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Calculation of generalized indicators of radiation-ecological risk for areas of the Barents and Kara Seas exposed to the influence of nuclear and radiation hazardous objects

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Abstract. Most of the potential sources of radioactive contamination in the Arctic are located in the Barents and Kara Seas. In this regard, scientific research is regularly carried out in these territories, the results of which can be used to determine and analyze radiation and environmental risk. The goal and objective of the work is to calculate integral indicators of radionuclide pollution and generalized indicators of radiation-ecological risks in water and bottom sediments of the Barents and Kara Seas areas exposed to nuclear and radiation hazardous facilities. It is shown that the index ranges from $9.5 \cdot 10^{-5}$ to $4.1 \cdot 10^{-4}$ for water and from $1.2 \cdot 10^{-4}$ to $1.3 \cdot 10^{-2}$ for bottom sediments, which is much less than one. Calculated values of the risk indicator for K-159 range from 3 to 6, which corresponds to an insignificant radiation impact on the marine environment, for bays and the Novaya Zemlya depression from 12 to 18, which is characterized by a weak impact on the radiation situation. Thus, the objects under assessment have an insignificant and weak impact on the radiation situation in the Arctic region, but, taking into account the potential danger, they require constant monitoring of the components of the marine environment in order to timely detect radiation-ecological changes.

Keywords: Arctic, radiation-ecological risk, integral indicator of pollution, reference level, marine biota

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Расчет обобщенных показателей радиационно-экологического риска для районов Баренцева и Карского морей, подверженных воздействию ядерно и радиационно опасных объектов

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Аннотация. Большая часть потенциальных источников радиоактивного загрязнения Арктики находится в Баренцевом и Карском морях. В связи с этим на указанных территориях регулярно проводятся научные исследования, результаты которых могут использоваться для определения и анализа радиационно-экологического риска. Целью и задачей работы является расчет интегральных показателей загрязнения радионуклидами (ИПЗ) и обобщенных показателей радиационно-экологических рисков (ОПР) в воде и донных отложениях районов Баренцева и Карского морей, подверженных воздействию ядерно и радиационно опасных объектов (ЯРОО). Показано, что ИПЗ составляет от $9{,}5 \cdot 10^{-5}$ до $4{,}1 \cdot 10^{-4}$ для воды и от $1{,}2 \cdot 10^{-4}$ до $1{,}3 \cdot 10^{-2}$ для донных отложений, что на много меньше единицы. Расчетные значения ОПР для К-159 составляют от 3 до 6, что соответствует незначительному радиационному воздействию на морскую среду, для заливов и Новоземельской впадины от 12 до 18, что характеризуется слабым воздействием на радиационную обстановку. Таким образом, объекты оценки оказывают незначительное и слабое воздействие на радиационную обстановку в Арктическом регионе, но, с учетом потенциальной опасности, нуждаются в постоянном мониторинге компонентов морской среды для своевременного выявления радиационно-экологических изменений.

Ключевые слова: Арктика, радиационно-экологический риск, интегральный показатель загрязнения, контрольный уровень, морская биота

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Introduction

Every year, the Arctic region of Russia becomes more and more important for the environment and world economy. The “Northern Sea Route” passes through the Russian Arctic, which is the shortest communication between Europe and Asia. The northern route is three times shorter than the classical route through the Mediterranean Sea and the Indian Ocean. The Arctic is rich in bio-resources and hydrocarbons, and natural processes in the region have an impact on global climate [1].

In the past, the Arctic was exposed to radiation from such sources as: nuclear weapons tests in the 20th century; dumping of liquid radioactive waste from European plants; flooded and sunken nuclear submarines, nuclear and radiation-hazardous objects (NRHO); atmospheric discharges after the Chernobyl nuclear power plant accident [1]. The largest impact of radionuclide sources was on the western seas of the Arctic region, namely Barents and Kars Seas. The Barents Sea is characterized by a high biological diversity, due to the favorable temperature of the water, which is caused by the warm Nordkaps current. The Arctic Sea biota is more vulnerable than temperate water-dwelling marine habitats [2].

