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Chapter 16

The Behaviour of Natural and Artificial Radionuclides in a River System: The Yenisei River, Russia as a Case Study

Lydia Bondareva, Valerii Rakitskii and Ivan Tananaev

Additional information is available at the end of the chapter

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Abstract

The Yenisei River is one of the largest rivers in the world. There is Mining and Chemical Combine (MCC) of Rosatom located at Krasnoyarsk, on the bank of the River Yenisei, 50 km downstream of the city of Krasnoyarsk. Since 1958 MCC used river's water for cooling of industrial nuclear reactors for the production of weapon plutonium—^{238}Pu. Besides the pollution caused by industry-related radionuclides, pollution by natural radionuclide—uranium and its isotopes— are also investigated. Besides the natural uranium isotopes (^{234}U, ^{235}U, ^{238}U), exclusive artificial isotope—^{236}U was also found. Yenisei water was also polluted by high tritium content: from 4 Bq/L (back road value) to 200 Bq/L (some sample of water). The total amount of radionuclides investigated was about 20 radioisotopes. These radionuclides have different physical and chemical properties, different half-lives, and so on. Thus, the data on artificial radionuclides entering the Yenisei River water were obtained by long-term monitoring, which is likely to be connected with the activity of the industrial enterprises located on the river's banks of the studied area.

Keywords: Yenisei River, migration, radionuclide, Siberia, isotopes, Russia

1. Introduction

The major part of population of Krasnoyarskii region lives on the banks of Yenisei River. Yenisei is—one of the largest rivers in the World: its length from junction of Big Yenisei and Small Yenisei is 3487 km, from Small Yenisei's rise—4287 km and from Big Yenisei's rise—4123 km. The place of junction of Big and Small Yenisei near city of Kyzyl is considered as geographical centre of Asia. Rising in the south, in the mountain deserts of Mongolia, Yenisei flows in the

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north direction for nearly 3000 km, crosses various latitudinal geographical zones, falls into the Arctic Ocean, forming estuary zone up to 30 km wide. Length of Yenisei exceeds the same of Danube River (2857 km), Mississippi (3770 km) and Indus (3180 km). Yenisei River is the most affluent river of Russia with a runoff rate of 624 km^3/year. Mean water consumption in the estuary is 19,800 m^3/s and the maximal value is 190,000 m^3/s. With respect to basin area (2580 thousand km^2) Yenisei holds second place (after the Ob) and the seventh place among all rivers of the world. The nominal border between Western and Eastern Siberia lies along Yenisei. There are three hydroelectric power plants (HPP) on the Yenisei River and on the rivers falling into it. River's waters are characterized by high transparency (up to 3 m) and low mineralization (mean value is 54 mg/l) and also by high oxygen concentration. Flow velocity and river width can change considerably: from 1.5 to 12–15 km/h and from 0.2–0.5 to 3–5 km, respectively. Solids of the channel in the uppers are faceted soils that are changed into gravelly sand in the middle course and into sandy-clay in the lower course near the fall into the Arctic Ocean.

There is a constant mixing of water layers because of hydroelectric power plant's activity, thus not affecting water temperature from the depth of water flow even on higher distances after HPP stanch. At the beginning of July, water temperature in Krasnoyarsk district and after 100–150 km further down the course is ~10°C, at the end of July–August it is 15–17°C. River's ecosystem is related to oligotrophy with fauna-rich river, there are more than 500 species of algae and diatoms [1].

There is Mining and Chemical Combine (MCC) in Rosatom, located at Krasnoyarsk, on the bank of the River Yenisei in 50 km downstream of the city of Krasnoyarsk. There are atomic reactors and radiochemical production in the MCC. Since 1958 MCC used water for cooling industrial nuclear reactors for the production of weapon plutonium –^{238}Pu. River water, while passing through the cooling system of reactors, returned to Yenisei. Effluent waters contained a great amount of radionuclides that were formed during neutron activation of traces (solid slurry and dissolved compounds), which are present in river water. Two direct flow reactors were withdrawn in 1992, because the activity level of the effluent waters of MCC was remarkably decreased.

2. Radionuclides (natural and artificial) in the streams of the Yenisei River

As a result of long-term activity of MCC, the Yenisei's ecosystem contains considerable amounts of industry-related radionuclides [2]. In particular, an increased level of radioisotope contents in bed deposits and alluvial soils was found [2–6] and distribution and migration of radionuclides both in near-field influence of MCC [7, 8] and in significant distance away from effluent zone, including estuary of Yenisei, were indicated. As early as in the beginning 1970, the pollution zone of Yenisei's bottom land by ^{137}Cs was found by airborne gamma survey. In district of Yeniseysk city (island Gorodskoi around 300 km downstream of MCC), the specific activity of ^{137}Cs reaches 16,300 Bk/kg in some places, power of exposure (PE)—270 μR/h. According to present standards, bottom sediments and alluvial soils at this region are related to solid radioactive wastes. ^{137}Cs is the main radionuclide polluting soils and bottom sediments are $^{152+154}$Eu and ^{60}Co [9].

