Groundwater Quality Formation at Drinking Water Intakes Near a Flooded Pit (Middle Urals, Russia)

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Abstract

Mining is often accompanied by dewatering. Groundwater extracted by drainage wells outside of a pit usually has good quality and meets the requirements for drinking water. In the Middle Urals, water is supplied to some cities from such sources. However, after mining ceases and mine workings flood, the groundwater quality at such water intakes gradually deteriorates. Using the Lipovsky water intake as an example, a mass balance analysis indicated that dissolution of secondary sulfates in the internal dump was causing the contamination.

Keywords: secondary sulfates, mass balance, technogenic aquifer, dissolution, internal dump

Introduction

The availability of drinking groundwater resources and groundwater usability in areas disturbed by mining operations is determined by both natural and industrial factors, including the type of mineral being mined, the land remediation method, and water intake design (Palkin et al., 2011). Unlike deposits of solid minerals, groundwater is a renewable resource and a dynamic system: groundwater extraction leads to changes in existing and development of new hydrodynamic and hydrogeochemical conditions, redistribution of the system's balance constituents, and engagement of new sources in the formation of a deposit's resources (Rybnikova et al., 2017).

Fresh groundwater deposits within mining sites are continually exposed to changes in the groundwater balance structure by mining and even more so, by mine closure. In the post-mining phase, wet closure of the mine typically leads to redistribution of usable groundwater recharge sources, changes to the boundaries and area of the groundwater deposit, and emergence of new contaminating factors or entrapment of existing ones into the catchment area. Nevertheless, many water intake facilities are still operating due to the availability of a decades-long infrastructure (Rybnikova and Rybnikov, 2016).

The objective of this study was to assess the resource potential and patterns of change in drinking groundwater quality after the flooding of a nickel open pit mine, using the Lipovsky groundwater deposit as an example.

Case study and methods

The Lipovsky nickel silicate deposit is located on the eastern slope of the Middle Urals within the transition zone between the Folded-Mountain Urals and the Western Siberian Lowland, on the left-bank slope of the Rezh river valley (Sverdlovsk Region). The area has a continental climate with an average annual air temperature of 0.2°C and a winter that lasts about 5 months. The dewatering system of the Lipovsky mining pit served two functions: it protected the pit against flooding and served to supply drinking water to the town of Rezh (about 50 000 residents). To this end, a 20 km water supply line was constructed from the pit to the town (fig. 1).

The Lipovsky nickel silicate deposit is associated with development zones in the Mesozoic weathered crust formation atop the Paleozoic basement. The thickness of the weathered crust is greatest (up to 200 m) at tectonically disturbed contacts of serpentinites with marbles and at contacts of thin dikes of marbles with serpentinites and marbles. 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 (Emlin, 1991).

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), each having three to five 200 m deep extraction wells.

The most water-flooded types are carbonaceous rocks, limestones and marbles. The pre-mining groundwater level was at +220 m elevation. By 1991, when the mine was abandoned, the level was drawn down 127 m from the static level (elevation +93 m) by an average annual discharge rate of 250 L/s. The total recharge area is estimated to be about 100 km2, and the area of the active part of the depression cone about 30 km2. The mined-out space is 51 million m3. Mining was accompanied by the filling of the pit's eastern part with overburden rock and substandard ore.

After mining ceased, water withdrawal decreased to 100 L/s, which resulted in a partial recovery of the groundwater and the formation of a 120 m deep pit lake. In natural conditions, the groundwater was of hydrocarbonate-calcium and calcium-magnesium type, with a salt content of up to 0.2 g/L, a sulfate content of not more than 10-15 mg/L, and a chloride content of not more than 5–7 mg/L. The groundwater had a pH of 6.8 to 7.9 and an Eh of 239 to 310 mV.

The metallogenic characteristics of the area, represented primarily by a broad development of ultrabasites and nickel-bearing minerals, determine the presence in the groundwaters of a certain group of metals, such as nickel, cobalt, beryllium, arsenic, copper, zinc, cadmium, and chromium. However, the natural background concentrations of these elements are substantially lower than the standard values for drinking water. In particular, the natural background value for nickel is 0.002-0.004 mg/L against the permissible level of 0.02 mg/L. The characteristic feature is the presence of sulfides as dispersed mineralization in hydrothermal ore formations and in karst cavities (as pyrite, pyrrhotine, and marcasite). The deposit displays signs of recent mineral formation processes; the weathered serpetinites have water-soluble sulfates forming on them, such as epsomites and melanterite (Bizyaev, 2012).

Research results and discussion

Over the 30-year period of water drainage and intake until 1991, the groundwater quality changed, with most of the indicators increasing 1.5–2 times compared to their

