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GEOECOLOGIC SITUATION AT SITE OF DRAINAGE BRINE UTILIZATION DURING DEVELOPMENT OF PRIMARY DEPOSITS IN YAKUTIA

Development of primary diamond deposits in Yakutia is related to involvement of significant amount of brines from subpermafrost water complexes in mine working. Safe removal of them is important for diamond production and safe geoecologic conditions of the region. Geoecologic conditions of subsurface polygons of drainage waters at the industrial site of the Udachninsky mining-and-processing facility ("ALROSA" company) are estimated, based on analysis and generalization of the results of studies of microelement composition of soil of natural landscapes, ground of technogenically transformed landscapes, bottom sediments and surface water. Purposeful changes of cryosilic-hydrogeologic conditions at subsurface polygons of drainage water disposal provide the potential for diamond extraction and they uniquely and justifiably affect subsurface cryohydrosphere. But, at the same time, complexity and dynamism of cryo-hydrogeologic conditions, increase of water supply into the mine working and probable excess of capacity of drainage brine storages increase ecologic risks."Perennially frozen rocks – drainage brine" system represents natural-technogenic geosystem, which instability is determined by changes of temperature, mechanic, physical-chemical and chemical values of its components. Origin of emergences of highly mineralized water is due to the faults, changes of hydrogeodynamic conditions. Abiotic components of the ecosystem reflect variations of biogeochemical parameters of natural and technogenic geochemical anomaly of the area. Spatial distribution of microelement composition of soil, bottom sediments and surface water is characterized by increased concentrations of wide variety of elements, including strontium, lithium and barium – markers of highly mineralized subsurface water impact on abiotic components of the ecosystem.

Keywords: *geoecology, cryolithozone, hyfrogeology, geothermal section, industrial waste, drainage water, perennially frozen rocks, highly mineralized water, ecosystem, abiotic components.*

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Introduction

Under cryolithozone conditions, unstable natural ecosystems against a background of increasing potential of the mining industry, experience increasing technogenic pressure, which leads to irreversible ecologic consequences. Exploitation of large diamondiferous pipes is complicated by brine supply from subpermafrost high-pressure water-bearing horizons. Such problems are faced during development of Ekati and Diavik kimberlite pipes in Canada and Udachnaya, Mir, Yubileynaya ones in Russia [1–5].Composition of subsurface waters, amount of their inflow to the mine working cause problems for mining-and-geologic activities and production, affect utilization and disposal of drainage brines, impact on geoecologic situation in exploitation areas.

The purpose of the work: ecological assessment of consequences of drainage water utilization in subsurface polygons by the example of the "Udachnaya" pipe.

Theoretical treatment

The largest diamond deposit – "Udachnaya" kimberlite pipe is located in the Daldyn-Alakitsky diamond-bearing region of the West-Yakutian diamondiferous province, on the right bank of middle course of the Daldynriver. Territory of the Daldyn kimberlite field is confined to the area of conjugation of the south-western slope of the Anabar-Olenek anteclise and the north-eastern board of the Tungus syneclise [5]. It is composed of the Archean crystalline rocks, Vendian, Cambrian, Ordovician and Silurian carbonate and terrigenous-carbonate deposits, Carboniferous terrigenous formations. Geologic structure is complicated by sheet bodies and dikes of dolerites, volcanic pipes, dikes and veins of kimberlites, development of regional and local zones of tectonic faults of different level of occurrene, and affect of long period of cryolithozone formation [6].

In the territory of Udachninsky Mining Processing Plant (UMPP) of "ALROSA" company, which existed since 1971, sedimentary cover has a complicated geologic and tectonic structure. On one hand, it causes variety of hydrogeologic, geocryologic and geoecologic conditions, but on another hand it requires a detailed study of technologic problems, related to diamond extraction, spoil construction, disposition of tails storages and industrial waste. Mining of deep horizonsof diamond deposit is connected with inflow of significant amount of aggressive and ecologically dangerous chloride-calcic brines into the mine working, requiring further utilization.