In the case of radioactive pollution of the seas, the radiation pathways of marine organisms may be significantly different from those of humans. For example, marine biota that live permanently or periodically near the bottom are exposed to external radiation from sediment radionuclides. In this case, the anthropocentric approach of “Protected man = protected environment” should be abandoned in favor of an ecocentric one [3; 4]. ICRP has prepared a publication No. 108 “Environmental protection: concept of reference animals and plants” and a publication No. 124 “Environmental protection in various situations of irradiation”.[1,2] The IAEA’s basic safety standards require that it should be confirmed (not assumed) that the environment is protected from radioactive pollutants[3]. Also, in accordance with the Decree of the Government of the Russian Federation No. 639, an important principle of the functioning of the monitoring

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[1] ICRP Publication 108. Environmental protection: the concept and use of reference animals and plants. *Ann. ICRP.* 2009;38(4–6):251.

[2] ICRP Publication 124. Protection of the environment under different exposure situations. *Ann. ICRP.* 2014; 43(1): 59 p.

[3] Safety Standards Series, GSR Part 3. Radiation Protection and Safety of Radiation Sources. *International Basic Safety Standards*. IAEA, Vienna; 2014.

system is the improvement of tools and methods for detecting changes in the radiation situation, assessing and predicting radiological-environmental risks[4].

FSBI "Typhoon" NGO has developed recommendations for assessing the risk of radioactive environmental pollution based on radiation monitoring, which allow to perform an integral radioecological assessment[5]. One way to do this is to determine generalized risk indicators (RDI) in aquatic components with a preliminary calculation of integrated pollution indexes (IIP) for water and sediment radionuclides [7].

Every year, FSBI "Typhoon" NGO, during the expeditions, conducts radiation monitoring of marine environment components around NRHO. Some of the most dangerous, from a radio-ecological point of view, are:

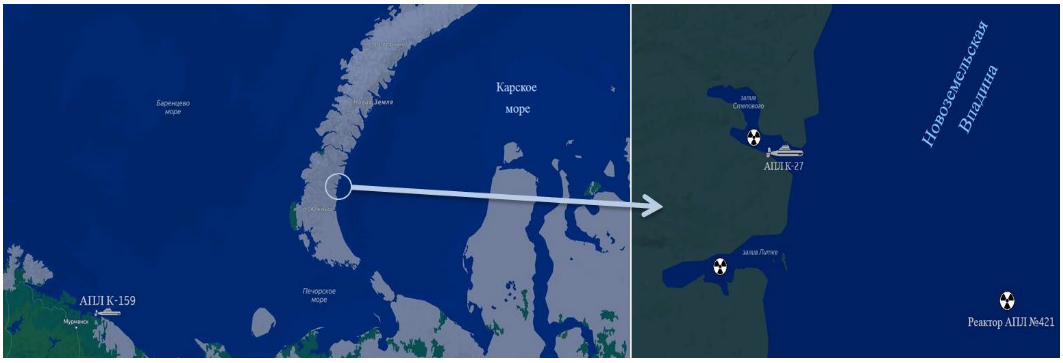
Nuclear submarine (NS) K-159, which sank during a tow in the Barents Sea on 30 August 2003 near Kildin Island;

– Litke Bay of the Novaya Zemlya archipelago, which is located in the area of past nuclear weapons tests;

– Stepovoy Bay of the Novaya Zemlya archipelago, which contains the flooded C-27 TKO and NS, and was also influenced by the 20th century nuclear tests;

– the Novaya Zemlya depth containing submerged solid radioactive waste and NS reactor of Order No. 421 [1]. The potential radiation-hazardous objects considered are shown in Figure.

The following radionuclides were found in water, sediment and biota around NRHO: ^{137}Cs, ^{90}Sr и ^{239,240}Pu [1; 7].



Map of study sites in the Barents and Kara Seas
Source: compiled by the authors.

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[4] *The Resolution of the Government of the Russian Federation "On the state monitoring of radiation situation in the territory of the Russian Federation" dated 10.07.2014 No. 639* (assessed: 26.03.2021).

[5] Kraushev II, Pavlova NN, Sazykina TG et al. *Recommendations of Roshydrometh P 52.18.923 2022. Procedure for assessing the risk of radioactive pollution from radiation monitoring. Radiological monitoring.* Obninsk: FSBI "Typhoon NGO"; 2022.

Materials and methods

Several factors are taken into account in determining the generic risk indicator: spatial scale, intensity and duration of radiation exposure to the environment.

