not exert any considerable impact on the radiological situation in the nature reserve. Data obtained during the study indicate that the overall radiological situation in the reserve is acceptable and meets the relevant radiation safety standards. High levels of radiocesium were found in the moss and bottom sediments of the nature reserve, which requires additional research to determine a wider pattern of distribution of anthropogenic radioactivity across the adjacent territories and to study the processes of buildup and migration of radionuclides in aquatic organisms of Kamennoye Lake.

Keywords

bottom sediments, radioactive elements, radiocesium, the Kostomuksha Nature Reserve

Environmental monitoring of state nature reserves is a vital task formulated by Russian laws on specially protected natural reservations. The importance of monitoring background pollution levels in pristine natural areas is dictated by the need to preserve the original state of ecosystems and minimise human impact. As a rule, such studies in specially protected natural reservations seek to examine man-made air pollutants, heavy metals in the soil and water bodies, as well as migration of pollutants across the food chains of organisms (Panteleyeva 2000), while the radioecological state of natural objects is given a lot less attention. During this study, we completed radioecological investigations in the Kostomuksha State Nature Reserve located in Kostomuksha Urban District of the Republic of Karelia, on the border with Finland.

The radiological state of land and water areas shaped by the decay of lithospheric, cosmogenic and anthropogenic radionuclides has always been in the focus of public attention. North-western territories of Russia were severely exposed to the effects of anthropogenic radioactivity during the trials of nuclear weapons on the Novaya Zemlya archipelago, as well as in the follow-up to the global fallout caused by nuclear tests worldwide, underground nuclear explosions for peaceful purposes, and the Chernobyl and Fukushima disasters. Moreover, major industrial enterprises may act as sources of secondary pollution of the land by changing the course of migration of radioactive substances, extraction to the daylight surface of rocks untypical of a given environment, building up mine dumps, etc. The environmental conditions within the limits of the Kostomuksha Nature Reserve are shaped by the presence of a heavy-duty mining and processing enterprise developing the Kostomuksha iron ore deposit and located 20 km north-east of the reserve lands.

Geoecological investigations intended to evaluate the impact of development of the Kostomuksha deposit and the concentration of iron ore on environmental components have been carried out by a number of researchers (Atlasov 1993, Fedorets and Solodovnikov 2013, Vinogradova and Ivanova 2013, Fedorets et al. 2015, Panteleyeva 2006a). It has been found, for instance, that the land is exposed to dust pollution within a 10 km radius of the plant (Lazareva et al. 1992, Krutov 1997) and the area exposed to pollution by gas and aerosol emissions stretches 20–50 km from the plant (Opekunova and Senkin 2001) (Opekunova and Senkin 2001). The areas of land pollution around the quarries are secondary halos and flows of scattering of Fe, Mn and Ni (Litinsky 1996, Panteleyeva 2006c, Panteleyeva 2007), and around the tailing dump – Fe, Mn, Pb, Cr and Co (Novikov 2006, Panteleyeva 2009a). Bottom sediments of the tailing dump were found to have high concentrations of Zn, Ni, Cr As and Co (Novikov 2016). The territory that has suffered from maximum exposure to heavy metals lies within a 10 km radius of the plant (Panteleyeva 2009b, Fedorets 2001, Panteleyeva 2006b). These investigations also demonstrated that the plant exerts a significant geochemical impact on different environmental components, including soils, bottom sediments, the atmosphere and biota. Several radon springs were found around the deposit, indicating that the subsurface of the area contains highly radioactive rocks that may be uncovered during excavation of the quarries (Gorkovets and Sharov 2015). Nevertheless, the degree of pollution of the environmental components with radioactive elements as a result of plant operations and deposit development activities has not been properly studied to date, despite the relevance of investigating this aspect of pollution. Thus, proximity of the Kostomuksha Nature Reserve to the mining enterprise poses a potential threat to the ecosystems in the reserve.

Radioecological investigations within the limits of the Kostomuksha State Nature Reserve were carried out in 2012–2015 by the staff of the Environmental Radiology Laboratory of the Institute of Environmental Problems of the North, Ural Branch of Russian Academy of Sciences (today – Federal Centre for Integrated Arctic Research named after N.P. Laverov, Russian Academy of Sciences), as part of the Federal Research Project "Radioisotopic examination of natural and man-caused transformation of the environment in the European North", as well as under a research cooperation contract with the Kostomuksha State Nature Reserve. These investigations included

