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Current radiation environment in the Central Ecological Zone of the Baikal Natural Territory

B.P. Chernyago [a], A.I. Nepomnyashchikh [a,*], V.I. Medvedev [b]

[a] *A.P. Vinogradov Institute of Geochemistry, Siberian Branch of the Russian Academy of Sciences, ul. Favorskogo 1a, Irkutsk, 664033, Russia*
[b] *Sosnovgeos Research and Development Enterprise, ul. Gogolya 53, Irkutsk, 664039, Russia*

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Abstract

The main natural and human-induced radiation factors were assessed on the basis of long-term targeted radioecological studies in the Central Ecological Zone of the Baikal Natural Territory as a world heritage site. We identified areas with a problematic level of different radiation parameters determining the current radiation environment. Such areas should be taken into account in the development and implementation of nature management plans in the Baikal region, including ecotourism.

Keywords: radiation environment; natural radionuclides; artificial radionuclides; conservation

Introduction

Following the decision of the UNESCO World Heritage Committee to include Lake Baikal in the World Heritage List, the federal law “On the Conservation of Lake Baikal” (no. 94-FZ, 1 May 1999) was passed. An important stage in the fulfillment of the UNESCO requirements was the discussion and establishment of the boundaries of the Baikal Natural Territory (BNT) and its ecological zones (Government order no. 1205-r, 29 August 2006). The boundaries of the Central Ecological Zone (CEZ) roughly coincide with those of the world heritage site (Toropov, 2009) (Fig. 1).

As a world heritage site, Lake Baikal and its shore are national and international tourist attractions. To sustain interest and attract investment from Russia and other countries, the Russian Government decreed that recreation and tourism special economic zones (SEZ) should be established on the western and eastern shores of Lake Baikal (no. 68, 3 February 2007).

For successful development of tourism, the Baikal region is characterized by diverse environments, climates, and resort conditions, mainly owing to the geologic peculiarities of Cisbaikalia. However, it should be kept in mind that diversity is also typical of the radiation environment, both natural and human-induced. On one hand, the presence of localities with elevated background radiation might stimulate extreme and environmental tourism or the creation of spa (for example, radon) therapeutic facilities and resorts; on the other, it might be unfavorable to residents and guests in the case of long-term stay. Therefore, all aspects of the current radiation environment should be taken into account in the development of long-term nature management plans.

The present publication is an attempt at analyzing and interpreting the studies conducted in the Baikal Territory by different organizations under special-purpose programs of the Siberian Branch of the Russian Academy of Sciences, the Ministry of Natural Resources, the administration of the Irkutsk Region, and local district authorities over the last two decades. According to these studies, the CEZ is a part of the BNT with a contrasting and, therefore, tense radiation environment.

Materials and methods

Analysis of the radiation environment in the CEZ of the BNT relied on the results of massive in situ measurements of the radiation field obtained during prospecting for radioactive raw materials, which has been conducted in the Baikal region for more than 60 years. Also, we used multipurpose geochemical maps, scale 1 : 1,000,000 (MGM-1000) (Koval’ et al., 1993), covering the Baikal geoecological test ground (>110,000 km^2), and data from targeted radioecological

* Corresponding author.
E-mail address: ainep@igc.irk.ru (A.I. Nepomnyashchikh)

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studies, scale 1 : 200,000–1 : 500,000, covering the Irkutsk, Slyudyanka, and Ol'khon areas, the Ust'-Orda Buryat District of the Irkutsk Region, and some regions of Buryatia. The area of targeted radioecological studies has been extended since 2000 to the entire CEZ of the BNT and considerable parts of its buffer zone and the zone of atmospheric effect.

The targeted integrated radioecological studies were conducted in compliance with the requirements of the "Radon" federal special-purpose program, the research program "The Semipalatinsk Test Site–Altai," and other departmental programs and projects. The gamma radiation dose rate was measured at each site, with the sampling of several environmental components: bedrocks, soils, bottom sediments, water from underground and surface watercourses, and vegetation in Cisbaikalian natural landscapes.

To assess the Rn hazard, soils and ground were usually studied near and in populated places, mainly rural ones, and the Rn flux from soil was measured along with the Rn isotope concentration in the indoor air of residential and public buildings (Chernyago et al., 2008). In addition, the bulk activity of Rn isotopes in soil air was measured at more than 600 sites in natural landscapes and near Cisbaikalian villages, and ~300 residential and public buildings were examined for Rn in 25 populated places in the CEZ.

Human-induced radioactive contamination was studied predominantly in the undisturbed (virgin) soil of natural landscapes, usually on glades or in sparse forests, on the gentle slopes and highlands of foothills, or, less often, in pastures and grasslands, that is, in places with minimum, if any, surface migration of radionuclides owing to outwash or supply with atmospheric or flood water (Sukhorukov, 1996). Soil samples for assessing human-induced radioactive contamination were taken layer by layer, every 5 cm, to a depth of up to 40 cm or more, including horizons A_0, A, B, and C. The activity of the radionuclides under study was summed for all the layers or estimated only for the upper soil layer to correct for the origin of contamination and the contribution of radionuclides to the effective dose.

The CEZ is ~57,700 km^2 in size, without the Lake Baikal water area (Map..., 2006). In this work, we analyzed data from 1100 sites of comprehensive observation (sampling) in the CEZ. This number of sites corresponds to the sampling density on a scale of 1 : 500,000.

