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^{210}Po in Crimean salt lakes

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of radioecological monitoring study of natural radionuclide ^{210}Po in 11 lakes located in different regions of the Crimean peninsula. These investigations of the Crimean salt lakes were conducted for the first time in the history. The main objectives of this work were: to determine the features of the ^{210}Po behavior in the salt lakes ecosystems, as well as calculation of the doses received by the lakes hydrobionts from α-radiation of absorbed ^{210}Po. Concentrations of ^{210}Po in the water, suspended matter, the bottom sediments and biota were determined by radiochemical processing and α-spectroscopy measurements. The concentrations of dissolved ^{210}Po in the water of investigated lakes were in 0.9–327.1 times higher than in the Black Sea closest regions. The highest concentrations of ^{210}Po in water were determined in the lakes of the Kerchenskaya group. These lakes are located on the territory of Crimea where oil is produced. The ^{210}Po activity concentrations in the bottom sediments from Crimean salt lakes were comparable with those of the Black Sea coastal zone. Concentration ratio (CR) of polonium in suspended matter ranged from 10 to 10^4 for different lakes. A significant trend in a decrease of CR values of ^{210}Po for suspended matter with increasing water salinity was revealed. High levels of ^{210}Po accumulation were noted for adult crustacean *Artemia spp.* (typical inhabitant of the Crimean saline lakes). The CR of ^{210}Po for adult *Artemia spp.* reached 10^5 while the CR of this radionuclide by their cysts was significantly lower. The absorbed doses from ^{210}Po α-radiation calculated for adult *Artemia spp.* were more than 60 times lower than the permissible dose rate for biota (IAEA, 1992).The obtained results will be used to identify the biogeochemical peculiarities in behavior of the main dose-formative radionuclide ^{210}Po, in the water ecosystems with different salinity, including water reservoirs poorly studied in the radioecological aspect and having extreme condition for the existence of lots of species of hydrobionts, such as hypersaline Crimean lakes.

1. Introduction

Polonium-210 is a naturally occurring radionuclide the ^{238}U decay series. It's a high-energy (5.305 MeV) pure alpha-emitter with a half-life of 138.4 days and accumulates at high levels in most aquatic organisms. These properties mean that ^{210}Po is the main contributor to the natural radiation doses received by hydrobionts (Cherry and Shannon, 1974; Cherry and Heyraud, 1982; Carvalho, 1988; Aarkrog et al., 1997; IAEA, 2017). Atmospheric deposition is the main source of the ^{210}Po input in bodies of water as a decay product of ^{222}Rn (IAEA, 2017). Volcanic activity is considered to be an important natural uncontrolled source of ^{210}Po into the atmosphere (and then into the biosphere) of the Earth, resulting in sharp increases of ^{222}Rn and its daughter radionuclides (Le Guern et al., 1982; Rubin et al., 1994). Additional ^{210}Po sources include liquid wastes from industries associated with the mining and processing of ores containing uranium, thorium, rare earths and phosphorus compounds, and oil and gas produced wastes (Baxter, 1996; Haridasan et al., 2001; IAEA, 2002; IAEA, 2003; Othman and Al-Masri, 2007).

^{210}Po entering in the natural water bodies becomes included in the biogeochemical processes. It associates with the suspended organic matter and accumulate in hydrobionts (Cherry et al., 1975; Heyraud and Cherry, 1983; Carvalho, 1997; Kim and Church, 2001; Rutgers van der Loeff and Geiber, 2008; Lazorenko and Polikarpov, 2002; Lazorenko

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et al., 2009; IAEA, 2017). Then the ^{210}Po is transferred to the bottom sediments together with the organic remains (Wei and Murray, 1994; Turekian et al., 1977; Lazorenko, 2000; IAEA, 2017). Therefore, ^{210}Po is considered the most informative tracer of biosedimentation processes in different fresh and sea water ecosystems in the oceans (Nozaki et al., 1997, 1998; Kim and Church, 2001; Rutgers van der Loeff and Geiber, 2008). It is known that aquatic animals absorb ^{210}Po only from their food i.e. this radionuclide could be used as a natural tracer of the food chain in aquatic ecosystems (Cherry and Shannon, 1974; Heyraud and Cherry, 1979; IAEA, 2017). Thus, the study of behavior of ^{210}Po in aquatic ecosystems in different regions of the Worlds Oceans seems to be an important task (Cherry and Shannon, 1974; Heyraud and Cherry, 1979; Aarkrog et al., 1997; Stewart et al., 2008; Carvalho, 2011; IAEA, 2017).

There is quite a lot data referenced concerning ^{210}Po in the Black Sea (Wei and Murray, 1994; Lazorenko, 2000, 2008; Lazorenko and Polikarpov, 2002, 2010; Mirzoeva and Lazorenko, 2004; Polikarpov et al., 2008; Lazorenko et al., 2009) while numerous lakes located on the Crimean Peninsula remained unstudied.

Crimea is the largest peninsula in the Black Sea and has many water bodies with mineralization from 0 to 400 g l^{-1} (Kurnakov et al., 1936; Anufriieva et al., 2017; Anufriieva and Shadrin, 2018). In the Crimea, there are more than 300 lakes and estuaries, most are salty and included in this number are 48 large salty lakes, 26 of which are larger than 1 km^2 located along the coast of the Black Sea (Pasinkov et al., 2014; Sotskova et al., 2015). Salt lakes, including the Crimean ones, are very valuable ecosystems (Ponizovskii, 1965; Anufriieva et al., 2017; Anufriieva and Shadrin, 2018; Shadrin and Anufriieva, 2018). Many of the Crimean salt lakes are used for recreational and economic purposes. Salt lakes are of great benefit for the production of bioproducts, which are used in the chemical industry, agriculture, biotechnology, aquaculture and medicine (Pervolf, 1953; Ponizovskii, 1965; Pasinkov et al., 2014; Sotskova et al., 2017). Crimean salt lakes contain practically inexhaustible reserves of sodium, magnesium, bromine and other chemical elements (Ponizovskii, 1965), therefore, a potential powerful raw material base for the chemical industry. Curative mud formed as a result of all biota functions inhabiting the lake is widely used (Nissenbaum, 1993). The therapeutic properties of water and the bottom sediments of the salt lakes are often associated with an increased level of radon (Pervolf, 1953). ^{222}Rn, one of the daughter products of the uranium radioactive decay chain, concentration in natural waters is often in direct ratio to the salinity levels (Buesseler and Benitez, 1994; Mohamed and Siang, 2010). The high salinity of the water in the Crimean salt lakes is maintained mainly due to intense evaporation, especially in summer. This can result in high concentration of many chemical elements, including radioactive ones (Bulyon et al., 1989; Balushkina et al., 2005). Natural radioactivity of natural water bodies is mainly due to the presence of ^{222}Rn, ^{220}Rn (thoron), $^{224,\ 226,\ 228}$Ra, $^{234,\ 238}$U, ^{4}K, ^{210}Po, ^{210}Pb (Collection of state standards, 1994; Bulatov, 1996).

The first radioecological studies of the Crimean salt lakes were started in 2009 (Gulina and Gulin, 2011). The vertical distribution of 5 natural (^{238}U, ^{232}Th, ^{226}Ra, ^{210}Pb, ^{4}K) and 1 artificial (^{137}Cs) radionuclides in the bottom sediments from Lake Koyashskoe was studied in this scientific work. Subsequent, radioecological studies of the Crimean salt lakes deal with the behavior of artificial post-accident radionuclides (^{90}Sr, ^{137}Cs) in the ecosystems of these water bodies (Mirzoyeva et al., 2015, 2018; Mirzoeva et al., 2020).

The results presented in this paper are novel as this study is pioneering for the Crimean salt lakes.

The purpose of this scientific work is to define the peculiarities of the behavior of the natural radionuclide ^{210}Po in the abiotic and biotic components of the aquatic ecosystems of the Crimean salt lakes.

In accordance with the assigned objectives, the following tasks in this investigation were achieved: to determine the ^{210}Po concentrations in the components of the ecosystems of the Crimean salt lakes; to carry out a comparative analysis of the ^{210}Po content in water, aquatic organisms and the bottom sediments of the Crimean salt lakes and the Black Sea ecosystems located close to the lakes; to determine peculiarities of the ^{210}Po distribution on the components of the salt lakes ecosystems; calculate the radiation dose received by different hydrobionts of the Crimean salt lakes from ionizing radiation of ^{210}Po.

2. Materials and methods

2.1. Sampling sites and samples taken

The samples for this study were sampled during 2016–2018 from 11 salt lakes located on North, North-Western, Western and Eastern parts of Crimea (Fig. 1, Table 1). It should be noted that one of the salt lakes investigated was the Sasyk-Sivash, which is the largest Crimean salt lake (75.3 km^2) (Ponizovskii, 1965; Oliferov and Timchenko, 2005; Pasinkov et al., 2014; Sotskova et al., 2015). Sampling was carried out over 1–2 day field trips to the salt lakes by staff from the Department of Radiation and Chemical Biology of the IBSS.

The location of the investigated salt lakes and the coordinates of the sampling points are shown in Fig. 1 and in Table 1.

Samples of water, bottom sediments and water plants were collected simultaneously from the same salt lake on the dates shown in Table 1. Practically all the studied lakes have liman origin, all of them are without outflow. Each group of lakes differs in water balance, concentration and chemical composition of saline brines (Ponizovskii, 1965).

