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# Characterization of biocenoses in the storage reservoirs of liquid radioactive wastes of Mayak PA. Initial descriptive report

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ABSTRACT

As a result of operation of the Mayak Production Association (Mayak PA), Chelyabinsk Oblast, Russia, an enterprise for production and separation of weapon-grade plutonium in the Soviet Union, ecosystems of a number of water bodies have been radioactively contaminated. The article presents information about the current state of ecosystems of 6 special industrial storage reservoirs of liquid radioactive waste from Mayak PA: reservoirs R-3, R-4, R-9, R-10, R-11 and R-17. At present the excess of the radionuclide content in the water of the studied reservoirs and comparison reservoirs (Shershnyovskoye and Beloyarskoye reservoirs) is 9 orders of magnitude for $^{90}$Sr and $^{137}$Cs, and 6 orders of magnitude for alpha-emitting radionuclides. According to the level of radioactive contamination, the reservoirs of the Mayak PA could be arranged in the ascending order as follows: R-11, R-10, R-4, R-3, R-17 and R-9. In 2007–2012 research of the status of the biocenoses of these reservoirs in terms of phytoplankton, zooplankton, bacterioplankton, zoobenthos, aquatic plants, ichthyofauna, avifauna parameters was performed. The conducted studies revealed decrease in species diversity in reservoirs with the highest levels of radioactive and chemical contamination.

This article is an initial descriptive report on the status of the biocenoses of radioactively contaminated reservoirs of the Mayak PA, and is the first article in a series of publications devoted to the studies of the reaction of biocenoses of the fresh-water reservoirs of the Mayak PA to a combination of natural and man-made factors, including chronic radiation exposure.



## 1. Introduction

The problem of radiological protection of biocenoses is one of the main current challenges that radiological protection faces nowadays (ICRP, 2008; Bréchignac et al., 2012). In accordance with ICRP Publication 108, now there is an accepted organism-based approach to the radiological protection of biota similar to the protection of a person (ICRP, 2008). Alongside with it, IUR puts forward arguments proving that this approach has weaknesses and cannot ensure protection of ecosystems since it does not consider indirect radiation effect mediated through interactions between species (Bréchignac, 2003; Bréchignac et al., 2012; Bradshaw et al., 2014).

The information about the pattern defining the biocenosis reactions (changes in the structure and function of the community) taking into account indirect effects, can be obtained while studying natural ecosystems, exposed to radioactive contamination at various levels. In 1950–1960 a part of the territory of the Southern

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Urals (Russia) near Mayak PA has been significantly polluted with radiation (Malyshev et al., 1997; Aleksakhin et al., 2001). The peculiar feature of radioactive contamination of the environment is the pollution of a large number of hydrosphere objects: lakes, reservoirs, rivers with a wide range of radioactive contamination from background to the extremely highest levels (total activity of beta-emitting radionuclides in water $2.3 \times 10^7$ Bq/l; total activity of alpha-emitting radionuclides in water $3.1 \times 10^3$ Bq/l) (Pryakhin et al., 2012; Atamanyuk et al., 2012). The biota of these reservoirs has been under radiation exposure for more than 50–60 years.

From a scientific point, the storage-reservoirs of liquid radioactive wastes (LRW) of Mayak PA are of high interest since the biota of these reservoirs have been in relatively stable conditions for tens up to hundreds of generations and hydrobionts' immigration from clean ecosystems has been very limited. It means that over 50–60 years all possible direct and indirect effects of radiation exposure could obviously have taken place. Thus, the existence of such a unique radioecological situation allows to assess ecological effects on real grounds due to radioactive contamination of freshwater ecosystems, based on the determination of the reaction pattern of certain organisms, populations, communities and whole ecosystem in response to the level of chronic radiation exposure.

Different research teams have conducted studies of these reservoirs at different times. In the present paper the authors reviewed available data on the status of the ecosystems of the special industrial reservoirs. This review is the first paper in a series of publications devoted to the studies of the reaction of biocenoses of the fresh-water reservoirs of the Myak PA to a combination of natural and man-made factors, including chronic radiation exposure.

## 2. Brief historical overview of the radiation situation on the Mayak PA reservoirs

Mayak PA is situated in the north of the Chelyabinsk region (Fig. 1). Creation of Mayak PA was connected with the defense tasks of the USSR in the post-World War II period. The history of establishment and development of Mayak PA has been described in details in previously published monographs (Malyshev et al., 1997; Kruglov, 2002). Currently there are 8 storage reservoirs of LRW (Report on ecological safety FSUE, 2012). These reservoirs of Mayak PA are nuclear facilities “storages of radioactive waste”, which have hydrotechnical constructions to limit the inflow of LRW into the open hydrographic network. Four of them were created on the upper stream of the Techa River (so called “the Techa Reservoir Cascade (TRC)”), which are used as storages of low-level LRW. They are shown as R-3, R-4, R-10, R-11 at the Fig. 1. The three upper reservoirs R-3, R-4 and R-10 operate in a flowing mode and R-11, the last in the cascade of reservoirs, operates in a closed mode (Fig. 1). The construction of the TRC allowed to immobilize a significant number of radionuclides due to their accumulation and decay in bottom sediments, in order to eliminate direct discharge of Mayak PA industrial waste into the Techa River.

Two reservoirs of Mayak PA, R-17 (Staroye Boloto) and R-9 (Lake Karachay), are storages of medium-active LRW (Fig. 1) (Glagolenko et al., 2003). According to the classification of radioactivity levels (Basic Sanitary Rules for Radiation Safety…, 2010), low-active solid and liquid waste represents by concentration of $^{90}Sr$, $^{137}Cs$ and transuranic alpha-emitting radionuclides ranging from $10^2$ to $10^3$ kBq/kg, $10^1$–$10^3$ kBq/kg and 1–$10^1$ kBq/kg, respectively. To medium-active waste pertain solid and liquid radioactive waste with specific concentration of beta-emitting radionuclides (except tritium), ranging from $10^3$ to $10^7$ kBq/kg; with specific concentration of transuranic alpha-emitting radionuclides ranging from $10^1$ to $10^5$ kBq/kg. And high-level radioactive waste consist of solid and liquid waste with specific concentration of beta-emitting radionuclides (except tritium) exceeding $10^7$ kBq/kg; with specific concentration of transuranic alpha-emitting radionuclides – $10^5$ kBq/kg. Reservoir R-17 is situated in a natural depression, where after the creation of dams in 1952 and 1954 an artificial reservoir appeared and still exists (Stukalov, 2007, 2010).

In the late 1960s – early 1970s volumes and total activity of LRW produced significantly decreased. Total activity of discharged beta-emitting radionuclides was reduced by 2 times. The reservoir system is now used for storing only low-level LRW. The main part of all discharged radionuclides activity, therefore, refers to the period of reservoir operation in 1956–1966. The history of creation, the dynamics of contamination and the results of studies of reservoir R-17 are given in details in the works previously published (Stukalov, 2007, 2010).

Lake Karachay (reservoir R-9) is an open medium-activity LRW storage, created in October 1951 in the place of the natural stagnant upland reservoir, having the same name. Operation of the Lake Karachay started as a temporary measure aimed to reduce LRW discharges into the open hydrographic system (the Techa River). Until 1951 reservoir R-9 was a natural swampy Lake Karachay with variable supply. The history of creation, the dynamics of contamination and the results of studies of reservoir R-9 are given in details in the works previously published (Aleksakhin, 2007).

Mayak PA has developed a concept for removing reservoirs from operation, and is implementing a set of measures to improve their safety. Since 1986 reservoir R-9 has been undergoing the process of liquidation – filling it with rocky ground and concrete blocks. In the 1980s the open part of the water area of the reservoir was 36 ha. By the end of 2014, the open part of the water area of the reservoir reduced down to 2.7 ha. The water area of Lake Karachay is to be completely filled with concrete blocks and sand by the end of 2015. Reservoir R-17 is also to be closed with rocky ground by 2023. Thus, reservoirs R-9 and R-17 will be evaluated as subsurface items of special conservation and burial of radioactive wastes. Reservoirs of the TRC should be under controlled storage (about 150–200 years). The fulfilled studies show that by 2025 the water in the reservoirs will cease to qualify as LRW, and after 150 years, the value of the specific activity of radionuclides in bottom sediments of the previous reservoirs will fall below the limit of solid radioactive waste (SRW) and the reservoirs will therefore be allowed to be removed from regulatory control.

## 3. History of hydrobiological studies

In the early years of Mayak PA operation (1949–1951) no radioecological studies were conducted. Information about the dynamics and radionuclide composition of LRW discharges into the Techa River in this period has been reconstructed from the historical data and summarized in the following papers (Glagolenko et al., 2006a, 2006b; Degteva et al., 2012; Shagina et al., 2012). An overview of the radioecological status of the Techa River and the reservoirs located on it in 1950–1956 is given in previously published works (Ilyin, 2005a, 2005b, 2005c; Marey et al., 2009). In later periods radioecological condition of the TRC and the Techa River has been further described in (Malyshev et al., 1997; Amundsen et al.,2004; Akleev and Kisselyov, 2002; Sadovnikov et al., 2002).