All the samples of soil, bedrocks, and bottom sediments underwent quantitative gamma-ray spectrometrical analysis for natural radionuclides of ^{238}U (by ^{226}Ra), ^{232}Th, and ^{40}K (^{238}U, ^{232}Th, ^{40}K) and artificial radionuclides of ^{137}Cs in the certified laboratory of Sosnovgeologiya State Enterprise (samples MGM-1000) and that of the United Institute of Geology, Geophysics and Mineralogy (UIGGM) (samples derived from targeted radioecological studies), which is the base laboratory for the program "Semipalatinsk Test Site–Altai." Part of the samples were analyzed at the Vinogradov Institute of Geochemistry and in Radon Specialized Integrated Radiation Safety Plant (Irkutsk). The soil samples underwent quantitative analysis for artificial radionuclides of ^{90}Sr and ^{239,240}Pu at the Analytical Center of the UIGGM (Novosibirsk) and the Testing Laboratory Center of the State Sanitary and Epidemiological Surveillance Department in the Krasnoyarsk Territory.

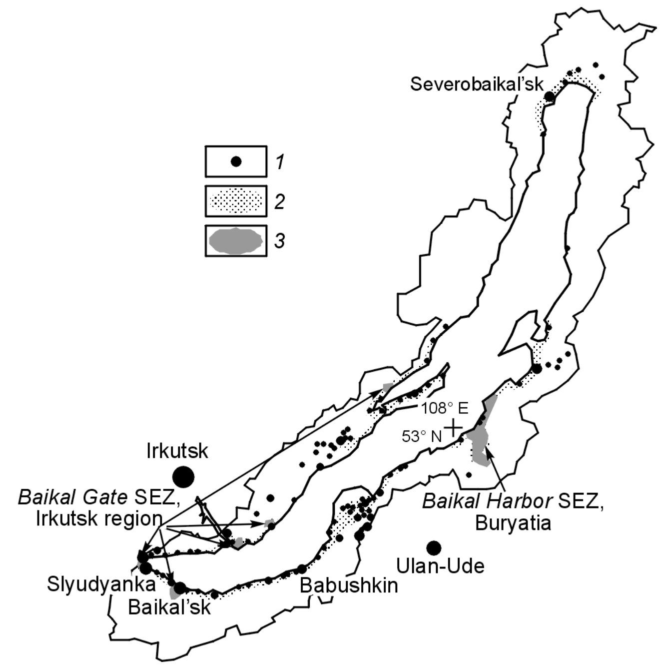

Fig. 1. Populated places, promising sites for tourist camps, and special ecoomic zones (SEZ) within the Central Ecological Zone (CEZ) of the Baikal Natural Territory. *1*, permanent-residence populated places; *2*, prospective sites for permanent, seasonal, or temporary tourist camps or other accommodation; *3*, recreation and tourism SEZ in the CEZ.

Interlaboratory comparative and control measurements were taken regularly to test and validate the results of the quantitative analyses. External control was exercised in the laboratories of Taifun Research and Development Enterprise, the University of Wisconsin, and the National Nuclear Center of Kazakhstan.

In total, the content of natural and artificial radionuclides in soil from the CEZ was determined in the following analyses: ~10,000 samples (4–10 per site) for ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs, >100 samples for ^{90}Sr, and 34 samples for Pu.

All the data on the activity of ^{137}Cs and ^{90}Sr in soil, obtained in 1994–2005 and presented in this publication, were converted with regard to radioactive decay as of 2010.

Results and discussion

The radiation environment in the CEZ is diverse owing to the geomorphologic and radiogeochemical features of the area. It is tentatively divided into natural and artificial components depending on the sources and ways of radionuclide supply.

To assess the current radiation environment in the CEZ, it would be reasonable to use the average annual effective dose received by a local (adult) resident, with regard to all the current radiation sources in the human environment and natural surroundings of Cisbaikalia. The main parameters of

Table 1. Main primary parameters determining the radiation environment and their background values in Cisbaikalia

Parameter	Regional background*	Reference level for abnormality
Parameters for an integrated description of the natural and human-induced external radiation background		
1. Effective dose rate of external gamma radiation (DR)	0.10-0.15 μSv/h	0.40 μSv/h
Parameters determining the natural radiation background and Rn hazard in the area		
2. Specific effective activity of the bedrocks and soils (A_{eff})	85 Bq/kg	370 Bq/kg (SP 2.6.1.2523-09)
3. Specific U activity in the soils (A_U)	12.0 Bq/kg	40 Bq/kg
4. Specific activities of U, Ra, and/or Rn in the water-supply sources (A_{wU}, A_{wRa}, A_{wRn})	0.01 (U, Ra) and 1.5 (Rn) Bq/l	0.1 (U, Ra) and 60 (Rn) Bq/l (SP 2.6.1.2523-09)
5. Bulk activity of Rn isotopes in soil air (BA_{Rn}, BA_{Tn})	3.0 (Rn-222) 10 kBq/m^3 (Rn-220)	10 (Rn-222) 50 kBq/m^3 (Rn-220) (SP-98)
Parameters determining radiation from human-induced radioactive contamination		
6. Fallout density of ^{137}Cs in the soils (C_{Cs}) with regard to decay (2010) and that of other artificial radionuclides (C_{Sr}, C_{Pu}) or their specific activities (A, Bq/kg)	1.5 Bq/m^2 global background (Chernyago and Nepomnyashchikh, 2008; Nepomnyashchikh et al., 1999)	2.2 kBq/m^2
7. Fallout density of natural radionuclides (U, Ra, Po, Pb, Th, K) in the soils and snow (C_U, C_{Ra}, C_{Po}, C_{Pb}, C_{Th}, C_K) or their specific activities in the upper soil layer and vegetation (A, Bq/kg)	0.2 kBq/m^2 (U and Th in the soddy upper soil layer)	0.5 kBq/m^2 (U, Th)
8. Contents (specific activity) of radionuclides in local food (milk, potatoes)**	(Radiation-Hygienic..., 2007)	SanPiN 2.3.2.1078-01

* The so-called "regional background" of a parameter is the median or average (arithmetic or geometric) value of this parameter, obtained as a result of long-term targeted studies in the Baikal region.
** Radionuclide contents of food were not determined in the present study. To estimate their contribution to the total dose, we used data from the radiation-hygienic description of the Irkutsk Region (Radiation-Hygienic..., 2007).

the current radiation environment in the CEZ are shown in Table 1. Their contribution to the annual effective dose from all the radiation sources (except occupational doses and those from medical radiation treatment) received by the population in the study area will be considered below. Parameters 1, 2, 3, 6, and 7 (Table 1) determine the external irradiation of the human body, especially in open areas, whereas parameters 4, 5, 8, and, to some extent, 2 and 3 determine internal irradiation, received with inhaled air, ingested food, and water. Other parameters of radiation fields and radionuclides make a minor contribution to the total effective dose.

