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TECHNICAL ARTICLE

Pit Lake and Drinking Water Intake: Example of Coexistence (Middle Urals, Russia)

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Abstract

The dewatering system of the Lipovsky nickel mining pit (Middle Urals, Russia) has performed a dual role. From 1961 to 1991, while nickel was being mined there, it protected the pit from flooding with groundwater; since 1989, it has been the principal source of drinking water for the town of Rezh (≈ 50,000 residents). After mining ceased, water withdrawal from the drainage wells decreased 2.5 times (to 100 L/s), resulting in a 120 m deep pit lake. A mass balance analysis has shown that water from the pit lake has become the leading source of water intake. However, the concentrations of the water's basic constituents at the eastern edge of the pit are several times higher than at the western edge. The reason for the significant increase in the water withdrawn by the wells of the western intake is the fact, that during the working of the main ore body, the eastern part of the pit was filled with overburden rock and substandard ore with dispersed sulfide mineralization. Flooding of the pit created a single aquifer between the pit lake and the eastern water intake facility, including an artificial aquifer within the refilled part of the pit. The rise of the groundwater level in the artificial aquifer to an elevation above 150 m (after 1994) led to active chemical weathering of sulfide-containing minerals and dissolution of secondary sulfates, which accounts for the increasing levels of constituents in the eastern part of the pit. The artificial aquifer has become a generator of salts. The dumping of sulfidic wastes and subsequent recovery of the water table have led to the release of sulfate, calcium, and metals into the local groundwater. To prevent the formation of an artificial aquifer, it is necessary to either completely remediate the unflooded portion using non-acid generating material or completely inundate the pit. Partial remediation would be the worst scenario as it could destabilize the hydrogeochemical processes and render long-term coexistence of the drinking water intake and the flooded pit problematic.

Keywords Groundwater · Nickel · Drinking water supply · Mining operations · Post-mining · Artificial aquifer · Mass balance

Introduction

The formation of potable groundwater deposits in areas disturbed by mining operations and the possibility of using groundwater after mining activities are completed are determined by both natural an operational factors, including the type of the mineral resource, method of remediation, and the design of the water intake facility.

Groundwater deposits are a renewable resource and a dynamic system, which makes them essentially different from solid mineral deposits. Extraction of groundwater leads to changes in the existing hydrodynamic and hydrogeochemical conditions: new sources of groundwater are engaged and the balance constituents of water withdrawal are redistributed. The feasibility and practicality of using the groundwater produced by dewatering a solid mineral deposit for other purposes is estimated when taking stock of the solid mineral deposit's balance reserves and designing the drainage system. There are successful examples of this practice of drinking and utility water supply systems set up in Kazakhstan, Ukraine, in Russia in the area of the Kursk magnetic anomaly, and some solid mineral deposits in the Ural region (Rybnikova and Rybnikov 2016).

In accordance with Russian legislation, the use of groundwater for drinking is regulated by sanitary-epidemiological requirements for drinking water supply sources (SanPiN 2.1.4.

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1074-01 2002; SanPiN 2.1.4. 1110-02 2003; GN 2.1.5. 1315-03 2003). One of the most essential requirements is the need to set up a sanitary protection zone around the water intake, including three belts to ensure protection against microbial and chemical contamination throughout the entire period of its operation. The regulations prohibit the installation of any facilities associated with a risk of microbial or chemical contamination of the groundwater, including underground burial of solid wastes and subsoil operations.

To meet these requirements, it is essential to control the hydrodynamic conditions of the solid mineral deposit during mining so that drinking water intake recharge sources are derived from clean areas. This can be achieved by using external dewatering systems located outside the mine and pit workings (peripheral dewatering systems (wells from the surface) or underground drainage facilities) and autonomous withdrawals from underground workings not connected with the mine drainage. The groundwater is thus derived from sources outside the possible areas of contamination, such as where water and the sulfide ore minerals are interacting. This can prevent deterioration of the drainage water quality due to the oxidation of ore minerals where there is free access of oxygen (Rybnikova and Rybnikov 2019a).

The dewatering scheme changes in the course of solid mineral mining, as does the sanitary ecological conditions within the area being drained, in particular due to substandard ore dumping, abandoned pit refilling, etc. After mining, the mine pit is typically flooded (Geller et al. 2013; Wolkersdorfer 2008), which results in the formation of a pit lake and redistribution of usable groundwater recharge sources, changes to the boundaries and area of the deposit, emergence of new contaminating factors, and entrapment of existing contaminants into the catchment area (Rybnikova and Rybnikov 2019b). Nevertheless, many water intake facilities continue because over the period of mining operations, the dewatering system in the mining area becomes an important component of the water supply system for nearby cities and towns. The possibility of using such systems as a source of drinking water supply after mine closure requires consideration of redistributing or reducing water withdrawals, creation of barrage (protective) water drainage, and design of water treatment systems. The purpose of this paper was to assess the post-mining groundwater formation processes and to provide justification for using a drinking water intake facility near a flooded pit of the Lipovsky nickel deposit (Middle Urals, Russia).