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In this chapter, the results of research conducted mainly in the middle course of Yenisei in the 15 km region (from fall place of Ploskiy river (0 km) to Bolshoy Balchug (15 km), **Figure 1**) are described. In this region, at a water flow rate Q = 4085 m^3/s the depth and current velocity were defined as $H \approx 7$ m, v = 1.25–1.8 m/s, respectively. Jet with industrial wastes spends along the right bank not more than 0.1 of river's width, i.e. along bottom land, where current velocity and depth are several times lower.

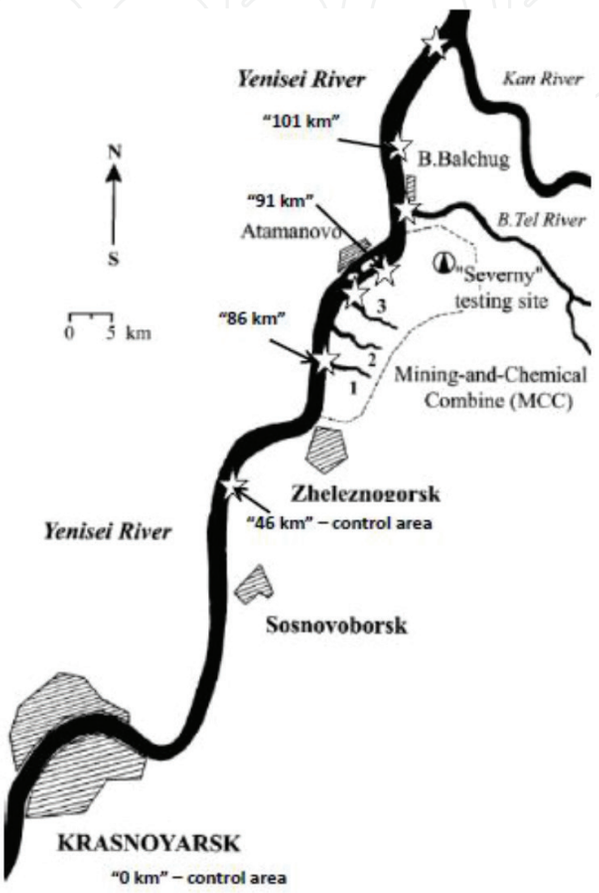


Figure 1. Sketch-map of the some region of the Krasnoyarsk Territory near the Mining—Chemical Combine of the Rosatom—surface water of the Yenisei River basin. 1: Shumikha River; 2: Stream No. 2; 3: the Ploskii Stream; – – – – : the boundary of the MCC sanitary-protective zone. ☆point of collection. Sampling points: '0 km'—56°27′05″N, 93°36′31″E; '2 km'—56°23′18″N, 93°37′13″E, '5 km'—56°23′40″, '15 km'—56°27′05″, 93°42′22″E.

2.1. Uranium: natural and artificial

Besides the pollution caused by industry-related radionuclides, pollution by natural radionuclide—uranium and its isotopes are also investigated.

The total uranium content is the main factor to determine the radiation level of water sources, its value is standardized and controlled by ecological services. Uranium in water is truly dissolved and found in the form of uranyl carbonate complex anions. In general, river waters contain 600 ng/l of dissolved uranium. Despite that main natural transport agents—water carries uranium in small amounts, one should not exclude that there can be local transfers of uranium in significant amounts [10].

The main feeders, contributing to the radioactive pollution of the Yenisei, are majorly the right bank feeders, situated near MCC outlet: river Kan, on the bank of which the electrochemical plant (ECP, Zelenogorsk city) is situated, and river Bolshaya Tel', flowing along the border of testing area 'Sverniy' MCC (Zheleznogorsk city).

According to data, presented in the monograph [9], the most of the region's waters, related to the bottomland of Kan, contain from 0.04 to 3 μg/l of uranium that is considered as highly pure with respect to natural radionuclide content. In addition, there was no trend in uranium content from the location of selection. Only in one place at the turn of Kan's course to the north vs. course of Bogunay river, it was revealed that all of the waters contain uranium from 1 to 3.3 μg/l. Industrial waters discharged by ECP into Kan near the plant administration were similar to natural uranium content and contained 0.05–0.08 μg/l of uranium.

Natural stream feeding Syrgyl river contained from 0.03–0.07 to 1.0–7.3 μg/l of uranium. The contents in the range 0.3–5.0 μg/l were shown to be natural geochemical background of uranium in the studied region, in particular, in the bottomland of Kan. All of the excesses are considered as abnormal.

The analysis data [1–12] shows that the geochemical background level of uranium in the Yenisei River is in agreement with the mean statistical level for the basins with major contribution of natural uranium resources, e.g. Baikal Lake and rivers of Altai region: from 0.15 to less than 2.0 μg/l.