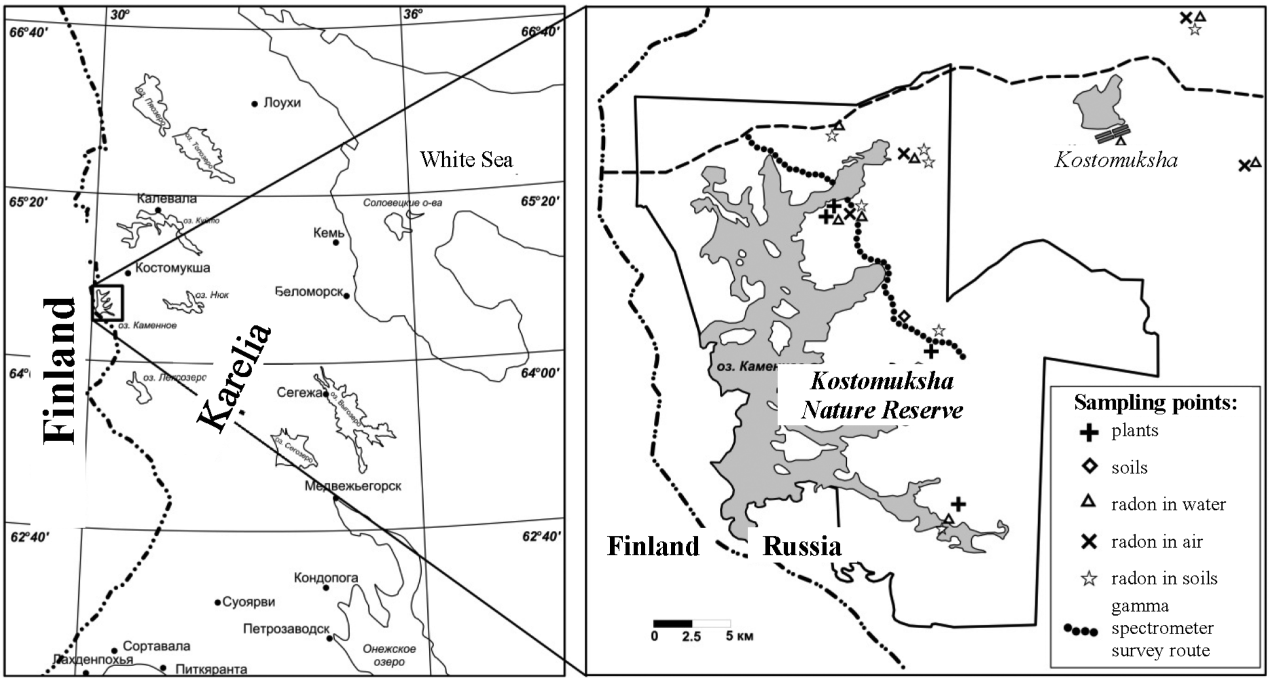

Fig. 1. Location of the study subject – the Kostomuksha Nature Reserve

a survey of natural and anthropogenic radioactivity in the environmental components of the reserve and adjacent territories, including soils, plants, bottom sediments, ambient air and natural waters.

The Kostomuksha State Nature Reserve was established in 1983. The reserve is a single land plot with a surface area of 475.69 km^2 located on the border between the Republic of Karelia and Finland (Anonymous 2017) (Fig. 1).

The nature reserve was designed to be part of a regional environmental complex and its original intent was to neutralise the adverse effects of industrial operations by the booming Kostomuksha Mining and Processing Plant (MPP). The Kostomuksha Nature Reserve became a trans-border reserve after the Friendship Finnish-Russian Nature Reserve was established in 1990 (Smirnova and Shaposhnikov 1999, Sikkilya et al. 2015, Tarkhova 013).

The study area is located on the northern slope of the West Karelian Heights. It has a tectonic denudation topography represented by rolling plain waterlogged in depressions and alternating with ridged hills (Potakhin 2007).

The study area has an extensive drainage network discharging into the White Sea basin. The territory lies in the watershed of four fluviolacustrine systems: Livo – Tolloyoki, Kenti – Kento, Kamennaya – Komosozero, and Ryahme – Lahno. The area has numerous small lakes (lambines) supplied by swamp waters, as well as small mixed-feed rivers (Gorkin 2006). The largest water body within the reserve limits is Kamennoye Lake, which occupies almost a quarter of the entire surface area of the nature reserve. It is of glacial-tectonic origin and takes up almost a quarter of the reserve's territory with a surface area of 105.5 km^2. The lake is 23 km long, 15 km wide, and has an average depth of 8 metres. The lake's shore line is 193 km long and is highly irregular. There are 98 islands on the lake (Belousova et al. 1988).

Soils in the area are mostly represented by podzols – humic-illuvial, humic-ferruginous-illuvial, ferruginous, surface-podzolic, peaty and peaty-gley humic-illuvial on top of boulder loams, sands and sand clays, in combination with peat-bog soils (Krasilnikov 1995).

The area's geology is represented by early Archean and late Archean crystalline formations. The land of the nature reserve consists of ancient (early Archean) crystalline rocks – diorite gneiss, granodiorite gneiss, tonalite, gneiss-granite and migmatite, which make the foundation for volcanic sediments of the Upper Archean (Gorkovets and Rayevskaya 1997, Gorkovets and Raevskaya 2009, Gorkovets et al. 2011).

Materials and methods

To conduct the radiological investigations in the Kostomuksha Nature Reserve, the research team collected samples of plants (moss and lichens), as well as leaves, branches and the trunk of a birch tree, making a total of seven samples. Samples of bottom sediments (99 samples) were taken from Kamennoye Lake with the help of a motor boat and a bottom scoop. A soil pit was also extracted at the nature reserve and five samples of different genetic horizons were collected from it. Collected samples of plants, soils and bottom sediments were placed in plastic bags and marked, and appropriate sample details were recorded in the field log. After delivery to the laboratory, the samples were dried in a drying box at 105 °C to constant weight, and the bottom sediments were studied to determine their grain composition.