Near the deposit, there all types of subsurface waters, typical for cryolithozone: suprapermafrost, intrapermafrost and subpermafrost (**Fig. 1**).

Subpermafrost subsurface water is predominant. Suprapermafrost water is represented by fresh water of the seasonal-thawed layer, water of hydrogenous underflow and sublacustrinetaliks [7, 8]. Mineralization of subsurface water increases with depth from salt water to brines. Subsurface water of the Upper Cambrian complex is represented mainly by chloride magnesium-calcic brines with mineralization from 72 to 177 g/L, Cl relative content changes from 97,3 to 99,98%-mol. Subsurface water of the

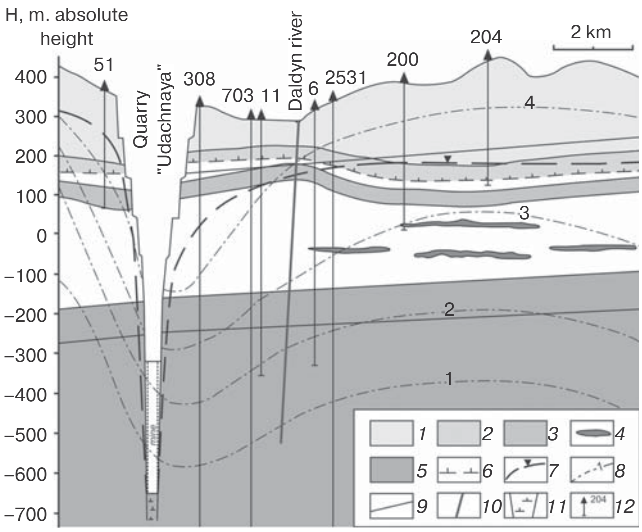

Fig. 1. Permafrost-hydrogeologic section:
1 – fresh subsurface water in a solid phase; *2* – brackish subsurface water in a solid phase; *3* – Upper Cambrian subpermafrost water-bearing complex; *4* – lenses of strong brines; *5* – Middle Cambrian water-bearing complex; *6* – perennially frozen rock bottom; *7* – piezometric level; *8* – isotherms, °C; *9* – boundaries of deposits of different age; *10* – tectonic faults; *11* – kimberlite pipe; *12* – hydrogeologic well and its number

Middle Cambrian complex has mineralization up to 369 g/L, of predominantly chloride-calcic composition with stable high Cl content — 99%-mol. Acid-alkali characteristics of the brines changes with mineralization increase and depth of occurrence — from neutral to high acid (pH = 2,9÷5,0). Draining and pumping-out of brines from quarry and mine working of the "Udachnaya" mine are carried out in water-bearing complexes near the deposit, thatleads to form the cone of depression. In addition, cone of depression is very steep near mine working, with filtration gradient at the western flank — up to 4–5 [9, 10].

Brine composition records increased concentrations of Br, Li, Rb, Cs, Sr. Key place belongs to Sr, which content changes from 438,1 to 894,2 mg/L [7]. Concentrations of rare alkali elements are directly related to K^+ concentrations. Li content changes from 67,4 to 165,9 mg/L, Rb — from 4,89 to 18,9 mg/L, Cs in brines no more 0,01 mg/L,Br — up to 5,45 g/L. Brines belong to mineral bromine waters, they are highly aggressive due to high mineralization, ion composition and increased values of pH. Calcium chloride occupies first places regarding aggressive impact on metals.

From the moment of systematic supply of subsurface mineralized water into the quarry in July 1985, on the adjacent areas of the deposit, located within the Daldyn flexure and Oktyabrsky fault, exploration works in search for favorable structures for pumping drainage water of the quarry "Udachnaya" into water-bearing sequence began. As a result, method of disposal of high-priority amounts of drainage brines in the Upper Cambrian water-bearing complex in the north-western flank of the Oktyabrsky fault with pumping the main amount into the Middle Cambrian water-bearing complex was developed and carried out. Discharge regime – free-flow, with maintaining of water level in the massif on certain ecologically safe marks (+280 m absolute height).