The first comprehensive studies of the status of the biota of the Techa River were performed in 1951–1952 by a group of scientists under the leadership of A.N. Marey (Marey et al., 2009). They have studied all through the Techa River.

It was shown that in 1951–1952 in the upper reaches of the Techa River the death of certain groups of hydrobionts was observed.The demersal and benthic organisms, such as mollusks

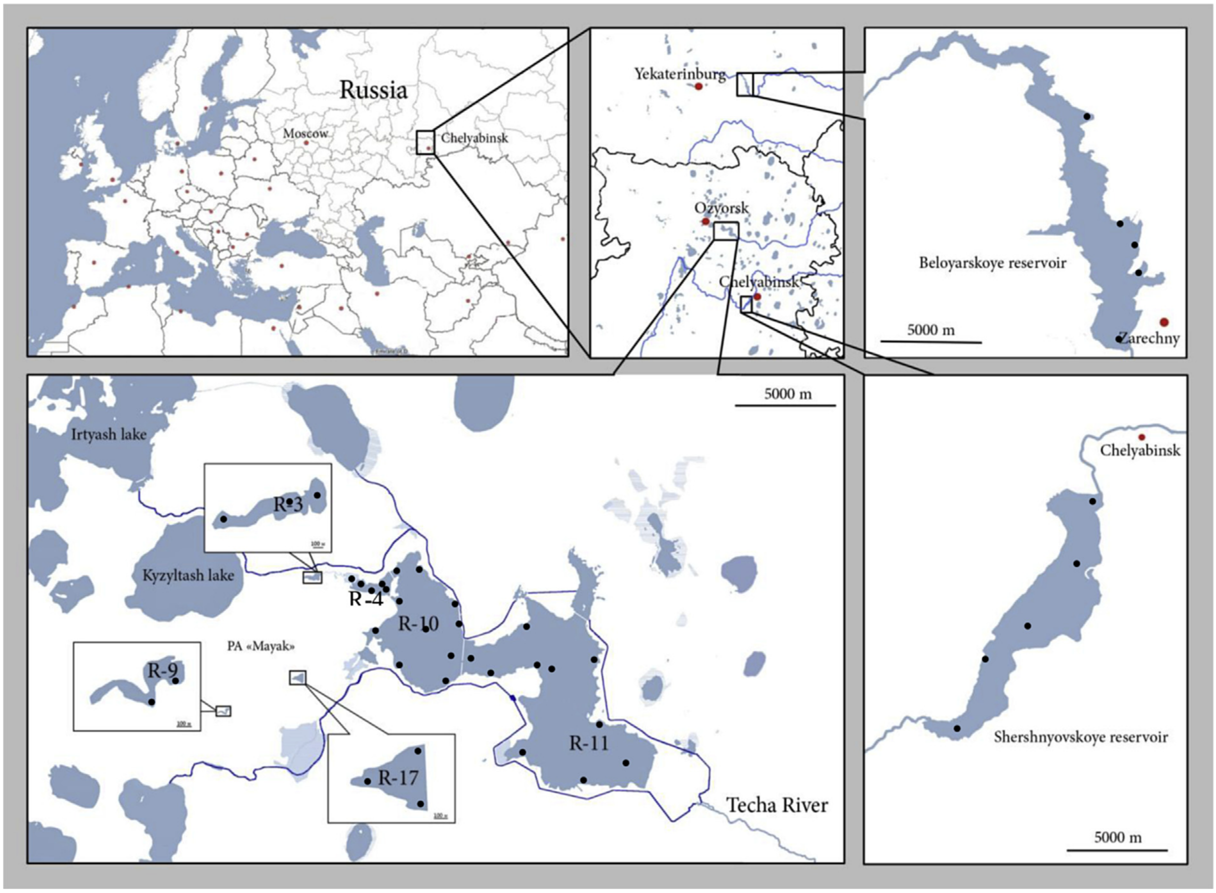


**Fig. 1.** Schematic map of location of special industrial reservoirs of the Mayak PA. Dots in the figure mark sampling stations on the studied reservoirs. The status of the reservoir R-9 is given as of 2011. As for the other reservoirs the current parameters are given.

and crawfish were subjected to the highest exposure (Marey et al., 2009).

No markedly expressed effect of radiation on aquatic vegetation and plankton was established in this research. It was demonstrated that the radionuclide content in silt exceeding $7.4 \times 10^8$ Bq/kg is lethal to all zoobenthic animals. Tubificidae and insects larvae appear in zoobenthos samples at lower levels of radiation. When the content of β-emitting radionuclides is less than $1.9 \times 10^7$ Bq/kg wet weight the restoration of the normal near-bottom life of the water-body occurs, except for mollusks that survive if the concentrations are much lower (not more than $7.4 \times 10^4$ Bq/kg wet weight) (Marey et al., 2009).

In 1965–1973 field studies were performed in TRC reservoirs on the assessment of the biological effect of the chronic radiation exposure on fresh water fish (Pitkyanen, 1971; Shvedov et al., 1982). It was shown no changes in the growth parameters in fish ($^{90}$Sr and $^{137}$Cs concentrations in water were $1.0 \pm 0.05 \times 10^4$ Bq/l and $5.9 \pm 3.7 \times 10^2$ Bq/l, respectively); however disturbances of the reproductive function, manifested in decreased fertility of the adult species and increased amount of abnormalities in progeny were registered in perch and pike. For pike were determined dose rates for bone tissue (0.33 cGy / day), muscle (0.12 cGy / day), gonads (0.06 - 0.57 cGy / day) and for the eggs after discharge them into the water (0.295 cGy / day). (Pitkyanen et al., 1978; Shvedov et al., 1982).

Research in the 1980s was aimed at calculating dose rate to internal organs of fish inhabiting the reservoir R-10, which on the average was found to be 2–3 Gy/year (Smagin, 2006). The analysis of some parameters of the reproductive function in fish detected that the amount of the normal yolk sac larvae hatched from the eggs of the pike from the reservoir R-10 did not differ from that in fish from the control water body (Lake Alabuga, Chelyabinsk Oblast). The growth rate of fish from the reservoir R-10 was lower than that of the fish from the comparison population, although some increase in the frequency of development abnormalities in prolarvae was observed (Smagin, 2007).

Investigations performed in 2002 revealed increase in the frequency of erythrocytes with micronuclei in the peripheral blood of pike and roach from the reservoir R-10 as compared to the same parameters in the same fish species from uncontaminated reservoirs of Sverdlovsk Oblast (Lake Shitovskoye, Nizhne-Isetsky pond) (Smagin, 2007). In the research conducted in 2005 scientists detected changes in the shape of perch inhabiting the reservoir R-10 as compared to fish from the comparison water body (Lake Irtyash, Lake Kozhakul', Lake Uelgi in Chelyabinsk Oblast) (Baranov et al., 2006).

Research conducted within the period from 2004 to 2008 studied the status of the phytocenosis of the TRC reservoir R-3 and accumulation of the long-lived radionuclides by macrophytes (Menyshich, 2010). In the course of these studies species composition and biomass of the aquatic plants of the reservoir R-3 were determined; coefficients of $^{90}$Sr and $^{137}$Cs accumulation were estimated on the basis of the ratio of specific activity of radionuclides in macrophytes (Bq/kg dry weight) to radionuclide activity in water (Bq/l). It was founded that depending on the species, coefficients of accumulation amounted to 20–1790 (L/kg) for $^{90}$Sr and to 40–1370 (L/kg) for $^{137}$Cs.

## 4. Current status of the ecosystems of the reservoirs

Since 2007 the system of the industrial environmental monitoring of the special industrial reservoirs of the Mayak PA was updated by research on the biota status, which includes the study of the biocenosis of the reservoirs in terms of bacterioplankton, phytoplankton, zooplankton, zoobenthos, water plants, ichthyofauna parameters, and since 2012 the biological monitoring includes the determination of the parameters of the status of the avifauna of the reservoirs. The herring gull (Larus argentatus Pontoppidan) was used as the object of the research.

The system of biological monitoring presupposed setting up a network of sampling stations on the studied reservoirs. Ten stations were set in each of the reservoirs R-11 and R-10 (3 of them were situated along the old riverbed of the Techa River, the others were set at the shore of the reservoir (Fig. 1)). Five stations were set on the reservoir R-4: three stations characterize the riverside biotopes at various parts of the surface area of the reservoir, and 2 stations are located in the deep part of the reservoir near the dam. Three sampling stations were set in each of the reservoirs R-3 and R-17, located in various parts of the water area. Two near-shore stations were set on the reservoir R-9.

Sampling of plankton and benthos was carried out at each of the stations during hydrobiological summer from one to three times a year. The description of aquatic vegetation was carried out at each of the in-shore stations one time in the period 2007–2012 during summer. Fish capture was performed once or twice during summer in the coastal areas of reservoirs (no fish capture has been performed on reservoirs R-17 and R-9). Bird catching and egg collection were implemented in the colonies of gulls on reservoir R-11.