Radiological investigations of the environmental components within the limits of the Kostomuksha Nature Reserve and adjacent territories were carried out using a variety of radiometric instruments with different functional purposes, including a mobile gamma spectrometer RS-700 (Radiation Solution, Canada), laboratory gamma spectrometer Progress-Gamma (NPP Doza, Russia), and automatic radon radiometer RRA-01M-03 with sampling extension POU-04 (NTM-Zashchita, Russia).

Terrain radioactivity surveys were carried out in situ using a high-precision mobile scintillation gamma spectrometer system RS-700 (2017). The RS-701 system is built with an advanced digital spectrometer (ADS) that has a high definition capability (1024 channels) and can be used for real-time measurements of total radioactivity in cps, as well as separate measurement of total concentrations of uranium (ppm), thorium (ppm) and potassium (% wt.). The system has an integrated GPS receiver for precision geo-referencing of each measurement. The system's RAD Assist software allows the measurement data to be processed in the field.

Measurements were made at a height of 1 metre above ground level from a vehicle. In total, the profile of gamma spectrometer survey of the nature reserve territory includes over 4500 measurement points for each of the monitored parameters.

Laboratory tests of radioactive elements in the samples of plants, soils and bottom sediments were carried out with the help of a stationary gamma spectrometer Progress-Gamma. Energy calibration of the gamma spectrometer to ensure parameter security was carried out after each measurement using a proprietary calibration source OISN-137-1 ($^{137}Cs+^{40}K$). A measuring cell (Marinelli beaker) was used for exposure of the loads.

Studies of the volumetric activity of radon in natural waters, soil air and ambient air were conducted in situ using an automatic radon radiometer RRA-01M-03 with sampling extension POU-04 and included examination of 19 radon samples in total.

Findings

The results of measuring gamma activity on the nature reserve territory from north-west to south-east demonstrate lack of uniformity and significant variations in the distribution of total radioactivity. Total gamma activity of the terrain varies from 0.006 mcSv/hr to 0.071 mcSv/hr at an average of 0.04 mcSv/hr. The differentiation of total radioactivity and a large spread of measurement values in the nature reserve is a consequence of the complex geology with diversity of magmatic rocks and presence of faults and dikes. At the same time, maximum values of total radioactivity in the reserve are approximately 0.1 mcSv/hr lower than the average value of natural background gamma radiation (Smyslov 1974), which meets the prescribed radiation safety standards. Concentrations of naturally occurring radioactive elements U, Th and K in the nature reserve are also determined by the variety of rocks in the area. The content of naturally occurring uranium varies in the range of 0.5 to 9.9 ppm, sometimes exceeding the bulk earth values for the earth crust (~4 ppm) by a factor of two. Thorium was also found to have higher than normal (13 ppm) bulk earth concentrations reaching 30 ppm. These high concentrations of U and Th correspond to their natural concentrations typical of alaskite granites, as well as of nephelinic and agpaitic syenites that occur widely across the study area (Smyslov 1979). Percentage abundance of potassium in the earth crust is at 2.4% (Smyslov 1974). The highest concentrations of potassium (up to 4.8 %) that were double its bulk earth value were observed in the acid rocks of the nature reserve.

Presence of rocks within the limits of nature reserve and adjacent territories that feature high concentrations of radioactive elements requires an investigation of their decay products in different media; their primary decay product is the radon gas, which may pose a significant hazard by adding to the background radiation dose. Moreover, several radon sources were found around the town of Kostomushka and within the limits of the nature reserve (Kolomytsev and Shiltsova 1998). One of these sources, to the south-west of the town, is properly organised and used for balneotherapy.

The results of in situ measurements of radon activity within the limits of the nature reserve and adjacent territories in the ambient air, soil air and natural waters are provided in Table 1.

Recorded concentrations of radon in the ambient air were remarkably low, not exceeding 21 Bq/m^3, except in the area around the radon spring near Shchuchya Lambine in the north-east of the reserve, where volumetric activity of radon was recorded at 539 Bq/m^3. In contrast, the ambient air around the Kostomushka healing radon water spring is characterised by low activity of ^{222}Rn (< 20), which is explained by the fact that the spring is enclosed, and there is no direct emission of radon into the air. The values of radon activity in the air of the nature reserve and adjacent territories away from radon springs generally match the average yearly activity of ^{222}Rn typical of the north-western regions, which equals 21 Bq/m^3 [1].

Radon activity in the soil air varies from below 20 Bq/kg to 629 Bq/kg. The wide range of values is explained by presence of radium in the bottomset beds and permeability of the medium. The measured values generally remain within the range typical of the rocks in this area (Korshunov et al. 2012). No radon was found in the soil air of the swampy area in the north-east of the reserve, because water-flooded peat bogs make a perfect screen that blocks migration of radon ^{222}Rn from underlying rocks to the surface.