Case Study

The Lipovsky nickel silicate deposit is located on the eastern slope of the Middle Urals within the transition zone between the folded Ural mountains and the western Siberian lowland, on the left-bank slope of the Rezh River valley (Ob River basin, Arctic Ocean), in the territory of the Sverdlovsk region, 90 km northeast of Ekaterinburg. The area has a continental climate with a long-time average annual air temperature of 0.2 °C and a winter that lasts about five months. It is located within a humid zone with a long-time average annual humidity level of 73%.

The dewatering system of the Lipovsky mining pit performed two functions: during the mining operation, from 1961 to 1991, it protected the pit from flooding with groundwater; since 1989, it has been the principal source of drinking water for the town of Rezh (≈ 50,000 residents) by a specially constructed 20 km water supply line.

The Lipovsky deposit is associated with a group of small tabular bodies of serpentinite measuring ≈ 2.5 km^2 in total, 30–300 m thick, and extending from 100 m to 2 km, occurring among marble, gneiss, and amphibolite strata of the Murzinskaya suite. These rocks form a brachysyncline sandwiched between Murzinsky, Aduisky, and Sokolovsky granite masses, which are invaded with numerous dikes of granite, aplite, and pegmatite and capped with Mezozoic-Cenozoic continental sediments (Fig. 1). The continental sediments are composed of bauxite-like clay of the Early Cretaceous, sandy clays and sands with Upper Cretaceous lignite interbeds, arenaceous-argillaceous deposits with Oligocene lignite interbeds, and Neogen and Anthropogen clays and loams. The Cretaceous and Paleogene deposits occur directly over karst formations and ores in karst depressions in the marble.

The nickel silicate deposit is associated with development zones in the Mesozoic weathering crust formation atop the Paleozoic basement. The thickness of the weathering crust is the greatest (up to 200 m) at tectonically disturbed contacts of serpentinite with marble and at contacts of thin dikes of marble with serpentinite and marble. The main nickel carrier minerals are decomposed serpentine, nontronite, nepouite, garnierite, montmorillonite, kerolite, iron oxides of the goethite-hydrogoethite series, psilomelane group, and karst ore matter of carbonaceous-argillaceous composition. The characteristic feature is the presence of sulfides as dispersed mineralization in hydrothermal ore formations and in karst cavities (as pyrite, pyrrhotite, and marcasite).

The deposit displays signs of recent mineral formation processes: the weathered serpentinites have water-soluble sulfates forming on them, such as epsomite (which can contain nickel), and melanterite. This process is fairly well known (Appelo and Postma 2005) and has been considered in particular with reference to the mining facilities in the Middle Urals (Rybnikova and Rybnikov 2017, 2019).

The tectonic and geological structure of the area determines its specific hydrogeological conditions and groundwater flow from a large water catchment area: here, three troughs converge to a single knot, there are numerous