Plankton samples (1 L each) were collected using a sampler from the following levels: the surface, 0.5*S, S, 2*S, (2*S + d)/2 and the bottom; where S – transparency of water according to Secchi disk, d – depth of the reservoir at the sampling site. Further on, samples of water were mixed, and 0.5 l out of the total volume was taken for the study of phytoplankton. The remaining volume was concentrated using a network with a mesh size of 25 × 25 μm to about 50 ml volume and was used for the study of zooplankton. Iodine fixative was used for the preservation of plankton samples (5 g of KI, $I_2$ and $CH_3COONa$, distilled water to 100 ml with addition of 10 mg of phenol). Zoobenthos samples were taken using bucket dredges from the top layer of bottom sediments 0.025 $m^2$ in area. The samples were washed through a network with a mesh size of 420 × 420 mm and fixed with 10% formalin. Fish was caught using electric rods Samus-725 MP and gillnets with mesh 15, 20, 30, 40, 50, 60, 70, 80 mm. Birds were caught using square tent spring traps (base dimensions are 85 × 85 cm).

Basicaly, two approaches can be used for risk assessment in contaminated aquatic ecosystems; 1) comparison on current and initial (prior to man-made contamination) ecosystem statuses; 2) comparison of contaminated ecosystem with similar one (in terms of geographic, morphological, hydrological and hydrochemical similarity). The reservoirs of the Techa Reservoir Cascade over 50 years have been under radioactive contamination, and the only possible way to assess the status of the ecosystem of these reservoirs is to conduct a comparative analysis with similar comparison reservoirs. Among the reservoirs of the Urals region the most suitable in terms of quality comparison water bodies for the reservoirs R-10 and R-11 are Shershnyovskoye reservoir located in Chelyabinsk oblast (Pryakhin et al., 2010a) and Beloyarskoye reservoir – cooling pool of the Beloyarskaya nuclear power station (Sverdlovsk oblast) (Trapeznikov et al., 2008; Trapeznikov, 2010). These two comparison waterbodies are artificial reservoirs, as well as the reservoirs R-10 and R-11; they were created approximately at one and the same time; they are comparable in morphological parameters and are located in one and the same geographical zone.

In accordance with the classification of water body salinity (Kitaev, 2007), all the reservoirs can be separated to brackish waters (R-17, R-9) and fresh waters (each others reservoirs mentioned above) (Atamanyuk et al., 2012; Pryakhin et al., 2011, 2010a; Trapeznikov et al., 2008; Trapeznikov, 2010). Peculiar feature of the chemical composition of the water of reservoirs R-11 and R-10 is its high concentration of sulfate-ions (500 mg/l and 300 mg/l, respectively), maximum permissible concentration for fishery ponds (MPCfp) – 100 mg/l (Order of the Federal Agency, 2010), long-term average concentration in Shershnyovsloye reservoir – 41 mg/l; reservoirs R-17 and R-9 are characterized by a high content of nitrate-ions in water (2500 mg/l and 4400 mg/l, respectively), MPCfp – 40 mg/l, long-term average concentration in Shershnyovsloye reservoir – 0.2 mg/l; increased content of organic matter – increase in the parameters of dichromate oxidation (R-10 – 66,3 mg O/l; R-4 – 85,7 mg O/l; Shershnevskoye reservoir – 36 mg O/l), $BOD_5$ (R-10 – 2.2 mg $O_2$/l; R-4 – 4.3 mg $O_2$/l; Shershnevskoye reservoir – 2.5 mg $O_2$/l), concentration of phosphate (R-10 – 0.69 mg/l; R-4 – 1.51 mg/l; Shershnevskoye reservoir – 0.2 mg/l), – is typical of the reservoirs R-10 and R-4 (Khodorovskaya et al., 2013; Atamanyuk et al., 2012; Pryakhin et al., 2011, 2010a).

It should be particularly emphasized that the investigated reservoirs of the Mayak PA differ in morphological parameters, hydrological regime, water chemistry and radionuclide content. Table 1 shows main morphological parameters of the studied reservoirs. Reservoirs R-11, R-9 and R-17 are operated in non-flowing mode, and reservoirs R-10, R-4 and R-3, as well as comparisons reservoirs are operated in flowing mode.

Tables 2 and 3 present the parameters characterizing current levels of the radioactive contamination of the special industrial reservoirs of the Mayak PA and comparison reservoirs: the excess of the radionuclide content in the water of the studied reservoirs is 9 orders of magnitude for $^{90}Sr$ and $^{137}Cs$, and 6 orders of magnitude for alpha-emitting radionuclides. According to the level of radioactive contamination the reservoirs of the Mayak PA could be arranged in the ascending order as follows: R-11, R-10, R-4, R-3, R-17, R-9.

## 5. Summary of biocenoses studies, 2007–2012

The studies of the biocenoses during 2007–2012 showed the following results.

### 5.1. Bacterioplankton

Parameters of the bacterioplankton growth of the reservoirs R-11 and R-10 practically did not differ from the parameters of the abundance and biomass of the bacterioplankton of the comparison water bodies – Shershnyovskoye and Beloyarskoye reservoirs. The abundance of bacteria corresponds to that of fairly clean waters (1.6–2.5 × $10^6$ cells/ml). Among bacterioplankton of the studied reservoirs the coccus forms predominated. In reservoir R-4 the abundance of bacteria turned out to be much higher, making up on average 5.8 × $10^6$ cells/ml (Pryakhin et al., 2011). Such bacterioplankton growth testified to a manifest organic contamination of the reservoir. Here, too, the coccus forms prevailed. In general, the development of bacterioplankton communities in TRC reservoirs, reservoirs R-17 and R-9 in terms of abundance and biomass was quite typical of standing water bodies with expressed processes of eutrophication (Trifanova, 1990). In reservoir R-9, at the highest levels of radioactive contamination, the parameters of the bacterioplankton growth were lower (0.9 × $10^6$ cells/ml), than in other studied reservoirs, but it still of the same order of magnitude.

**Table 1**
Major parameters of the studied reservoirs.

| Parameters | [2]SR | [3]BR | [1]R-11 | [1]R-10 | [1]R-4 | [1]R-3 | [1]R-17 | [1]R-9 |
|---|---|---|---|---|---|---|---|---|
| Year of reservoir creation | 1965 | 1963 | 1965 | 1956 | 1951 | 1951 | 1949 | 1951 |
| Water-surface area, $km^2$ | 39.1* | 38.0* | 44.2* | 18.6* | 1.3* | 0.8* | 0.13 | †0.07 |
| Maximum depth, m | 14* | 20* | 12.3* | 9.3* | 3.5* | 2.5* | 6.5 | 5.2 |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir. *values at normal maximum operating level. [1](Malyshev et al., 1997). [2](Pryakhin et al., 2010a). [3](Lenchenko et al., 1964). † Data on reservoir R-9 is given as of 2005. (Alexakhin et al., 2007).

**Table 2**
Parameters of radioactive contamination of the water of the special industrial reservoirs of the Mayak PA, 2007–2012, Bq/l.

| Reservoir | Total activity of β-emitting radionuclides | $^{137}Cs$ | $^{90}Sr$ | Total activity of α-emitting radionuclides |
|---|---|---|---|---|
| SR | – | $1.9\ (1.4–2.3) \cdot 10^{-2}$ n = 10 | $2.2\ (1.5–2.7) \cdot 10^{-2}$ n = 10 | – |
| *BR | $1.1\ (1.0–1.2) \cdot 10^{-1}$ n = 2 | $5.7\ (2.9–8.4) \cdot 10^{-3}$ n = 2 | $2.5\ (2.1–2.8) \cdot 10^{-2}$ n = 2 | $5.0\ (1.0–2.0) \cdot 10^{-2}$ n = 2 |
| R-11 | $2.3\ (0.9–3.0) \cdot 10^{3}$ n = 17 | $1.5\ (0.3–5.5) \cdot 10^{0}$ n = 17 | $1.3\ (0.4–1.9) \cdot 10^{3}$ n = 17 | – |
| R-10 | $4.7\ (1.0–6.4) \cdot 10^{3}$ n = 20 | $2.9\ (0.6–15.2) \cdot 10^{1}$ n = 20 | $2.6\ (0.2–4.0) \cdot 10^{3}$ n = 20 | $1.6\ (1.0–2.0) \cdot 10^{-1}$ n = 4 |
| R-4 | $6.4\ (4.0–10.0) \cdot 10^{3}$ n = 19 | $3.9\ (0.3–16.0) \cdot 10^{2}$ n = 19 | $3.7\ (1.3–8.3) \cdot 10^{3}$ n = 19 | $4.2\ (0.3–7.5) \cdot 10^{0}$ n = 7 |
| R-3 | $6.5\ (3.6–13.0) \cdot 10^{3}$ n = 15 | $7\ (1.3–17.0) \cdot 10^{2}$ n = 15 | $3.3\ (1.5–5.7) \cdot 10^{3}$ n = 15 | $7.2\ (1.0–23.5) \cdot 10^{1}$ n = 6 |
| R-17 | $4.7\ (4.1–5.3) \cdot 10^{5}$ n = 2 | $4.1\ (0.4–21.0) \cdot 10^{4}$ n = 10 | $2.1\ (0.7–3.9) \cdot 10^{5}$ n = 10 | $2.2\ (0.4–7.1) \cdot 10^{2}$ n = 5 |
| R-9 | – | $6.8\ (0.1–20.0) \cdot 10^{6}$ n = 5 | $1.0\ (0.1–3.5) \cdot 10^{7}$ n = 5 | $8.3\ (0.9–26.0) \cdot 10^{4}$ n = 5 |

Note: The table presents average values of the studied samples, min and max values are given in brackets; SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir; *BR – according to (Trapeznikov and Trapeznikova, 2012) as of 2011; n – number of samples; "-" – data are not available.