The recommendations of FSBI "Typhoon" Roshydrometh NGO were used to calculate and analyze the generalized risk indicator. The risk indexes were calculated by formula:

$$\mathrm{GRI} = A_{\mathrm{sp}} \cdot A_{\mathrm{temp}} \cdot \mathrm{REI_d}, \tag{1}$$

where A_{sp} – ratio taking into account the spatial scale of the area, disproportionate; A_{temp} – ratio, taking into account the time scale of radiation impact, disproportionate;

$\mathrm{REI_d}$ – indicator of the intensity of radiation effects on marine components, imdimensional [6].

These indicators were defined according to the gradations of the recommendations. Using scaling, they estimated how much area the pollutant occupies and how long a radiation object affects the environment.

A_{sp} and A_{temp} are determined based on monitoring data, model or expert assessments. A_{sp} is 1 if the area of the radiation object does not exceed 10 km^2; 2 for areas up to 100 km^2, 3 for areas over 100 km^2. If the radiation object affects the environment for no more than a month, then A_{temp} is 1; no more than a year – 2; more than a year – 3.

One way to determine the $\mathrm{REI_d}$ is to compare it with an integral pollution indicator, calculated by formula (2). If the IIP is not significantly different from the baseline, then $\mathrm{REI_d}$ is 1; for $\mathrm{IIP} < 0{,}1$ $\mathrm{REI_d}$ is 2; for $\mathrm{IIP} < 1$ $\mathrm{REI_d}$ is 3; for $\mathrm{IIP} \geq 1$ $\mathrm{REI_d}$ is 30 [10].

$$IIP = \sum_i \frac{A_i}{A_{i,\ \min}}, \tag{2}$$

where A_i – specific activity (SA) i-th radionuclide in the marine environment component (water, sediment, Bk/kg raw weight); $A_{i,\ \min}$ – reference level (RL) of i-th radionuclide activity in the relevant marine component (water, sediment, Bq/kg raw weight)[7].

The reference level of radionuclides in marine water is an indicator of environmental quality that can ensure acceptable ecological risk by not exceeding the criterion of maximum permissible radiation and environmental impact on marine environment objects (dose threshold, mGy/day). The reference levels are

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[6] Kraushev II, Pavlova NN, Sazykina TG et al. *Recommendations of Roshydrometh P 52.18.923 2022. Procedure for assessing the risk of radioactive pollution from radiation monitoring. Radiological monitoring.* Obninsk: FSBI "Typhoon NGO"; 2022.

[7] Ibid.

measured by Bq/l and Bq/kg in water and sediment, respectively, making them convenient for operational monitoring.

To obtain the reference levels of radionuclides in water and bottom sediments for regional biota, FSBI “Typhoon” NGO has developed recommendations [8] and approved by Roshydromet. The formula of the recommendations reflects a direct dependence of the control level with the maximum permissible dose rate, which does not lead to the occurrence of deterministic effects in the biota. Thus, the reference level is the ratio of dose strength to the indicators reflecting: characteristics of the biota living in the region under consideration; type of ionizing radiation from a certain radionuclide; accumulation of radionuclides in the biota (accumulation coefficient); Distribution of radionuclides between seawater and sediments (coefficient of distribution). To determine the accumulation and distribution coefficients, specific radioactivity data obtained during monitoring of “Typhoon” NGO and values from literature sources [14; 15] were used. The RL of radionuclides in the components of Barents and Kara Seas have been calculated previously and reported in publications [15; 16].

The specific activity of radionuclides in water and bottom sediments of Barents, Kara Seas and their areas exposed to NRHO is presented in Table 1.

Table 1. **Specific activities of technogenic radionuclides in water and bottom sediment samples taken near nuclear hazardous waste sites of the Barents and Kara Seas (2006–2021)**