Concentrations of radon in the water of two adjacent radon springs located near Shchuchya Lambine in the north-east of the reserve are 250 Bq/l and 27.5 Bq/l, respectively. These springs are found in the wetland; they are low-yield springs draining into the lambine on top of the moss cover. Radon activity values of 1300 Bq/l for the first spring and 250 Bq/l for the second spring were recorded in 1998 (Kolomytsev and Shiltsova 1998). The difference in radon concentrations in the water is most likely explained by changes in the dynamic state of the springs that occurred over more than a decade after the initial observations. Radon activity in the water of the organised Kostomushka healing radon water spring is 478.8 Bq/l. Surface waters of the nature reserve and adjacent territories, as well as municipal water in the town of Kostomushka, show very low concentrations of radon, below 2.8 Bq/l, while health standards allow a radon concentration of 60 Bq/l in drinking water.[2]

Data on soil radioactivity measured at different genetic horizons is provided in Table 2.

Podzolic soil is characterised by a rich content of radiocesium in horizon A_oA_1 (2–5), with concentrations reaching 142 Bq/kg. Horizons A_2B (5–10) and

---

[1] Commentary on Radiation Safety Standards (NRB-99/2009). Approved by Decree No. 47 of the Chief State Sanitary Doctor of the Russian Federation G.G. Onishchenko dated 7 July 2009 and effective as of 1 September 2009.

[2] SanPiN 2.6.1.2523-09. Radiation safety standards (NRB-99/2009). Approved by Decree No. 47 of the Chief State Sanitary Doctor of the Russian Federation G.G. Onishchenko dated 7 July 2009 and effective as of 1 September 2009.

Table 1. Radon in the atmosphere, soil air and natural waters of Kostomuksha Nature Reserve and adjacent territories

Sample No.	Coordinates		Measurement point description	Volumetric activity for Rn, Bq/m³
	N	E		
Radon activity in the atmosphere				
1	64°33.298’	30°20.451’	“Quarry”, Kostomushka Nature Reserve	< 20
2	64°37.682’	30°43.219’	4 km S-W of MPP	21 ± 10
3	64°31.515’	30°15.099’	Kostomushka Nature Reserve. Radon spring No. 1 near Shchuchya Lambine	539 ± 97
4	64°32.936’	30°48.195’	Kostomushka healing radon water source	< 20
Radon activity in the soil air				
5	64°33.298’	30°20.451’	“Quarry”, Kostomushka Nature Reserve (wetland, peat)	< 20
6	64°33.316’	30°20.461’	“Quarry”, Kostomushka Nature Reserve (hill, fine gravel)	301 ± 60
7	64°37.682’	30°43.219’	4 km S-W of MPP (gravel, pebbles, covered with moss)	89 ± 25
8	64°34.246’	30°15.752’	Kostomushka Nature Reserve, phenological route	100 ± 27
9	64°31.496’	30°15.135’	Kostomushka Nature Reserve, N-W of Shchuchya Lambine (pebbles)	164 ± 37
10	64°22.184’	30°23.539’	South of the Kostomushka Nature Reserve, Pier on Kamennoye Lake (gravel, sand)	174 ± 40
11	64°27.672’	30°22.751’	Kostomushka Nature Reserve, 100 m from Kamennaya River (podzol)	629 ± 113
Radon activity in natural waters				
12	64°33.314’	30°20.403’	Lambine near “Quarry”, Kostomushka Nature Reserve	0.8
13	64°37.682’	30°43.219’	Pond, 4 km S-W of MPP (gravel, pebbles)	2.4
14	64°34.239’	30°15.752’	Kostomushka Nature Reserve, stream, 100 m from the road to Finland	None
15	64°31.515’	30°15.099’	Kostomushka Nature Reserve. Radon spring No. 1 near Shchuchya Lambine	139.4
16	64°31.515’	30°15.156’	Kostomushka Nature Reserve. Radon spring No. 2 near Shchuchya Lambine	27.5
17	64°22.213’	30°23.568’	South of the Kostomushka Nature Reserve, Pier on Kamennoye Lake	None
18	64°32.937’	30°48.195’	the Kostomushka healing radon water source	478.8
19	64°35’19.9’	30°36’08.8’	Municipal water in the town of Kostomushka, Visitor Centre of the Kostomushka Nature Reserve	2.8

Bfe (10–25) are rich in radium and potassium, which is explained by the presence in these horizons of parent rock represented by small pebbles. In general, natural radioactive elements in genetic horizons of podzolic soils are within the range of prescribed bulk earth values (Smyslov 1974).

The content of radionuclides in woody plants of the reserve was found to be lower than, for example, on the Kola Peninsula (Melnik and Kiseyev 2006).

The sphagnum samples collected in the reserve showed a high activity of ^{137}Cs isotope among the other studied plant samples (431 Bq/kg). This value is much higher than in the moss samples collected in the Arkhangelsk Region, with a mean radioactivity of ^{137}Cs around 40 Bq/kg (Kiselev and Druzhinin 2009), which means that a more in-depth study of the activity of radionuclides in the moss of the nature reserve must be conducted.