### 5.2. Phytoplankton

In summer period massive phytoplankton growth was registered in the studied water bodies. Typically, the maximum of species diversity occurs in August, green algae being notable for the greatest diversity. As far as phytoplankton communities are concerned, each water body had its own peculiar features.

**Table 3**
Parameters of radioactive contamination of the bottom sediments in the special industrial reservoirs of the Mayak PA, mean values as of from 2007 to 2012, Bq/kg dry weight.

| Reservoir | $^{137}Cs$ | $^{90}Sr$ | Total activity of α-emitting radionuclides |
|---|---|---|---|
| SR | $1.8\ (0.9–2.6) \cdot 10^{1}$ n = 10 | $2.5\ (1.3–4.8) \cdot 10^{1}$ n = 5 | - |
| *BR | $3.3\ (1.9–4.7) \cdot 10^{2}$ n = 2 | $5.1\ (4.9–5.3) \cdot 10^{1}$ n = 2 | - |
| R-11 | $9.1\ (0.03–57.3) \cdot 10^{4}$ n = 19 | $3.2\ (0.2–6.2) \cdot 10^{5}$ n = 19 | - |
| R-10 | $1.4\ (0.2–2.3) \cdot 10^{6}$ n = 5 | $2.0\ (0.2–3.6) \cdot 10^{5}$ n = 5 | - |
| R-4 | $1.6\ (0.7–3.3) \cdot 10^{7}$ n = 6 | $2.5\ (1.1–3.6) \cdot 10^{6}$ n = 3 | - |
| **R-3 | $2{,}2\ (1.7–2.5) \cdot 10^{7}$ n = 3 | $6.2\ (2.9–9.9) \cdot 10^{6}$ n = 3 | - |
| R-17 | $9.6\ (0.3–23.2) \cdot 10^{7}$ n = 7 | $2.0 \cdot 10^{7}$ n = 1 | $1.5\ (0.2–2.8) \cdot 10^{6}$ n = 2 |
| ***R-9 | $2.4 \cdot 10^{11}$ n = 1 | $1.7 \cdot 10^{11}$ n = 1 | $1.6 \cdot 10^{10}$ n = 1 |

Note: The table presents average values of the studied samples, min and max values are given in brackets; SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir; *BR – according to (Trapeznikov and Trapeznikova, 2012) as of 2011; **R-3 – data are given as of 2014; ***R-9 according to (Aleksakhin et al., 2007) as of 2002; n – number of samples; "-" – data are not available.

Studied algocenoses of the reservoirs R-11, R-10, R-4, and R-3, as well as of the comparison water bodies (Shershnyovskoye and Beloyarskoye reservoirs) are typical of this kind of water bodies of the submountain region of the forest-steppe zone of the Southern Urals (Snityko and Sergeyeva, 2003) and are comparable with respect to the overall level of species diversity (Table 4). However, it should be noted that in terms of the average number of species in a sample, shallow flowing water reservoir R-3, rich in water plants, has greater species diversity as compared to much deeper and larger water bodies.

The phytoplankton growth (abundance and biomass) in summer period varies greatly. For the TRC reservoirs and Shershnyovskoye reservoir the level of phytoplankton biomass increased from insignificant values at the beginning of June (1–5 $g/m^3$) up to high values in the end of August (60–70 $g/m^3$ and more in the riverside accumulation of the cyanobacteria), besides, if in the beginning of summer the major part of phytoplankton biomass was determined by green and diatomic algae, in July and August, as a rule, the proportion of cyanobacteria increased (Table 5). Algocenosis of reservoirs R-11 and R-10 is caracterised by a monodominant structure of the phytoplankton with the prevalence of cyanobacteria species *Planktothrix agardhii* (Gom.) Anagn. et Kom. (60-70% of total phytoplankton biomass) in the second half of summer. The dominance of this species in phytoplankton points out to an eutrophication. In reservoirs R-4 and R-3 usually several co-dominant species were registered: species of the genus *Microcystis* and *Anabaena* (cyanobacteria), of the genus *Scenedesmus* (green algae) and others. In the comparison water bodies the dominant species were cyanobacteria too. The dominant species were represented by *Planktothrix agardhii* either by the species of the genus *Aphanizomenon* or *Microcystis*.

Phytoplankton of the reservoir R-17 was notable for decreased species diversity. Extremely low number of species was detected in reservoir R-9 (Table 4). At the same time in the majority of samples

**Table 4**
Number of species of the phytoplankton organisms found in the studied reservoirs.

| Reservoir | Median and (min–max) of the number of species per sample | Total number of found species | | | | |
|---|---|---|---|---|---|---|
| | | Cyanophyta | Bacillariophyta | Chlorophyta | Other | Total |
| SR, n = 25 | 42 (21–68) | 31 | 27 | 78 | 26 | 162 |
| *BR, n = 5 | 50 (46–52) | 15 (37) | 20 (46) | 40 (107) | 10 (37) | 85 (227) |
| R-11, n = 31 | 46 (27–62) | 31 | 46 | 77 | 29 | 183 |
| R-10, n = 36 | 57.5 (28–94) | 35 | 27 | 91 | 26 | 179 |
| R-4, n = 20 | 44.5 (28–68) | 34 | 23 | 64 | 17 | 138 |
| R-3, n = 6 | 71 (64–82) | 18 | 26 | 76 | 34 | 154 |
| R-17, n = 23 | 14 (9–32) | 15 | 12 | 31 | 8 | 66 |
| R-9, n = 6 | 3.5 (2–4) | 3 | 2 | 4 | 1 | 10 |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir; the data are given for the whole period of studies (for R-11and R-17 – 2008-2012, for SR, R-10, R-4, R-9 – 2009-2012, for R-3 – 2011-2012, for BR –2012); *for Beloyarskoye reservoir in brackets the number of found species is given with due account of the data provided in (Trapeznikov et al., 2008) as of from 1986 to 1991, and as of 2003; n – number of samples.

from these reservoirs absolute dominance of the cosmopolitan eurytopic species of cyanobacteria *Geitlerinema amphibium* Ag. ex Gom was observed. The biomass of the algae in these reservoirs could vary within the range from 0.04 g/m$^3$ up to 37 g/m$^3$ during summer (Table 5).

The level of phytoplankton biomass, ecological peculiarities of the dominant species and prevailing development of cyanobacteria are connected with the process of anthropogenic eutrophycation both of the TRC reservoirs, and the comparison water bodies (Shershnyovskoye and Beloyarskoye reservoirs).

The peculiarities of the phytoplankton of the reservoirs R-17 and R-9 could also be due to manifestations of the ecological regress of the ecosystem. In favorable conditions the number of species is high, but each of them is represented by a small amount of specimen. In communities of extreme habitats species diversity decreases, some sensitive species disappear, which leads to the reduction of competition and high level of development of certain more resistant forms. Thus, the parameters associated to species richness of the phytoplankton are more sensitive to the influence of adverse factors, than the parameters of the algae growth (Dukhovnaya et al., 2011a).