The following were sampled and analysed: 19 samples of water, 10 samples of suspended matter, 29 samples of bottom sediments, 12 samples of hydrobionts: *Crustacea* (*Artemia spp.,* adults and cysts), *Amphipoda,* larvae of *Chironomidae,* bivalve mollusk *Cerastoderma edule* L.*;* water plants: *Cladophora sp.*, *Potamogeton crispus* L., *Stuckenia pectinata* ((L.) Börner).

2.1.1. ^{210}Po radiochemical procedures

Water samples were acidified with hydrochloric acid to pH = 2. The suspended matter was separated by filtration through a pre-weighed fiberglass filter "Wathman GF/F" (porosity 0.7 μm). Filters with collected suspended particles were dried to constant weight then weighed again. ^{210}Po was extracted from filtered water by co-precipitation with Co-APDC (Ammonium pyrrolidinedithiocarbamate). The precipitate was separated by filtration using "Wathman GF/A″ filter.

Samples of bottom sediments were dried at room temperature to a constant weight, and then an aliquot of about 0.5 g was taken for polonium analysis.

Samples of aquatic organisms were washed with water, excess moisture removed with filter paper and then weighed to determine fresh weight. 1–10 g of hydrobionts were used for further radiochemical analysis of ^{210}Po.

After pretreatment, the samples were radiochemically processed to determine the ^{210}Po (Chen et al., 1998). The samples were treated with mixtures of concentrated hydrochloric and nitric acids, as well as heated with 30% hydrogen peroxide (Marey and Zykova, 1980; Chen et al., 1998).

The samples were then put into a 0.3M HCl solution and the polonium was then spontaneously plated onto the surface of silver discs by heating to 85–90 °C for 3.5–4 h. ^{208}Po (half-life 2.898 years, the energy of alpha particles 5.114 MeV) was used as a tracer to check the chemical yield of the ^{210}Po. The polonium plating onto the silver discs was carried out as soon as possible to avoid errors due to correction for the ^{210}Po ingrowth from its progenitor (^{210}Pb).

Prepared counting sources were measured using alpha spectrometer "Octete" (ORTEC-Ametek), which has 8 vacuum chambers equipped with semiconductor (PIPS) detectors. Software "Maestro" and "Alpha Vision" were used to control the spectrometer and process the alpha spectrum. Standard sources were used to energy calibrate and determine the efficiency of the detectors.

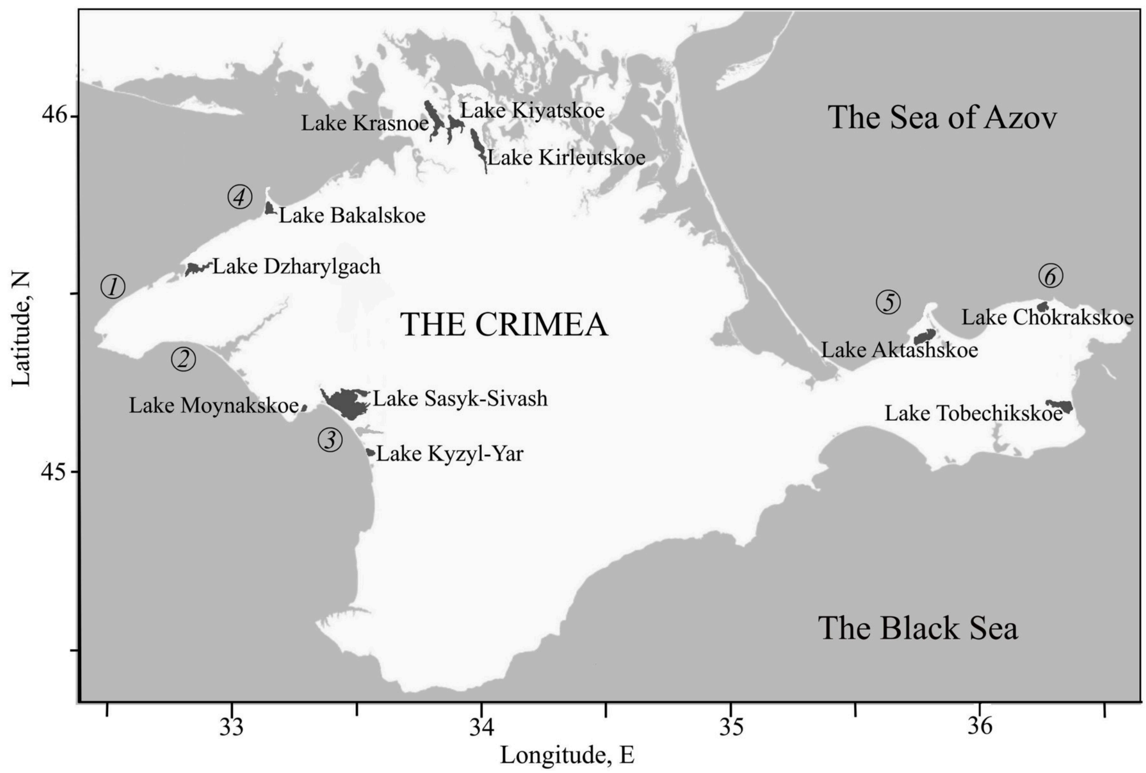

Fig. 1. Location of the investigated Crimean salt lakes (1–6 – control sampling points in the Black Sea).

The concentration of ^{210}Po in the water samples is given in Bq·m^{-3}, Bq·kg^{-1} dry weight (d.w.), for the bottom sediment, suspended particles matter, plankton and for other biota – in Bq·kg^{-1} wet weight (w.w.). The results are reported as average value determined for the samples/organisms and standard deviation (SD) for each group of data.

^{210}Po activity concentration in the samples was calculated according to the methods described in (EPA , 1984). The permissible error of ^{210}Po determination (Urbakh, 1964; Mayer, 1999) did not exceed 20% for water, and 10% for the bottom sediments and the hydrobionts.

2.1.2. Radiological dose calculation

To calculate the absorbed dose rates formed by the radiation of ^{210}Po alpha particles in live organisms, the approaches and criteria described in (Blaylock et al., 1993; Thomas and Liber, 2001; IUR. International Union of Radioecology, 2002; Kryshev et al., 2002) was used, as well as the formula proposed by B. J. Blaylock et al. (1993):

$$D = 5.04 \cdot 10^{-6} \cdot C_{org} \cdot E, \qquad (1)$$

where D – absorbed dose received by organism during the year from accumulated α–emitting radionuclide, (Gy·year^{-1});

C_{org} – concentration of this radionuclide in the organism (Bq·kg^{-1} wet weight);
E – energy of the studied radionuclide, MeV.

The effect of alpha-emitting radionuclides is evaluated for the inside only for the hydrobionts because the contribution of the external irradiation (from water and bottom sediments) is excluded due to the physical properties of alpha particles. Conversion factor equal to 20 for α-emitters was used to calculate equivalent doses for aquatic organisms (Blaylock et al., 1993; Thomas and Liber, 2001).

3. Results

3.1. ^{210}Po in water environment

The concentrations of the ^{210}Po in the water of the Crimean salt lakes were determined for the first time in the history in these investigations. The results of the measured ^{210}Po concentrations in the water of 10 of the studied Crimean lakes are presented in Table 2.

It was determined (Table 2) that the concentrations of dissolved ^{210}Po varied in the range from 0.5 to 229.0 Bq·m^{-3}. In all the lakes being studied, with the exception of the Kerchenskaya group of lakes (Lake Tobechikskoe and Lake Chokrakskoe), the concentration of dissolved ^{210}Po was within the concentrations noted for oxic waters (up to 5 Bq·m^{-3}) (IAEA, 2017). The concentration of dissolved ^{210}Po in the Chokrakskoe and Tobechikskoe lakes was 45.8 and 15.1 times higher than the concentrations of this radionuclide taken for oxic waters, and 13.5 and 4.5 times higher than those taken for anoxic waters. At the same time, it was in the range of ^{210}Po concentrations observed in the drinking water of Finland (IAEA, 2017), which indicates the possibility of the presence of such concentrations in open natural waters.

Water samples from the Bakalskoe and Aktashskoe lakes before filtration through a 0.7 μm filter were previously passed through filter paper (20–25 μm) to determine how the particle size of the suspended matter can affect their concentrating ability concerning polonium. It was determined for Lake Bakalskoe, that the fraction >20 μm contained 33.8 Bq·kg^{-1} dry weight, and the smaller (˂ 20 μm) – 8.7 Bq·kg^{-1} dry weight. For Lake Aktashskoe these values were 22.7 and 3.5 Bq·kg^{-1}dry weight, respectively.

Thus, it was found that in both cases a larger fraction of the suspended matter accumulated a higher activity of ^{210}Po, despite the hydrochemical and geographical differences between these lakes (Table 1). Perhaps, this is due to the fact that the larger fractions include living organisms that can actively concentrate polonium in the process of feeding, absorbing suspended and dissolved organic matter.

Concerning the range of concentrations of ^{210}Po in the suspended

Table 1
Coordinates and characteristic of sampling stations.