Object of assessment	Radionuclide	Specific activity in water, Bq/l	Two-sided confidence interval of SA in water	Specific activity in bottom sediments, Bq/kg	Two-sided confidence interval of SA in sediments
Barents Sea					
K-159	^{137}Cs	$2.0 \cdot 10^{-3}$	$[1.1 \cdot 10^{-3}-4.3 \cdot 10^{-3}]$	$2.5 \cdot 10^{0}$	$[1.6 \cdot 10^{0}-3.4 \cdot 10^{0}]$
	^{90}Sr	$2.8 \cdot 10^{-3}$	$[1.9 \cdot 10^{-3}-3.8 \cdot 10^{-3}]$	$9.7 \cdot 10^{-1}$	$[3.6 \cdot 10^{-1}-1.4 \cdot 10^{0}]$
	^{239,240}Pu	$4.7 \cdot 10^{-6}$	$[1.4 \cdot 10^{-6}-6.1 \cdot 10^{-6}]$	$2.8 \cdot 10^{-1}$	$[9 \cdot 10^{-4}-1.1 \cdot 10^{0}]$
Open Barents Sea	^{137}Cs	$1.7 \cdot 10^{-3}$	$[6.2 \cdot 10^{-4}-2.8 \cdot 10^{-3}]$	$6 \cdot 10^{-1}$	$[2 \cdot 10^{-1}-2.5 \cdot 10^{0}]$
	^{90}Sr	$1.8 \cdot 10^{-3}$	$[1.0 \cdot 10^{-3}-3.9 \cdot 10^{-3}]$	$7 \cdot 10^{-1}$	$[4.9 \cdot 10^{-1}-7 \cdot 10^{-1}]$
	^{239,240}Pu	$4.8 \cdot 10^{-6}$	$[2.4 \cdot 10^{-6}-1.1 \cdot 10^{-5}]$	$8.3 \cdot 10^{-1}$	$[3.1 \cdot 10^{-1}-1.1 \cdot 10^{0}]$
Kara Sea					
Litke Bay	^{137}Cs	$1.5 \cdot 10^{-3}$	$[1.3 \cdot 10^{-3}-1.8 \cdot 10^{-3}]$	6.98	[0.38-13.05]
	^{90}Sr	$2.4 \cdot 10^{-3}$	$[1.9 \cdot 10^{-3}-2.9 \cdot 10^{-3}]$	0.58	[0.1-0.88]
	^{239,240}Pu	$2.2 \cdot 10^{-6}$	$[1.4 \cdot 10^{-6}-3.3 \cdot 10^{-6}]$	0.32	[0.29-0.37]
Stepovoy Bay	^{137}Cs	$2.1 \cdot 10^{-3}$	$[3.5 \cdot 10^{-4}-1.4 \cdot 10^{-2}]$	23.51	[0.59-1079]
	^{90}Sr	$3.2 \cdot 10^{-3}$	$[2.1 \cdot 10^{-3}-6.2 \cdot 10^{-3}]$	0.9	[0.1-29.57]
	^{239,240}Pu	$2.9 \cdot 10^{-6}$	$[1.3 \cdot 10^{-6}-5.0 \cdot 10^{-6}]$	0.28	[0.22-0.6]
Novaya Zemlya depression	^{137}Cs	$5.0 \cdot 10^{-4}$	$[3.5 \cdot 10^{-4}-7.2 \cdot 10^{-4}]$	5.1	[0.67-7.1]
	^{90}Sr	$2.1 \cdot 10^{-3}$	$[1.7 \cdot 10^{-3}-2.7 \cdot 10^{-3}]$	0.65	[0.21-3.67]
	^{239,240}Pu	$8.4 \cdot 10^{-6}$	$[1.0 \cdot 10^{-6}-1.6 \cdot 10^{-5}]$	0.34	[0.31-0.82]
Open Kara Sea	^{137}Cs	$3.6 \cdot 10^{-4}$	–*	1.54	[0.31-3.74]
	^{90}Sr	$1.8 \cdot 10^{-3}$	–*	0.20	–*
	^{239,240}Pu	$1.1 \cdot 10^{-6}$	–*	0.33	–*

* – insufficient data to determine the confidence interval.
Source: compiled by the authors.

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[8] *Procedure of calculation of control levels of radionuclides in marine waters. Recommendations. P 52.18.852-2016*. Obninsk: FSBI “Typhoon NGO”; 2016.

Results and discussion

The Integral Indicators of Pollution (IIP) of the water and seabed sediments of the Barents Sea were calculated by formula 2.

The integrated pollution indicators for K-159, the Bays of Litke, Stepovoy and Novozemelskoy depth were calculated on the maximum values of specific activities in order to estimate the radiation-environmental risk at the most polluted locations of the NRHO. The results of the calculation of the integral pollution indicators are presented in Tables 2 and 3.