Existence of the organisms in extreme habitats presupposes development of adaptive reactions. To find out the peculiarities of the phytoplankton adaptation to the conditions typical of the studied radioactively contaminated water bodies, algologically clean cultures of the green algae *Scenedesmus quadricauda* were selected from the phytoplankton samples taken from TRC reservoirs (R-11, R-10, R-4) and R-17 and the comparison water body (Shershnyovskoye reservoir). In the laboratory experiments it was revealed that cultures from the radioactively contaminated water bodies are characterized by a decreased cell size, increased speed of the culture growth which correlated with the level of the contamination of the water body (Dukhovnaya et al., 2011b). It was also stated that algologically clean cultures of the green algae *Scenedesmus quadricauda* isolated from the TRC reservoirs and reservoir R-17 showed increased radioresistance in case of culturing in non-radioactively contaminated media in terms of cell survival. It was evaluated judging by the number of colonies of algae cells after plating of cell suspension in a solid media. On the contrary, when these cultures were grown in water, containing radionuclides from the respective reservoirs, increase in radiosensitivity was observed. The enumerated peculiarities of the

**Table 5**
Abundance, biomass and composition of major groups of the phytoplankton of the studied reservoirs.

| Reservoir | Parameter | Minimum | Q1 | Median | Q3 | Maximum | Cyanophyta, % | Bacillariophyta, % | Chlorophyta, % | Other, % |
|---|---|---|---|---|---|---|---|---|---|---|
| SR | A | 3 | 13 | 30 | 46 | 110 | 91 ± 16 | 4 ± 7 | 4 ± 10 | 1 ± 2 |
| BR | A | 28 | 44 | 61 | 80 | 140 | 97.2 ± 1.7 | 0.59 ± 0.28 | 1.9 ± 1.3 | 0.28 ± 0.19 |
| R-11 | A | 25 | 97 | 140 | 280 | 1100 | 99 ± 2 | 0.2 ± 0.4 | 0.9 ± 1.8 | 0.043 ± 0.037 |
| R-10 | A | 50 | 200 | 300 | 510 | 1500 | 98.5 ± 2.5 | 0.4 ± 1.2 | 1.0 ± 1.6 | 0.114 ± 0.079 |
| R-4 | A | 22 | 360 | 420 | 490 | 820 | 90 ± 6 | 1.2 ± 1.4 | 8.7 ± 5.4 | 0.12 ± 0.11 |
| R-3 | A | 60 | 110 | 140 | 270 | 630 | 92 ± 7 | 1.3 ± 1.1 | 5.7 ± 5.4 | 1.3 ± 1.2 |
| R-17 | A | 0.4 | 57 | 610 | 1200 | 2500 | 98 ± 6 | 0.39 ± 0.35 | 1.7 ± 5.5 | 0.32 ± 0.87 |
| R-9 | A | 50 | 120 | 360 | 960 | 1200 | 94 ± 19 | 0.02 ± 0.02 | 5 ± 19 | 0.39 ± 0.23 |
| SR | B | 0.8 | 2.7 | 4.1 | 9.0 | 31 | 27 ± 22 | 47 ± 32 | 4.6 ± 6.9 | 21 ± 30 |
| BR | B | 4.4 | 6.1 | 8.0 | 12 | 12 | 58 ± 17 | 4.5 ± 1.9 | 7.2 ± 4.2 | 30 ± 15 |
| R-11 | B | 2.8 | 6.9 | 10 | 18 | 67 | 82 ± 15 | 4.3 ± 8.4 | 3.1 ± 2.9 | 11 ± 9 |
| R-10 | B | 5 | 15 | 20 | 31 | 100 | 84 ± 13 | 5 ± 11 | 2.8 ± 3.7 | 8.3 ± 4.2 |
| R-4 | B | 2.8 | 16 | 21 | 28 | 67 | 70 ± 17 | 10 ± 9 | 16 ± 13 | 4.9 ± 4.4 |
| R-3 | B | 21 | 32 | 41 | 52 | 78 | 51 ± 24 | 8 ± 6 | 18 ± 21 | 23 ± 20 |
| R-17 | B | 0.04 | 1.4 | 14 | 22 | 37 | 75 ± 25 | 11 ± 11 | 7 ± 16 | 7 ± 13 |
| R-9 | B | 1.6 | 4.9 | 16 | 27 | 36 | 65 ± 23 | 0.1 ± 0.2 | 17 ± 31 | 18 ± 13 |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir, A – abundance, bln cells. m$^{-3}$, B – biomass, g m$^{-3}$, Q1 – first quartile, Q3 – third quartile; the data are given for the whole period of studies (for R-11and R-17 – 2008-2012, for SR, R-10, R-4, R-9 – 2009-2012, for R-3 – 2011-2012, for BR – 2012); the fractions of separate groups – weighted average ± SD.

cultures probably represent adaptive reactions of the green algae to chronic radiation exposure.

In order to define the role of radioactive and chemical contamination (high content of nitrates in water) in the effects detected in algocenoses of the reservoirs R-17 and R-9, experiments have been conducted to assess the influence of the combined effect of acute γ-radiation and nitrates on the growth of the culture *Scenedesmus quadricauda*. It was demonstrated that the combined effect of nitrates and γ-radiation are characterized by antagonistic interactions. The results drive us to conclude that the limiting factor for the Reservoir R-17, which determines the inhibition of green algae development, is chemical contamination, and for reservoir R-9, probably both factors: chemical and radioactive contamination which are significant for the explanation of the algocenosis degradation (Triapitsyna et al., 2012a, b).

### 5.3. Zooplankton

The analysis of the samples from the studied water bodies demonstrated that the zooplankton comprised three major groups of crustaceans: rotifers (Rotifera), cladocerae (Cladocera, Crustacea) and copepods (Copepoda, Crustacea). In general in a row R-11, R-10, R-4, R-17 and R-9 a decrease in the number of species in a sample and reduction of the list of the species, were observed (Table 6). Reservoir R-3 was noted to have the highest average amount of species per sample and considerable total amount of detected species. Phytophilous rotifers significantly contributed in the species diversity of the zooplankton in this small flowing water reservoir with a high level of macrophytes growth.

The level of the zooplankton growth in reservoirs R-11, R-10, R-4 and R-3 was comparable to that of the comparison water bodies (Table 7). In all these reservoirs rotifers prevailed in terms of abundance, reaching a level of extremely high abundance in reservoir R-3. As for the biomass, in the comparison water bodies and in the reservoir R-10 cladoceran crustaceans prevailed, and in reservoir R-11 the contribution of cladocerans and copepod crustaceans into the biomass development was equal. In reservoir R-4 rotifers accounted for almost half of the biomass, which is associated with high content of phosphates in water, and consequently with change in the trophic state of the reservoir to hypereutrophic (Andronikova, 1996; Dorgham, 2014; Gliwicz, 2004).

In reservoir R-3 rotifers comprised more than one half of the biomass, and the contribution of large infusoria was also significant (Osipova et al., 2013). In general, larger reservoirs are characterized by a greater biomass of zooplankton due to the development of large forms of crustaceans, and in some cases, large carnivorous rotifers (*Asplanchna priodonta* Gosse). Due to the development of carnivorous rotifers and large ciliatas, the zooplankton of reservoir R-3 did not fall short of the community of plankton animals in large water bodies in terms of the biomass parameters. The zooplankton of the reservoir R-17 consisted mainly of rotifers, among which the absolute dominant were *Brachionus calyciflorus* Pallas. In the majority of cases the level of the zooplankton growth did not significantly differed from that of the control water bodies. In various years the zooplankton of the reservoir R-9 was represented by almost one population of the three species of the rotifers (*B. calyciflorus*, *Brachionus urceus* (Linnaeus) and *Hexarthra fennica* (Levander)), which changed each other for three years of investigations. The abundance and biomass were one and two orders of magnitude lower, respectively, than the similar parameters of reservoir R-17 and comparison water bodies. It is necessary to note greater outbursts of development of the zooplankton in reservoir R-9 as compared to all the other studied reservoirs.

Thus, reservoirs R-11, R-10, R-4, despite of the significantly increasing contamination of the environment by the radionuclides in this row, did not significantly differ in structure and zooplankton growth from the comparison water bodies. Reservoir R-3 was notable for important contribution of rotifers, which probably could be associated with a significant level of eutrophication and with its morphometric features (it is a small flowing water reservoir with a relatively uniform overgrowth of macrophytes). In reservoir R-17 the parameters of the zooplankton growth community did not differ from the control either, but its more simplified structure, connected with the disappearance of the crustaceans, was noted. In reservoir R-9 the zooplankton community was reduced: in each period one species reaches massive development, which abundance and biomass are one and two orders of magnitude lower, respectively, than similar parameters in the comparison water body, which should be viewed as the manifestation of extremely adverse conditions in the environment.

Under toxic effect in case of disappearance of certain species from the community, and consequent decrease in competition, massive development of certain, most resistant species, occurs, which is typical of the zooplankton of reservoir R-17, where the amount of rotifer species was extremely low but the abundance and biomass of the rotifers were comparable to the same parameters of the comparison water bodies. A further increase in toxicity of the environment promotes even bigger reduction of the species diversity and decrease in the parameters of the growth of the existing species.

**Table 6**
Number of species of the major groups of the zooplankton organisms, found in the studied reservoirs.

| Reservoir | Median of the number of species per sample | Rotifera | Cladocera | Copepoda | Total |
|---|---|---|---|---|---|
| SR, n = 24 | 16 | 41 | 17 | 7 | 65 |
| BR, n = 5 | 6 | 10 (19) | 5 (14) | 2 (6) | 17 (39) |
| R-11, n = 20 | 12.5 | 18 | 12 | 6 | 36 |
| R-10, n = 35 | 12 | 24 | 13 | 12 | 49 |
| R-4, n = 8 | 10 | 11 | 4 | 3 | 18 |
| R-3, n = 5 | 18 | 20 | 3 | 3 | 26 |
| R-17, n = 15 | 5 | 8 | 3 | 2 | 13 |
| R-9, n = 5 | 2 | 3 | 0 | 0 | 3 |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir, *for Beloyarskoye reservoir in brackets the number of found species in the numerator is given with due account of the data provided in (Trapeznikov et al., 2008) as of from 1986 to 1991, and as of 2003; n – number of samples.