Table 2. Content of radioactive isotopes in genetic horizons of podzolic soils in Kostomuksha Nature Reserve

Sampling point coordinates	Soil horizon (thickness, cm)	Description of soil horizon	Specific activity of radionuclides, Bq/kg			
			^{137}Cs	^{40}K	^{226}Ra	^{232}Th
64°28’24.4N, 30°20’20.8E	A_o (0–2)	Moss and lichen ground litter, leaf litter, needles	84 ± 26.1	<162	<3.1	<15.3
	A_oA_1 (2–5)	Humic brown soil, loose, with dense root tangle, moist, with clear boundary	142 ± 26	258 ± 191	<7	19.2 ± 18.8
	A_2B (5–10)	Dark-grey podzol, spotty, sandy, roots and small pebbles, moist, compacted, with wavy boundary	4.1 ± 2.5	587 ± 124	7.6 ± 4.2	7.3 ± 4.2
	Bfe (10–25)	Red ferruginised medium-grained sand, small pebbles, moist, compacted, with roots and rough boundary	<2	598 ± 126	6.9 ± 4.2	16.1 ± 5.1
	T (25 -)	Peat, dark-grown, highly decomposed, with wood residue and roots, moist	8.1 ± 3.4	<35	<0.7	<0.1

Table 3. Activity of radionuclides in plant samples from the Kostomuksha Nature Reserve

Sample	Description	Coordinates		Activity of radionuclides, Bq/kg				
		N	E	^{7}Be	^{137}Cs	^{226}Ra	^{40}K	^{134}Cs
СМ-Кз-12	*Sphagnum* moss	64°31.51’	30°15.10’	201.6 ± 45.6	431 ± 45.6	20.7 ± 9.6	–	14.7 ± 7.6
М-РИ-Кз-12	Moss from radon spring	64°31.513’	30°15.102’	21.4 ± 7.4	128.1 ± 15.7	–	333.2 ± 94	–
Л-Б-Кз-12	Birch leaves	64°27.68’	30°23.29’	308.2 ± 19.6	0.5 ± 0.9	4.2 ± 1.5	106.9 ± 35.4	–
В-Б-Кз-12	Birch branches			121 ± 15	4.3 ± 1.4	2.3 ± 1.6	43.6 ± 28.6	–
Ст-Б-Кз-12	Birch trunk			56 ± 18.5	–	3.2 ± 2.7	41.2 ± 38.3	–
Л-Кл-в-Кз-12	Top part of *Cladonia* lichen	77°03.440’	67°42.558’	232.3 ± 26.6	88.9 ± 11.9	24.1 ± 7.7	–	–
Л-Кл-н-Кз-12	Lower part of *Cladonia* lichen			27 ± 4	70 ± 10.7	16.4 ± 7.5	122 ± 107	–

Since radionuclides are chiefly accumulated by bottom sediments that absorb over 80% of the radioactivity (Trapeznikov 2007), examination of the bottom sediments appears to be a key objective of radioecological investigations. Bottom sediments in lakes constitute a vital component of the lake ecosystem, carrying exhaustive information about the history of water bodies (Subetto 2009) and accumulating harmful elements.

Some 46% of bottom sediment samples from Kamennoye Lake contained anthropogenic isotope ^{134}Cs, whose activity varied from 1 to 12 Bq per kg of dry weight. Mean activity of ^{134}Cs is 4.2 Bq/kg. Irregular distribution of the isotope and its presence only in pelite samples in small quantities (below 12 Bq/kg), plus its fairly short half-life (~2 years), may indicate that it is no longer being supplied to the bottom sediments at this time, while the measured values of its activity are residual values from past fallout and the probability of ^{134}Cs disappearing altogether over the next several years is very high.

Specific activity of ^{137}Cs in bottom sediments of the lake varies from 100 to 873 Bq/kg (Fig. 2).