Name of objects of study/ (material of research)	Sampling date	Sampling coordinates	Salinity, ‰	pH
1	2	3	4	5
Perekopskaya group of lakest				
Lake Krasnoe (water, bottom sediments (0–5 cm)	28.06.2018	45°59,275′N; 33°58,119′E	340.0	9.5
Lake Kiyatskoe (bottom sediments (0–5 cm))	23.11.2016	45°58.395′ N 33°55.364′ E	216.0	8.2
Lake Kirleutskoe (water, bottom sediments (0–5 m);	14.06.2016	45°55.231′ N 34°02.681′ E	235.0	7.9
Artemia spp. (adults))	28.06.2018	45°54.375′N; 34°02.533′E	318.0	6.0
Tarkhankutskaya group of lakes				
Lake Dzharylgach (water, bottom sediments (0–5 cm, *Artemia spp.* ((adults and cysts), larvae of *Chironomidae*)	18.05.2016	45°33.965′ N 32°54.599′ E	115.0	8.5
	08.11.2016	45°33.968′ N 32°51.582′ E	140.0	7.9
	14.07.2017	45°34,990′N; 32°51,505′E	140.0	8.0
	22.08.2018	45°34,198′N; 32°51,357′E	127.0	6.0
Lake Bakalskoe (water, bottom sediments (0–5 cm); water plants *Cladophora sp.,* Crustacea *Amphipoda,*	27.06.2016	45° 45.514′ N 33° 10.794′ E	46.5	8.6
mollusc *Cerastoderma edule; Artemia spp.* (adults animals))	14.07.2017	45°43,921′N; 33°10,936′E	62.0	8.2
	18.07.2018	45°43.873′N; 33°10.828′E	62.0	7.0
Yevpatoriyskaya group of lakes				
Lake Kyzyl-Yar (water, bottom sediments (0–5 cm); water plants *Potamogeton crispus, Stuckenia pectinata*)	18.05.2016	45°03.560′ N 33°35.360′ E	3.5	7.9
	25.07.2018	45°03.059′N; 33°35.063′E	7.0	6.0
Lake Sasyk-Sivash (water, bottom sediments (0–5 cm; *Artemia spp.* (cysts)))	27.06.2016	45° 09.151′ N 33° 30.447′ E	280.0	7.7
	08.11.2016	45° 12.282′ N 33° 31.526′ E	322.0	7.8
	25.07.2018	45°09.375′N; 33°30.428′E	280.0	6.2
Lake Moynakskoe (water, bottom sediments (0–5 cm); water plants *Stuckenia pectinata*)	18.05.2016	45°10.518′ N 33°18.597′ E	47.0	8.2
1	2	3	4	5
Kerchenskaya group of lakes				
Lake Chokrakskoe (water, bottom sediments (0–5 cm))	08.06.2016	45°27.508′ N 36°18.325′ E	226.0	7.9
	25.04.2018	45°27,835′N 36°18,526′E	260.0	7.0
Lake Aktashskoe (water, bottom sediments (0–5 cm))	11.04.2016	45°22.219′ N 35°46.421′ E	270.0	7.4
	25.04.2018	45°23,133′N; 35°50,028′E	200.0	6.5
Lake Tobechikskoe (water, bottom sediments (0–5 cm))	07.06.2016	45°09.118′ N 36°22.490′ E	176.0	8.2
	25.04.2018	45°11,366′N 36°22,898′E	310.0	7.4
Adjacent stations of the Black Sea along the coast of the Crimea				
The sea near Lake Bakalskoye (water)	18.05.2016	45° 47.190′ N 32° 59.740′ E	17.5	8.4
	22.08.2018	45° 47.200′ N 32° 59.700′ E	17.0	8.0
The sea near Tarkhankut Cape (water, bottom sediments (0–5 cm))	09.06.2016	45° 15.500′ N 32° 29.670′ E	17.3	8.4
the Black Sea, Yevpatoria Bay (water, bottom sediments)	22.04.2016	44°23.000′ N 33°40.330′ E	17.3	8.3
Sevastopol bays, the Black Sea (water, bottom sediments)	06.06.2016	44° 36.554′ N 33° 28.215′ E	17.0	8.2
the Black Sea, the Kerch Strait (water, bottom sediments)	24.04.2016	45°49.978′ N 36°00.089′ E	17.2	8.5

matter of all the investigated lakes (Table 2) it was determined, that in Lake Bakalskoe (higher limit of concentration range) it was 2.6 times higher, and in Lake Dzharylgach (lower limit of concentration range) it was 2.8 times lower than that determined for the Black Sea. In all other lakes, the ^{210}Po content on suspension was of the same order as in the marine suspended matter. Concentration Ratio of ^{210}Po by suspended matter (CR) (Table 2) from the studied lakes ranged from n·10^1 to n·10^4. In the Black Sea this value was equal to n·10^4.

3.2. *^{210}Po in hydrobionts*

Concentrations of ^{210}Po were determined in samples of plankton collected in a number of lakes using a plankton net (>50 μm). The results of these determinations are presented in Table 3.

Table 2
Concentrations of ^{210}Po in water of the Crimean salt lakes and adjacent stations of the Black Sea along the Crimean coast.

Objects of study	Sampling date	Salinity, ‰	Concentration ^{210}Po		CR* (suspended matter)
			Dissolved, Bq·m^{-3}	Suspended matter, Bq·kg^{-1} d.w.	
Perekopskaya group of lakes					
Lake Krasnoe	28.06.2018	340	5.6 ± 0.1	12.9 ± 1.8	2.2E+03
Lake Kirleutskoe	28.06.2018	318	5.8 ± 0.1	18.4 ± 4.3	3.1E+03
Tarkhankutskaya group of lakes					
Lake Bakalskoe	27.06.2016	46.5	0.5 ± 0.01	no data	no data
	18.07.2018	46.5	2.3 ± 0.1	42.5 ± 0.8	1.8E+04
Lake Dzharylgach	22.08.2018	188	2.7 ± 0.1	5.7 ± 0.8	2.1E+03
Yevpatoriyskaya group of lakes					
Lake Kyzyl-Yar	18.05.2016	3.5	1.4 ± 0.2	no data	no data
	25.07.2018	7.0	0.6 ± 0.01	16.7 ± 2.1	2.8E+04
Lake Sasyk-Sivash	25.07.2018	280	–	28.9 ± 1.5	–
Lake Moynakskoe	18.05.2016	47.0	0.8 ± 0.02	no data	no data
Kerchenskaya group of lakes					
Lake Chokrakskoe	25.04.2018	260	229.0 ± 1.1	12.4 ± 0.7	5.4E+01
Lake Tobechikskoe	25.04.2018	310	75.7 ± 1.0	30.1 ± 2.2	4.0E+02
Lake Aktashskoe	25.04.2018	200	3.5 ± 0.2	23.9 ± 1.0	6.8E+03
Adjacent area of the Black Sea	2016–2018 (averaged for years of research)	16–17	0.7 ± 0.02	16.1 ± 0.9	2.3E+04

**CR – Concentration Ratio of ^{210}Po by suspended matter.

Table 3
Concentration of ^{210}Po in the plankton of the Crimean salt lakes.

Objects of study	Sampling date	Salinity, ‰	Concentration ^{210}Po Bq·kg^{-1}, d.w.**	CR* by plankton
Lake Chokrakskoe	25.04.2018	260	83.6 ± 1.0	3.4E+02
Lake Krasnoe	28.06.2018	340	25.3 ± 7.8	4.3E+03
Lake Kirleutskoe	28.06.2018	318	34.4 ± 6.6	5.6E+03
Lake Bakalskoe	18.07.2018	46.5	130.3 ± 14.7	5.7E+04
Lake Kyzyl-Yar	25.07.2018	7.0	20.8 ± 3.4	3.5E+04

CR* – Concentration Ratio of ^{210}Po by plankton; ** - mean wet/dry ratio = 10.

It is known that ^{210}Po concentrations in marine plankton vary from studied regions: 18–35 Bq·kg^{-1} d.w. – in the Black Sea plankton (Lazorenko and Polikarpov, 2002; Lazorenko, 2008), 27–431 Bq·kg^{-1} d.w. – in the Mediterranean Sea plankton (Strady et al., 2015) and up to 800 Bq·kg^{-1} d.w. – for unidentified zooplankton in different oceans (Stewart et al., 2008; Fowler, 2011), 190–290 Bq·kg^{-1} d.w. ^{210}Po – for freshwater plankton (IAEA, 2017). The lower limits of the concentration range of ^{210}Po in the plankton of the Crimean salt lakes (Table 3) correspond to those for water ecosystems with different levels of salinity (the Black Sea, the Mediterranean Sea, freshwater plankton).The upper limits of the ^{210}Po concentration ranges in the plankton from the Crimean salt lakes were 3.7 times higher than for the plankton from the BlackSea (Lazorenko, 2008) and 2.2, 3.3 and 6 times lower for the plankton from fresh water bodies, the Mediterranean Sea, and from various oceans, respectively (Stewart et al., 2008; Fowler, 2011; Strady et al., 2015; IAEA, 2017).

It should be noted that plankton is the main food for many aquatic organisms that live in the Crimean salt lakes, in particular for the gill-footed crustaceans (*Anostraca*), such as *Artemia spp.*

As a result of the research conducted, data on ^{210}Po accumulation of some of the most widespread aquatic organisms inhabiting the Crimean salt lakes were obtained. It is known, that hyperhaline lakes do not differ in the diversity of their species composition (Anufriieva et al., 2017). One of the mass inhabitants of such lakes is the brine shrimp *Artemia spp.* Polonium concentrations were determined not only in adult animals, but also in their cysts (Table 4).

In addition to *Artemia*, a relatively high activity of ^{210}Po was found in the bivalve mollusk *Cerastoderma edule* from Lake Bakalskoe and the larvae of *Chironomus* from Lake Dzharylgach. The ^{210}Po concentrations in these organisms were 120.9 ± 3.5 and 110.1 ± 3.3 Bq·kg^{-1} wet weight, respectively. Comparatively low concentrations of ^{210}Po were noted both for *Amphipoda* and for the aquatic plants (Table 5).