Regional background levels should be defined to analyze the spatial distribution of the above parameters, estimate the total effective dose for the CEZ, and detect anomalous areas. The regional background level for natural radionuclides is calculated from clarkes in the environmental components (Petrova and Levitskii, 1984), whereas the background for artificial radionuclides is calculated from the level of global fallout (Chernyago and Nepomnyashchikh, 2008; Nepomnyashchikh et al., 1999) (Table 1).

A radiation anomaly generally means a statistically significant increase in the average regional (background) level of one or several parameters of the radiation environment. If the values of the given parameter show a normal distribution over the area, a locality with the three or more times greater distribution-function variance from the regional average or two or three times greater average value of this parameter will be considered anomalous. An anomaly exceeds the existing sanitation standard. Radiation-hygienic levels (SP 2.6.1.2523-09, 2009; SP-98, 1998 are used to detect anomalies from the effective specific activity of the rocks, the bulk activity of Rn in soil, and the gamma radiation dose rate.

Speaking about one or several anomalous parameters of the radiation environment, we should realize that these conditions are adverse or hazardous most probably only in the case of long-term exposure. For example, exposure to high Rn activity in indoor air or the use of building materials with elevated radionuclide contents can hardly be immediately dangerous to the life or health of residents or tourists, but it would be unreasonable to delay solving the problem. Unfavorable conditions should be taken into account and mitigated in design, construction, provision of amenities, and the planning of the regional development.

Let us consider the spatial distribution of the above parameters in the CEZ as they are listed in Table 1.

Effective gamma radiation dose rate

The natural background gamma radiation in open areas usually consists of 30–40% space radiation and 60–70% ambient natural radionuclides and artificial gamma-emitting radionuclides (the latter result from human-induced contamination). The gamma radiation dose rate (DR) in an open area can have several components:

$$DR = DR_{sp} + DR_{NR} + DR_{RC}, \quad (1)$$

where DR_{sp} is the space radiation DR; DR_{NR}, terrestrial natural radionuclides as a DR component; DR_{RC}, the DR resulting from human-induced radioactive contamination.

The Lake Baikal surface is located at an elevation of ~450 m asl. The DR_{sp} value is here ~0.03–0.04 μSv/h. The altitude difference in the CEZ is usually no more than 1000 m; therefore, if DR_{sp} varies slightly at these altitudes (Kozlov, 1991), the average annual DR_{sp} value can be considered almost constant in the entire CEZ.

By the natural gamma radiation DR, the areas adjacent to the taiga and mountain taiga of the BNT are zones of moderate (0.07–0.10 μSv/h) and elevated (0.10–0.14 μSv/h) natural radiation (Vysokoostrovskaya et al., 1996). Elevated DR are due to the widespread occurrence of sedimentary and felsic igneous rocks rich in natural radionuclides and the occurrence of soddy and sod-podzol soils.

The regional background radiation DR in Cisbaikalia is taken to be 0.10–0.15 μSv/h, with regard to natural variations with time (mainly from the space component) (Chernyago and Nepomnyashchikh, 2008). In this case, a DR of 0.4 μSv/h will be considered anomalous (though there are no limitations for natural gamma radiation in open areas in the national sanitary regulations or international recommendations on radiation protection).

The DR for a source of natural gamma-emitting radionuclides (^{226}Ra, ^{232}Th, ^{40}K) on the Earth's surface, which is uniformly distributed throughout the half-space, is expressed as

$$DR_{NR} = (k_{Ra} \times A_{Ra} + k_{Th} \times A_{Th} +$$

$$k_K \times A_K) \times 10^{-3}, \ \mu Sv/h, \quad (2)$$

where DR_{NR} is the effective gamma radiation DR at an altitude of 1 m from the Earth's surface (μSv/h); A_{Ra}, A_{Th}, A_K, specific activities of U radionuclides (by ^{226}Ra), ^{232}Th, and ^{40}K, respectively (Bq/kg); k_{Ra}, k_{Th}, k_K, factors of conversion to dose ((nSv/h)/(Bq/kg)); a factor of 10^{-3} is used to convert nSv to μSv.

If we take into account that artificial gamma-emitting radionuclides of ^{137}Cs occur everywhere, including the soils of the BNT, the item $k_{Cs \times} A_{Cs}$ should be added to the total DR_{NR}:

$$DR_{RC} = k_{Cs} \times A_{Cs} \times 10^{-3}, \ \mu Sv/h. \quad (3)$$

According to calculations, 80% of the external dose at an altitude of 1 m from the Earth's surface is determined by gamma-emitting (natural and artificial) radionuclides in the upper soil layer 3–5 cm thick (Clouvas et al., 2000; United..., 2000). The factors depend on the energy spectrum of radionuclide radiation, the chemical composition of soil, its density, moisture content, etc. (Nageswara Rao et al., 1996). Table 2 shows the most typical values of the factors used to convert specific activities of radionuclides to dose and their values from (Kuznetsov, 1996), obtained for Cisbaikalian soils as a result of comparing laboratory measurement data on samples taken from the 5-cm-thick upper soil layer with data from in situ measurements in an open area with a field gamma-ray spectrometer, as in (Quindos et al., 2004).