Table 2. **Integral indicators of water pollution in the open Barents and Kara Seas and their areas exposed to nuclear hazardous waste**

Object of assessment	Radionuclide	Specific activity in water, Bq/l	Reference level, Bq/l [15; 16]	Integral indicator of pollution	Radionuclide contribution, %	Σ Integral indicator of pollution
Barents Sea						
K-159	^{137}Cs	$4.3 \cdot 10^{-3}$	115	$3.7 \cdot 10^{-5}$	39	$9.5 \cdot 10^{-5}$
	^{90}Sr	$3.8 \cdot 10^{-3}$	439	$8.6 \cdot 10^{-6}$	9	
	^{239,240}Pu	$6.1 \cdot 10^{-6}$	0.124	$4.9 \cdot 10^{-5}$	52	
Open Barents Sea	^{137}Cs	$1.7 \cdot 10^{-3}$	115	$1.5 \cdot 10^{-5}$	27	$5.8 \cdot 10^{-5}$
	^{90}Sr	$1.8 \cdot 10^{-3}$	439	$4.1 \cdot 10^{-6}$	7	
	^{239,240}Pu	$4.8 \cdot 10^{-6}$	0.124	$3.9 \cdot 10^{-5}$	66	
Kara Sea						
Litke Bay	^{137}Cs	$1.8 \cdot 10^{-3}$	51.8	$3.5 \cdot 10^{-5}$	29	$1.2 \cdot 10^{-4}$
	^{90}Sr	$2.9 \cdot 10^{-3}$	298	$9.7 \cdot 10^{-6}$	9	
	^{239,240}Pu	$3.3 \cdot 10^{-6}$	0.0412	$8.1 \cdot 10^{-5}$	67	
Stepovoy Bay	^{137}Cs	$1.4 \cdot 10^{-2}$	51.8	$2.7 \cdot 10^{-4}$	66	$4.1 \cdot 10^{-4}$
	^{90}Sr	$6.2 \cdot 10^{-3}$	298	$2.1 \cdot 10^{-5}$	51	
	^{239,240}Pu	$5.0 \cdot 10^{-6}$	0.0412	$1.2 \cdot 10^{-4}$	29	
Novaya Zemlya depression	^{137}Cs	$7.2 \cdot 10^{-4}$	51.8	$1.4 \cdot 10^{-5}$	3	$4.1 \cdot 10^{-4}$
	^{90}Sr	$2.7 \cdot 10^{-3}$	298	$8.9 \cdot 10^{-6}$	2	
	^{239,240}Pu	$1.6 \cdot 10^{-5}$	0.0412	$3.9 \cdot 10^{-4}$	95	
Open Kara Sea	^{137}Cs	$3.6 \cdot 10^{-4}$	51.8	$6.8 \cdot 10^{-6}$	18	$3.8 \cdot 10^{-5}$
	^{90}Sr	$1.8 \cdot 10^{-3}$	298	$5.8 \cdot 10^{-6}$	15	
	^{239,240}Pu	$1.1 \cdot 10^{-6}$	0.0412	$2.5 \cdot 10^{-5}$	67	

Source: compiled by the authors.

Table 2 shows that the minimum values of the integral indicators of radionuclide contamination ^{137}Cs, ^{90}Sr and ^{239,240}Pu are valid for the open Barents and Kara Seas. The total rate of water contamination by radionuclides in the area of K-159 NS flooding is 1.6 times higher than the value for the open Barents Sea. The largest contribution to the integral water pollution near K-159 was by the radionuclide $^{239.240}$Pu (52%).

The values of the total integral indicators of water pollution of Stepovoy Bay and the Novaya Zemlya depth are approximately higher than for the open Kara Sea. Among the objects of the Kara Sea considered, the highest values of IIP water ^{137}Cs and ^{90}Sr are characteristic for the Stepovoy Bay, ^{239,240}Pu – for the Novaya Zemlya depth. The main contribution to the integrated pollution of the water of the Litke

Bay and the Novaya Zemlya depth was made by the radioisotope ^{239,240}Pu (67 and 95% respectively), which is explained by the biological efficiency of α-radiation. For the integral indicator of pollution of the Stepovoy Bay, the dominant radionuclide was ^{137}Cs (66%), which indicates its exceedance in comparison with the value of the open Kara Sea.