From 2001, frainage water of the quarry "Udachnaya" and mine were removed to the Kiengskypolygon, in 2013 the Levoberezhny polygon was put into operation. Today, within industrial area of the Udachninsky MPP there are three subsurface polygons of drainage water disposal – "Oktyabrsky", "Kiengsky" and "Levoberezhny" with total area of technogenic impact on geocryologic and hydrogeologic conditions – 20×20 km^2.

The Daldyn river, left tributary of the Markhariver, is the main water object of the area. Absolute marks of the river head – 465 mandmouth – 252 m, elevation difference – 213 m, or 154 cmper 1 km. The Daldynriver can be divided into two sections by natural character of the riverbed. The first one (60,4 km) from headwaters to the mouth of the Sytykan river, and the second one (77,6 km) from outfall of the Sytykan river to the mouth. The first section of the river represents small-scale stream, abounding in stone channel bars [10–14]. At the second section of the river, valley width on the surface is 8–9 km, it decreases above the Orto-Bysytakh creek up to 5 km. Main part of technogenic pressure falls precisely at the second section of the river, where quarry of the Udachnaya pipe, spoils, tails storage on the Novy creek, Kiengsky polygon are located on the right bank. Subsurface water is involved insignificantly. Since the early 60-ies of the last century, water composition of the river average is not changed considerably and remains constant. It belongs to hydrocarbonate class: hydrocarbonate-ions prevail in anion composition, calcium and magnesium prevail in cation composition. Water highest reaches its biggest values at the end of winter, and lowest values in the periods of flood time (high water), on average the Daldyn river belongs to water courses of medium hardness. During different periods, total mineralization of water varies within wide limits, and it is on average — 207,1–750,0 mg/L; insignificant exceeding of maximum acceptable concentrations of Br^-, Mn, Zn, Fe, Cr and Cu are observed for commercial fishing [14–17].

Methods and objects of studies

Results of generalization of file materials and published materials on complex ecologic monitoring in the Sytykan-Daldyn-Markha interfluve, covering industrial area of "ALROSA" UMPP and built-up area of the town Udachny are the basis for preparation of the article [14, 18–19]. Detailed summary of the industrial area of UMPP and additional sampling were performed in 2017 in relation to the study of Diamond and Precious Metal Geology Institute on "Ecologic-geochemical conditions of storages of mine-processing plants in Western Yakutia and assessment of the level of technogenic massif toxicity by the example of the Udachninsky MPP".

Chemical-analytical studies of samples of soils, bottom deposits, surface water and drainage brines are carried out with the methodological framework on integrated standard methods, using atomic-absorption, chemical and spectrophotometric approaches in the laboratories of physical-chemical methods of analysis of NEFU Research Institute of Applied Ecology of the North (2013–2017) and Center of multiple access physical-chemical methods of analysis of Diamond and Precious Metal Geology Institute (2017). Each analysis is carried out twice at d =15–30%, ρ = 0,95. Reliability of scientific results is provided by created data bank – results of chemical analysis of over 2000 samples of surface water, bottom deposits, soil, obtained using precise methods.

Table 1. Element features of cation-anion composition of the main abiotic components of the geoecosystem in the subsurface polygons of drainage water disposal

Element	Component of the geoecosystem								
	Drainage brines, mg/L, n = 4	Soil		Ground		Bottom sediments		Surface water	
		C, ppm, n = 27	Kk	C, ppm, n = 7	Kk	C, ppm, n = 25	Kk	C, mg/L, n = 25	Kk
Ca^{2+}	425,4–16071,7	241,3	**1,5**	400,0	**1,7**	180,0	0,9	71,6	1,2
Mg^{2+}	34000–44600	32,1	**1,6**	60,8	**1,8**	76,5	0,9	41,3	**1,7**
Na^{+}	9020–10700	71,5	**1,7**	155	**4,5**	207,7	0,9	11,7	1,0
K^{+}	14800–19000							6,5	1,4
HCO_3^-	<10,0	321,2	**1,8**	579,5	**2,0**	359,9	1,0	193,3	1,4
Cl^-	190400–212510	158,0	**2,3**	402,5	**2,7**	234,5	0,9	112,7	**1,8**
SO_4^{2-}	108–200	356,6	1,1	432,0	1,3	312,0	0,9	43,7	**2,4**
NO_3^-	<0,2	–		–		–		1,6	**4,3**

Notes. Hereinafter in Table 2: C — geometric mean. Кк — concentration factor regarding regional background.
Highlighted Кк ≥ 1,5.