The effective gamma radiation DR is determined mainly by natural radionuclides. Even in Cs anomalies, the contribution of artificial radionuclides to the total gamma radiation dose is no more than 10%.

Note that elevated external gamma radiation DR (>0.6 μSv/h) are recorded in some areas adjacent to the Lake Baikal shore. This is explained by the elevated content of natural radionuclides in the rocks (mainly granites and quartzites) and soils, which inherit these radiogeochemical features from the bedrocks. Such areas are located mostly on hard-rock outcrops, in relatively remote, underpopulated, and undervisited mountain regions.

Areas and localities with gamma radiation DR hazardous to different extents (Fig. 2) are moderately developed in the CEZ. They are located within the mountain framing of Lake Baikal and the East Sayan mountain system and confined to outcrops of rocks with U mineralization (potentially uraniferous) of granitic, gneissic, and volcanoterrigenous assemblages of Archean–Early Proterozoic and Riphean ages (Petrova and Levitskii, 1984).

The potentially hazardous areas, which make up ~8% of the CEZ, are outcrops of highly radioactive rocks with gamma radiation DR of 0.4–0.6 μSv/h and close radioactive anomalies with gamma radiation DR of >0.6 μSv/h. They form trails of isolated areas 50–1800 km^2 in size, which are located along the western and northeastern shores of Lake Baikal and within the East Sayan, south and west of Irkutsk (Fig. 2).

Areas affected by hydrothermal metasomatism are characterized by a hazardous level of the gamma radiation field. They are small (10–20 km^2) rock outcrops with surface gamma radiation DR of 0.6–0.8 μSv/h and local radioactivity anomalies with gamma radiation DR of 0.6–2.0 μSv/h.

Table 2. Factors for the conversion of radionuclide activities to the gamma radiation dose rate at an altitude of 1 m from the surface of "standard" and real soil

Factor (nSv/h)/(Bq/kg)	k_{Ra}	k_{Th}	k_K	k_{Cs}
Cisbaikalian soils (Kuznetsov, 1996)	0.57 ± 0.03	0.85 ± 0.03	0.044 ± 0.002	0.053 ± 0.003
"Standard" soil (Clouvas et al., 2000)	0.52	0.71	0.047	–
In situ and *in lab* measurements for soils in different regions (Quindos et al., 2004)	0.46	0.58	0.043	–

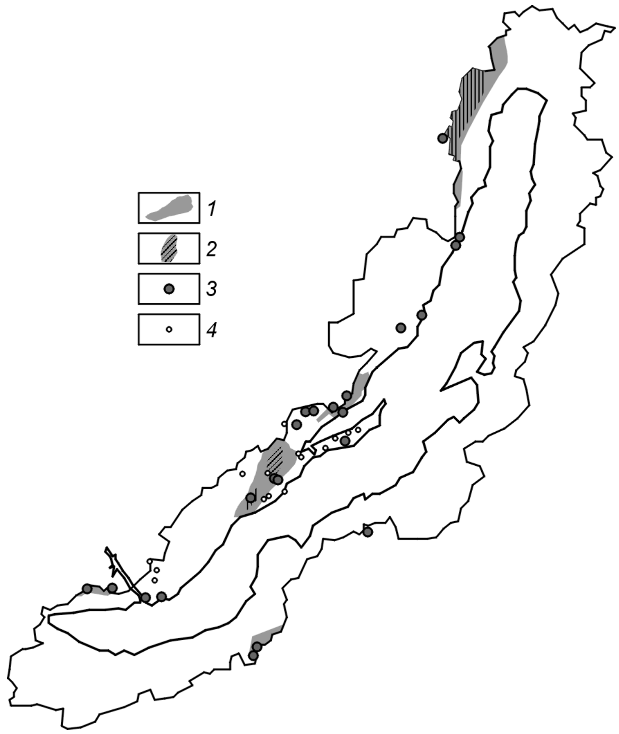

Fig. 2. CEZ localities with elevated gamma radiation DR and specific effective activities of the rocks. *1*, areas with gamma radiation DR of >0.4 μSv/h and specific effective activities of >370 Bq/kg; *2*, areas with gamma radiation DR of >0.6 μSv/h and specific effective activities of >740 Bq/kg; *3*, occurrences with DR of >1.0 μSv/h and effective activities of >1200 Bq/kg; *4*, elevated ^{222}Rn (>60 Bq/l), ^{238}U, and/or ^{226}Ra (>0.1 Bq/l) concentrations in water (springs, wells).

Some U occurrences and numerous radioactive anomalies with gamma radiation DR of >1.0 (up to 33) μSv/h belong to the extrahazardous localities of the CEZ. They all have a local character and are no more than 1 km^2 in size, but they were stripped by open-pit mines during the exploration, and this caused local radioactive contamination. The totality of local radioactive areas and anomalies with hazardous or extrahazardous gamma radiation DR are controlled by the uraniferous structures and complexes of western Transbaikalia, Cisbaikalia, and the East Sayan and make up <1% of the CEZ (Fig. 2).

Effective specific activity of the bedrocks. The concentrations of natural radionuclides (U, Ra, Th, K) in the environmental components of the Baikal region are determined by the facies composition. The Central and Buffer ecological zones of the BNT, which make up the western flank of the Transbaikalian U province, are dominated by ancient metamorphic rocks and granitoids, among which varieties rich in natural radionuclides occur widely (Petrova and Levitskii, 1984).

The ecological zone of atmospheric effect is located in the Siberian Platform and consists of Cambrian carbonate-terrigenous and Jurassic carbonaceous sedimentary rocks with predominantly background radionuclide contents, in which areas with a tense radiation background are present to a considerably smaller extent than in the CEZ.