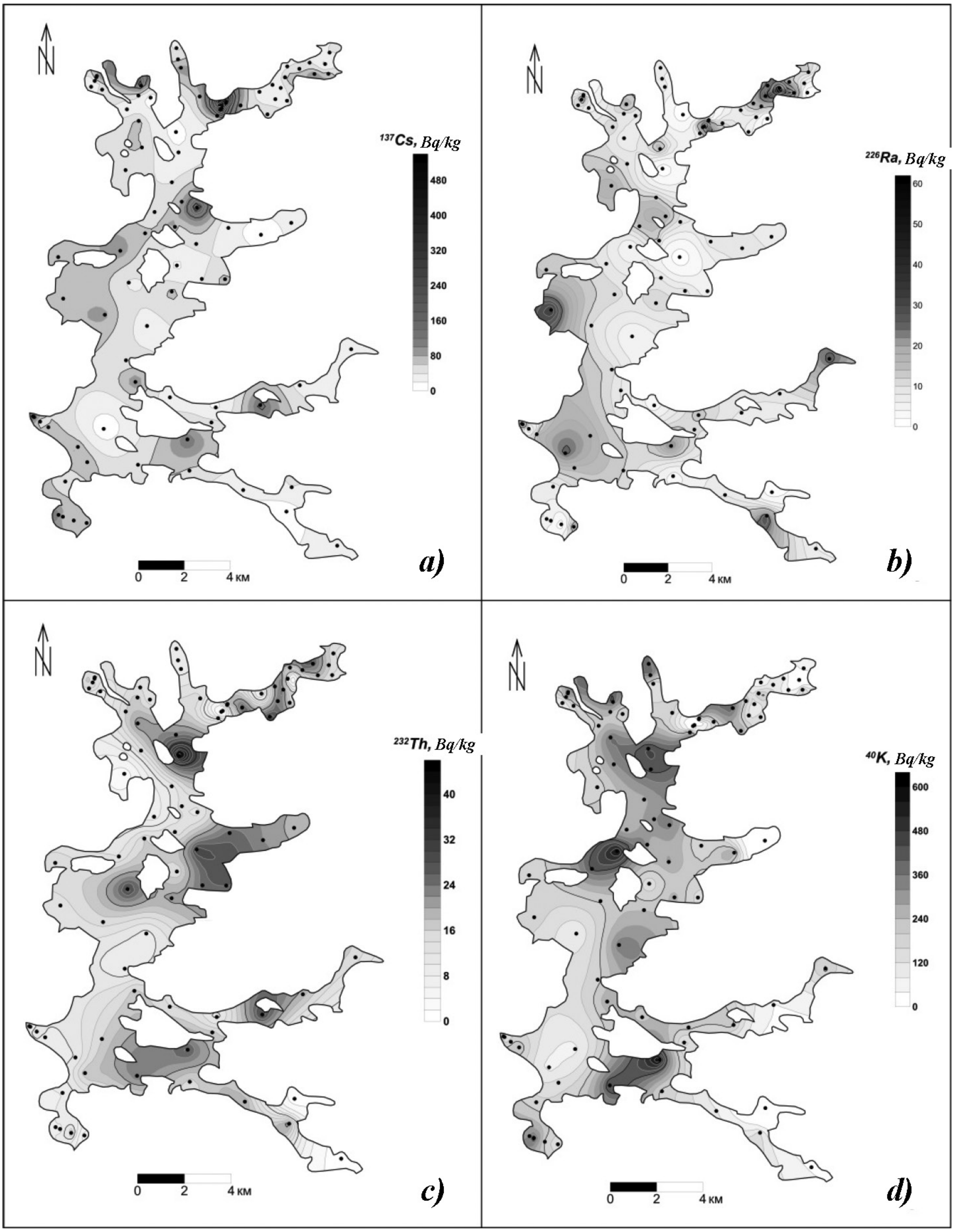

Fig. 2. Distribution of specific activity of radionuclides in bottom sediments of Kamennoye Lake: a) cesium-137; b) radium-226; c) thorium-232; d) potassium-40. Dots on the maps show bottom sediment sampling points

Maximum specific activity of ^{137}Cs isotope (682 to 873 Bq/kg) was found in brown and light-brown silty pelites, and minimum activity (up to 14 Bq/kg) – in grey and brown fine sands. A distinctive feature of the distribution of anthropogenic isotopes ^{134}Cs and ^{137}Cs is the direct correlation between their presence and the grain composition of the soil. These radionuclides accumulate only in silty pelite sediments. It should be noted that tests of bottom sediment samples from Kamennoye Lake revealed the highest values of activity of anthropogenic ^{137}Cs (>800 Bq/kg) among all the studied lakes of Karelia and the Arkhangelsk Region. Mean values of specific activity of radiocesium for the lakes of Karelia and Arkhangelsk Region are within the range of 30 Bq/kg (Kiselev et al. 2017). Similarly high activities of ^{137}Cs were observed in the bottom sediments of lakes around the Kostomushka iron ore deposit located in close proximity to the nature reserve. These samples showed cesium activity values of up to 547 Bq/kg (Kiselev et al. 2017). When processing the body of data on the activity of cesium in the lakes of Karelia and the Arkhangelsk Region, we discovered that activity of ^{137}Cs varies depending on the longitude of the lake's location. Concentration of ^{137}Cs in bottom sediments increases significantly to the west, reaching its maximum at a longitude of 30°E, at the boundary of the study area near the border with Finland (Kiselev et al. 2017). This pattern is quite likely explained by the nature of global fallout of anthropogenic radiocesium, specifically by the accident at the Chernobyl Nuclear Plant, since the density of soil pollution in Finland and Sweden after the accident was much higher than in Karelia (Bakunov 2013).

In the regional perspective, maximum values of ^{226}Ra reaching 76 Bq/kg were found in the north-east of the lake, while in the other parts of the lake this isotope's activity does not exceed 20 Bq/kg, on average. The distribution of the specific activity of ^{232}Th varies from 1.2 to 45 Bq/kg, with a mean value of 16.2 Bq/kg. The activity of ^{40}K varies from 27.9 to 624 Bq/kg, with a mean value of 230.9 Bq/kg. Mean activities of natural radionuclides in the bottom sediments remain within the range of prescribed bulk earth values.

Discussion

Measurement data acquired during the radioecological investigations in the Kostomushka State Nature Reserve bring us to the following highlights of the study.

Total radioactivity in the territory of the nature reserve is around 0.04 mcSv/hr, which is almost twice lower than mean global values for natural gamma background radiation. Concentrations of naturally occurring radionuclides in the nature reserve are governed by differences in rock composition. The measured concentrations that were in excess of the bulk earth values for U, Th and K are natural for acid magmatic rocks forming the terrain in the study area.

The ambient air of the study area shows increasingly low concentrations of radioactive radon gas that do not exceed 21 Bq/m^3. The concentration of ^{222}Rn in the ambient air increases rapidly to 539 Bq/m^3 in the area where radon water springs up to the surface. At the organised source of healing radon water near the town of Kostomushka, where there is no direct emission of radon gas into the air, activity of ^{222}Rn in the air remains below the limit of detection.