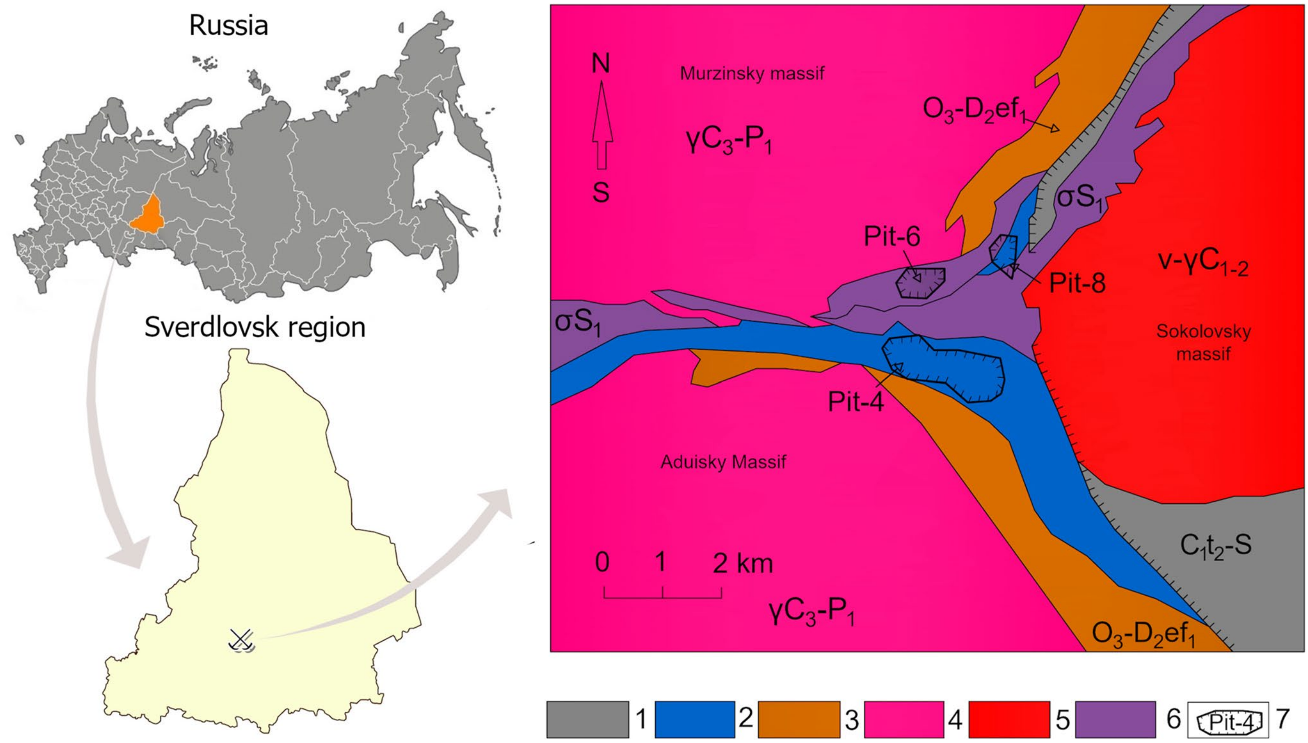

Fig. 1 Schematic geological map of the Lipovsky deposit (Kisin et al. 2014). Legends: 1 – terrigenous sedimentary rock; 2 – marbles; 3 – terrigeneous sedimentary rock metamorphically altered; 4 – granitoids of the Murzinsky and Aduisky masses; 5 – granitods of the Sokolvsky mass; 6 – ultrabasic rock; 7 – pits

tectonic disturbances in the rocks forming troughs, and carbonaceous, cavernous rocks are well represented. The catchment basin has low slopes, large forested areas, and is characterized by low-thickness soil.

The area under consideration has four types of rocks that contain water. The loose Meso-Cenozoic sediments are weakly and sporadically water-logged. The argillo-arenaceous weathered crust and karst formations and fractured and fractured-karst rocks have a higher water content. The gneisses and crystalline schists are characterized by a low water content. The water yield of the serpentinites outside of the contact and tectonic faulting zone is also low. A similar non-uniform water content is displayed by the granites as well. The greatest water yield is provided by the granites in areas with extensive veined bodies and in contact zones with talc-carbonate and other rock species, as well as in crushed and tectonic faulting zones. Outside of these areas, the granites do not contain any significant amount of water. The most water-abundant rocks are carbonates: limestones and marbles. They are characterized by non-uniform fracturing and cavernous porosity and, as a consequence, non-uniform water content. Wells demonstrate the greatest output if made in tectonically disturbed and extensively karstic zones (typically 90 L/s).

The groundwater is mainly recharged through the infiltration of atmospheric precipitation. Discharge is directed into local depressions of the terrain and onwards into the river valleys.

From 1961 until the early 1990s, the peripheral drainage system of the Lipovsky nickel ore pit ensured safe mining of the mineral. It had two water drainage intake structures (on the western and eastern edges of the pit) with 200 m deep wells (Fig. 2). The western water intake facility consists of four wells, which penetrate into the water-bearing zone of Paleozoic carbonaceous rocks. The eastern water intake facility has four wells, which penetrate into the zone of Riffean-Paleozoic carbonaceous rocks.

By 1991 when the mine was abandoned, the level was drawn down by 127 m from the static level (elevation + 93 m) at an average annual discharge rate of 250 L/s. The total recharge area is estimated to be around 100 km^2, and the area of the active part of the depression cone was ≈ 30 km^2. The pit's volume is 51 million m^3. The mining operation was accompanied by the filling of the pit's eastern part with overburden rock and substandard ore. After closure of the nickel mining pit, water withdrawal decreased to 100 L/s, which resulted in partial recovery of the groundwater level and formation of a 120 m deep pit lake.