**Table 7**
Abundance, biomass and composition of major groups of the zooplankton of the studied reservoirs.

| Reservoir | Parameter | Minimum | Q1 | Median | Q3 | Maximum | Rotifera, % | Cladocera, % | Copepoda, % | Other, % |
|---|---|---|---|---|---|---|---|---|---|---|
| SR | A | 4 | 140 | 520 | 1400 | 5900 | 88 ± 10 | 5.6 ± 5.9 | 6.1 ± 7.9 | 0.001 ± 0.014 |
| BR | A | 30 | 190 | 200 | 600 | 1700 | 84.6 ± 6.5 | 7.1 ± 4.4 | 8.3 ± 9.7 | 0 |
| R-11 | A | 90 | 580 | 1000 | 1600 | 2300 | 64 ± 19 | 15 ± 12 | 21 ± 11 | 0.07 ± 0.24 |
| R-10 | A | 7 | 330 | 1200 | 2700 | 9900 | 78 ± 13 | 12 ± 10 | 10.5 ± 5.3 | 0.03 ± 0.56 |
| R-4 | A | 90 | 300 | 1000 | 2300 | 4700 | 84.9 ± 7.5 | 2.1 ± 1.4 | 13.0 ± 7.7 | 0.003 ± 0.012 |
| R-3 | A | 1500 | 5900 | 19,000 | 25,000 | 27,000 | 94.5 ± 8.5 | 0.2 ± 0.09 | 2.9 ± 1.4 | 2.4 ± 8.5 |
| R-17 | A | 6 | 260 | 650 | 900 | 5900 | 99.99 ± 0.02 | 0.005 ± 0.02 | 0 | 0.002 ± 0.015 |
| R-9 | A | 11 | 15 | 32 | 56 | 10,466 | 100 ± 0 | 0 | 0 | 0 |
| SR | B | 0.012 | 0.59 | 3.7 | 12 | 51 | 37 ± 31 | 52 ± 30 | 11.3 ± 8.5 | 0 |
| BR | B | 0.12 | 0.93 | 1.1 | 2.2 | 6.3 | 30 ± 33 | 57 ± 35 | 12.9 ± 7.5 | 0 |
| R-11 | B | 0.3 | 3.0 | 4.1 | 18 | 33 | 4.5 ± 9.1 | 47 ± 26 | 48 ± 27 | 0 |
| R-10 | B | 0.4 | 2.0 | 6.8 | 14 | 65 | 6.4 ± 8.7 | 78 ± 15 | 15.6 ± 9 | 0 |
| R-4 | B | 0.027 | 0.29 | 0.92 | 2.8 | 6.3 | 50.7 ± 9.1 | 12.6 ± 9 | 36 ± 15 | 0.299 ± 1.958 |
| R-3 | B | 0.9 | 7.6 | 8.7 | 8.9 | 20 | 53 ± 39 | 0.47 ± 0.48 | 7.4 ± 6.8 | 40 ± 45 |
| R-17 | B | 0.006 | 0.15 | 0.56 | 0.81 | 5.4 | 99.2 ± 3.2 | 0.6 ± 2.4 | 0 | 0.2 ± 2.2 |
| R-9 | B | 0.009 | 0.010 | 0.014 | 0.016 | 2.9 | 100 ± 0 | 0 | 0 | 0 |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir, A – abundance, thous. species $m^{-3}$, B – biomass, g $m^{-3}$, Q1 – first quartile, Q3 – third quartile; the data are given for the whole period of studies (for R-4 – 2009-2010, for R-17 and R-9 – 2009-2011, for SR, R-11, R-10 – 2009-2012, for R-3 – 2011-2012, for BR –2012); the fractions of separate groups – weighted average ± SD.

### 5.4. Zoobenthos

In reservoir R-11 concerning zoobenthos communities the greatest species diversity was noted for chironomids, gastropods and oligochaetes (Table 8). In general species diversity of the reservoir was dominated by pelophilous gastropods, first of all prosobranch (Prosobranchia), genus Valvatidae and Bithyniidae, and also various species of pulmonate gastropods (Pulmonata). Zoobenthos communities of the reservoir R-11 and Shershnyovskoye reservoir did not markedly differ in species composition and growth (Pryakhin et al., 2010b, 2011). In reservoir R-10 oligochaetes and chironomids (Diptera, Insecta) exhibited the greatest development (Table 9). Great abundance of oligochaetes was combined with low species diversity: only two eurytopic species *Tubifex tubifex* (Mueller) and *Limnodrilus hoffmeisteri* Claparede were found in the reservoir. Species diversity of chironomids is comparable to that of the reservoir R-11 (Table 8). The greatest contribution to the abundance and biomass was that of the large larvae of the genus *Chironomus*. In the relatively small and shallow water reservoir R-4 species diversity of chironomids was the greatest among all the studied reservoirs of the Mayak PA. Gastropods, inhabiting the reservoir R-4, are phytophilous and throughout their life cycle inhabit the water plants. The major zoobenthos biomass of the reservoir is composed of gastropods, large-size larvae and oligochaetes. Zoobenthos species diversity of the reservoir R-3 was relatively poor, and mainly represented by chironomids. At the same time the chironomids growth was insignificant. The biomass was mainly composed of gastropods and larvae (Table 9). Gastropods in this reservoirs are phytophilous as in the reservoir R-4, and do not have close straightforward connection to the bottom surface. In reservoir R-17 benthos communities consist only of chironomids (Pryakhin et al., 2011). Here chironomids reach the highest abundance among the storage-reservoirs of the LRW. Zoobenthos biomass is mainly determined by large-size chironomids *Psectrotanypus sibiricus* Kruglova and Chernovskij.

**Table 8**
Number of species of oligochaetes and chironomids, found in the studied reservoirs.

| Reservoir | Oligochaeta | Chironomidae |
|---|---|---|
| SR, n = 10 | 8 | 21 |
| BR, n = 5 | 5 | 17 |
| R-11, n = 20 | 5 | 17 |
| R-10, n = 25 | 2 | 16 |
| R-4, n = 11 | 5 | 23 |
| R-3, n = 6 | 1 | 10 |
| R-17, n = 14 | 0 | 5 |
| R-9 | – | – |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir; n – number of samples; "–" – data are not available.

The most pronounced changes in zoobenthos communities of the studied reservoirs were observed in the populations of the pelophilous mollusks. Evident decrease in the density and biomass of small mollusks was noted starting with the reservoir R-10. It was most pronounced in reservoir R-10 where sharp decrease in the abundance and biomass of small bivalve mollusks was observed and in reservoir R-4 where these mollusks almost disappeared. At the same time in all the studied reservoirs in zoobenthos samples giant bivalve mollusks, Anodonta cygnea, were often found. The study of the zoobenthos samples from the TRC reservoirs demonstrated that small gastropods, inhabiting the soil, representatives of the families *Bithyniidae* and *Valvatidae*, typical of the reservoirs of such type of moderate zone, were present in great amount only in reservoir R-11. In reservoirs R-10 and R-4 they were almost absent. At the same time gastropods inhabiting the plants, were observed in all the TRC reservoirs. As concerns bivalve mollusks, the following peculiarities were observed. Small mollusks of the families *Euglesidae* and *Pisidiidae*, the whole reproductive cycle of which occurs on the surface of bottom sediments (ovoviviparous), greatly decreased in abundance in reservoir R-10 and disappeared in reservoir R-4. Simultaneous presence of the giant bivalve mollusks, swan mussels, in all the studied TRC reservoirs, is probably due to the fact that their larval stage (glochidia) occurs in the water layer as they parasitize on fish. The results obtained allowed us to conclude that the most sensitive group of organisms with respect to radioactive contamination of the water ecosystem at a level of contamination equal to that of R-10 (Tables 2 and 3) is represented by small mollusks, living on the surface of bottom sediments throughout their life cycle. High levels of radioactive and chemical contamination of reservoir R-17, evidently, became the reason for the absence of benthic animals, inhabiting and passing through all the development stages in the water environment of this reservoir.