Result discussion

Every natural reservoir for industrial water (wastes) storage in cryolithozone is characterized by interdependent parameters of environment, responsible for its filtration-capacity properties, physical-chemical values of the environment for the storage; temperature regime of rock sequences and overlying massif used for the pumping; compatibility of natural water and pumped industrial water (wastes); sealing properties of perennially frozen rocks and their dynamics over time. Notice that, drainage water does not quite belong to specific wastes of any producing operations. These are usual for the studied area subsurface brines, extracted during quarry dewatering, i.e. natural component of geoecosystem of the area. They are additionally affected by admixture of surface water and interaction with kimberlites in the area of mining works, as well as free contact with atmospheric gases. That is why drainage and subsurface waters are chemically homogenous chloride solutions with similar set of cations, completely intermixing with each other. They co-exist with host rocks for millions years, and therefore they are in equilibrium with them. Pumping does not lead to radical change of their quality. At 99% – these are chlorides [18, 20], with the highest migration ability among other components of water solutions.

Zones of perennially frozen rocks, potentially suitable for drainage brine storage, where polygons of disposal of drainage and highly mineralized water, are confined to the divide area. Soil formation takes place against a backdrop of a previous period of long denudation; as a result, at the level of modern erosion section, the Early Paleozoic carbonate rocks became predominant, acting as a soil-forming substrate,thus defining "carbonate" trend of existing geochemical processes with dominant position of Ca–Fe–Mg.

Level of macro- and microelement content ofsedimentary rocks corresponds to parameters of regional geochemical background and reflects the nature general geochemical specialization of abiotic components of the ecosystem within natural, and technogenic geochemical anomalies, genetically related to the areas of the known kimberlite bodies, including the Udachnaya and Zarnitsa pipes, with zones of deep faults of different orientation and disjunctive disturbances [19].

In general, "above-ground" part of the "Oktyabrsky" and "Kiengsky" polygons of disposal of drainage and highly mineralized water is characterized by wide element spectrum in the system soil (or ground) – bottom sediments– subsurface water (**Table 1**). The ground records development of processes of subsurface salinization with increase of portion of Cl-Na-K component. The Daldynriver and small creeks, especially in the area of the "Kiengsky" polygon impact, are characterized by high concentrations of the main cations and anions regarding regional background, among them the most significantly increased are nitrates, sulfates, chlorides and magnesium cations.

Against the regional background, spatial distribution of microelement composition of soil and ground in the polygons is characterized by Li, Zn, Mn, Co, Sr and V increased concentrations (**Table 2**).

Elements — indicators of kimberlite magmatism, abundant in the Ordovician and Cambrian rocks at the zone of exocontact with kimberlites of the Udachnaya pipe – Ni, Co and Cr. Their content in soil of the polygons is minor (Кк = 0,8–1,4). Li, Sr, Pb, Ni, Cu, Y and Sn concentrations are increased in microelement composition of the ground. Regarding content of bulk and mobile forms in soil of the studied area, influence of the industrial area of the Udachninsky MPP on soil cover is expressed by formation of technogenic poly-element anomaly:

- "Oktyabrsky" polygon $Li_{10,4}>Mn_{3,9}>Sr_{3,3}>Sn_{2,1}>Pb_{2,0}>Ga_{1,9}>$B (Sc, Zn-Ag-Co) $_{1,6}$.
- "Kiengsky" polygon $Li_{9,9}>Sr_{7,5}>Mn_{3,5}>V_{3,4}>Ag(Pb)_{2,7}>Sn_{2,1}>Cu_{1,7}>$Ga (Y) $_{1,6}$.