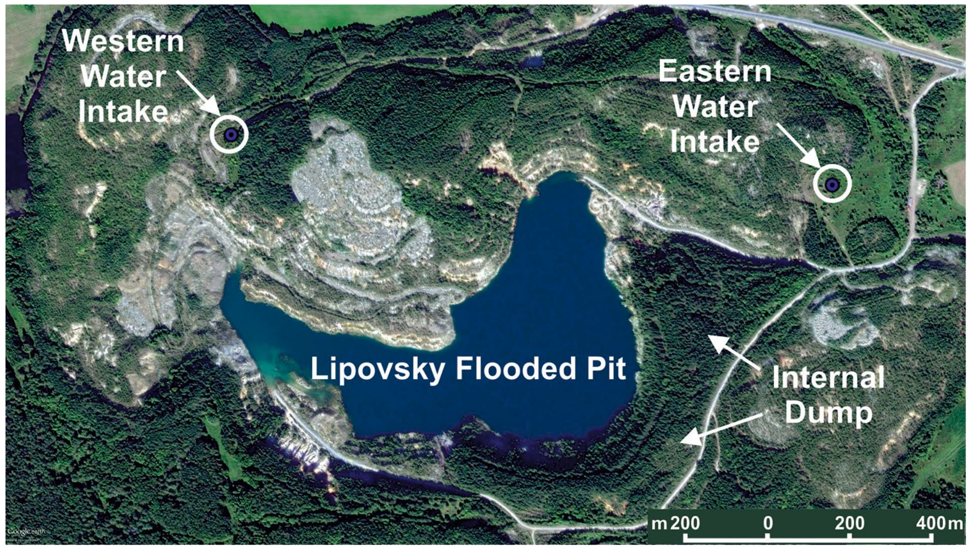

Fig. 2 The location of the flooded pit of the Lipovsky nickel deposit and drinking water intakes

Sampling and Methods

Hydrochemical testing data were used to characterize the composition of the ground and surface waters, starting with those obtained during the exploration of the nickel deposit in 1980 till 2017, a total of 148 analyses (Tables 1, 2). The chemical analyses were performed at certified laboratories using authorized testing procedures. During the above period, samples of river water, groundwater, mine drainage water, and pit lake water were obtained. These were used for measuring conductivity, pH, major cation and anion contents, and the concentrations of potentially toxic metals (Cu, Zn, Pb, Cd, Fe, Mn, Ni, Co). The latter were determined by atomic absorption spectrometry AAS-novAA 300 spectrometer). The ionic-cationic composition of the waters was determined by titration.

Research Results and Discussion

In the summer of 1993, interval water testing was performed in the pit lake. No dependence of water composition on testing depth was revealed. The total dissolved solids (TDS) in the pit water varied from 262 to 334 mg/L; the sulfate content ranged from 26 to 86 mg/L, and the nickel content amounted to 110–380 µg/L, whereas the drainage water never exceeded 20–100 µg/L during the mining operations.

The interval hydrochemical testing data obtained in the pit lake in 2000 showed no changes in chemical composition with depth while the variations of the main indicators were found to be lower: thus, the total solids varied from 312 to 328 mg/L, the sulfate content varied in the range of 78–86 mg/L, and the nickel content from 190 to 230 µg/L.

In natural conditions, the groundwater is of hydrogen, carbonate, calcium, and calcium-magnesium type with total dissolved solids up to 0.2 g/L, sulfate content of 26 mg/L, and chloride content of 6.7 mg/L. The metallogenic characteristics of the area, represented primarily by a broad development of ultrabasites and nickel-bearing crusts of weathering, determine the presence of a certain group of metals, such as nickel, cobalt, beryllium, arsenic, copper, zinc, cadmium, and chromium in the groundwater. However, the concentrations of these elements in the natural conditions are substantially less than the standard values for drinking water. In particular, the natural background value for nickel is 2–4 µg/L against the permissible level of 20 µg/L (GN 2.1.5.1315-03). Over the 30 year period of water drainage and intake at full capacity (until the end of 1991), the quality of the groundwater changed; most of the indicators increased 1.5–2 times compared with the natural levels (Figs. 3, 4; Tables 1, 2).

After the flooding of the pit, the quality of the water at the western and eastern edges of the pit became essentially different: at the western edge, the trend of changes was about the same as previously, while the water quality at the eastern edge started displaying a more rapid growth in all indicators. The concentration of sulfate ions in the water intake wells of the western edge increased to 48–92 mg/L, while at the eastern edge it rose to 120–157 mg/L. Meanwhile, the concentration of sulfate ions in the pit lake was about 80 mg/L. The water in the artificial pit lake is weakly alkaline, with pH = 7.7–7.9; the groundwater from the eastern intake has pH = 6.8 ÷ 8.2; and that from the western intake pH = 6.7 ÷ 8.1; Eh = 239 ÷ 310 mV.