Table 3. **Integral indicators of pollution of bottom sediments of the open Barents and Kara Seas and their areas exposed to nuclear hazardous hazardous waste**

Object of assessment	Radionuclide	Specific activity in water, Bq/l	Reference level, Bq/l [15; 16]	Integral indicator of pollution	Radionuclide contribution, %	Σ Integral indicator of pollution
Barents Sea						
K-159	^{137}Cs	$3.4\cdot10^{0}$	$4.9\cdot10^{4}$	$6.9\cdot10^{-5}$	54	$1.2\cdot10^{-4}$
	^{90}Sr	$1.4\cdot10^{0}$	$1.9\cdot10^{5}$	$7.4\cdot10^{-6}$	6	
	^{239,240}Pu	$1.1\cdot10^{0}$	$2.3\cdot10^{4}$	$4.8\cdot10^{-5}$	40	
Open Barents Sea	^{137}Cs	$6\cdot10^{-1}$	$4.9\cdot10^{4}$	$1.2\cdot10^{-5}$	24	$5.1\cdot10^{-5}$
	^{90}Sr	$7\cdot10^{-1}$	$1.9\cdot10^{5}$	$3.6\cdot10^{-6}$	7	
	^{239,240}Pu	$8.3\cdot10^{-1}$	$2.3\cdot10^{4}$	$3.5\cdot10^{-5}$	69	
Kara Sea						
Litke Bay	^{137}Cs	13.05	83 100	$1.6\cdot10^{-4}$	48	$3.3\cdot10^{-4}$
	^{90}Sr	0.88	298 000	$2.9\cdot10^{-6}$	1	
	^{239,240}Pu	0.37	2180	$1.7\cdot10^{-4}$	51	
Stepovoy Bay	^{137}Cs	1079	83 100	$1.3\cdot10^{-2}$	97	$1.3\cdot10^{-2}$
	^{90}Sr	29.57	298 000	$9.9\cdot10^{-5}$	1	
	^{239,240}Pu	0.6	2180	$2.8\cdot10^{-4}$	2	
Novaya Zemlya depression	^{137}Cs	7.1	83 100	$8.5\cdot10^{-5}$	18	$4.7\cdot10^{-4}$
	^{90}Sr	3.67	298 000	$1.2\cdot10^{-5}$	2	
	^{239,240}Pu	0.82	2180	$3.8\cdot10^{-4}$	80	
Open Kara Sea	^{137}Cs	1.54	83 100	$1.8\cdot10^{-5}$	12	$1.6\cdot10^{-4}$
	^{90}Sr	0.20	298 000	$7.1\cdot10^{-7}$	1	
	^{239,240}Pu	0.33	2180	$1.4\cdot10^{-4}$	87	

Source: compiled by the authors.

Table 3 shows that the lowest values of total integral sediment pollution are found in the open Barents and Kara Seas. It is worth noting that the value for the bottom sediments of the Kara Sea is 3 times higher than the pollution rate of the component of the Barents Sea. The integral pollution of bottom sediments in the area of K-159 flooding is 2.3 times higher than the value of the open Barents Sea, the dominant radionuclide is ^{137}Cs (54%).

Total values of the sedimentation of Litke Bay, the Novaya Zemlya depth and Stepovoy Bay are 2.1; 2.9 times and two orders higher respectively than for the open Kara Sea. The maximum values of the integral contamination of sediment ^{137}Cs and ^{90}Sr according to calculations were 1.3 10-2 and 9.9 10-5 for the Stepovoy Bay, $^{239.240}$Pu – 3.8 10-4 for the Novaya Zemlya depth. The dominant radionuclide in the pollution of the bottom sediments of Litke Bay and Novaya Zemlya depth is ^{239,240}Pu (51 and 80% respectively), for Stepovoy Bay main contribution to the integral pollution index was 137Cs – 97%. Thus, Stepovoy Bay bottom sediments exceed ^{137}Cs compared to the value in the open Kara Sea.

Further, using the obtained integral indicators of radionuclide contamination of water and sediment, by formula (1), generalized risk indicators for open Barents, Kara Seas and their areas exposed to NRHO were calculated. The following factors were required for the calculation of the summary risk indicators: a ratio taking into account the spatial scale of the contamination (A_{sp}); a ratio taking into account the temporal scale of the radiation exposure (A_{temp}); the intensity of radiation exposure to natural environment components (REI_{d}).

The analysis of integrated pollution indicators showed that the need for an assessment of generalized risk indicators is only directly available for NRHO locations.

For water and sediment in the area of NS K-159 A_{sp} was estimated 1, as the local area of impact is not more than 10 km^2. The components of the Kara Sea deposits have a local environmental impact (from 10 to 100 km^2), because A_{sp} was chosen 2. Using the scale of spatial radiation exposure on the natural environment components for open seas, a factor of 3 was chosen, because the area of exposure is more than 100 km^2.