As a result of a surface slope, basis vector of technogenic streams is directed to the Daldyn river. Average content of Li, Sr, Ba, Cr, Ni, Mn, Cu and Fe in the Daldynriver is high enough. It is more likely that, Fe-group elements come into water course due to subsurface water.

It is known that, tectonic fault zones generate favorable conditions for active migration of subsurface water and its emergence to the surface, in case of hydrogeodynamic condition upset [16].

That is why "perennially frozen rocks – drainage brine" system represents natural-technogenic geosystem, which instability is determined by changes of temperature, mechanical, physical-chemical and chemical values.

Table 2. Characteristic of microelement composition of the main abiotic components of the geoecosystem on the territory of subsurface polygons of drainage water disposal

Element	Component of the geoecosystem												
	Drainage brines, mg/L, n = 4	Soil				Ground				Bottom sediments		Surface water	
		Total content		Mobile forms		Total content		Mobile forms					
		C, ppm, n = 22	Kk	C, ppm, n = 22	Kk	C, ppm, n = 7	Kk	C, ppm, n = 7	Kk	C, ppm, n = 25	Kk	C, mg/L, n = 25	Kk
Li	14,8–102,0	818.4	**9.9**	N/d**		852.00	**10.4**	N/d		N/d		0.25	**3.8**
Sr	3.06	207.51	**1.6**	N/d		428.15	**3.3**	N/d		N/d		0.19	0.3
Ba	18.0–34.0	424.32	0.9	N/d		388.20	0.8	N/d		N/d		1.03	1.4
Pb	0.013	3.21	0.3	0.40	0.2	3.24	**2.0**	0.81	0.5	1.27	1.0	<0.002	–
Ni	0.03–0.26	36.69	1.0	2.44	0.6	43.70	1.1	3.15	0.8	3.55	0.8	0.01	1.0
Mn	1.019–1.127	510.83	**4.1**	44.51	0.2	440.30	**3.5**	43.64	0.2	138.45	**1.5**	0.009	0.7
Cd	0.00072	N/d		0.05		N/d		0.04		0.039	**2.0**	<0.0002	–
Co	N/d	14.49	**1.7**	1.51	0.5	13.51	**1.6**	1.67	0.56	1.57	0.5	<0.0025	–
Cr	0.0046	50.34	0.6	0.89	0.7	42.87	0.5	1.69	1.4	1.09	1.2	0.0029	1
Zn	N/d	286.66	**5.3**	5.90	0.7	262.21	**4.9**	5.04	0.6	3.62	0.3	<0.25	–
Cu	0.015–0.033	12.25	0.4	N/d		12.16	**1.7**	N/d		0.2	0.1	0.0089	**2.2**
As	0.267	N/d		0.20	1.3	N/d		0.09	0.6	0.11	0.3	<0.005	–
Fe	0.33–6.29	18.06*		N/d		22.45*		N/d		N/d		0.045	0.5
V	N/d	34.65	**3.4**	N/d		27.91		N/d		N/d		N/d	
Sc	N/d	6.77		N/d		7.47		N/d		N/d		N/d	
Nb	N/d	60.54		N/d		83.27		N/d		N/d		N/d	
Zr	N/d	220.02		N/d		239.15		N/d		N/d		N/d	
Y	N/d	27.20	1.1	N/d		26.47	**1.6**	N/d		N/d		N/d	
Yb	N/d	2.34		N/d		2.60		N/d		N/d		N/d	
Ge	N/d	0.97		N/d		0.99		N/d		N/d		N/d	
Sn	N/d	3.46	1.4	N/d		3.00	**2.1**	N/d		N/d		N/d	

* Total iron content in soil is given in g/kg. **N/d – not determined.

At every point of sedimentary rock, solution should be in equilibrium with a mineral in contact with it. Any changes of thermodynamic conditions lead to the fact that, pore solution on one hand, becomes an active solution medium, on another hand – medium of initial accumulation and redistribution of chemical elements and combinations [17]. These processes become more intense, in case of abnormality of general piezometric level of subsurface water and due to changes of parametric pressure; elevation of highly mobile chemical elements to a day surface becomes more intense. Now, functional capacities of subsurface natural reservoirs of the "Oktyabrsky" and "Kiengsky" polygons in ecologically safe intervals of cryolithozoineare filled.Furthermore, after a certain point, capacities of the polygons were exceeded, that resulted in overflow of disposed water with emergence on a day surface.