Uranium content in waters which were collected from Bol'shaya Tel' in the September 2007 at the 1000 m place from the estuary is 3–60 times higher than values obtained for uranium (mean value 0.33 ± 0.08 μg/l) in background samples (Yenisei, tideway). Moreover, this period was indicated by significantly higher uranium concentrations as compared with other studied months. This increase becomes remarkable for the 1000 m place, where uranium concentration is 16 μg/l that is very close to the accepted in Canada and Australia standards for the minimal allowed uranium concentration—20 μg/l and by 8 times exceeds accepted by WHO standard—2 μg/l. Despite that obtained values are lower than the level of exposure (LE = 75 μg/l) accepted by in NRS of Russian Federation [9, 10], uranium concentration in some places of Bol'shaya Tel' in September is, in general, can be considered as abnormal. It is known that natural uranium is a mixture of three isotopes: ^{238}U—99.2739% ($T_{1/2} = 4.468 \times 10^9$ years), ^{235}U—0.7024% ($T_{1/2} = 7.038 \times 10^8$ years) and ^{234}U—0.0057% ($T_{1/2} = 2.455 \times 10^5$ years). In contrast to other isotope pairs, last two isotopes are in constant proportion, regardless of high migration activity of uranium and geography: $^{238}U/^{235}U = 137.88$ [13, 14]. The presence of uranium was truly established in the waters of Bol'shaya Tel', it can only be originated artificially: in the sample from 1000 m (October 2006) ~0.05 ng/l and in the sample from Bol'shaya Tel' (March 2007) ~0.03 ng/l. In addition, the ratio of $^{236}U/^{234}U$ at these places is 1:0.8, respectively.

Besides, water samples obtained in September provided information about anion content of NO_3^- (~2 mg/l, while the maximum permissible concentration (MPC) is 45 mg/l), CH_3COO^- (~7 mg/l) in the waters of Bol'shaya Tel' (1000 m from estuary). It is considered that the presence of such anions can indicate the non-equilibrium conditions in basin solution. Such situation is considered rather usual for liquid radioactive wastes, where acetate and nitrate, due to kinetic limitations of the acetate oxidation by nitrate, can coexist even at high (about 100°C) temperatures [10].

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Generalized information about the total uranium content in water samples of the Yenisei River is given in **Figure 2**.

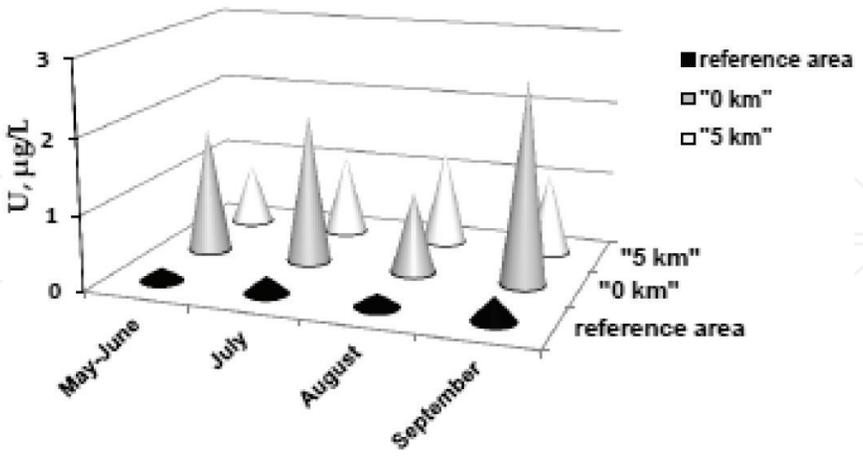


Figure 2. Results of determination of total uranium content in Yenisei water at distances from water discharge of MCC '0 km' and '5 km', taken 2006–2009, 'distance from water discharge MCC'.

Presented data indicate uranium content in the estuary of Ploskiy river '0 km' to exceed by 6–9 times background values of uranium typical for Yenisei. Further investigation of isotope composition of indicated water samples revealed that a ratio of uranium isotopes differ from natural isotopes and also the presence of ^{236}U can also evidence the industrial origin of high uranium concentrations as compared with background values. Isotope analysis of some samples has been carried out.

In water samples of Yenisei (pick point '0 km') the ratio of $^{238}U/^{235}U$ is 119:120. Besides, artificial uranium isotope ^{236}U ($T_{1/2} = 2.39 \times 10^7$ years) was found, the ratio of which to ^{234}U equals $^{236}U/^{234}U$ ~0.1–0.2. Thus, one can state that high uranium concentration in Yenisei waters is caused by MCC activity.

2.2. Tritium and other radionuclides

2.2.1. Tritium

Besides artificial radionuclides, Yenisei water was also polluted high tritium content. To prove this, the tritium content was determined in the picked water samples. Results are given in **Figure 3**.