Each water intake facility withdraws water from two sources: the pit lake and the groundwater resources. The balance components of water withdrawal may be estimated using sulfate ion content as a marker. Thus, for the western intake, the mass balance is given by:

Table 1 Average value and interval (min–max) for TDS, pH, concentration of major ions in surface and groundwater in the Lipovsky region

Water samples ID (see Fig. 4), sampling site and number of samples		TDS (mg/L)	pH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)
I	Lipovka River ($n=1$)	190	7.6	28	7	4.7	3.5	5	125
II	Mostovka River ($n=1$)	196	7.5	33	6	6	7.1	10	128
IIIa	Groundwater in natural conditions ($n=4$)								
	Average	201	7.3	38	20	7.3	6.7	11	181
	Min	164	6.8	33	13	3.0	5.3	7	82
	Max	220	7.6	45	27	9.2	8.9	18	220
IIIb	Pit lake 1993 ($n=6$)								
	Average	306	8.0	62	20	6.4	5.0	78	211
	Min	292	7.5	50	18	5.5	3.5	69	174
	Max	334	8.3	73	23	7.7	7.1	82	229
IIIa	Pit lake 2000 ($n=7$)								
	Average	320	7.8	70	20	4.8	3.5	83	233
	Min	312	7.7	68	20	4.7	1.8	78	226
	Max	328	7.9	71	21	4.9	7.1	86	238
IVa	Eastern intake before 1992 ($n=24$)								
	Average	273	7.6	59.8	15.5	8.6	6.6	27	239
	Min	180	7.0	50.1	10.9	0.2	3.5	16	201
	Max	336	8.2	70.1	27.9	18.9	14.2	37	262
IVb	Eastern intake in 1993–2004 ($n=12$)								
	Average	410	7.4	96	19	6.5	10.1	99	255
	Min	314	6.9	78	17	4.8	3.6	79	189
	Max	486	8.1	123	21	7.6	14.2	126	290
IVc	Eastern intake after 2005 ($n=22$)								
	Average	450	7.5	106	21	8.1	11.5	139	260
	Min	345	6.8	86	19	4.1	3.8	120	215
	Max	524	8.2	136	23	7.8	14.2	157	305
Va	Western intake before 1992 ($n=25$)								
	Average	251	7.6	58	14	7.6	6.5	24	222
	Min	161	6.9	22	5	0.4	3.5	8	131
	Max	334	8.2	84	18	37.3	14.2	46	256
Vb	Western intake in 1993–2004 ($n=24$)								
	Average	285	7.5	62	15	5.4	4.3	46	218
	Min	212	6.7	45	11	4.3	3.4	19	195
	Max	336	8.2	73	17	7.2	7.1	72	235
Vc	Western intake after 2005 ($n=19$)								
	Average	302	7.6	65	17	6.5	5.9	65	231
	Min	215	6.8	47	13	4.7	3.9	48	187
	Max	347	8.1	77	19	7.5	11.8	92	249

$$Q_i^W C_i^W = Q_p^W C_p^W + Q_n^W C_n^W,$$

where Q_i^W, Q_p^W, Q_n^W represent water discharge rates at the western intake, resources from the pit lake, and the groundwater resources with corresponding concentrations C_i^W, C_p^W, C_n^W in the water intake, pit lake, and aquifer. Thus, when $C_i^W = 60\text{mg/L}, C_p^W = 80\text{mg/L}$, and $C_n^W = 10\text{mg/L}$, the fraction of resources drawn from the lake by the western intake amounts to more than 50%.

Assuming that the discharge rate of the eastern intake is also formed at the expense of water from the pit lake (50%) and groundwater (50%), then the mass balance for the eastern water intake facility may be represented as:

Table 2 Average value and interval (min–max) for trace elements in surface and groundwaters in the Lipovsky region