In November 2012, in the Daldyn river basin, in the area of the Kieng-Yuryakh creek (Kiengsky polygon), emergence of highly mineralized water was found, it represented local spring with clear boundaries and a flowing out brooklet, in July 2013 an ice was observed on the water surface (**Fig. 2a, b**).

In 2017, track vehicles damaged the surface, and that is why emergence of highly mineralized water has unclear boundaries, and the area represents an artificial dead water 8x20 m, which water is characterized by high mineralization (up to 3,9 g/L) and weakly acid medium. Water composition is mainly chloride-sodium-calcium-magnesium. Excess of standardsis observed on Sr (26 times more), Li

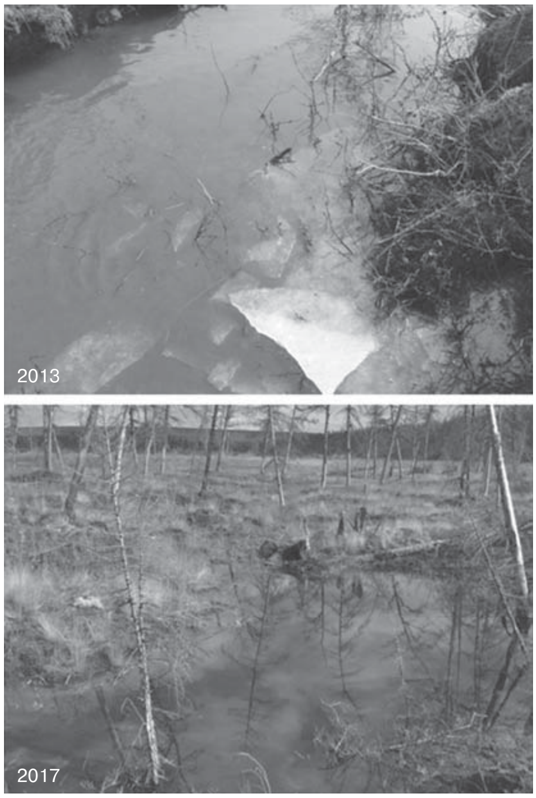

Fig. 2. Emergence of mineralized water on the Daldynriver during 2013, 2017 studies

Table 3. Mineralization of surface water of the Daldynriver at the segment of the emergence of highly mineralized water

Geographical reference of the sampling point	Mineralization of water, g/L			Notes
	2013	2014	2017	
Daldyn river 350 m above the mouth of the Sytykan river	0.23	0.39	0.21	Monitoring of the Daldyn river at the segment of the emergence of highly mineralized water to the surface
Daldyn river 500 m below the mouth of the Sytykan river	0.24	0.30	0.22	
Sytykan river mouth	0.22	0.40	0.22	
Daldyn river 1 km above the spring of Emergence of Highly Mineralized Water	0.30	0.33	0.42	
Spring of Emergence of Highly Mineralized Water 140 m south-west of the emergence of mineralized water from under ice crust in 2012-2013	269.55	91.12	3.9	
Daldyn river 100 m below the spring of mineralized water	0.45	0.56	0.83	
Daldyn river 500 m below the spring of mineralized water on a right bank	0.32	0.52	0.88	
Pravy Kieng creek, mouth	0.36	0.36	0.76	
Daldyn river, 1956 – 1966 [11,12]	0.08–0.74			Before commercial production at the Daldyn kimberlite field
Daldyn river middle course, 1994 [15]	0.43			Putting into operation of the Oktyabrsky polygon
Daldyn river middle course, 2012-2013 [16]	0.38			Putting into operation of the Kiengsky polygon