The highest gamma radiation DR in the CEZ are observed on mountain exposures and bedrock outcrops with elevated contents of natural radionuclides. It was noted in Cisbaikalia that bedrocks with elevated contents of natural radionuclides and the overlying soils, which inherit their principal, including radioactive, properties, are associated mainly with Early Proterozoic granitoid intrusions and active tectonic faults as well as river valleys, whose sediment is removed from the areas of these radioactive intrusions.

Archean bedrocks and Jurassic and Quaternary sediments usually have low contents of natural radionuclides. In fens and wide river floodplains, in which the bedrocks are covered with thick Neogene, Quaternary, or recent sediments, the radiation background level is usually lower than the average regional background.

Specific effective activity (A_{eff}, Bq/kg) is an integral characteristic of bedrock radioactivity and calculated from the following formula (SP 2.6.1.2523-09, 2009):

$$A_{eff} = A_U + 1.3 \times A_{Th} + 0.09 \times A_K, \text{ Bq/kg}. \quad (4)$$

Actually, this formula is similar to (2), especially regarding the origin of the source of elevated gamma radiation in the anomalous areas, in which the soil layer is thin or absent (for example, rock outcrops). Therefore, the areas with elevated gamma radiation roughly coincide with those whose bedrocks have anomalous contents of natural radionuclides.

The localities with anomalous A_{eff} are not widespread in the region; they are concentrated within the East Sayan and Khamar-Daban Ridges (lower reaches of the Selenga River), approximately in the same areas as those with a high gamma radiation DR. The areas with unfavorable A_{eff} values vary in size from 1 to 3000 km^2; they all show a clear zoning like all geochemical anomalies.

Potentially hazardous areas are those with A_{eff} averaging around 370–740 Bq/kg. In fact, small areas with A_{eff} values of 200–370 and 370–1200 Bq/kg alternate here; each of them cannot be mapped; in general, they are closest to "the control zone" (potentially hazardous). In total, these areas make up ~8% of the CEZ. Outside the CEZ, these are individual areas in the East Sayan Mts., 50–100 to 500 km^2 in size, and a sizable area of 3000 km^2 south of Ulan-Ude, which is the western flank of the Transbaikalian uranium-ore belt.

The areas with a hazardous level of the average A_{eff} field, 740–1200 Bq/kg, have a local character and are situated within the potentially hazardous areas. Their size varies from 50 to 200 km^2, and their total area makes up ~0.7% of the CEZ. Individual localities with A_{eff} values of up to 1200 Bq/kg are also found outside these areas.

The total area with potentially hazardous or hazardous A_{eff} values is 5100 km^2 in size (8.8% of the CEZ).

Specific activity of U in the soils. The specific activity of U in the soils as a radiation hazard criterion was also used to assess the radiation environment in the Baikal region and the CEZ, though there are no sanitary regulations for the U content of soils. Elevated U contents of soils are a chemical rather than a radiation hazard (Lean, 1985).

Areas with potentially hazardous (3.5–5.0 mg/kg, or 44–62 Bq/kg ^{226}Ra) and hazardous (5–10 mg/kg, or 62–124 Bq/kg) U contents of the humus layer of soil account for 3.3 and 2.9% of the CEZ, respectively. Most of them are confined to highly radioactive outcrops of the mountain framing of Lake Baikal and located in the middle part of the CEZ, on the western and southwestern shores of the lake.

In general, these natural radiogeochemical anomalies are less distinct than the areas with high U contents of the bedrocks or unfavorable gamma radiation DR and A_{eff} values; they occupy smaller areas and only partly reflect highly radioactive rock outcrops. The data on the U content of the soils make a small contribution to refining the general radioecological situation in the region, but they present another important aspect of the radiation hazard.

Specific activity of U, Ra, and Rn in water. An additional parameter for assessing the radiation environment is the data available on (elevated) U, Ra, or Rn contents of drinking- and household water sources: wells and natural springs (the normal contents of some radionuclides in drinking water were defined in the sanitary regulations (SP 2.6.1.2523-09, 2009; MU 2.6.1.1981-05, 2005).

Water from Lake Baikal is characterized by a very low mineralization, 0.1 g/l (Toropov, 2009), and, therefore, a low concentration (activity) of ^{238}U, 0.4 μg/l (0.005 Bq/l) (Bukharov, 2001). However, the water entering the lake from some tributaries, let alone groundwater, might have an elevated content of natural radionuclides (Pöschl and Nollet, 2007).

As a rule, elevated contents of natural radionuclides (U, Ra, Rn) in water are observed near natural radiation anomalies in rocks and soils. Anomalous water sources are mostly observed on the southwestern shore of Lake Baikal (Fig. 2). However, high contents of natural radionuclides might not be found in underground water supplies or wells in other parts of the CEZ.

Therefore, when using water, especially ground (artesian) water, we have to analyze it for radionuclides, including Rn, at least at the beginning.

Bulk activity of Rn isotopes in soil air. Areas with elevated natural gamma radiation usually present a Rn hazard. Outcrops of bedrocks with elevated contents of ^{238}U and ^{232}Th radionuclides and associated tectonic faults, resulting from the rifting nature of Lake Baikal, release considerable amounts of ^{222}Rn and ^{220}Rn (Tn) into the atmosphere.

Radon isotopes and their daughter decay products are known to make up 50–90% of the total radiation dose received by the population of Cisbaikalia (Chernyago and Nepomnyashchikh, 2000). The Rn hazard is due to the penetration of Rn into residential buildings from ground or utilized groundwater. One-story wooden houses, which are widespread in villages, are least protected from Rn, because forced ventilation is almost absent and soil gases freely penetrate the rooms from the cellar. It is there that high Rn contents might be observed.