The largest concentration of ^{210}Po among the collected aquatic plants was in filamentous alga *Cladophora sp.* from Lake Bakalskoe (26.5 Bq·kg^{-1} w.w.), Table 5. The Concentration Ratio of ^{210}Po for all the studied aquatic organisms is in the range from 10^2 (for *Artemia* cysts) to

Table 4
Concentration of ^{210}Po in the cysts and adult organisms of *Artemia spp.* from the Crimean salt lakes.

Hydrobionts	Objects of study	Sampling date	^{210}Po, Bq·kg^{-1} (w. w.)	CR*
cysts	Lake Dzharylgach	Average 2016–2018	10.1 ± 2.4	nE+02
cysts	Lake Sasyk-Sivash	08.11.2016	14.3 ± 2.2	–
adult organisms	Lake Dzharylgach	Average 2016–2018	125.9 ± 13.3	nE+04
adult organisms	Lake Kirleutskoe	23.06.2017	25.3 ± 3.6	–
adult organisms	Lake Bakalskoe	18.07.2018	190.6 ± 16.5	nE+04

CR* – Concentration Ratio of ^{210}Po by cysts and adult organisms of *Artemia spp.*

Table 5
Concentration of ^{210}Po in the hydrobionts from the Crimean salt lakes.

Objects of study	Sampling date	Hydrobionts	^{210}Po Bq·kg^{-1} w. w.	CR*
Lake Kyzyl-Yar	18.05.2016	*Amphipoda*	12.1 ± 1.3	8.6E+03
Lake Bakalskoe	14.07.2017	*Amphipoda*	10.2 ± 1.2	2.0E+04
Lake Bakalskoe	27.06.2016	mollusc *Cerastoderma edule*	120.9 ± 3.5	2.4E+05
Aquatic plants				
Lake Kyzyl-Yar	18.05.2016	*Potamogeton crispus*	16.4 ± 1.5	1.2 E+04
Lake Kyzyl-Yar	18.05.2016	*Stuckenia pectinata*	7.4 ± 0.6	5.3 E+03
Lake Moynakskoe	18.05.2016	*Stuckenia pectinata*	7.6 ± 0.6	9.5 E+03
Lake Bakalskoe	27.06.2016	*Cladophora sp.*	26.5 ± 1.6	5.3 E+04
the Black Sea	27.06.2016	*Zostera sp.*	4.5 ± 0.5	6.4 E+03

CR* – Concentration Ratio of ^{210}Po by hydrobionts.

10^5 (for molluscs).

The absorbed dose rates to determine of the effect of ^{210}Po alpha-radiation on hydrobints, which have a significant concentration of the radionuclide in the body, were calculated (Table 6.).

To evaluate the absorbed dose rates received by hydrobionts from alpha-emitting radionuclides only internal irradiation is significant, since the contribution of the external component (from water and bottom sediments) is not considered due to the physical properties of alpha particles (Blaylock et al., 1993; Thomas and Liber, 2001).

3.3. ^{210}*Po in bottom sediments*

The concentrations of ^{210}Po in the bottom sediments of Crimean salt lakes are presented in Tables 7 and 8.

It was determined, that for all the studied lakes, the average concentration of ^{210}Po was within the same order and varied in the range from 17.9 to 67.6 Bq·kg^{-1} dry weight.

4. Discussion

4.1. ^{210}*Po in water environment*

It was shown (Table 2 and Fig. 2) that the average concentrations of ^{210}Po in the filtered water samples of salt lakes as a whole were 0.9–327.1 times higher than those in the Black Sea. The concentration of ^{210}Po that we determined in the course of this research for the water of the Black Sea corresponded to the average value for the Crimean coast: 0.7 Bq·m^{-3} (Lazorenko, 2000, 2008; Lazorenko et al., 2009).

The highest concentrations of ^{210}Po are determined in the lakes of the Kerchenskaya group of the Crimean salt lakes. The concentration of dissolved ^{210}Po in the water of Lake Tobechikskoe was 108.1 times higher, and Lake Chokrakskoe 327.1 times that of the Black Sea. At the same time, the ^{210}Po concentration, noted in Lake Chokrakskoe, corresponded to the maximum activity values of ^{210}Po, which are found in groundwater areas of uranium deposits and in areas of emanating tectonic zones (Bakhur et al., 2009), moreover, it is twice the standard value for drinking water (0.11Bq·kg^{-1} (RSS-99/2009 (NRB-99/2009). Radiation Safety Standards, 2009)). Although the available literature contains practically no data on the concentration of ^{210}Po in hypersalt lakes (probably due to difficulties in determining polonium in such water bodies), the published data also show very high values of ^{210}Po concentration: from 0.7 to 320 Bq·l^{-1} in the water of the salt Lake Sambharb in India (Yadav and Sarin, 2009).

In our investigation higher concentrations of ^{210}Po were related to the lakes of one geographic group. This allows us to conclude that the main factor influencing the increased content of ^{210}Po in the Tobechikskoe and Chokrakskoe lakes are the sources of radionuclide input into the water ecosystems of theses lakes only.

Table 6
Maximum concentrations of ^{210}Po in cysts, adult *Artemia spp.* and mollusc *Cerastoderma edule*, as well as doses formed by internal irradiation of animals.

Hydrobionts	Lake	Sampling date	^{210}Po, Bq·kg^{-1}, w.w. ±1σ	Absorbed dose, Gy·year^{-1}
Artemia spp. (cysts)	Lake Dzharylgach	18.05.2016	16.0 ± 2.0	8.6E-03
Artemia spp. (adult organisms)	Lake Dzharylgach	14.07.2017	198.3 ± 16.5	1.1E-01
Artemia spp. (adult organisms)	Lake Bakalskoe	18.07.2018	210.9 ± 17.5	1.1E-01
mollusc *Cerastoderma edule*	Lake Bakalskoe	27.06.2016	120.9 ± 11.2	5.7E-02

Table 7
^{210}Po in bottom sediments (0–5 cm) in the Crimean salt lakes.

Lake	Sampling date	Concentrations of ^{210}Po, Bq·kg^{-1}, d.w. ± 1σ
Lake Sasyk-Sivash	27.06.2016	71.3 ± 6.8
	05.11.2016	119.9 ± 14.3
Lake Dzharylgach	18.05.2016	50.5 ± 4.1
	05.11.2016	115.8 ± 10.7
Lake Kiyatskoe	23.11.2016	57.8 ± 7.5
Lake Bakalskoe	27.06.2016	18.8 ± 4.4
Lake Kyzyl-Yar	18.05.2016	45.0 ± 3.9

Table 8
Average concentrations of ^{210}Po in the upper (0–5 cm) bottom sediments layer (2016–2018).

Lakes	^{210}Po range, Bq·kg^{-1} d.w.	^{210}Po, Bq·kg^{-1} d.w.	CR*	%**
Perekopskaya group of lakes				
Lake Krasnoe	–	24.1 ± 1.0	4.0E+03	53.5
Lake Kiyatskoe	18.6–20.1	32.2 ± 4.2	–	–
Lake Kirleutskoe	17.5–39.3	28.4 ± 5.4	4.7E+03	64.8
Tarkhankutskaya group of lakes				
Lake Bakalskoe	14.6–18.8	16.7 ± 3.0	1.2E+04	254.5
Lake Dzharylgach	39.6–115.8	62.3 ± 5.7	2.3E+04	9.1
Yevpatoriyskaya group of lakes				
Lake Sasyk-Sivash	30.4–119.9	67.6 ± 12.5	–	42.8
Lake Kyzyl-Yar	23.3–44.5	33.3 ± 3.9	3.3E+04	50.2
Lake Moynakskoe	–	17.9 ± 2.2	2.2E+0	–
Kerchenskaya group of lakes				
Lake Aktashskoe	4.8[a]–53.6[b]	29.2 ± 3.5	8.3E+03	81.8
Lake Chokrakskoe	60.4–35.9	48.2 ± 17.3	2.4E+02	25.7
Lake Tobechikskoe	18.2–32.4	25.3 ± 8.8	3.1E+02	63.6

CR* – Concentration Ratio of ^{210}Po by bottom sediments.
** – % ratio of concentrations of ^{210}Po in suspended matter to that in the bottom sediments.
[a] Sand.
[b] Silt.

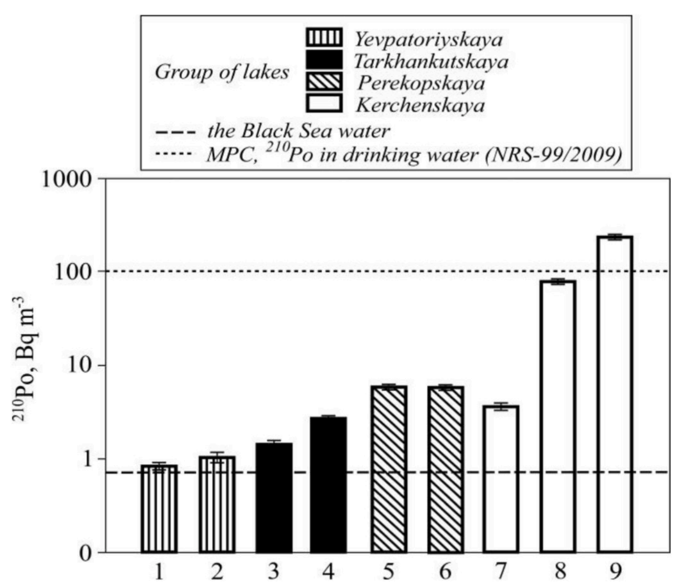

Fig. 2. Dissolved ^{210}Po in water of the Crimean salt lakes (1 – Lake Moynakskoe, 2 – Lake Kyzyl-Yar, 3 – Lake Bakalskoe, 4 – Lake Dzharylgach, 5 – Lake Krasnoe, 6 – Lake Kirleutskoe, 7 – Lake Aktashskoe, 8 – Lake Tobechikskoe, 9 – Lake Chokrakskoe).