**Table 9**
Abundance, biomass and composition of major groups of the zoobenthos of the studied reservoirs.

| Reservoir | Parameter | Minimum | Q1 | Median | Q3 | Maximum | Oligochaeta, % | Gastropoda, % | Bivalvia, % | Insecta, % | Other, % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SR | A | 40 | 6300 | 13,000 | 17,000 | 27,000 | 36 ± 24 | 7 ± 7 | 19 ± 11 | 22 ± 8 | 16 ± 17 |
| BR | A | 600 | 640 | 4200 | 7800 | 8600 | 41 ± 22 | 11 ± 11 | 4 ± 4 | 43 ± 20 | 1.1 ± 5.1 |
| R-11 | A | 400 | 2200 | 3200 | 5800 | 18,000 | 12 ± 15 | 59 ± 28 | 4.1 ± 4.2 | 24 ± 18 | 0.4 ± 11 |
| R-10 | A | 80 | 1500 | 5700 | 14,000 | 64,000 | 52 ± 20 | 0 | 0.2 ± 1.7 | 48 ± 20 | 0.2 ± 11 |
| R-4 | A | 40 | 720 | 1100 | 4400 | 77,000 | 88 ± 27 | 5 ± 18 | 0.2 ± 0.2 | 7 ± 16 | 0.5 ± 18 |
| R-3 | A | 800 | 900 | 1300 | 1700 | 2800 | 15 ± 17 | 37 ± 20 | 0 | 48 ± 13 | 0 |
| R-17 | A | 240 | 1900 | 4000 | 8600 | 36,000 | 0 | 0 | 0 | 100 ± 0 | 0 |
| R-9 | A | – | – | – | – | – | – | – | – | – | – |
| SR | B | 0.02 | 29 | 45 | 61 | 98 | 10 ± 12 | 47 ± 38 | 10 ± 10 | 32 ± 26 | 0.4 ± 0.9 |
| BR | B | 2.3 | 31 | 35 | 36 | 54 | 23 ± 33 | 50 ± 39 | 2.7 ± 5.1 | 24 ± 21 | 0.8 ± 1.4 |
| R-11 | B | 3.6 | 13 | 32 | 52 | 210 | 1 ± 2 | 73 ± 29 | 1.1 ± 1.4 | 24 ± 28 | 0.1 ± 0.2 |
| R-10 | B | 0.002 | 9.8 | 22 | 40 | 97 | 19 ± 20 | 0 ± 1 | 0.2 ± 2.2 | 81 ± 20 | 0.5 ± 1 |
| R-4 | B | 0.6 | 2.1 | 3.6 | 11 | 44 | 32 ± 28 | 6 ± 17 | 0 | 61 ± 29 | 0.8 ± 2.9 |
| R-3 | B | 3.9 | 4.7 | 6.7 | 7.6 | 8.1 | 2 ± 4 | 50 ± 20 | 0 | 47 ± 17 | 0 |
| R-17 | B | 0.5 | 3.7 | 6.3 | 10 | 35 | 0 | 0 | 0 | 100 ± 0 | 0 |
| R-9 | B | – | – | – | – | – | – | – | – | – | – |

Note: SR – Shershnyovskoye reservoir; BR – Beloyarskoye reservoir, A – abundance, thous. species. m$^{-3}$, B – biomass, g m$^{-3}$, Q1 – first quartile, Q3 – third quartile; the data are given for the whole period of studies (for SR, R-11, R-10, R-17 – 2009-2012, for R-4 – 2010-2012, for R-3 – 2011-2012, for BR – 2012); the fractions of separate groups – weighted average ± SD; "-" – data are not available.

### 5.5. Water plants

In reservoir R-11 the majority of phytocenoses of the riverside plants is represented by one-layered reedbed (Table 10). Helophyte belt was mainly built up of the southern reed (*Phragmites australis* (Cav.) Trin. ex Steud.) and open overgrowth of the graceful cattail (*Typha laxmanii* Lepechin). Hydatophyte belt was made of shining pondweed (*Potamogeton lucens* L.), meakin (*Myriophyllum spicatum* L.), and morass-weed (*Ceratophyllum demersum* L.). In reservoir R-10 the distribution of the vegetation is non-uniform, surface of weediness of water is less than 5%. In general, formations typical of this reservoir are built up predominately of graceful cattail. The weediness of the northern and north-eastern banks of the reservoir is markedly greater than that of western shores. Here, the reed and cattail often form relatively stretched islands, the width of the helophyte belt could reach 50 m. At the south-western bank quite a distinct zone distribution of vegetation is observed. Helophyte belt is formed mainly by reed, hydrophyte belt up to 2 m depth is built of fennel-leaved pondweed (*Stuckenia pectinata* (L.) Börner) and morass-weed (*Ceratophyllum submersum* L.). In reservoir R-4 the distribution of vegetation is quite uniform, the surface of weediness of the shallow-water part is almost 70%, in deeper areas the weediness is observed mainly along the banks. In north-eastern and northern parts of the reservoir the belt of aero-aquatic plants forms a wide dense line. Formations of graceful cattail as well as those of the southern reed could be distinguished. Water herbs consist of morass-weed and pondweeds. At the south-western bank of the reservoir the density of the helophytes is lower, hydrophytes are represented solely by hornweed.

The bottom of the western, shallow-water part of the reservoir is entirely covered with thinned overgrowth of hydrophytes. About 20% of the surface area of the reservoir is covered with floating islands, mainly at the northern part. Banks and riverside shallow-waters of the reservoir R-3 are covered with bushes of two species of the cattail (*Typha latifolia* L., *Typha angustifolia* L.) with admixture of sedge (*Carex*), nearly half of the reservoir surface area is covered with floating islands. Formation of floating islands characteristic of reservoirs R-3 and R-4 is predetermined by small size of these reservoirs, constant water level, and absence of waves.

In reservoir R-17 macrophytes are represented by single islands of the southern reed up to 1–2 m in diameter. The banks of the reservoir R-9 are filled with gravel and concrete blocks, and there are no water plants on the water area and banks.

In the course of the analysis of the aquatic plants in the studied reservoirs no significant differences were observed in species composition for the reservoir R-11, and Shershnyovskoye reservoir. The composition and structure of plant communities in Mayak PA reservoirs is determined by the influence of such factors as the depth, the size of the reservoir, flow. The role of radiation exposure in the differences of water plant communities, as well as the contribution of the high content of nitrates in the reservoirs R-17 and R-9 is not clear to the present time.

### 5.6. Ichthyofauna

In the course of the research into the status of the ichthyofauna of the studied special industrial reservoirs of the Mayak PA in the catches from the reservoirs R-11, R-10, R-4 the following fish species were registered: roach *Rutilus rutilus* L., tench *Tinca tinca* L., crucian carp *Carassius carassius* L., ide *Leuciscus idus* L., perch *Perca fluviatilis* L., pike *Esox lucius* L. In the catches from reservoir R-3, which freezes from top to the bottom, and demonstrates the presence of fish kill phenomena in winter, only roach and perch were found. In reservoirs R-17 and R-9 fish is absent. Taking into account the age when fish reaches maturity: pike – at the age of 3 (males), and 4 (females), perch – at the age of 3 (males), and 4 (females), and roach – at the age of 3 (both males and females) (Berg, 1948–1949), then by 2012 these fish species could have undergone 11–16 generational changes in reservoir R-11; 14–19 generational changes – in reservoir R- 10. As for reservoirs R-3 and R-4, then starting from the onset of the Techa River contamination (autumn, 1948), when Koksharov and Metlinsky ponds were located in place of these reservoirs (Glagolenko, 2007), 16–21 generations of these fish species could have changed.

Using comet assay the research of the status of the nuclear DNA of the peripheral blood erythrocytes of roach (*Rutilus rutilus* L.) from the reservoirs R-11, R-10 and R-4 has been conducted. Roach from the Shershnyovskoye reservoir (Chelyabinsk Oblasts) was used as the control species. The study showed that fish from the reservoirs R-10 and R-4 had increased level of the nuclear DNA damage, increase of the induction of the damage after additional γ-exposure and activation of the DNA repair processes (Styazhkina et al., 2012).

In the course of the cytogenetic investigations with the use of the micro-nucleus test in the peripheral blood erythrocytes, statistically significant two-fold increase in the frequency of

**Table 10**
Species composition of aquatic and helophytic plants of TRC reservoirs, R-17, and Shershnyovskoye reservoir.

| Ecomorpholo-gical group | Plant species | SR | R-11 | R-10 | R-4 | R-3 | R-17 | R-9 |
|---|---|---|---|---|---|---|---|---|
| I. Helophytes | Common reed *Phragmites australis* (Cav.) Trin ex Stend. | + | + | + | + | − | + | − |
| | Cattails *Typha latifolia* L. | + | + | − | − | + | − | − |
| | Lesser Bulrush *Typha angustipholia* L. | + | − | − | + | + | − | − |
| | Graceful Cattail *Typha laxmannii* Lepechin | − | + | + | + | − | − | − |
| | Common water-plantain *Alisma plantago- aquatica* L. | − | + | − | − | − | − | − |
| | Flowering rush *Butomus umbellatus* L. | + | − | − | − | − | − | − |
| II. Hydrophytes | Yellow floating-heart *Nymphoides peltata* (S.G. Gmel.) Kuntze | + | − | − | − | − | − | − |
| 1. Floating on top of the surface | Longroot smartweed *Polygonum amphibium* L. | − | + | + | − | − | − | − |
| | Common frogbit *Hydrocharis morsus-ranae* L. | + | − | − | − | − | − | − |
| | Common duckweed *Lemna minor* L. | + | + | + | + | − | − | − |
| | Star duckweed *L. trisulca* L. | + | + | − | − | − | − | − |
| | Greater duckweed *Spirodela polyrrhiza* (L.) Schleid. | + | + | − | − | − | − | − |
| II. Hydrophytes | Least pondweed *Potamogeton filiformis* L. | + | − | − | − | − | − | − |
| 2. Submerged in the water | Shining pondweed *Potamogeton lucens* L. | + | + | − | − | − | − | − |
| | Hairlike pondweed *Potamogeton trichoides* Cham. et Schlecht. | − | − | − | + | − | − | − |
| | Fennel pondweed *Stuckenia pectinata (L.) Börner* | − | − | + | + | − | − | − |
| | Coontail*Ceratophyllum demersum* L. | + | + | + | + | − | − | − |
| | Eurasian watermilfoil *Myriophyllum spicatum* L. | − | + | − | − | − | − | − |
| | Whorlleaf watermilfoil Myriophyllum verticillatum L. | − | + | − | − | − | − | − |

Note: Reservoirs R-11, R-17 and Shershnyovskoye reservoir – data are given as of 2011, reservoir R-10 – data are given as of 2009, reservoir R –4 – data are given as of 2010, reservoir R –3 – data are given as of 2012; "+" – presence of species; "−" – absent of species.

erythrocytes with micronucleus was observed in roach from the reservoirs R-11, R-10 and R-4 as compared to fish from the comparison water body (Shershnyovskoye reservoir). No statistically significant differences in the parameters were observed while comparing the frequency of erythrocytes with micronuclei in roach from the reservoirs R-11, R-10 and R-4, which are characterized by different levels of radioactive contamination (Pryakhin et al., 2012b). Also increase in the frequency of erythrocyte with pyknosis of the nucleus was detected in roach from the reservoirs R-11, R-10, and R-4; the dependence of this parameter on the level of radiation exposure of fish was registered (Pryakhin et al., 2012b).