Radon hazard in the sanitary regulations (SP 2.6.1.2523-09, 2009) is assessed on the basis of the average annual concentration (activity) of Rn isotopes in indoor air. The limiting average annual activity of Rn daughter products in residential buildings for the population is 200 Bq/m^3. A hazardous level of activity, 400 Bq/m^3, needs special measures: reducing Rn activity to an acceptable level by engineering and construction methods or rehousing.

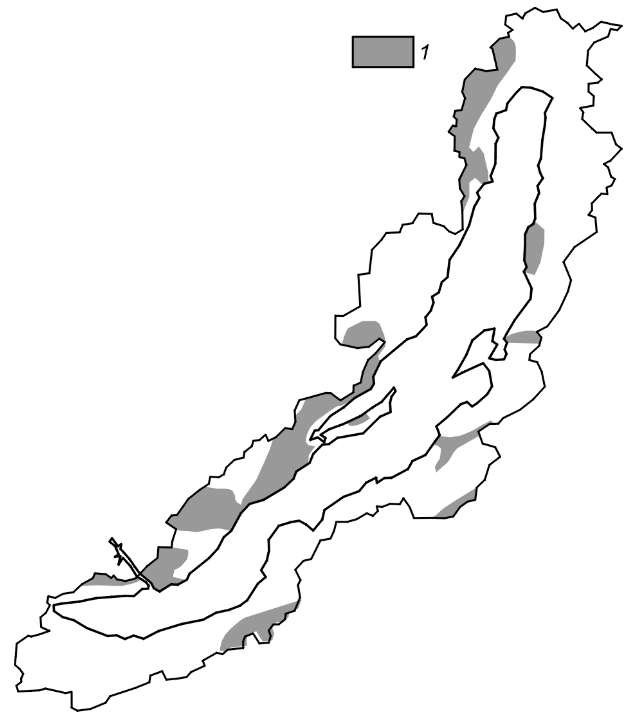

Fig. 3. Sketch map of the distribution of elevated Rn bulk activities in the soil air of the CEZ. *1*, soil-air bulk activity of ^{222}Rn higher than 10 kBq/m^3 and/or that of ^{220}Rn higher than 50 kBq/m^3.

Only in about ten villages of 150 populated places in the CEZ, the most complete in situ studies of the Rn environment were conducted, with measurements of average annual Rn activity in the indoor air of residential and public buildings. Therefore, the predictive estimate of the Rn hazard relied on the data showing the widest and most uniform distribution over the study area—the bulk activity of Rn isotopes in soil.

The content of Rn and its daughter products in indoor air in the Cisbaikalian villages was found to depend on Rn isotope activity in soil (Chernyago et al., 2008). Considering this relationship, we take a Rn isotope activity in soil (BA_{Rn}) exceeding 10 kBq/m^3 to be a criterion for hazardous localities (SP-98, 1998).

According to the above criteria, ~30% of the CEZ is hazardous or potentially hazardous in terms of Rn (Fig. 3). The hazardous areas usually coincide with the extrahazardous ones, identified on the basis of the gamma radiation DR and specific effective activity of the rocks and soils. These are the same outcrops of highly radioactive rocks in Transbaikalia, the mountain framing of Lake Baikal, and the East Sayan, which are usually confined to active tectonic faults.

Fallout density of artificial radionuclides in the Central Ecological Zone (^{137}Cs in the soils). Note that there is no radioactive contamination in the environmental components of the BNT, from the sanitary standpoint. The point is that the artificial-radionuclide contents of soil in the study area exceed

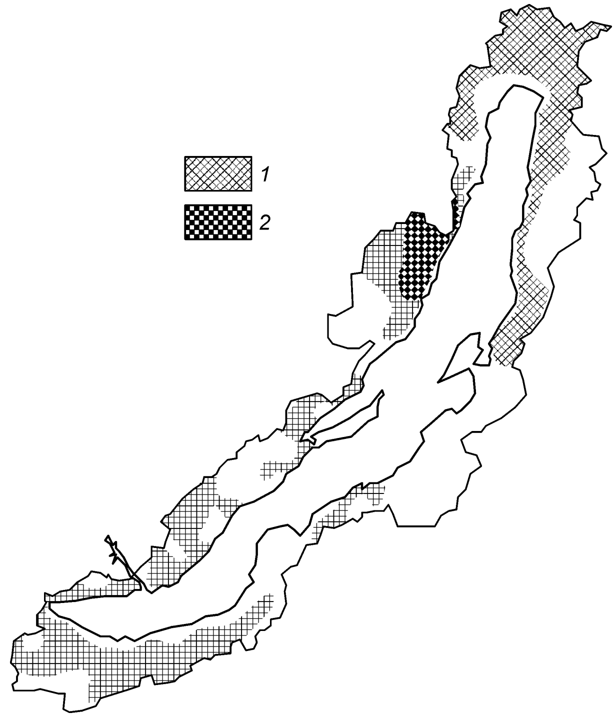

Fig. 4. Sketch map of ^{137}Cs radionuclide fallout density in the soils of the CEZ. *1*, ^{137}Cs fallout density in soil higher than 2.2 kBq/m^2; *2*, the same, higher than 5.5 kBq/m^2.

the regional and/or global background level. The current artificial-radionuclide content of the local soils and food complies with the Russian and international standards (Radiation Safety Standards—NRB-99/2009 (SP 2.6.1.2523-09, 2009)), is safe, and does not limit economic activity.

Elevated contents of artificial radionuclides (^{137}Cs, ^{90}Sr) in the area adjacent to Lake Baikal were recorded by an aerial gamma-ray survey of the entire Soviet territory as early as 1974 (Boltneva et al., 1977) and confirmed by further studies of local research and geological organizations (Chernyago and Nepomnyashchikh, 2008; Medvedev et al., 1996; Nepomnyashchikh et al., 1999). This contamination is due to the transregional atmospheric migration of radioactive products of the nuclear surface and air bursts carried out on test grounds in the former Soviet Union and the United States (Nevada) in 1949–1962. The impact and radioactive contamination from the Lob-Nor test ground (China) (until 1982) and the Chernobyl' disaster (1986) were insignificant for Cisbaikalia as compared with those from the Soviet (Semipalatinsk, Northern) test grounds.