It is known (Oliferov and Timchenko, 2005) that Lake Tobechikskoe has the liman origin. Mud volcanoes (Fig. 3) located along Lake Tobechikskoe, and emissions out of them can provide additional intake of natural radionuclides into the lake's water area.

Fig. 3. Mud volcano on Lake Tobechikskoe, 07.06.2016 (Photo taken by N. Mirzoeva).

Lake Chokrakskoe has liman origin and its water source is underground hydrosulfuric waters, sea water (Oliferov and Timchenko, 2005). During the field trips *in situ* studies of the water of the Chokrakskoe lake, we noted Eh = −326, which confirms the active water feeding of the lake from underground hydrosulfuric water sources. In turn, the latter contributes to the dissolution of minerals and leaching of the rocks, which contributes to the inflow of natural radionuclides into the ecosystem of this lake.

The increased content of ^{210}Po in the Chokrakskoe and Tobechikskoe lakes of the Kerchenskaya group is also possibly due to the presence of oil fields on the Kerch Peninsula. It is known, that elevated concentrations of natural radionuclides of uranium and thorium, including polonium which is formed upon decomposition of gaseous ^{222}Rn are observed in the ground and surface waters of such regions where gas and oil production is carried out. In these areas, the sources of natural radionuclides are produced water, which accompany the extraction of minerals.In addition, it is known, that very high concentrations of ^{210}Po (up to 19000 Bq·m^{-3}) were observed in high-saline groundwater (brine), whereas concentrations in ordinary groundwater did not exceed 30 Bq·m^{-3} (IAEA, 2017).

Since ^{210}Po in all other studied water bodies was within the concentrations noted for oxic waters (up to 5 Bq·m^{-3}) (IAEA, 2017), we believe that atmospheric input is the main source of this radionuclide intake, also in the Black Sea. The excess of ^{210}Po concentration in the water of the lakes compared to the sea is primarily due to the hydrological and hydrophysical features of the studied reservoirs.

The highest values of CR of ^{210}Po were obtained (Table 2) for suspended matter of the Bakalskoe and Kyzyl-Yar lakes, they corresponded to those for the Black Sea suspension (nE+04). The smallest CR of ^{210}Po in suspended matter was determined in Lake Chokrakskoe, which is another confirmation that the presence of hydrogen sulphide in the Chokrakskoe lake increases solubility ^{210}Po.

We identified a reliable trend (R^2 = 0.95) of a decrease in CR ^{210}Po for suspended matter with an increase in the salinity of the aquatic environment of the studied lakes (Fig. 4).

So, the accumulation of the present in water ^{210}Po by suspended matter decreases with an increase of the salinity in the water environment of the lakes.

4.2. *^{210}Po in hydrobionts*

It has been shown (Table 3, Fig. 5), that the activity of ^{210}Po practically in all the samples of plankton was higher than that determined for samples of suspended matter from the corresponding lakes.

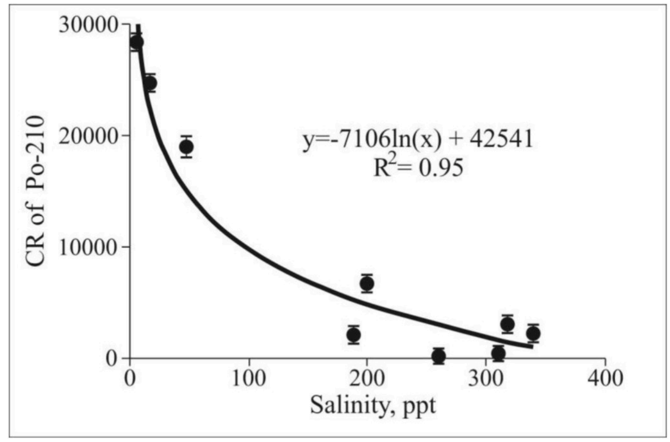

Fig. 4. Dependence of ^{210}Po Concentration Ratio (CR) in suspended matter from water salinity.

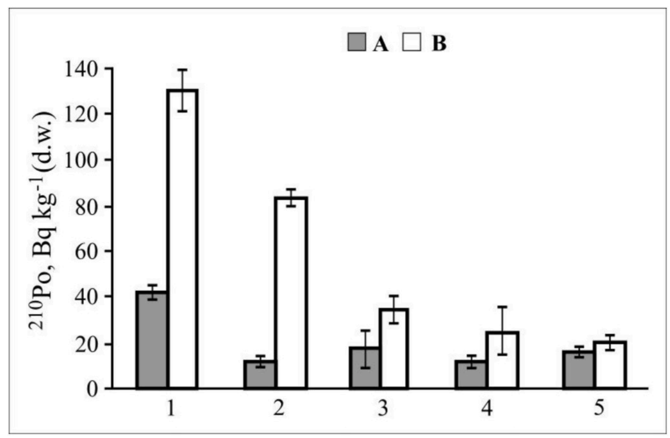

Fig. 5. ^{210}Po in suspended matter (A) and plankton (B) of some Crimean lakes: 1 – Lake Bakalskoe; 2 – Lake Chokrakskoe; 3 – Lake Kirleutskoe; 4 – Lake Krasnoe; 5 – Lake Kyzyl-Yar.

The largest difference in concentrations of ^{210}Po was found in Lake Chokrakskoe, whereas in the lightly salted Lake Kyzyl-Yar, the concentrations of ^{210}Po in suspended matter and plankton had similar values (Fig. 5).

A tendency towards a decrease of Accumulation coefficients of ^{210}Po by the plankton of salt lakes (as well as for suspended matter) with increasing salinity of water was observed.

It was noted that *Artemia* (adults animals) from the Lake Dzharylgach accumulated significant amounts of ^{210}Po (up to 200 Bq·kg^{-1} w.w.) while the concentrations of this radionuclide in its cysts were an order of magnitude lower (Table 4, Fig. 6).

This is explained by the fact that the intake of polonium into animal organisms occurs only by food (Heyraud and Cherry, 1979), therefore, the concentrations of ^{210}Po in cysts were insignificant. Similar to adult *Artemia*, the concentrations of ^{210}Po in larvae of *Chironomus* from Lake Dzharylgach indicate that these animals accumulate polonium from suspended matter and plankton organisms that have settled to the bottom of the reservoir.

It was found that the absorbed dose rate from ^{210}Po α-radiation obtained by *Artemia* (adult animals) is almost 2 times the maximum value determined for the Black Sea mussel *Mytilus galloprovincialis* (Lazorenko and Polikarpov, 2008). The absorbed doses for adult *Artemia* and for mollusc *Cerastoderma edule* regardless of the lakes habitat from the ionizing radiation of ^{210}Po were in the “Zone of ecological masking” and for cysts of *Artemia* they were in the “Zone of physiological masking”

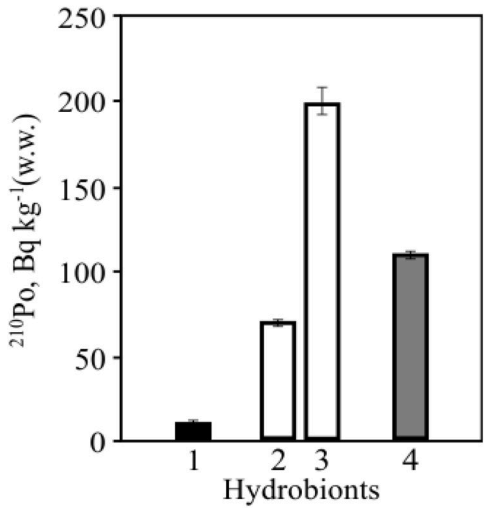

Fig. 6. ^{210}Po in hydrobionts from Lake Dzhetygara period 2016–2018:1 – cysts of *Artemia spp.*; 2 – adult *Artemia spp.* (min value); 3– adult *Artemia spp.* (max value); 4 – larvae of *Chironomidae*.

according to a scale of Zones of chronic dose rates and their effects in the Biosphere (Polikarpov, 1998), (Table 6, Fig. 7).

This indicates that the absorbed doses received by adult *Artemia* and mollusc *Cerastoderma edule* from ^{210}Po ionizing radiation are sufficient to produce real recorded effects in the studied hydrobionts (Polikarpov, 1998; Polikarpov et al., 2008).

Also this indicates about the food route of ^{210}Po intake into the adult hydrobionts.

These obtained results and previously published data (Mirzoyeva et al., 2019) indicate that ^{210}Po is the main dose-generating radionuclide for biota in the Crimean salt lakes. At the same time, the dose commitment on *Artemia* (adults animals) was more than 60 times lower than the dose rate recommended by the IAEA as permissible for biota (IAEA, 1992).