Tritium content in the picking site '0 km' exceeds by 15–20 times the background tritium content obtained via long-term monitoring and typical for Yenisei (4 ± 2 Bk/l) [15–20].

To prove industrial origin of tritium in water samples it is recommended to control content of gamma-emitting radionuclides. There is significant amount of artificial radionuclides in the studied water.

2.2.2. Radionuclides without tritium

Depending on the state of radionuclides that can be present as simple ions to molecules and hydrolyzed forms, colloids and pseudocoolloids, organic and inorganic particles [21, 22] and, respectively, migrates over long distances and be sorbed by ecosystem immediately near the

discharge area. Content of TUE in surface basins is extremely low and equals 10^{-10}–10^{-15} M, within limits of the most sensitive spectral techniques, e.g. mass-spectrometry [23, 24]. For the precise determination of TUE contents as well others radionuclides such as ^{90}Sr in water systems, the most frequently used methods are hybrid ones, combining preliminary concentrating and separating of radioisotopes with various detecting methods, e.g. alpha-, beta- and gamma-spectrometry [25–27].

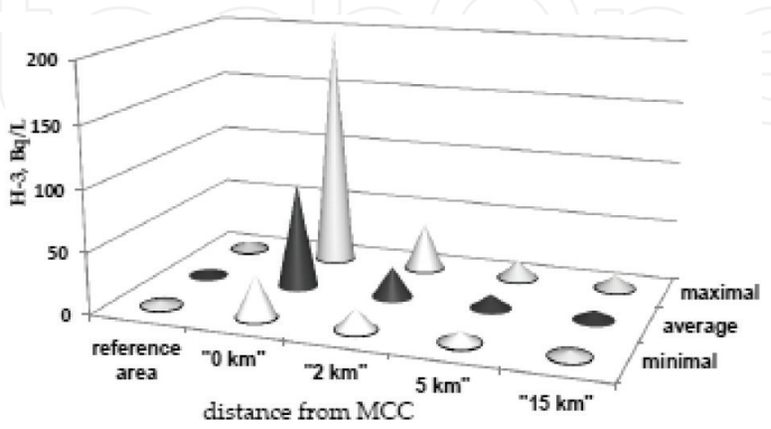


Figure 3. Average tritium content in water samples of Yenisei (distance down the stream from places of water discharge by MCC).

To increase the number of identified radionuclides, the method for concentrating the radionuclide from Yenisei water samples has been introduced [8]. Data obtained after concentration of water samples is given in **Tables 1** and **2**.

Water samples contain the bunch of artificial radionuclides. To increase the number of identified radionuclides, the method for concentrating the radionuclide from Yenisei water samples has been improved [8].

The method for concentrating the radionuclide was accepted on the basis of two widely known methods of co-precipitation with oxyhydroxide of Fe (III) and Mn (IV) oxide [28, 29].

Artificial radionuclides, which have different origin, have been found in water samples: induced (activated) radionuclides—^{24}Na, ^{46}Sc, ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{76}As and others; satellite radionuclides—^{99}Mo, ^{124}Sb, ^{131}I, ^{133}I, ^{141}Ce, ^{144}Ce and others. The most distinctive are trans-uranic radionuclides—^{239}Np, isotopes of Pu. In water samples, taken down the stream from MCC (5 km), besides the decreasing concentration of artificial radionuclides there were found some natural radionuclides: ^{210}Pb and ^{232}Th. There were included the presence of long-living satellite isotope ^{152}Eu ($T_{1/2}$ = 13.6 years) ~ 0.04–0.06 Bk/l and the presence of short-living activated radionuclide ^{58}Co ($T_{1/2}$ = 71.3 days) ~ 0.03–0.07 Bk/l in water samples.

2.3. Suspended matter of the Yenisei River: trucks for transport of radionuclides in the water flow

Because major part of radionuclides has been found in the suspended matter, transporting by water stream of Yenisei, more thorough studies of suspended matter of Yenisei have been conducted.