Water samples ID (see Fig. 4), sampling site and number of samples		Fe_{tot} (μg/L)	NO_2 (μg/L)	NO_3 (mg/L)	NH_4 (μg/L)	SiO_2 (mg/L)	Mn (μg/L)	Zn (μg/L)	Ni (μg/L)
I	Lipovka river ($n=1$)	20	25	10.7	400	10.0	15	19	2
II	Mostovka river ($n=1$)	25	50	13.5	0	22.0	18	15	5
IIIa	Groundwater in natural conditions ($n=4$)								
	Average	22	20	2.7	10	15.1	20	25	3
	Min	10	0	0.5	0	8.2	5	11	2
	Max	45	41	8.9	55	21.3	32	32	6
IIIb	Pit lake 1993 ($n=6$)								
	Average	81	10	9.5	30	18.9	10	100	280
	Min	32	0	6.3	0	14.8	0	0	110
	Max	155	40	13.5	200	26.0	30	230	380
IIIa	Pit lake 2000 ($n=7$)								
	Average	70	40	6.8	170	16.2	11	95	210
	Min	40	30	5.9	100	15.2	1	2	190
	Max	140	60	7.1	400	17.0	22	180	230
IVa	Eastern intake before 1992 ($n=24$)								
	Average	320	20	3.6	20	18.2	10	80	20
	Min	0	0	0.8	0	7.6	0	20	2
	Max	3800	300	10.0	400	23.1	40	430	60
IVb	Eastern intake in 1993–2004 ($n=12$)								
	Average	180	20	20.3	180	18.6	20	40	90
	Min	80	0	10.5	100	5.8	10	20	10
	Max	240	100	36.0	300	23.4	20	90	120
IVc	Eastern intake after 2005 ($n=22$)								
	Average	190	20	10.5	110	19.5	20	70	100
	Min	50	0	8.5	0	6.5	10	20	40
	Max	490	150	19.4	280	28.7	29	150	130
Va	Western intake before 1992 ($n=25$)								
	Average	330	10	2.5	20	17.0	60	50	20
	Min	50	0	0.7	0	6.0	0	10	0
	Max	800	70	10.0	100	25.2	700	460	100
Vb	Western intake in 1993–2004 ($n=24$)								
	Average	20	20	6.3	150	22.7	1	120	30
	Min	0	0	3.6	0	10.5	0	0	0
	Max	110	220	8.8	2000	27.8	5	40	80
Vc	Western intake after 2005 ($n=19$)								
	Average	120	30	5.8	12	21.8	50	15	40
	Min	60	0	0.5	0	12.5	0	10	10
	Max	170	190	9.7	650	25.7	90	50	70

$$Q_i^E C_i^E = Q_p^E C_p^E + Q_n^E C_n^E.$$

where Q_i^E, Q_p^E, Q_n^E represent water discharge rates at the western intake, resources from the pit lake, and groundwater resources with corresponding concentrations $C_i^E, C_p^E,$ and C_n^E in the water intake, pit lake, and aquifer. Then:

$$C_i^E = 0.5C_n^E + 0.5C_p^E; C_p^E = 2C_i^E - C_n^E$$

and for C_i^E=140 mg/L; C_n^E=10 mg/L, the concentration of sulfate ions in the water coming from the internal dump amounts to $C_p^E = 270$ mg/L, which is 3.5 times higher than that in the pit lake.

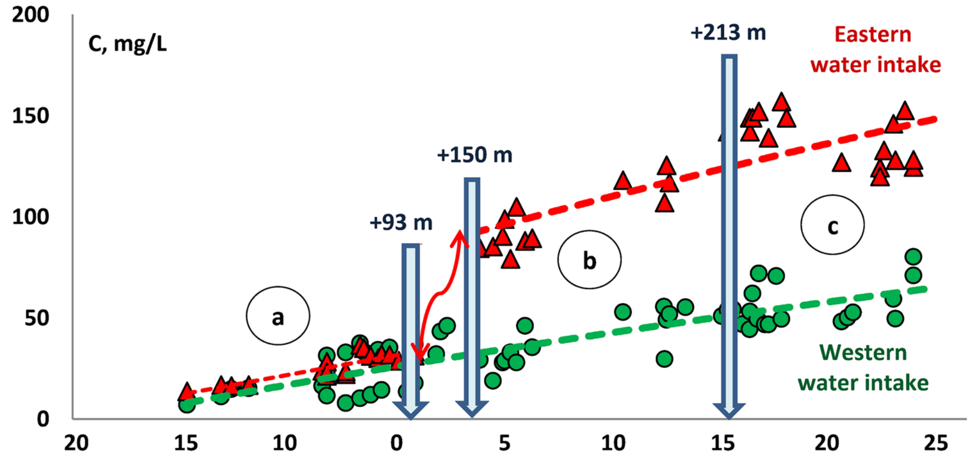

Fig. 3 Changes in the sulfate-ion contents of the groundwater from the wells of the eastern and western water intakes of the Lipovsky fresh groundwater deposit. The X axis plots time in years, «0» corresponds to the cessation of water withdrawal (the end of 1991) and beginning of pit flooding