4.3. *^{210}Po in bottom sediments*

It was obtained (Tables 7 and 8, Fig. 8) that concentrations of ^{210}Po

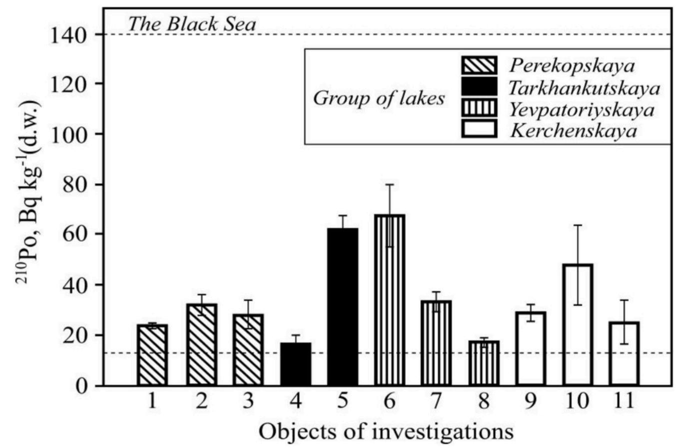

Fig. 8. ^{210}Po in the bottom sediments of the Crimean salt lakes (1 – Lake Krasnoe, 2 – Lake Kiyatskoe, 3 – Lake Kirleutskoe, 4 – Lake Bakalskoe, 5 – Lake Dzharylgach, 6 – Lake Sasyk-Sivash, 7 – Lake Kyzyl-Yar, 8 – Lake Moynakskoe, 9 – Lake Aktashskoe, 10 – Lake Chokrakskoe, 11 – Lake Tobechikskoe).

in the bottom sediments of Crimean salt lakes were in the range of values noted in the bottom sediments of the Black Sea (from 14 Bq·kg^{-1} d.w. to 242 Bq·kg^{-1} d.w. (own data), on average – 140 Bq·kg^{-1} d.w. The accumulation coefficients of ^{210}Po of bottom sediments of Crimean salt lakes varied in the range from n·10^{2}to n·10^{4}. Lowest coefficients were determined for the Kerchenskaya group (Eastern part of Crimea) (Tables 7 and 8), and the largest – for the Tarkhankutskaya and Yevpatoriyskaya group of lakes (Northern-Western part and Western part of Crimea).

As can be seen from the presented results (Tables 7 and 8, Fig. 8), the concentrations of ^{210}Po differed not only in different lakes, but in some cases, within the same water reservoir (Tables 7 and 8).

Thus, concentrations of ^{210}Po in the organic-rich muds of Lake Aktashskoe were an order of magnitude higher than in sand deposits from the same water ecosystem. Therefore, ^{210}Po in salt lakes is associated primarily with suspended organic matter. This is evidenced by the percents of the ratio of the concentration of ^{210}Po in suspended matter to that for bottom sediments (in most lakes this value exceeds 50%).

The exceptions are the Bakalskoe, Chokrakskoe and Dzharylgach

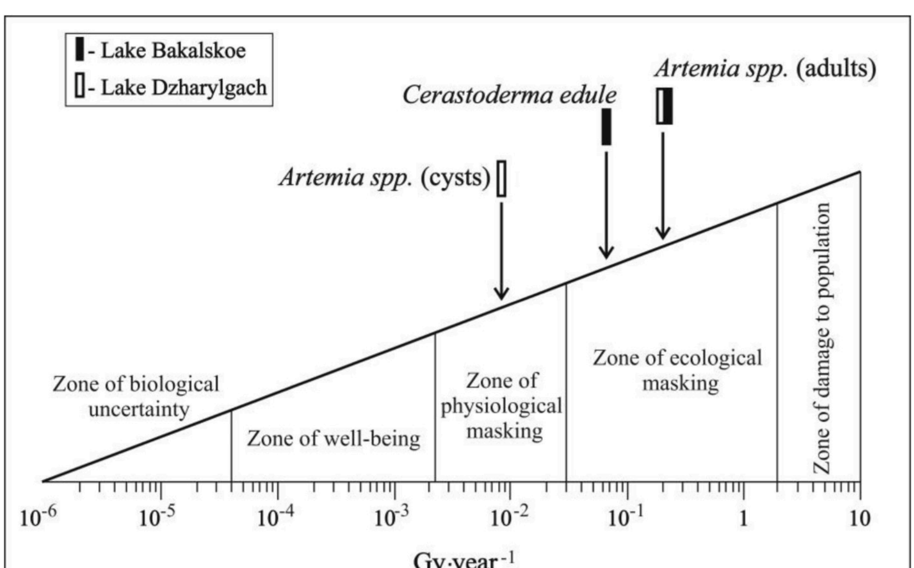

Fig. 7. Comparative absorbed doses (Gy per year) received by adults *Artemia spp.* and their cysts, as well mollusc *Cerastoderma edule* from the natural radionuclide ^{210}Po.

lakes, where these percents were: 254.5%, 25.7%, 9.1%, respectively.

It was shown, that the ^{210}Po was mainly on suspended matter in Lake Bakalskoe, redistributed between the dissolved form and bottom sediments in Lake Chokrakskoe, and in bottom sediments mainly in Lake Dzharylgach (Tables 7 and 8, Fig. 8). Differences were also observed in samples taken at different times from the same water ecosystem (Table 7). Thus, the concentrations of ^{210}Po in the upper layers of the bottom sediments selected in the Sasyk-Sivash and Dzharylgach lakes in November were significantly higher than the concentrations recorded in May–June. At the same time, the concentrations of ^{210}Po in the upper layer of bottom sediments from these lakes were quite close, and in the November samples were almost the same (Table 7). This can be explained by the sedimentation of the destructive organic matter (the largest amount of which is observed in the autumn period), into the bottom sediments (Garankina and Dagurova, 2009).

5. Conclusions

A monitoring radioecological study on the content of natural radionuclide ^{210}Po in aquatic ecosystems of Crimean salt lakes was carried out for the first time in the history of the existence of Crimean lakes.

The average concentrations of dissolved ^{210}Po in the water of salt lakes were 0.9–327.1 times higher than in the Black Sea (0.7 $Bq \cdot m^{-3}$). The excess of ^{210}Po concentration in the water of the lakes compared to the sea is primarily due to the hydrological and hydrophysical features of the studied reservoirs. In all the studied lakes, with the exception of the Kerchenskaya group of lakes (Lake Tobechikskoe (75.7 $Bq \cdot m^{-3}$) and Lake Chokrakskoe (229.0 $Bq \cdot m^{-3}$)), the concentration of ^{210}Po was within the concentrations noted for oxic waters (up to 5 $Bq \cdot m^{-3}$). The ^{210}Po concentration noted in Lake Chokrakskoe was twice the standard for drinking water (0.11 $Bq \cdot kg^{-1}$ (RSS-99/2009 (NRB-99/2009). Radiation Safety Standards, 2009)).

The main source of entry of ^{210}Po in the waters of the Crimean salt lakes is atmospheric deposition. For Lake Tobechikskoe, the additional sources of entry of natural radionuclides are groundwater and mud volcanoes around the lake, and for Lake Chokrakskoe, the active feeding of the lake from underground hydrosulfuric waters. The increased content of ^{210}Po in the Chokrakskoe and Tobechikskoe lakes of the Kerchenskaya group of lakes is also possibly due to the presence of oil fields on the Kerch Peninsula.

The concentration of ^{210}Po in the suspended matter of Lake Bakalskoe was 2.6 times higher, and in Lake Dzharylgach it was 2.8 times lower than that determined for the Black Sea. In all other lakes, the ^{210}Po content in suspended matter was of the same order as in the marine suspended matter.

The reliable trend of decrease of Concentration Ratio (CR) of the ^{210}Po in the suspended matter with an increase in the salinity of the water of the Crimean salt lakes was determined. The smallest CR of ^{210}Po in suspended matter was determined in Lake Chokrakskoe, which is another confirmation that the presence of hydrogen sulphide in Lake Chokrakskoe increases solubility of ^{210}Po.

The Concentration Ratio has been identified for the various components of the Crimean salt lakes. They were in the following ranges: for suspended matter: $n \cdot 10^1 – n \cdot 10^4$; for plankton: $n \cdot 10^2 – n \cdot 10^4$; for aquatic organisms: $n \cdot 10^2 – n \cdot 10^5$ (*Artemia* cysts $–n \cdot 10^2$; *Amphipoda* and aquatic plants – $n \cdot 10^3 – n \cdot 10^4$; for *Artemia* (adults animals) – $n \cdot 10^4$, for mollusk *Cerastoderma edule* – $n \cdot 10^5$ and for bottom sediments: $n \cdot 10^2 – n \cdot 10^4$.

The bottom sediments of the Bakalskoe and Moynakskoe lakes were less polluted by ^{210}Po (<20 $Bq \cdot kg^{-1}$ dry weight), while the highest concentrations were found in the Dzharylgach, Sasyk-Sivash and Chokrakskoe lakes. Such differences are associated with the sources of ^{210}Po intake into the water ecosystems, as well as with the hydrological and biogeochemical processes occurring in each individual studied lake. The ^{210}Po concentrations in the bottom sediments of Crimean salt lakes were in the range of values observed in the bottom sediments of the Black Sea.

Artemia spp. (adult animals) from the Crimean salt lakes accumulate significant amounts of ^{210}Po (up to 200 $Bq \cdot kg^{-1}$ w.w.), while the concentrations of this radionuclide in its cysts were an order of magnitude lower.