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№	Isotopes	2007	2008	2009
1	^{24}Na	2.5 ± 1.4	1.9 ± 0.2	–
2	^{46}Sc	0.21 ± 0.01	0.136 ± 0.006	0.086 ± 0.06
3	^{51}Cr	6.0 ± 0.2	2.7 ± 0.1	3.4 ± 0.1
4	^{54}Mn	0.014 ± 0.003	0.014 ± 0.003	0.007 ± 0.002
5	^{59}Fe	0.16 ± 0.01	0.11 ± 0.008	0.07 ± 0.01
6	^{60}Co	0.13 ± 0.01	0.17 ± 0.008	0.09 ± 0.01
7	^{65}Zn	0.11 ± 0.01	0.055 ± 0.007	0.03 ± 0.004
8	^{76}As	8.5 ± 0.6	4.5 ± 0.2	4.7 ± 0.6
9	^{85}Sr	–	0.014 ± 0.003	0.003 ± 0.001
10	^{99}Mo	–	0.093 ± 0.008	0.04 ± 0.01
11	^{103}Ru	0.027 ± 0.004	0.026 ± 0.003	0.012 ± 0.006
12	^{106}Ru	0.078 ± 0.025	–	0.04 ± 0.01
13	^{124}Sb	0.016 ± 0.003	0.020 ± 0.003	0.012 ± 0.004
14	^{131}I	0.051 ± 0.013	0.031 ± 0.005	0.028 ± 0.008
15	^{133}I	–	–	0.14 ± 0.02
16	^{137}Cs	0.057 ± 0.005	0.142 ± 0.009	0.09 ± 0.02
17	^{141}Ce	0.048 ± 0.006	0.050 ± 0.006	0.021 ± 0.007
18	^{144}Ce	0.08 ± 0.02	0.13 ± 0.02	0.04 ± 0.01
19	^{239}Np	29.5 ± 1.4	17.1 ± 0.3	10.3 ± 0.8

Table 1. Radionuclide content in water samples after concentrating, taken in the place of MCC discharge ("0 km"), Bk/l.

N	Isotopes	2006	2007	2008	2009
1	^{24}Na	–	–	–	0.07 ± 0.025
2	^{46}Sc	0.11 ± 0.02	0.09 ± 0.02	–	0.002 ± 0.001
3	^{51}Cr	2.6 ± 0.2	1.4 ± 0.2	0.037 ± 0.013	0.057 ± 0.009
4	^{58}Co	–	–	–	–
5	^{60}Co	0.14 ± 0.02	0.11 ± 0.04	0.006 ± 0.001	0.002 ± 0.001
6	^{65}Zn	0.10 ± 0.03	0.07 ± 0.02	0.003 ± 0.001	0.005 ± 0.002
7	^{76}As	3.1 ± 0.3	0.08 ± 0.03	1.07 ± 0.08	0.103 ± 0.015
8	^{106}Ru	0.3 ± 0.1	0.4 ± 0.3	–	0.0064 ± 0.0061
9	^{131}I	0.04 ± 0.01	–	0.002 ± 0.001	0.0023 ± 0.0009
10	^{137}Cs	0.07 ± 0.02	0.04 ± 0.01	0.001 ± 0.001	0.0015 ± 0.0013
11	^{140}La	0.16 ± 0.03	0.08 ± 0.03	–	0.006 ± 0.002
12	^{144}Ce	0.25 ± 0.07	0.04 ± 0.02	–	–
13	^{152}Eu	0.06 ± 0.02	0.04 ± 0.02	–	–
14	^{239}Np	0.27 ± 0.02	0.32 ± 0.04	0.39 ± 0.02	0.261 ± 0.007

Table 2. Radionuclide content in water samples, taken from Atamanovo region, after concentrating (taken at 5 km down the stream from the place of discharge), Bk/l.

The investigations were carried out in the middle reach of the River Yenisei at the site 15 km (from the inflow of the Plosky stream (0 km) to the village Bolshoy Balchug (15 km) (**Figure 1**). The stream with technogenic admixtures propagates along the bank of the river not more than 0.1 one-tenth of the width of the river, i.e. along the flood plain where the river flow speed and the width are several times less.

As a result of ultra-filtration method, it was found that the main part of the suspended particles (up to 90%) was concentrated in the pelitic fraction of >5 μm. The filters with the suspensions were fixed on the specimen mount with the help of the conducting double-sided adhesive carbon type and placed into the electron microscope chamber. The precipitate was found to contain particles of quartz, mica and iron-containing minerals (limonitic and magnetic iron), mainly, with the size not exceeding 10–15 μm. Moreover, the precipitate revealed the presence of a considerable amount of various biological objects (diatoms, annelids, plant spores, etc.). All the mineral particles and biota were covered with a layer of fine limonitic-clayish particles. Spectral analysis of some parts of the sample (selected particles, characteristic details) was carried out. The suspended matter contains a large colony of diatoms, for example, *Meridion circulare, some cyclotellas* and *opyphoros, Cyclotella vor. Jacutca* (**Figure 4**).

The fraction with the size of '5-1 μm' uniformly covers the filter surface with a layer of fine particles. The precipitate mainly consists of mineral components (calcite, clays, clayish minerals, quartz and gypsum debris).

The fraction '1.0–0.2 μm' uniformly covers the filter surface with a layer of fine particles of the micron and submicron size, they are mainly aluminosilicate compounds having various structure and composition, limonite, calcite and gypsum.