The radioecological studies conducted within the Baikal region revealed two main areas with elevated contents of artificial radionuclides in soil: the southern and northern localities in the CEZ (Fig. 4), associated with the impact of the Semipalatinsk and Northern test sites, respectively.

Of the long-lived artificial radionuclides, which entered the Cisbaikalian environment owing to nuclear tests, gamma-emitting ^{137}Cs radionuclides (half-life 30 years) are now the easiest to determine. The ^{137}Cs background, formed as a result of global fallouts, for 50–60° N, including southern Siberia, is estimated at 1.48 kBq/m^2 (40 mCi/km^2) as of 2010 (Medvedev et al., 2005; Nepomnyashchikh et al., 1999). Consequently, with regard to the mean square deviation for the global fallouts in Cisbaikalia (Chernyago and Nepomnyashchikh, 2008), the reference level for assignment to anomalous areas will be 2.2 kBq/m^2.

The fallout density (or concentration) of artificial radionuclides shows a nonuniform, spotty-mosaical distribution. The fallout density of ^{137}Cs reaches 3.7–7.4 kBq/m^2 in some areas in the southern part of the CEZ. The global ^{137}Cs radionuclide background in soil is exceeded by two or more times in the southern littoral parts of the Irkutsk Region and Buryatia, in a total area of ~15,000 km^2.

Within the studied area of northern Cisbaikalia in the CEZ, elevated (>2.2 kBq/m^2) fallout densities of ^{137}Cs in soil are observed in an area of ~12,000 km^2. In some localities on the northern shore of Lake Baikal, the concentration of ^{137}Cs radionuclides in soil reaches 8.0–15.5 kBq/m^2, exceeding the global and regional (southern Siberia) background levels by 6–10 times.

A level of 2.2 kBq/m^2 for ^{137}Cs is exceeded in an area of >25,000 km^2 (approximately half the CEZ). However, the most significant anomalies (>5.5 kBq/m^2) are recorded in an area of ~2000 km^2, in the northwestern part of the CEZ (3.5% of the total area), a remote, unpopulated mountain region.

As a rule, areas with anomalous ^{137}Cs levels are characterized by elevated contents of other (not gamma-emitting) artificial radionuclides in soil. The specific activity of Pu radionuclides in soil is 3–7 Bq/kg at some sampling sites, exceeding the background levels by ten times. The ^{90}Sr content of soil within the Cs anomalies is also elevated, up to 2.2–5.5 kBq/m^2 (60–150 mCi/km^2).

However, the content of long-lived artificial radionuclides in the Baikal region, and even in the anomalous areas which result from nuclear-weapon tests and indicate bygone radioactive fallouts, over the last 40 years has not threatened the population (Chernyago and Nepomnyashchikh, 2008).

The contents of artificial radionuclides in the local food (milk, potatoes, berries and other wild-growing plants, mushrooms, fish, and other products) are insignificant and considerably lower than the radiation-hygienic standards (Radiation-Hygienic..., 2007). The present dose received from gamma-emitting artificial ^{137}Cs radionuclides in the anomalous localities (up to 7.5 kBq/m^2, which is the maximum value in the southern part of the CEZ) is estimated at up to 0.2 mSv/yr (in the case of permanent residence), that is, up to 10% of the external gamma radiation background.

Fallout density of natural radionuclides in the soils, vegetation, and snow. Contamination with natural radionuclides takes place when mineral deposits are mined, when coal is burned in boiler houses and thermal-power stations, and during the evaporation of ash ponds and slag basins by enterprises, which are usually situated in immediate proximity to populated places. Emissions from thermal-power stations and the wind transport of dust, as well as the leaching-out of radionuclides from ash dumps and their penetration into surface and ground water, lead to the human-induced contamination of the most densely populated places.

Hard coal is known to possess natural radioactivity, which is typical of each deposit and sometimes fairly high (Rikhvanov, 1997). The activities of ^{226}Ra and ^{232}Th in the local coals are 3–50 Bq/kg. When coal is burned, the radionuclides pass into the combustion products, whose specific radioactivity is considerably higher than that of the original material. The effective specific activity (A_{eff}) of the ash–slag mixture on the ash dumps of the Ust'-Ilimsk, Cheremkhovo, and Shelekhov thermal-power stations is 202 ± 35, 323 ± 35, and 403 ± 77 Bq/kg, respectively (Sadovskaya et al., 2009).

Contamination with natural radionuclides near populated places is well detected by the geochemical survey of snow. The highest U fallout densities in snow samples are observed around industrial centers. Contamination around Irkutsk, Angarsk, and Slyudyanka exceeds the background U content of snow (2 ng/l) by up to ten times or more (Koval' et al., 1993).

The long-term contamination of the study area with natural radionuclides, including U and Th, is also shown by the gamma-ray spectrometrical analysis of the upper soil layers. The background U and Th contamination of soil is estimated at ~0.2–0.4 kBq/m^2 (5–10 mCi/km^2). Elevated contents of ^{238}U and ^{232}Th in the upper soil layer are recorded in industrially developed areas and around big populated places, including the CEZ. For example, elevated contents of natural radionuclides were detected in southern Cisbaikalia, Slyudyanka, and Kultuk (Sinitskii et al., 2009). The highest U contents in the upper soil layer (>1.5 kBq/m^2) are observed around Irkutsk, Angarsk, and Shelekhov. These anomalies coincide with the localities detected by the geochemical survey of snow.