The absorbed doses received by adult *Artemia* and mollusc *Cerastoderma edule* from ^{210}Po ionizing radiation are sufficient to produce real recorded effects in the studied hydrobionts. Obtained results indicate the food route of ^{210}Po intake into the adult hydrobionts. It was shown, that ^{210}Po is the main dose-generating radionuclide for biota in the Crimean salt lakes. At the same time, the dose commitment on *Artemia* (adults animals) was more than 60 times lower than the dose rate recommended by the IAEA as permissible for biota (IAEA, 1992).

The obtained results of the study allow evaluation of the previously unexplored effect of the radiation of alpha-particles of ^{210}Po on the quality of the aquatic environment, hydrobionts, and also to determine the role of living and abiotic components in the transport, migration and elimination of this radionuclide in the ecosystems of the Crimean salt lakes.

The study of behavior of ^{210}Po in aquatic ecosystems in different regions of the Worlds Oceans is important. The previously unexplored data about concentration, distribution and peculiarities of the behavior of the natural radionuclide ^{210}Po in the abiotic and biotic components of the aquatic ecosystems of the Crimean salt lakes, as well as the assessment of the radiation dose for salt lakes hydrobionts from ^{210}Po were shown in this scientific work. The results of scientific research presented in this work are pioneering.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aarkrog, A., Baxter, M.S., Bettencourt, A.O., Bojanowski, R., Bologa, A., Charmasson, S., Cunha, I., Delfanti, R., Duran, E., Holm, E., Jeffree, R., Livingston, H.D., Mahapanyawong, S., Nies, S., Osvath, I., Pingyu, Li, Povinec, P.P., Sanchez, A., Smith, J.N., Swift, D., 1997. A comparison of doses from ^{137}Cs and ^{210}Po in marine food: a major international study. J. Environ. Radioact. 34 (1), 69–90. https://doi.org/10.1016/0265-931X(96)00005-7.

Anufriieva, E.V., Shadrin, N.V., Shadrina, S.N., 2017. History of research on biodiversity in Crimean hypersaline waters, 70 Arid Ecosyst. 23 (1), 64–71 (In Russian).

Anufriieva, E.V., Shadrin, N.V., 2018. Diversity of fauna in Crimean hypersaline water bodies. J. Siberian Federal Univ. Biol. 11 (4), 294–305. https://doi.org/10.17516/1997-1389-0073 (In Russian).

Bakhur, A.E., Manuilova, L.I., Ovsjannikova, T.M., 2009. Po-210 and Pb-210 in environmental objects. Methods of determination. ANRI 1, 29–40 (In Russian).

Balushkina, E.V., Golubkov, S.M., Golubkov, M.S., Litvinchuk, L.F., Shadrin, N.V., 2005. Characteristic features of ecosystems of hyperhaline lakes of the Crimea. Proc. Zool. Inst. Russ. Acad. Sci. 308, 5–12 (In Russian).

Baxter, M.S., 1996. Technologically enhanced radioactivity: an overview. J. Environ. Radioact. 32 (1–2), 3–17. https://doi.org/10.1016/0265-931X(95)00076-M.

Blaylock, B.G., Frank, M.I., O'Neal, B.R., 1993. Methodology for Estimating Radiation Dose Rates to Freshwater Biota Exposed to Radionuclides in the Environment. Report ES/ER/TM–78: Prepared for the U.S. DOE, Contract DE-AC05-84OR21400. Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Buesseler, K.O., Benitez, C.R., 1994. Determination of mass accumulation rate and sediment radionuclide inventories in the deep Black Sea. Deep Sea Res. 1 (12), 1605–1615. https://doi.org/10.1016/0967-0637(94)90064-7, 11.

Bulatov, V.I., 1996. Radioactive Russia. CERIS, Novosibirsk (In Russian).

Bulyon, V.V., Anokhina, L.E., Arakelova, E.S., 1989. Primary production hypersaline lakes of the Crimea. Proc. Zool. Inst. USSR Acad. Sci. 205, 14–25 (In Russian).

Carvalho, F.P., 1988. ^{210}Po in marine organisms: a wide range of natural radiation dose domains. Radiat. Protect. Dosim. 24, 113–117.

Carvalho, F.P., 1997. Distribution, cycling and mean residence time of ^{226}Ra, ^{210}Pb and ^{210}Po in the Tagus estuary. Sci. Total Environ. 196, 151–161. https://doi.org/10.1016/S0048-9697(96)05416-2.

Carvalho, F.P., 2011. Polonium (^{210}Po) and lead (^{210}Pb) in marine organisms and their transfer in marine food chains. J. Environ. Radioact. 102, 462–472. https://doi.org/10.1016/j.jenvrad.2010.10.011.

Chen, Q., Dalhgaard, H., Nielsen, S.P., Aarkrog, A., 1998. Determination of ^{210}Po and ^{210}Pb in mussel, fish, sediment, petroleum. Dept. of Nuclear Safety Research and Facilities, Riso National Laboratory, Denmark. Nov.1998. 10 p.

Cherry, R.D., Fowler, S.W., Beasley, T.M., Heyraud, M., 1975. Polonium-210: its vertical oceanic transport by zooplankton metabolic activity. Mar. Chem. 3 (2), 105–110. https://doi.org/10.1016/0304-4203(75)90017-1.

Cherry, R.D., Heyraud, M., 1982. Evidence of high natural radiation doses in certainmid-water oceanic organisms. Science 218, 54–56. https://doi.org/10.1126/science.7123217.

Cherry, R.D., Shannon, L.V., 1974. The alpha radioactivity of marine organisms. Atom. Energy Rev. 12 (1), 9–45.

Collection of State standards, 1994. Moscow, Publishing house of standards. (In Russian).

EPA (Environmental Protection Agency, USA), 1984. Radiochemistry Procedures Manual Eastern Environmental Radiation Facility, p. 342. EPA 520/5–96–006, P.00.03.01–03.

Fowler, S.W., 2011. ^{210}Po in the marine environment with emphasis on its behaviour within the biosphere. J. Environ. Radioact. 102, 448–461. https://doi.org/10.1016/j.jenvrad.2010.10.008.

Garankina, V.P., Dagurova, O.P., 2009. Destruction in water and in sediments of the shallow water podolsky sor bay of lake baikal. Bull. Irkutsk State Univ.: Ser. "Earth Sci." 2 (2), 65–71.

Gulina, L.V., Gulin, S.B., 2011. Natural and man-made radionuclides in the ecosystem of Koyashskoe salt lake (South-East Crimea). Mar. J. Ecol. 1 (X), 19–25 (in Russian).

Haridasan, P.P., Paul, A.C., Desai, M.V.M., 2001. Natural radionuclides in the aquatic environment of a phosphogypsum disposal area. J. Environ. Radioact. 53, 155–165. https://doi.org/10.1016/s0265-931x(00)00121-1.

Heyraud, M., Cherry, R.D., 1979. Polonium–210 and lead–210 in marine food chains. Mar. Biol. 52 (3), 227–236. https://doi.org/10.1007/BF00412529.

Heyraud, M., Cherry, R.D., 1983. Correlation of ^{210}Po and ^{210}Pb enrichment in the sea-surface microlayer with neuston biomass. Continent. Shelf Res. 1 (3), 283–293. https://doi.org/10.1016/0278-4343(83)90028-6.

IAEA, 1992. Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards. IAEA, Vienna. IAEA Technical Report Series. 332.

IAEA, 2002. Management of Radioactive Waste from the Mining and Milling of Ores. IAEA Safety Standards Series. WS-G-1.2. IAEA, Vienna.

IAEA, 2003. Radiation Protection and the Management Radiation Protection of Radioactive Waste in the Oil and Gas Industry, vol. 34. IAEA, Vienna. IAEA Safety Reports Series.

IAEA, 2017. The Environmental Behavior of Polonium. IAEA Technical Reports Series. IAEA, Vienna, 484.

IUR. International Union of Radioecology, 2002. Protection of the Environment. Current State and Future Work. Report IUR 03, 2002. Østerås, vol. 23. IUR.

Kim, G., Church, T.M., 2001. Seasonal biogeochemical fluxes of ^{234}Th and ^{210}Po in the upper Sargasso Sea: influence from atmospheric iron deposition. Global Biogeochem. Cycles 15 (3), 651–661. https://doi.org/10.1029/2000GB001313.

Kurnakov, N.S., Kuznetsov, V.G., Dzens-Litovskiy, A.I., Ravich, M.I., 1936. Salt Lakes of Crimea. AS of USSR, Moscow-Leningrad (In Russian).

Kryshev, I., Sazykina, T., Kryshev, A., et al., 2002. Ecological Dosimetry Models. Radionuclides Uptake and Transfer in Pelagic Food Chains of the Barents Sea and Resulting Doses to Man and Biota. Project of NRPA, IMR, AUN, IET (Norway) and SPA TYPHOON (Russia), vol. 97. NRPA, Norway.

Lazorenko, G.E., 2000. Concentration of ^{210}Po by bottom sediments of the Black Sea. Rep. NAS Ukraine 9, 203–207 (In Russian).

Lazorenko, G.E., Polikarpov, G.G., 2002. ^{210}Po in Marine Biota. Regional Technical Co-operation Project RER/2/003 "Marine Environmental Assessment of the Black Sea" Working Material. Vienna: reproduced by the IAEA, 168–173.

Lazorenko, G.E., 2008. Distribution of naturally occurring radionuclide^{210}Po in the components of Black Sea ecosystem. In: Polikarpov, G.G., Egorov, V.N. (Eds.), Radioecological Response of the Black Sea to the Chernobyl Accident. Sevastopol, EKOSEA–Hydrophysics, pp. 118–128 (In Russian).