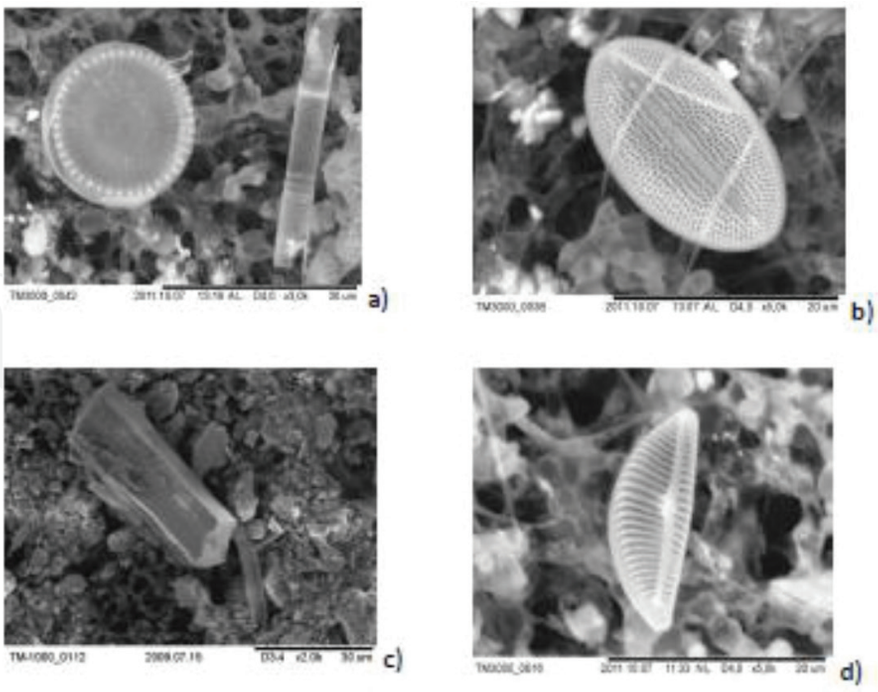


Figure 4. Material composition of the water suspensions (separated by the ultra-filtration method). The fraction ≥5 μm. Magnification power of 2000×.

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The material composition of the solid suspensions in the Yenisei River water generally corresponds to the mineral compositions of the rocks and the products of their hypergenesis which collected from the channel and the banks of the river. Occasionally, the admixture of the particles of technogenic origin (ash wastes from boiler stations) is observed.

Thus, it was shown that the suspended substance is similar to its geomorphology with the bottom sediments of the Yenisei River. However, the suspensions entering the river with the industrial discharge water significantly differ from the suspensions of the mainstream both in their composition and particle size.

At the sampling of the district runoff of radionuclides when the time of the discharge contact with the river water was insignificant, the radionuclides ^{3}H, ^{24}Na, ^{60}Co, ^{239}Np and ^{99}Mo (~90%) were mainly presented as a fraction <0.2 μm (filtrate). These can be both free ions in the molecular solution (e.g., $^{24}Na^{+}$), and molecules or sorbed ions in colloid particles which managed to pass through a 0.2 μm filter. ^{46}Sc, ^{214}Bi, ^{103}Ru are mainly presented in solid phase, while the last two isotopes being in the coarsest fraction (more than 90% of them). ^{85}Sr and ^{131}I have less uniform phase distribution. ^{76}As is almost absent in the most coarse fraction (>5 μm). In the samples taken 5 km downstream, there is a decrease of the total activity, first of all, due to the coarse particle sedimentation. The radionuclide redistribution according to the size fractions was found: almost the whole amount of ^{60}Co is concentrated in the fraction with the size of >1 μm, a considerable amount of ^{214}Bi is transformed into a solution (the fraction <0.2 μm), almost 40% of ^{99}Mo and up to 70% of ^{24}Na are transformed into the fraction of 1–0.2 μm. With the total background level decrease there appear natural radionuclides ^{212}Pb and ^{234}Th in the solid phase as well as ^{65}Zn in the solution.

3. Mathematical calculations of the mass transport of technogenic radionuclides in the water flow of the River Yenisei in the impact zone of the Mining and Chemical Combine

In the chapter, the results radiation-chemical situation in the middle reach of the Yenisei River located in the nearest zone of the influence of the Mining and Chemical Combine of Rosatom have been described. It has been shown that a wide range of radionuclides, heavy metals and organic substances of different genesis flow into the waters of the Yenisei River. It has been demonstrated that radionuclides and other pollutants are transported by the water flow in the form of molecular solution or colloids or with suspended matter. In this case, the suspended matter consists of pelitic finely dispersed mineral particles, plant and organic detritus and amounts of living biological objects.

Calculations have been made according to the described method in the area of the River Yenisei from the estuary of the river Plosky up to the island Atamanovsky. Assuming the water discharge to be Q = 4085 m^3/s the river depth $H \approx 7$ m and the flow rate v = 1.25–1.8 m/s in the given section are estimated based on the hydraulic model. According to an earlier estimation, the stream with the technogenic admixtures propagates along the right bank, not far than one tenth of the river width, i.e. along the flood plain where the flow rate and depth

are several times lower than those calculated based on the hydraulic model. According to the calculations: $H_n \approx 2.5$ m, $v_n \approx 0.38–0.44$ m/s.