Concentration of ^{222}Rn in the water of radon springs in the nature reserve was found to be much lower than during previous studies. This significant decrease in radon concentration in the water of radon springs is most likely explained by changes in ground water dynamics since the original observations. This speaks to the necessity of occasional monitoring of ^{222}Rn activity in the springs.

Mean specific activity values for natural radionuclides in bottom sediments of Kamennoye Lake, which covers almost a quarter of the reserve's surface area, are within the range of prescribed bulk earth values for such isotopes. The pattern of variation of specific activity of radionuclides in the lake's bottom sediments is governed by the grain and lithological composition of the bottom sediments, as well as the regional features of global fallout.

Development of the Kostomushka iron ore deposit, which involves extraction of rocks characterised by a naturally high content of radioactive elements (granitic gneiss), as well as the operations of the mining and processing plant, do not exert any considerable impact on the radiological situation in the nature reserve. Data obtained during the study indicate that the overall radiological situation in the reserve is acceptable and meets the relevant radiation safety standards. On the other hand, high levels of radiocesium found in the moss and bottom sediments of the nature reserve require additional research to determine the wider pattern of distribution of anthropogenic radioactivity across adjacent territories and to study the processes of buildup and migration of radionuclides in aquatic organisms of Kamennoye Lake.

References

- Anonymous (2017) Specially protected natural reservations of the Russian Federation. http://www.zapoved.ru/documents [accessed 20.11.2017]
- Atlasov RR (1993) Aerospace monitoring of geological conditions in the areas around Karelia's mining and processing enterprises in 1990–1993. Book 1. GNPP Aerogeologiya, MOMKAGE, Moscow.
- Bakunov NA (2013) Concerning the tolerance of freshwater bodies in the East Fennoscandia to sedimentation of 137Cs: Radiological aspect. In: Bakunov NA, Savatyugin LM (Eds) The Arctic: Ecology and Economy 1(9), 24–35.
- Belousova NA, Danilov PI, Zimin VB, et al. (1988) The Kostomushka Nature Reserve. Nature reserves of the USSR. Nature reserves in the European part of the RSFSR. Part 1. Mysl, Moscow, 90–100.
- Fedorets NG (2001) Local soil monitoring in the footprint of the Kostomushka Mining and Processing Plant. Bioecological aspects of monitoring forest ecosystems of Russia's north-west. Karelian Research Centre of the RAS, Petrozavodsk, 75–181.
- Fedorets NG, Bakhmet ON, Medvedeva MV, et al. (2015) Heavy metals in the soils of Karelia. Karelian Research Centre of the RAS, Petrozavodsk, 222 pp.
- Fedorets NG, Solodovnikov AN (2013) Impact of emissions from the Kostomushka Mining and Processing Plant on pinewood ground litter in the North Taiga subzone of Karelia. Materials by Karelian Research Centre of Russian Academy of Sciences. No. 6. Environmental Research series. Karelian Research Centre of the RAS, Petrozavodsk, 143–152.
- Gorkin AP (2006) Te Kostomushka iron ore deposit. Geography. A modern illustrated encyclopedia. Rosmen, Moscow, 624 pp.
- Gorkovets VYa, Maksimovich LA, Raevskaya MB (2011) The Kostomushka – the largest integrated ore complex in the Republic of Karelia. Geology of Karelia from the Archean until today: Materials of reports at the All-Russia Conference. Karelian Research Centre of the RAS, Petrozavodsk, 188–196.
- Gorkovets VYa, Raevskaya MB (2009) Geological features of crystalline basement at the Finland-Karelia border. Materials of Karelian Research Centre of the RAS No. 2, Petrozavodsk, 24–38.
- Gorkovets VYa, Rayevskaya MB (1997) Geology of the Kostomushka Nature Reserve. In: Lindholm T, Heikkila R, Hekkila M (Eds) Ecosystem, fauna and flora of the Finnish-Russian Nature Reserve Friendship. Fin. Environment Institute, Helsinki, 11–16.
- Gorkovets VYa, Sharov NV (2015) The Kostomushka Ore District (Geology, Deep Structure and Minerageny). Karelian Research Centre of the RAS, Petrozavodsk, 322 pp.
- Kiselev GP, Druzhinin SV (2009) Cosmogenic isotope beryllium-7 and other radioactive isotopes in the plants of the Arkhangelsk Region. Herald of Arkhangelsk State Technical University. Applied Environmental Geology series (Arkhangelsk State Technical University, Arkhangelsk) 82: 14–28.
- Kiselev GP, Yakovlev EYu, Druzhinin SV, Kiseleva IM, Bazhenov AV, Bykov VM (2017) Natural and anthropogenic radioactivity of bottom sediments in the lakes of Russia's north-west (Republic of Karelia and the Arkhangelsk Region). Achievements of Modern Natural Sciences 12: 152–157.
- Kolomytsev VA, Shiltsova GV (1998) Integrated ecological monitoring in Karelia (concept, program, methods and results in the period of 1992–1996). Karelian Research Centre of the RAS, Forest Institute, Petrozavodsk, 115 pp.
- Korshunov GI, Mironenkova NA, Potapov RV, Paltsev AI (2012) Monitoring of stress-strain behavior of the rock mass through observation of radiogenic gases. Mining Informational and Analytical Bulletin 6: 197–200.
- Krasilnikov PV (1995) Medium scale soil map of Karelia: concepts and methods, Ecology and geography of Karelian soils. Petrozavodsk, 102–106.
- Krutov VI (1997) The impact of gas and dust emissions from JSC Karelsky Okatysh on the phytosanitary condition of pine