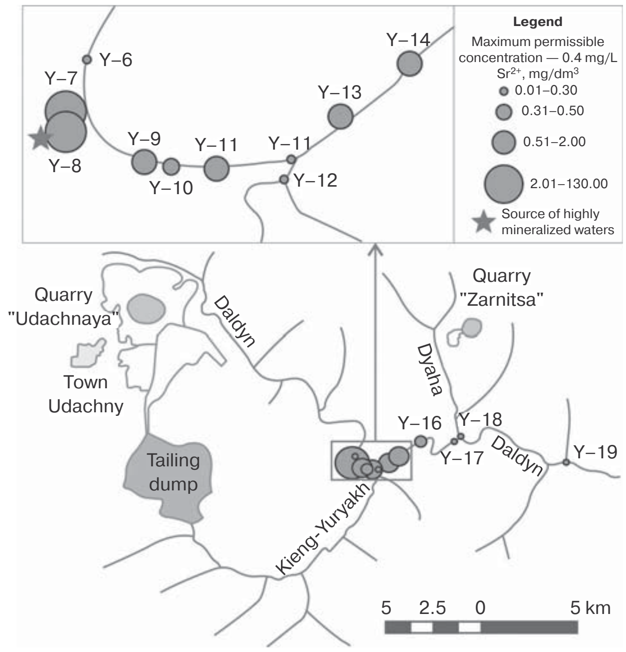

Fig. 3. Diagram of strontium content in surface water of the Daldynriver and near emergence of mineralized water spring

(16 times), Cu (14 times), Cl (9,8 times), Mg (5,1 times), K (2,9 times) and Na (2,3 times). Presence of extremely high content of lithium, strontium, chlorides and copper in a dead water determine impact of emergence of subsurface highly mineralized water, because there are no any other sources of inflow of these elements to subsurface water at this segment of the river.

In general, in the Daldyn river basin, impact of highly mineralized water can be traced by increase of chloride content, presence of high concentrations of lithium, strontium, barium (**Fig. 3**), and inflow of manganese, copper and iron with surface-water flow. Thus, major influence of mineralized water is traced on soil by Li, Sr, Ga high concentrations on the whole area, and on the Daldyn river surface — by huge values of Cl, Li, Sr, Ba.

Putting new polygon "Levoberezhny" into operation in 2013 slightly relievedgeoecologic stress, that immediately affected hydrochemical composition of surface water of the Daldynriver, particularly on mineralization value. At the areas outside the impact zone of technogenesis,mineralization of the Daldyn river surface water is stable and it is within limits 215–203 mg/L (**Table 3**). Increased mineralization of water is observed in the area of highly mineralized water emergence to the surface.

The “Levoberezhny” site has an estimated capacity – 11–13 million m^3, that provides brine disposal with yields from 270 to 350 m^3/hour for 5, may be even 6 years. In case of increase of functional capacities of the "Levoberezhny" polygon, there are fears of radioactive contamination of drainage water below sarcophagus of "Krystall" peaceful nuclear explosion and its further distribution on the disposal areas and so forth [21]. Thus, it is necessary to intensify exploration on the site (off the quarry) perspective for drainage water disposal — the Sugunakhsky block, and to put it into operation urgently.

Conclusions

In general, subsurface storage of drainage brines in perennially frozen rocks provides a possibility of exploitation of diamondiferous pipes and becomes extraordinary and justified impact on subsurface cryohydrosphere in the broadest sense. But, complex hydrogeologic situation requires major efforts to control it, forecast and timely correct originating complications, related to matters of safety, including geoecologic ones. Notice that, geoecologic situation on the polygons of drainage brine and highly mineralized water disposal is due to the combination of existing polyelemental anomalies of technogenic and natural character. The whole area of the "Oktyabrsky" and "Kiengsky" polygons with an emergence on the Daldynriver is located in geographical range of moderate and dangerous level of contamination. Chloride surface salinization is developed in the ground of the "Oktyabrsky" polygon. Emergence of mineralized water is traced in soil by Li, Sr, Ga high concentrations on all the profile, and on the Daldyn river surface water – Cl^-, Li, Sr, Ba huge values.

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