Transport of radionuclide along the Yenisei River is based on a modified one-dimensional model proposed by Schnoor et al. [30]. For the whole length of the Yenisei, a homogeneous distribution of radionuclides over the cross-section is presupposed. It is assumed that both in the water column and in the active sediment layer the radionuclides are present in two forms: soluble and adsorbed forms. The most important processes influencing the behaviour of radionuclides include adsorption and desorption, sedimentation of suspended particles from the river water and resuspension from the active sediment layer, activity exchange between the pore water of the sediment and overlying water due to diffusion through the boundary and radioactive decay.

The calculations presented in this chapter are limited to the abiotic form of substance transport since the contribution of the biogenic component is considered to be insignificant [9].

Complex fresh water systems, such as large rivers, are assumed to be composed of a chain of interconnected 'elementary segments (ES)' that are comprised of: (a) the water column, (b) an upper sediment layer strongly interacting with water ('interface layer'), (c) an intermediate sediment layer below the 'interface layer' ('bottom sediment'), (d) a sink sediment layer below the 'bottom sediment', (e) the right and left sub-catchments of each ES.

Depending on the water discharge rate and geometry of the river bed the stream velocity varies which determines the transport of the sediment suspensions and sediment disturbance-sedimentation. To estimate the accumulation of radionuclides in the bottom sediments, a mathematical model described by Belolipetsky and Genova was used [31].

The concentrations of radionuclides on solid particles were assumed to be proportional to the area of the particle surface. We used the field data the fraction distribution of radionuclides in the initial solution. Then, the particle transport and sedimentation along the river bed was estimated. In the channels and floodplain (in the areas with small stream velocities) there occurs sedimentation of the sediment suspensions. During the periods of the increased water discharge rate (spring floods, increased volume of the hydroelectric station), the sediment disturbance is also possible as well as transport of impurities downstream (secondary pollution).

To describe the sediment suspension transport in a turbulent flow of non-compressible liquid a simplified equation is used:

$$\partial Si/\partial t + u_в \, \partial Si/\partial x = qSi/h + q/\omega \cdot Siq \tag{1}$$

where S_i is the concentration of the ith fraction [kq/m^3]; S_{iq} is the concentration of an impurity of the ith fraction, entering with the tributary on the way q; q_{Si} is sediment disturbance-sedimentation of the impurity of the i-th fraction; t is time; x is a coordinate directed along the current; Q is the discharge rate; ω is the cross-section area of the river bed; $u_в = Q/\omega$ is the cross-section; average velocity h is the depth.

The bottom exchange is determined by the formula

$$qSi = (Si\,tr - Si0) \cdot wgi, \; Si\,tr = 0.01 \cdot \alpha i \cdot Str, \; qS = \sum qSj \tag{2}$$

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$$S_{tr} = \begin{cases} 0.2 \cdot u_в / gh\, w_g, \text{ if } w_g < w_* \\ w_g = (\rho_S - \rho_в)/\rho_в \cdot g/18\nu \cdot d^2_{cp} \\ 0, \text{ if } w_g \geq w_* \end{cases} \quad (3)$$

The transport capability of the flow S_{tr} depends on the depth-average flow velocity, depth and hydraulic coarseness; q_S is the mass exchange with the bottom.; S_{i0} is the concentration of the *i*-th fraction near the bottom; α_i is the percent content of the *i*-th fractions in the bottom sediments. When calculating $S_{i\,tr}$ using Eq. (3) it should be taken into account that $S_{i\,tr}$ cannot exceed the concentration of the *i*-th fraction in the bottom sediments ($S_{i\,\text{day}}$), therefore, when $S_{i\,tr} > S_{i\,\text{day}}$ it is assumed that $S_{i\,tr} = S_{i\,\text{day}}$. If the concentration of the *i*-th fraction in the bottom sediments is equal to zero, then $S_{i\,tr} = 0$.

The main change in the bottom sediment composition is assumed to be due to sediment disturbance and sedimentation. When $q_s > 0$, the bottom sediments enter the flow (washing out, sediment disturbance) and when $q_s < 0$ the silting of the river bed is observed (sedimentation of the suspended particles).

Let z_* be the thickness of the active layer of the bottom sediments. Assuming that the formation of the upper layer of the bottom sediments (with the thickness z_*) results in the sediment disturbance-sedimentation, the mass conservation equation for the *i*-th fraction in the bottom sediments $S_{i\,\text{day}}$ is written as follows:

$$\partial(z_* \cdot S_{i\,day})/\partial t = -q_{Si} \quad (4)$$

Since $\sum q_{Si} = q_S$, $\sum S_{i\,\text{day}} = \rho$, from Eq. (4) one obtains the equation to find z_*:

$$\partial z_*/\partial t = -q_S/\rho \quad (5)$$

The calculation algorithm for the suspended and bottom sediment dynamics consists of the following stages:

Stage 1. The water flow rates u_w are determined as well as the depth *h* from the solution of the Saint-Venant equation.