Lazorenko, G.E., Polikarpov, G.G., 2008. Assessment of radiation exposure on hydrobionts of the Black Sea from alpha particles radiation of natural radionuclide ^{210}Po. In: Polikarpov, G.G., Egorov, V.N. (Eds.), Radioecological Response of the Black Sea to the Chernobyl Accident. Sevastopol, EKOSEA–Hydrophysics, pp. 381–388 (In Russian).

Lazorenko, G., Polikarpov, G., Osvath, I., 2009. ^{210}Po accumulation by components of the Black Sea ecosystem. Radioprotection 44 (5), 981–986. https://doi.org/10.1051/radiopro/20095175.

Lazorenko, G.E., Polikarpov, G.G., 2010. Polonium-210 in the Black Sea fishes. Radiation biology. Radioecology 50 (4), 398–404 (In Russian).

Le Guern, F., Le Roulley, J.C., Lambert, G., 1982. Condensation du polonium dans les gaz volcaniques. C. R. Acad. Sci. 294, 887–890 (In French).

Mayer, K., 1999. IAEA Regional Advanced Training Course on Quality Management in Environmental Applications of Nuclear Analytical Techniques, 23 August – 3 Sep. 1999. European Commission, Join Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany.

Marey, A.N., Zykova, A.S., 1980. Methodical Recommendations for the Sanitary Control of the Content of Radioactive Substances in the Environment. Nauka, Moscow (In Russian).

Mirzoeva, N., Lazorenko, G., 2004. Radiological Doses to Marine Biota. Regional Technical Co-operation Project RER/2/003 "Marine Environmental Assessment of the Black Sea" Working Material, Vienna, pp. 174–175.

Mirzoyeva, N., Gulina, L., Gulin, S., Plotitsina, O., Stetsuk, A., Arkhipova, S., Korkishko, N., Eremin, O., 2015. Radionuclides and mercury in the Crimean salt lakes. Chin. J. Oceanol. Limnol. 33 (6), 1413–1425.

Mirzoyeva, N.Yu, Arkhipova, S.I., Kravchenko, N.V., 2018. Sources of inflow and nature of redistribution of ^{90}Sr in the Crimean salt lakes. J. Environ. Radioact. 188, 38–46. https://doi.org/10.1016/j.jenvrad.2017.10.018.

Mirzoyeva, N.Yu, Korotkov, A.A., Lazorenko, G.E., 2019. Present-day radiation doses formed by anthropogenic ^{137}Cs and natural radionuclides on the gill-footed Crustaceous *Artemia spp.* from the Crimean salt lakes. Radiation biology. Radioecology 59 (4), 419–429. https://doi.org/10.1134/s0869803119030081.

Mirzoeva, N., Shadrin, N., Arkhipova, S., Miroshnichenko, O., Kravchenko, N., Anufriieva, E., 2020. Does salinity affect the distribution of the artificial radionuclides 90Sr and 137Cs in water of the saline lakes? A case of the Crimean Peninsula. Water 12 (2). https://doi.org/10.3390/w12020349. Article no. 349 (15 p.

Mohamed, C.A.R., Siang, T.C., 2010. Seasonal variation of ^{210}Po in different salinity: case of Kuala Selangor river, west coast Peninsular Malaysia. Coast. Mar. Sci. 34 (1), 186–194.

Nissenbaum, A., 1993. The Dead Sea – an economic resources for 10000 years. Hydrobiologia 267, 127–141. https://doi.org/10.1007/BF00018795.

Nozaki, Y., Zhang, J., Takeda, A., 1997. ^{210}Pb and ^{210}Po in the equatorial Pacific and the Bering Sea: the effects of biological productivity and boundary scavenging. Deep-Sea Res., Part 2 44 (9–10), 2203–2220. https://doi.org/10.1007/s11430-004-5233-y.

Nozaki, Y., Dobashi, F., Kato, Y., Yamamoto, Y., 1998. Distribution of Ra isotopes and the ^{210}Pb and^{210}Po balance in surface seawaters of the mid Northern Hemisphere. Deep-Sea Res. Part I. 45 (8), 1263–1284.

Oliferov, A.N., Timchenko, Z.V., 2005. Rivers and Lakes of the Crimea. Dolya, Simferopol, Ukraine (InRussian).

Othman, I., Al-Masri, M.S., 2007. Impact of phosphate industry on the environment: a case study. Appl. Radiat. Isot. 65 (1), 131–141.

Pasinkov, A.A., Sotskova, L.M., Shepherd, V.I., 2014. Environmental problems of conservation and sustainable use balneological resources of Crimean salt lakes, 2 Sci. Notes of V. I. VernadskyTaurida Nat. Univ. 27 (66), 97–117 (In Russian).

Pervolf, YuV., 1953. Silts and conditions of theirs silt production in the Crimean salt lakes. J. Proc. Laboratory Limnol. AS USSR 2, 154–228 (In Russian).

Polikarpov, G.G., 1998. Conceptual model of responses of organisms, populations and ecosystems in all possible dose rates of ionizing radiation in the environment. Radiat. Protect. Dosim. 75 (1–4), 181–185. https://doi.org/10.1093/oxfordjournals,rpd.a0322, 25.

Polikarpov, G.G., Lazorenko, G.E., Tsitsugina, V.G., Tereshenko, N.N., Mirzoeva, N. Yu, Egorov, V.N., 2008. Comparison of dose pressure from radiations of natural Po-210 and Chernobyl radionuclides Sr-90, Cs-137 and Pu-238, 239, 240 on hydrobionts of the Black Sea and other reservoirs of Ukraine. In: Polikarpov, G.G., Egorov, V.N. (Eds.), Radioecological Response of the Black Sea to the Chernobyl Accident. Sevastopol, EKOSEA–Hydrophysics, pp. 389–395 (In Russian).

Ponizovskii, A.M., 1965. Salt Resources of the Crimea. Simferopol, Crimea, Russia (In Russian).

RSS-99/2009 (NRB-99/2009) Radiation Safety Standards, 2009. The Sanitary Rules and Regulations 2.6.1.2523-09. Registered by the Ministry of Justice 14.08.2009. Reg. No 14534. http://base.garant.ru/4188851/#1000/. accessed 07.07.2009), (In Russian).

Rubin, K.H., Macdougall, J.D., Perfil, M.R., 1994. ^{210}Po–^{210}Pb dating of recent volcanic eruptions on the seafloor. Nature 368, 841–844. https://doi.org/10.1038/368841a0.

Rutgers van der Loeff, M.M., Geiber, W., 2008. U- and Th - series nuclides as tracers of particle dynamics, scavenging and biogeochemical cycles in the oceans. U-Th series nuclides. In: Krishnaswami, S., Cochran, J.K. (Eds.), Aquatic Systems. Elsevier, Amsterdam, pp. 227–268 (Chapter 7).

Shadrin, N.V., Anufriieva, E.V., 2018. Ecosystems of hypersaline water reservoirs: structure and trophic relationships. J. Common Biol. 79 (6), 418–427 (In Russian).

Sotskova, L.M., Smirnov, V.O., Okara, I.V., Malishchuk, I.O., 2015. Preservation of the balneological resources of mud saline lakes of the western Crimea. Modern Sci. Res. Innov. 7 (4). http://web.snauka.ru/issues/2015/07/56691/. accessed 07.01.2019.

Sotskova, L.M., Smirnov, V.O., Protciv, A.V., Fil, P.P., 2017. Problems of preservation of salty lakes of northwest and western coasts of the Crimea, 3–1 Sci. Notes of V. I. Vernadsky Crimean Federal Univ. Biol. Chem. 3 (69), 240–250 (In Russian).

Stewart, G.M., Fowler, S.W., Fisher, N.S., 2008. The bioaccumulation of U-Th series radionuclides in marine organisms. U-Th Ser. Nucl. Aquat. Syst. 13, 269–305.

Strady, E., Harmelin-Vivien, M., Chiffoleau, J.F., Veron, A., Tronczynski, J., Radakovitch, O., 2015. ^{210}Po and ^{210}Pb trophic transfer within the phytoplanktone-zooplanktone-anchovy/sardine food web: a case study from the Gulf of Lion (NW Mediterranean Sea). J. Environ. Radioact. 143, 141–151. https://doi.org/10.1016/j.jenvrad.2015.02.019.

Thomas, P., Liber, K., 2001. An estimation of radiation doses to benthic invertebrates from sediments collected near a Canadian uranium mine. Environ. Int. 27, 341–353.

Turekian, K.K., Nozaki, Y., Benninger, L.K., 1977. Geochemistry of atmospheric radon and radon products. Annu. Rev. Earth Planet Sci. 5, 227–255. https://doi.org/10.1146/annurev.ea.05.050177.001303.

Urbakh, V.Yu, 1964. Biometrical Methods. Nauka, Moscow (In Russian).

Wei, C.-L., Murray, J.W., 1994. The behaviour of scavenged isotopes in marine anoxic environments: ^{210}Pb and ^{210}Po in water column of the Black Sea. Geochem. Cosmochim. Acta 58, 1795–1811. https://doi.org/10.1016/0016-7037(94)90537-1.

Yadav, D.N., Sarin, M.M., 2009. Ra-Po-Pb isotope systematic in waters of Sambhar Salt Lake, Rajasthan (India): geochemical characterization and particulate reactivity. J. Environ. Radioact. 100 (1), 17–22. https://doi.org/10.1016/j.jenvrad.2008.09.005.