### 5.7. *Avifauna*

Research into the status of the avifauna of the studied special industrial reservoirs of the Mayak PA was started in 2012. The first phase of ornithological studies was devoted to the assessment of the hematological parameters of embryos and chicks of the herring gulls, that are forming 4 colonies on the reservoir R-11. In these studies, the analysis of erythroid lineage in chicks and embryos of the herring gull from the reservoir R-11 revealed statistically significant decrease in the relative number of erythroblasts in the peripheral blood smears to compare with indeces of chicks and embryos of herring gull from comparison reservoir – Kurlady Lake, Chelyabinsk Oblast (Mogilnikova et al., 2014).

In the analysis of the leukocyte lineage of the peripheral blood of chicks from the reservoir R-11 statistically significant decrease in the total percentage of leukocytes was detected to compare with the indeces of chicks from comparison reservoir. No statistically significant changes in the relative amount of peripheral blood leukocytes was found in the embryos of the herring gull inhabiting the reservoirs R-11 and Kurlady Lake (Mogilnikova et al., 2014).

## 6. Conclusion

One of the major tasks of the present-day radiation safety is the determination of the permissible levels of radiation exposure that are safe for both particular representatives of biota, and for the natural ecosystems on the whole. The necessary components of the solution of this task are the determination of the exposure (dose), determination of the effects at various organizational levels of the biological systems, determination of the dose-effect dependences (Bréchignac, 2003; Bréchignac et al., 2012; Bradshaw et al., 2014). The system of environmental protection suggested by ICRP on the basis of organismic approach does not predict response of biocenosis as a whole, taking into account the interaction of ionizing radiation with other abiotic factors and taking into account indirect effects associated with biotic interaction of hydrobionts.

Since 1951 at Mayak PA a system of industrial ecological monitoring of the radioactively-contaminated aquatic ecosystems was developed that included regular studies of the composition of the industrial releases into the storage reservoirs of liquid radioactive waste, determination of the chemical composition of the water, control of the contamination of the groundwaters, radionuclide content in water, bottom sediments, sometimes in biota, receipt of the meteorological data. From 2007 this system was updated by a monitoring of the status of the major ecological groups of hydrobionts.

The results of hydrobiological studies (2007–2012) demonstrated that in reservoir R-11 up to present time no marked changes in the status of biota was revealed as compared to biological parameters of the comparison water bodies and water-bodies of a given geographical zone. In terms of biological parameters the status of the ecosystem of the reservoir R-11 is characterized by a sufficient biological diversity and could be considered satisfactory. In the ecosystem of the reservoir R-10 adverse effects are registered in the zoobenthos community associated with the decrease in the number and biomass of the group of pelophilous mollusks, whose life cycle entirely occurs aground. In reservoirs R-3 and R-4 the parameters of the phytoplankton growth did not differ from the parameters of the reservoirs R-11 and R-10, although the decrease in the abundance of the cladocerans and copepods was registered in the zooplankton community (Osipov et al., 2011), and absence of the small mollusks living aground throughout their life cycle was observed in the zoobenthos community. In reservoir R-3 there were no carnivorous fish species in the composition of the ichthyofauna either. In reservoir R-17 the following phenomena were observed: complete absence of ichthyofauna, considerable decrease in species diversity of phytoplankton, zooplankton was represented only by rotifers, and zoobenthos – by gnat larvae. In reservoir R-9 ichthyofauna was absent, phytoplankton was represented practically by a monoculture of cyanobacteria *Geitlerinema amphibium* (Pryakhin et al., 2012a). Zooplankton of the reservoir R-9 in various years was basically a population of one of the three species of rotifers (*Brachionus calyciflorus*, *B. urceus* and *Hexarthra fennica*), interchangeably. In all the above mentioned reservoirs the parameters of the bacterial plankton growth were at the level typical of the standing water reservoirs of the given geographic zone.

It was established that radioactively contaminated ecosystems of the special industrial reservoirs of the Mayak PA R-11, R-10, R-4, R-3, R-17, R-9 have biocenoses with various degree of degradation, and even the biocenosis of the reservoir R-9 consists of communities of producers, consumers and reducers.

Next stage in the studies devoted to the assessment of the reaction of aquatic hydrobionts to chronic radiation exposure presupposes the adverse man-made exposure assessment. It is important for the study of the dependences of the radionuclide distribution in abiotic and biotic components with the account of hydrobiological regime peculiarities, chemical composition of the water, morphological parameters of the studied aquatic ecosystems. It should be noted that together with the radiation factor, it is necessary to take into account other natural abiotic and biotic factors as well as anthropogenic factors, first of all chemical pollutants. Dosimetric research together with mandatory use of standard tools, e.g. Erica Assessment Tool (Brown et al., 2008) (to provide standardization and consistency) should include methods and approaches: on the basis of the actual radionuclide content in organs and tissues of hydrobionts, usage of voxel phantoms, use of thermo-luminescent dosimeters – calculation of doses to hydrobionts, including doses to critical organs and tissues. From the point of view of assessing radiation effect, besides individual doses, it is necessary to calculate doses for certain groups of hydrobionts (bacterioplankton, phytoplankton, aquatic plants, zooplankton, zoobenthos, ichthyofauna, avifauna), as well as to develop dosimetric parameters for the assessment of radiation effect on the biocenosis as a whole.

Besides, it is necessary to: accumulate long-term data on the status of the studied ecosystems in terms of phytoplankton, zooplankton, zoobenthos, water plants, ichthyofauna, avifauna parameters; study of radiation-induced effects on all the levels starting with subcellular up to the level of biocenosis.

A peculiar feature of anthropogenic impact on the biocenoses of the Mayak PA reservoirs is simultaneous influence of natural and man-made abiotic factors (reservoir morphology, hydrological regime, water chemistry, chronic radiation exposure, and others) and also of biotic factors (changes in community structure: reduction of species diversity, loss of certain species (fish) and groups of hydrobionts (small bivalve mollusks), etc.; increase in the amount of cyanobacteria accompanied by the development of hypoxia in reservoirs, mainly in the near bottom areas, and toxic effect on hydrobionts due to cyanotoxins, the role of adaptive reactions and others.).

Another aspect of biocenotic reactions to man-made, including radiation, exposure is the possibility of indirect effects development. Thus, loss of certain species or entire groups of hydrobionts will inevitably lead to a restructuring of biocoenosis. Biocenosis of the reservoir R-9 can serve as a vivid example of indirect effects. In this case, with a sharp reduction in species diversity of the community, indirect effects result in hypertrophied development of certain species which are rare under normal conditions. High levels of radioactive and chemical (mainly due to high concentration of nitrates) contamination led to the death of most of the species, reduction in species diversity of the communities up to the absolute domination of one species on a trophic level: cyanobacteria *Geitlerinema amphibium* and certain species of non-predatory rotifers. In the absence of pressure on the part of consumers of the second order (predators) and competitors (other types of zooplankton) survived rotifers can achieve high amount and relatively high biomass. Cyanobacteria also reach high abundance and biomass when pressure of consumers of the first order drops, and there is no competition with other micro-algae and plants. In other ecosystems (reservoirs R-10, R-4, R-3, R-17) changes in the structure of biocenoses were also identified. This allows suggesting the presence of indirect effects associated with man-made contamination of these reservoirs. However, a more detailed discussion of this issue requires further research and analysis.

The issue of the impact of chronic radiation exposure on the biocenosis under the simultaneous influence of other factors, listed above, could be solved in laboratory experiments aimed to assess the combined effect of the studied factors using monocultures of hydrobionts and microcosms, and with adequate selection of comparison water bodies (comparable in all other characteristics, except for radionuclide content). A set of such studies based on ecosystem approach would clarify the reaction of fresh water ecosystems to chronic radiation exposure.

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