The specific activity of ^{238}U (by ^{226}Ra) and ^{232}Th in the upper soil horizon is higher than that in deeper layers by 12 and 7.5%, respectively. Such a distribution of Ra and Th is typical of human-induced changes in soil radioactivity associated with atmospheric fallouts. The coexistence of these two radionuclides in fallout indicates that their likeliest sources are coal-based thermal-power stations, at which both radionuclides coexist.

The calculated external doses from the natural radionuclides present in the upper soil layers of the study area, supplementing the natural background radiation, might reach 0.1 mSv/yr in the most contaminated localities near big populated places of the CEZ (Kultuk, Slyudyanka, Babushkin). For comparison, the average annual natural background of external gamma radiation in the region is ~1 mSv.

Predicted average annual effective dose. There are definitely no places on the Lake Baikal shore in which one might receive a hazardous radiation dose over a relatively short period. However, the radiation environment in some places is unfavorable to permanent or long-term residence. A predictive estimate of the radiation environment in the study area has to be conservative, that is, meant for permanent residence.

The average annual effective dose is the total contribution of all the radiation sources. The predicted average annual

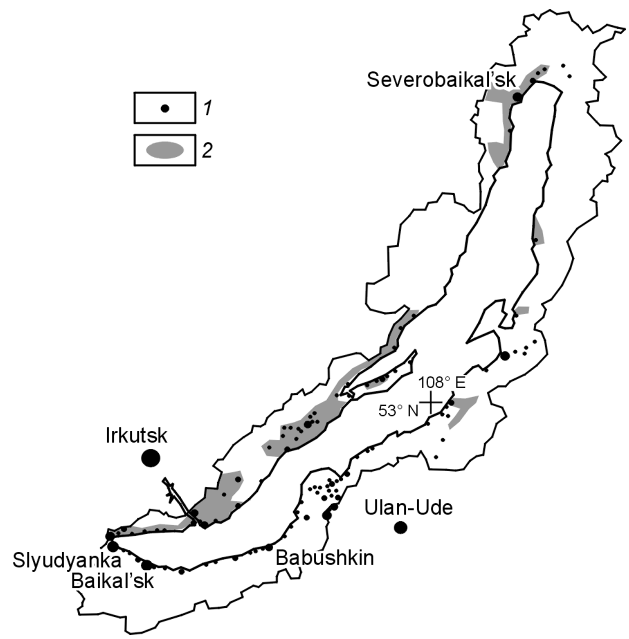

Fig. 5. Sketch map of predicted average annual effective doses of natural radiation for the CEZ population. *1*, permanent-residence populated places; *2*, localities in which the predicted average annual doses might exceed 5 mSv.

effective dose is a sum of all the above parameters with corresponding coefficients, which determine their contribution to the effective dose in the case of external and internal radiation:

$$D = D_{ext} + D_{int} = 8.760 \times DR + (0.031 \times BA_{Rn} + D_{prod}),\ \text{mSv/yr}, \quad (5)$$

where $8.760 \times DR$ (μSv/h) is the annual external dose in an open area (mSv/yr), which is a product of the gamma radiation DR and the number of hours in a year; $0.031 \times BA_{Rn}$ (Bq/m^3) is the internal dose of Rn (mSv/yr), which is a product of the dose factor, equilibrium coefficient, indoor-to-soil bulk activity ratios, and Rn isotope activity in soil; and D_{prod} (mSv/yr), the annual internal dose received with local food (mSv/yr).

Daughter products of natural Rn contribute the most to the total dose. Gamma radiation is responsible for up to 30%. The portion of artificial radionuclides in the Cisbaikalian environment is insignificant both in external and internal radiation. The current contamination with artificial radionuclides and their content in local drinking water and food have no significant influence on the radiation environment (Radiation-Hygienic..., 2007).

The distribution of the predicted current dose over the CEZ was calculated from (5) with regard to the duration of stay (Fig. 5). The total background effective dose received by the CEZ population is ~2.5 mSv/yr. The areas with the highest radiation stress (average predicted dose >5 mSv/yr) roughly coincide with those of increased Rn hazard.

Judging by the criteria for natural and human-induced radiation risks, the current radiation environment on the Lake Baikal shore complies with the national radiation safety standards (NRB-99/2009 (SP 2.6.1.2523-09, 2009)), is safe for living, and does not hinder economic activity, including tourism industry, but we need a correlation between the localities and a certain radiation environment and, if necessary, application of protective measures in the construction and utilization of buildings and facilities.

Examples of successful use of such a balanced approach to the implementation of ecotourism projects include the 2008 radioecological studies of the recreation and tourism SEZ near Bol'shoe Goloustnoe Village (part of the Baikal Gate SEZ). According to these studies, the locality was characterized by a ^{137}Cs radionuclide content of soil at the global background level and low specific effective activity of ground and hard rocks, which permit their unlimited use in construction; the effective gamma radiation DR and the U content of soil within the prospective construction site correspond to the background level, fully complying with radiation safety standards. At the same time, the construction site was found to be hazardous in terms of Rn; this requires detailed studies at the design stage and, if necessary, Rn protection.

Conclusions

Targeted radioecological studies in the Central Ecological Zone of the Baikal Natural Territory confirm that this area is characterized by a contrasting and tense radiation environment, which is determined by natural and human-induced sources.

The tense radiation environment is mainly due to the distribution of natural radionuclides (U, Ra, Rn, Th, K) in nature. Up to 30% of the CEZ is marked by potentially hazardous, hazardous, or extrahazardous Rn contents of soil air and groundwater.

The current fallout density of natural and artificial radionuclides in the environmental components of the Baikal region, including soil, has no significant influence on the radiation environment.

Judging by the criteria for natural and human-induced radiation risks, the current radiation environment in the Baikal region complies with the national radiation safety standards, is safe for living, and does not hinder economic activity, including tourism, but we need a correlation with a certain radiation environment and, if necessary, Rn protection in the construction and utilization of buildings and facilities.

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