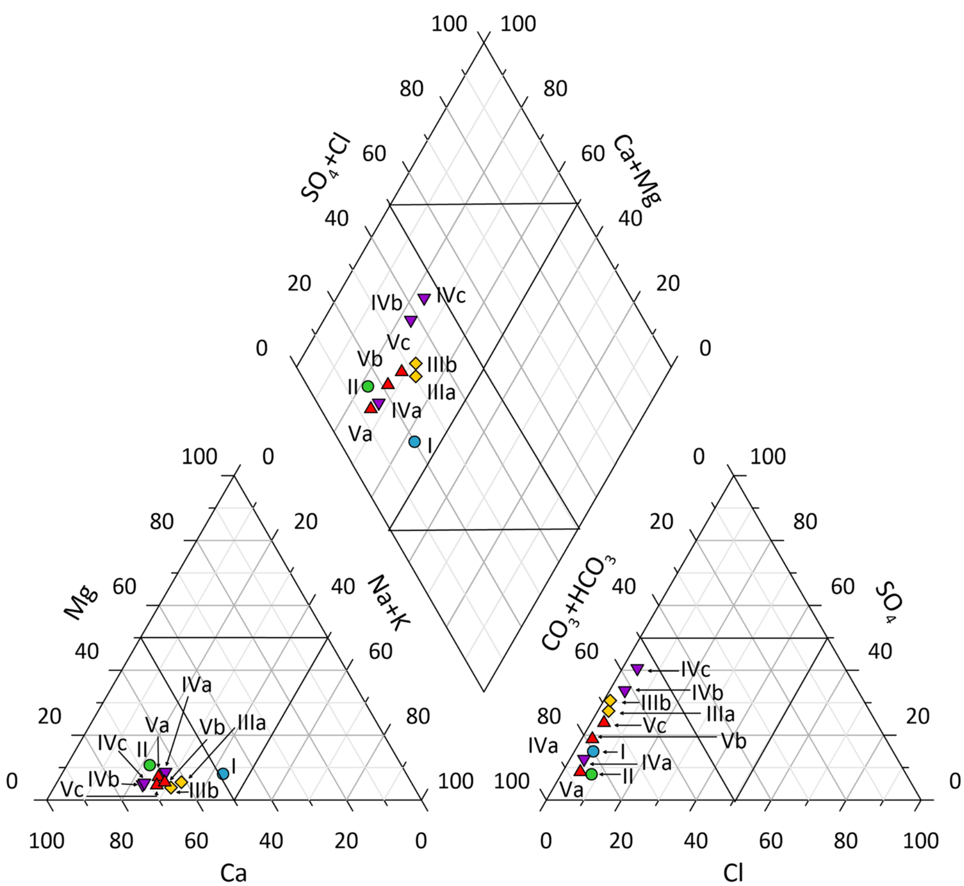

Fig. 4 Piper tri-linear diagram of hydrogeochemical facies of water samples from the Lipovsky region. For water sample IDs see Table 1

The concentration of sulfate ions in the water withdrawn by the wells of the eastern intake is considerably increased due to its location on the pit edge that was filled with overburden and substandard ore with dispersed sulfide mineralization during the mining of the main ore body (Figs. 2, 5). In fact, the remediation project provided for filling all the pits of the Lipovsky deposit on closure, level with the ground surface; this is practiced at many abandoned mines in Russia (Rybnikova et al. 2017).

Decreased water withdrawal after 1991 led to the filling of the cone of depression, flooding of the pit, rising of the water level in the pit lake and, as a consequence, formation of a unified aquifer between the pit lake and the eastern intake, including an artificial aquifer within the filled part of the pit. The rising of the groundwater table in the artificial aquifer to an elevation of + 150 m and higher (after 1994) with free access of oxygen has led to active geochemical weathering of the sulfide-containing minerals