forests. Forest phytopathology and mycology issues. Abstracts of the IV International Conference, Moscow, 41–43.
- Lazareva NP, Kuchko AA, Kravchenko AV, et al. (1992) The impact of airborne man-caused pollution on the condition of pinewoods in North Karelia. Karelian Research Centre of the RAS, Petrozavodsk, 49 pp.
- Litinsky Pyu (1996) Remote evaluation of forest degeneration in the area affected by emissions from the Kostomushka Mining and Processing Plant. The issues of man-made transformation of forest ecosystems in Karelia. Karelian Research Centre of the RAS, Petrozavodsk, 182–192.
- Melnik NA, Kiseyev AN (2006) Radioecological examinations of coniferous trees. Herald of Moscow State Technical University 9(3): 429–433.
- Novikov SG (2006) Heavy metals in the soils of Karelia. Karelian Research Centre of the RAS, Petrozavodsk, 120–135.
- Novikov SG (2016) Heavy metals content in the soils of the Kostomushka. Current Issues of Science and Education 5: 1–8.
- Opekunova MG, Senkin OV (2001) Ecological monitoring of the Kostomushka Nature Reserve and adjacent territories. St Petersburg State University, St Petersburg.
- Panteleyeva YaG (2000) Geochemical changes of the environment in the area affected by JSC Karelsky Okatysh mining enterprise (the Kostomushka, Republic of Karelia): Synopsis of a thesis by …, candidate of geological and mineralogical sciences. St Petersburg, 20 pp.
- Panteleyeva YaG (2006) Environmental assessment of the Kostomushka Area, Republic of Karelia, based on the findings of environmental and geochemical investigations. Records of the Mining Institute (St Petersburg Mining University, St Petersburg) 167(4.1): 26–28.
- Panteleyeva YaG (2006) Environmental assessment of the Kostomushka Area, Republic of Karelia, based on the findings of environmental and geochemical investigations. Records of the Mining Institute (St Petersburg Mining University, St Petersburg) 167(4.1): 26–28.
- Panteleyeva YaG (2006) Environmentally hazardous elements and minerals in the feedstock, products and waste of JSC Karelsky Okatysh and the degrees of contaminants accumulation in the environment. Geology, mineral resources and environmental geology of Russia's north-west. Materials of the XVII Youth Scientific Conference in memory of K.O. Kratz, Petrozavodsk, 236–238.
- Panteleyeva YaG (2007) Geochemical assessment of the impact of JSC Karelsky Okatysh mining and processing plant on the environment. New Developments in Geoscience, Geoengineering, Metallurgy and Mining Economics. Freiberger Forschungsforum 58: 68–72.
- Panteleyeva YaG (2009) Environmental and geochemical monitoring in the footprint of JSC Karelsky Okatysh iron ore enterprise. Materials of the X Inter-university Youth Scientific Conference. St Petersburg State University, St Petersburg, 233–236.
- Panteleyeva YaG (2009) Geochemical changes in the environment caused by the development of Korpanga deposit (the Kostomushka, Republic of Karelia). Materials of academic seminar of the 2008–2009 Mikhail Lomonosov Program scholars. Moscow, 163–166.
- Potakhin SB (2007) The atlas of Karelia. Petrozavodsk, 139.
- RS-700 MRMS (2017) RS-700 Mobile Radiation Monitoring System. http://www.radiationsolutions.ca [accessed 06.09.2017]
- Sikkilya NS, Varkoni G, Kravchenko AV [Eds] (2015) The Kostomushka State Nature Reserve. Thirty-year long scientific research in the Kostomushka Nature Reserve. Petrozavodsk, 229 pp.
- Smirnova OV, Shaposhnikov ES [Eds] (1999) Seral processes in Russia's nature reserves and the challenges of biodiversity preservation the Kostomushka Nature Reserve. RBO, St Petersburg. 549 pp.
- Smyslov AA (1974) Uranium and thorium in the Earth's crust. Nedra, Leningrad, 231 pp.
- Smyslov AA (1979) Thermal behavior and radioactivity of the Earth. Nedra, Leningrad, 345 pp.
- Subetto DA (2009) Lake bottom sediments: Paleolimnological reconstructions. Gertsen Russian State Pedagogical University, St Petersburg, 344 pp.
- Tarkhova N (2013) The Kostomushka State Nature Reserve. Ministry of Natural Resources and Ecology of the Russian Federation. The Kostomushka, 24 pp.
- Trapeznikov AV (2007) Migration of radionuclides in freshwater ecosystems. Ural State University Publishing Office, Ekaterinburg, 80 pp.
- Vinogradova AA, Ivanova YuA (2013) Anthropogenic burden on the ecosystems of the Kostomushka Nature Reserve: Atmosphere. Fismatlit, Moscow, 82 p.