A_{sp} on the marine water and bottom sediments for all sites considered was selected as 3, since the gradations refer to long-term environmental impacts of more than 1 year.

The radiation effect index was selected taking into account the integrated indicators of marine radionuclide contamination, according to a scale of recommendations. For open seas REI_{d} on water and bottom sediments selected equal 1. The rate of radionuclide contamination of water in the NS K-159 flood area did not significantly differ from the regional value on the open Barents Sea, respectively, REI_{d} was estimated as 1. For Litke Bay, Stepovoy Bay and Novaya Zemlya depth REI_{d} on the water was taken to be equal to 2, as the IIP exceeds the value on the open Kara Sea by an order and more. The results of the calculations for the pooled water and sediment risk indicators for NRHO affected areas are presented in Tables 4 and 5.

Table 4. **Results of calculations of generalized indicators of radiation-ecological risks in water for the open Barents and Kara Seas and their areas exposed to nuclear hazardous waste**

Object of assessment	Integral indicator of pollution	A_{sp}	A_{temp}	Radiation exposure index	Generalized risk indicator	Gradation of impact on the radiation situation
Barents Sea						
K-159	$9.5 \cdot 10^{-5}$	1	3	1	3	Minor
Kara Sea						
Litke Bay	$1.2 \cdot 10^{-4}$	2	3	2	12	Low
Stepovoy Bay	$4.1 \cdot 10^{-4}$	2	3	2	12	Low
Novaya Zemlya depression	$4.1 \cdot 10^{-4}$	2	3	2	12	Low

Source: compiled by the authors.

Table 4 shows that the summary water risk index in K-159 NS flood area was 3, therefore the object under consideration has a negligible impact on the radiation environment in the Barents Sea.

The generalized risk index in the water of the Novaya Zemlya depth, Litke and Stepovoy Bays was 12. According to the graduation from the recommendations, areas of the Kara Sea exposed to NRHO have a low radiation impact.

The value of the REI$_d$ for bottom sediments in the area of NS K-159, Litke Bay and Novaya Zemlya depth was estimated to be 2, due to the more than order exceeding the value of the integral pollution index for the open Kara Sea. Stepovoy bay, REI$_d$ was 3, because the integral index of radioisotope contamination of the bottom sediments of the assessment object is two orders higher than in the open Kara Sea.

Table 5. **Results of calculations of generalized indicators of radiation-ecological risks in bottom sediments for the open Barents and Kara Seas and their areas exposed to nuclear radiation exposure**

Object of assessment	Integral indicator of pollution	A_{sp}	A_{temp}	Radiation exposure index	Generalized risk indicator	Gradation of impact on the radiation situation
Barents Sea						
K-159	$1.2 \cdot 10^{-4}$	1	3	2	6	Minor
Kara Sea						
Litke Bay	$3.3 \cdot 10^{-4}$	2	3	2	12	Low
Stepovoy Bay	$1.3 \cdot 10^{-2}$	2	3	3	18	Low
Novaya Zemlya depression	$4.7 \cdot 10^{-4}$	2	3	2	12	Low

Source: compiled by the authors.

Table 5 shows that the summary risk index in bottom sediments of NS K-159 flood area was 6. Therefore, bottom sediments at the K-159 flood site are not hazardous to the environment. The consolidated risk index in bottom sediments for Litke Bay and the Novaya Zemlya depth was 12, for Stepovoy Bay – 18, according to the gradation from the recommendations. These areas need monitoring and analysis of the data obtained, in order to prevent negative effects on the waters of the Kara Sea and its biota.

Conclusions

The obtained estimates indicate that the sources of the introduction of man-made radionuclides into the Barents and Kara Seas are currently having little or no impact on the Arctic radiation environment. At present, the region does not need additional conservation measures to maintain a favourable environment. However, given the potential hazard, the risk of radionuclides leaking from submerged and sunken NRHO's and their further release into the marine environment, which could lead to their transfer with currents and migratory fish species, cannot be excluded. The area needs continued radiation and environmental monitoring of marine components, which will allow timely detection of changes in radioactivity levels and make every effort to preserve the water and its living biota. Radiation monitoring of bottom sediments in the area of Stepovoy Bay should be given special attention, as the generalized risk ratio exceeds the risk for the open Kara Sea by twice.

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