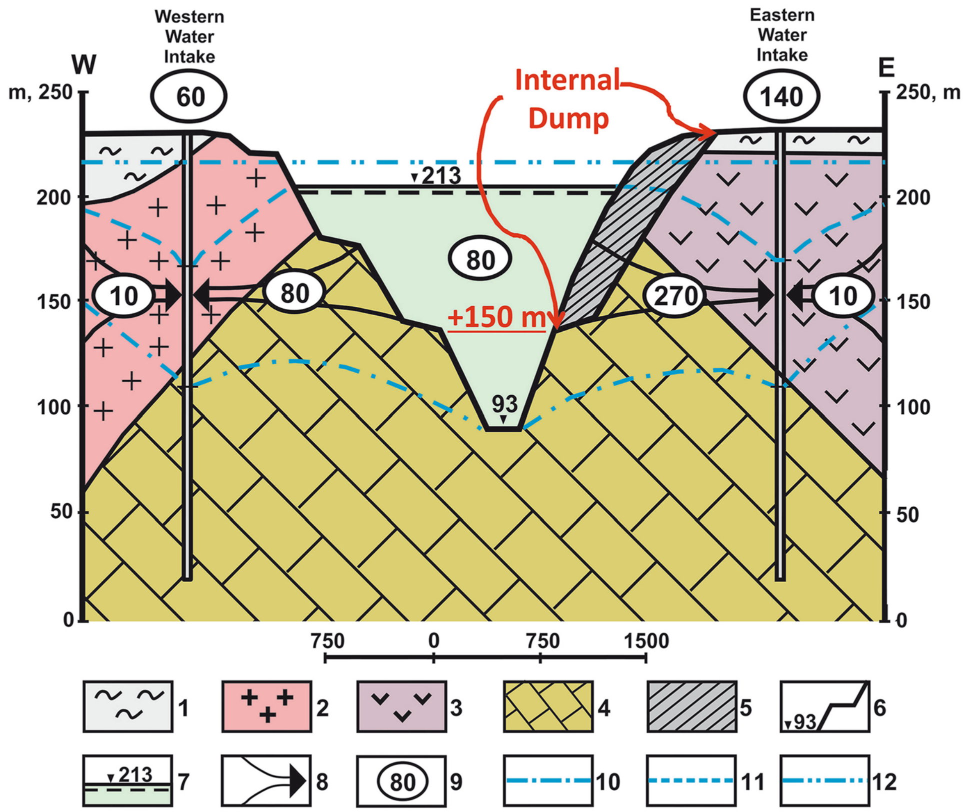

Fig. 5 Hydrogeochemical model of groundwater quality formation at the Lipovsky deposit. Legends: 1 – argillaceous weathering crust; 2 – intrusive rock aquifer (granites); 3 – Riffean-Paleozoic metamorphic rock aquifer (schist, serpentinites, siliceous rocks); 4 – Paleozoic carbonate rock aquifer (marbles, limestones); 5 – internal dump of overburden rock and substandard ore, artificial aquifer; 6 – open-pit outline and its bottom elevation mark; 7—water level in the pit after flooding; 8 –groundwater flow direction at the present time; 9 – sulfate-ion concentration, mg/L; 10 – 12 groundwater level by phase, 11 – during mining; 12 – at the present time; 13 – in natural conditions

and dissolution of secondary sulfates. This accounts for the increased concentrations of sulfate, nickel, and other components in the groundwater intake on the eastern edge of the pit. The artificial aquifer has thus become a generator of sulfate salts in the water withdrawn at the eastern water intake facility.

Conclusions

Thus, at the present time, the recharge sources of the Lipovsky groundwater deposit have fundamentally changed. For the western intake, the water from the open pit has a sulfate ion concentration of 80 mg/L and the natural groundwater from the catchment area has a sulfate concentration of 10 mg/L. The recharge water from the pit lake is additionally enriched by filtration through the artificial aquifer, in which the sulfate concentrations are 270 mg/L. The main process by which the waters are enriched with sulfates, nickel, and other elements is the chemical weathering of sulfide minerals and dissolution of secondary sulfates remaining in the unmined ore in the mining pit, overburden, and substandard ore that were used to fill the eastern part of the pit.

In recent years, the nickel content has persistently exceeded the permissible level, achieving 10–70 µg/L at the western intake (exceeding MAC 3.5 times) and 40–130 µg/L at the eastern intake (exceeding MAC up to 6.5 times; GN 2.1.5. 1315-03 2003). This water intake facility is currently still in use, being the only water supply source for the town of Rezh.

Without denying the significance of hydrochemical activity in weathering crusts (particularly in karst sinkholes) to groundwater chemistry (Bizyaev 2012), it should be pointed out that this factor apparently played a major role during the period when the water drainage system was operating, the artificial aeration zone was forming, and oxidation processes were intensifying across the entire cone of depression. The formation of the pit lake and artificial aquifer in the remediated part of the flooded pit provided more efficient sources of chemical redistribution after 1991 for the water intake facility. The basic processes of transformation at the Lipovsky post-mining system are not over, and the hydrogeochemical situation is far from being stable, which is supported by the continuing changes in the sulfate-ion contents of the eastern and western water intakes.

Analysis of transformations in the chemical composition of the groundwater in the area of the Lipovsky pit in the post-mining period suggests that the internal dump (partial filling of the pit with overburden and substandard ore) has become the leading cause of groundwater contamination after the flooding of the pit. To prevent the formation of an artificial aquifer with elevated TDS and concentrations of major ions (sulfate, calcium) and trace elements (nickel), it is necessary to either fully remediate the unflooded portion using non-acid generating material or completely inundate the pit. Partial remediation would be the worst scenario as it could destabilize the hydrogeochemical processes and render long-term coexistence of the drinking water intake and the flooded pit problematic.

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