Stage 2. Determination of the initial conditions. The granulometric composition of the bottom sediments in the section $X = X_j$ is taken to be (d_i, $a^0_{i\text{day},j}$), where d_i is the diameter of the *i*th fraction particle (mm), $a^0_{i\text{day},j}$ is the percentage of the *i*-th fraction in the bottom sediments, $i = 1, 2, \ldots, n$.

Stage 3. Establishment of the boundary condition in the initial section ($X = X_0$). In the initial section, $S^n_{i\text{day},0}$ are determined using relations employed for the second stage, $S^n_{i,0}$ are estimated using the field data.

Stage 4. Estimation of the mass exchange between the bottom water and water flows. From the condition $w_{gi} \leq w_*$, $w_* = 0.4u_*$ one determines the fractions which are suspended. Let the suspended fractions be assigned the following index $i = 1, 2, \ldots, i_*$, $a_{i,j}$ is the percentage of the suspended fractions in the section. The percentage of all the suspended fractions is $r_j = a_{1,\text{day},j} + a_{2,\text{day},j} + \ldots + a_{i,\text{day},j}$. Then, the percentage of the suspended *i*th fraction is

$$a_{i,j} = 100 \cdot r_j^{-1} \cdot a_{i,day,j}, \; i = 1, 2, \ldots..i \quad (6)$$

If $r_j = 0$ (the suspended fractions are absent), then, all $a_{i,j} = 0$.

Stage 5. Estimation of the concentrations of the suspended and bottom sediments as well as the location of the water-bottom interface.

Stage 6. Calculation of the granulometric composition of the bottom sediment:

$$a_{i,\ \partial H,j} = S^{n+1} \cdot \rho^{-1} \cdot 100 \tag{7}$$

Stage 7. Estimation of the bottom sediment radioactive contamination in the calculation sections.

Each fraction is assumed to be uniformly contaminated by radionuclides:

$$R^n{}_{i,j} = \lambda_i S^n{}_{i,j} \tag{8}$$

Knowing the contamination level in the initial section $R^n{}_{i,0} = \lambda_i S^n{}_{i,0}$, it is possible to estimate the level of the radionuclide contamination in the sections downstream the river

$$R^n{}_{i,j} = S^n{}_{i,j} \cdot (S^o{}_{i,j})^{-1} \cdot R^n{}_{i,0} \tag{9}$$

In the next time interval, the calculations are repeated (from stage 3 to stage 7).

The influence of the suspension-sedimentation processes on the admixture transport in the river flow close to the right bank of the River Yenisei in the studied area has been estimated.

The calculations made show that the concentrations of the lightest fraction in the calculation area almost do not change, while for the heavier fractions the decline of the suspended sediment concentrations is observed and the level of the radionuclide contamination also decreases (**Table 3**).

In the field data, the increase of the coarse fraction concentration is observed which is not connected with the suspension-sedimentation process. (*S_nat, R_nat* are the measured values, *S_calc, R_calc* are the calculated ones)

***d*, мм**	**0.00020**	**0.00045**	**0.005**	**0.01**
District reset MCC				
S^0, г/л	0.0001	0.0005	0.0043	0.0031
R^0, Бк/кг	118.904	0.1728	0.1165	1.8224
Island Atamanovsky				
S_nat	0	0.0001	0.0009	0.0583
S_calc	0.0001	0.0005	0.0039	0.0021
Island Atamanovsky				
R_nat	2.4727	0.01101	0.01596	0.0853
R_calc	118.9009	0.1727	01044	1.2065

Table 3. Concentrations of particulate matter size fractions: real and calculated data.

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Thus, the abiogenic mass-transport of the technogenic radionuclides, metals being among them, occurs mainly due to the coagulation of the suspended particles and contamination redistribution into bigger fragments.

Our calculations show that the concentration of the lightest fraction of the water on the current site remains virtually unchanged. However, we observed that concentrations of suspended sediment had decreased for heavier fractions and, consequently, decreased the level of contamination. In addition, our field data indicated an increase in the concentration of coarse fraction, which is associated not only with the resuspension-deposition, but also with the coagulation of suspended solids.

Thus, the data on artificial radionuclides entering the Yenisei River water obtained by long-term monitoring, which is likely to be connected with the activity of the industrial enterprises located on the river's banks of the studied area.

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Author details

Lydia Bondareva[1]*, Valerii Rakitskii[1] and Ivan Tananaev[2]

*Address all correspondence to: lydiabondareva@gmail.com

1 Federal Scientific Center of Hygiene named after F.F. Erismana, Moscow, Russia

2 Far Eastern Federal University, Vlodivostok, Russia

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