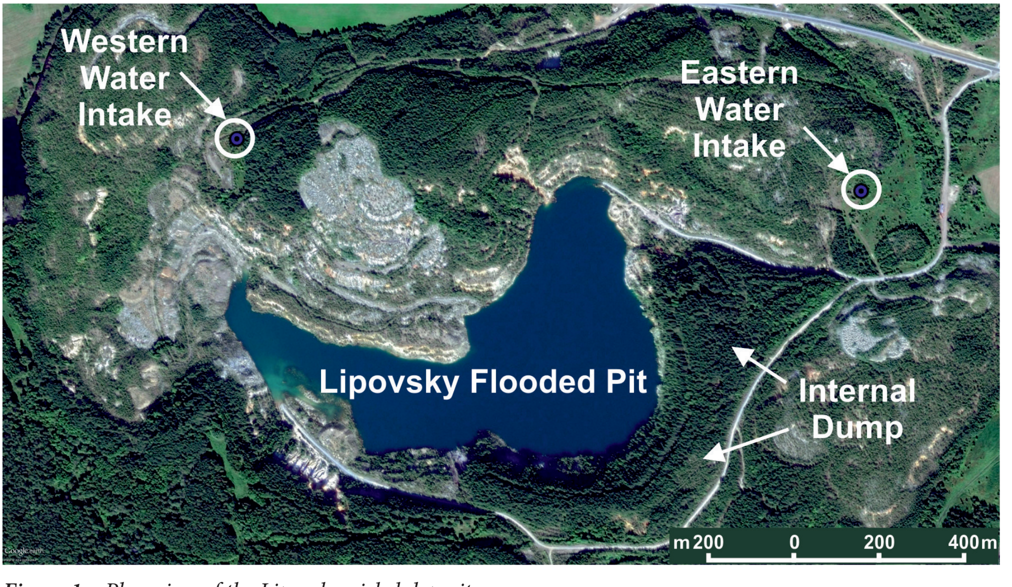

Figure 1 *– Plan view of the Lipovsky nickel deposit*

natural levels (fig. 2). It should be noted that the concentrations of the groundwater components on the western and eastern edges did not differ before water withdrawal decreased and the pit lake began to fill. Subsequently, the concentrations of the marker components (i.e., dissolved sulfate and nickel) increased considerably, particularly in the wells on the eastern edge of the pit, where the sulfate content increased 14-16 times (to 140–160 mg/L) and nickel increased 25-30 times (to 0.1 mg/L). In the wells on the western edge, this process was less rapid and the sulfate content increased 6-8 times (to 62–85 mg/L) and the nickel content 10-15 times (to 0.03 mg/L).

Previous research has demonstrated that the sulfate and nickel content water in the pit lake increases slightly with depth, from 79 mg/L (at a depth of 10 m) to 85 mg/L (at a depth of 70 m), and 0.19 mg/L (at 10 m) to 0.23 mg/L (at 70 m), respectively (Palkin and Palkin, 2002)

An essential geomigration estimate may be obtained based on a tentative mass balance calculation using sulfate ion content as the main marker (indicator) of change in groundwater quality. For the western water intake, the fraction of resources coming from the pit lake (Q_{wp}/Q_{wi}) may be estimated using the following balance equation:

$Q_{wi}*C_{wi} = Q_{wp}*C_{wp} + Q_{wn}*C_{wn}$,

where Q_{wi}, Q_{wp}, Q_{wn} represent water discharge rates at the western intake and recharge resources from the pit lake and aquifer in the area of resources formation, with the corresponding concentrations C_{wi}, C_{wp}, and C_{wn} in the water intake, pit lake and aquifer in the resource formation area. Then for the concentrations $C_{wi} = 60$, $C_{wp} = 80$ and $C_{wn} = 10$ mg/L, we obtain $Q_{wp}/Q_{wi} \approx 2/3$.

If we assume that the discharge rate of the eastern intake Q_{ei} is also formed at the expense of withdrawing pit lake waters (not less than half of $Q_{ep} = Q_{en} = 0.5Q_{ei}$), then in this case:

$Q_{ei}*C_{ei} = Q_{ep}*C_{ep} + Q_{en}*C_{en}$; $C_{ei} = 0.5C_{ep} + 0.5C_{en}$; $C_{ep} = 2C_{ei} - C_{en}$

and for $C_{ei} = 140$ and $C_{en} = 10$ mg/L, the sulfate content of the water from the pit lake would amount to $C_{ep} = 260$ mg/L, which is 3.5 times higher than what is formed in the pit lake itself.

The wells of the eastern intake are located on the pit edge, which was filled with overburden and substandard ore with dispersed sulfide mineralization during the mining of the main orebody (fig. 3).

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 a

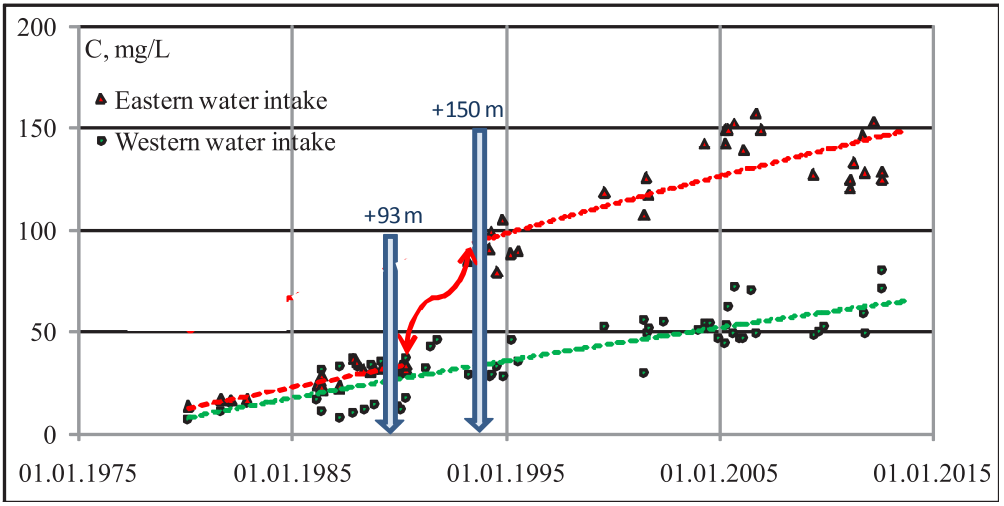

Figure 2 – Changes in the sulfate-ion contents of the groundwaters in the wells on the eastern and western edges of the Lipovsky fresh groundwater deposit. The blue arrows point at pit flooding stages: +93 m – beginning of flooding; +150 m – beginning of tecnogenic aquifer formation in the internal dump.

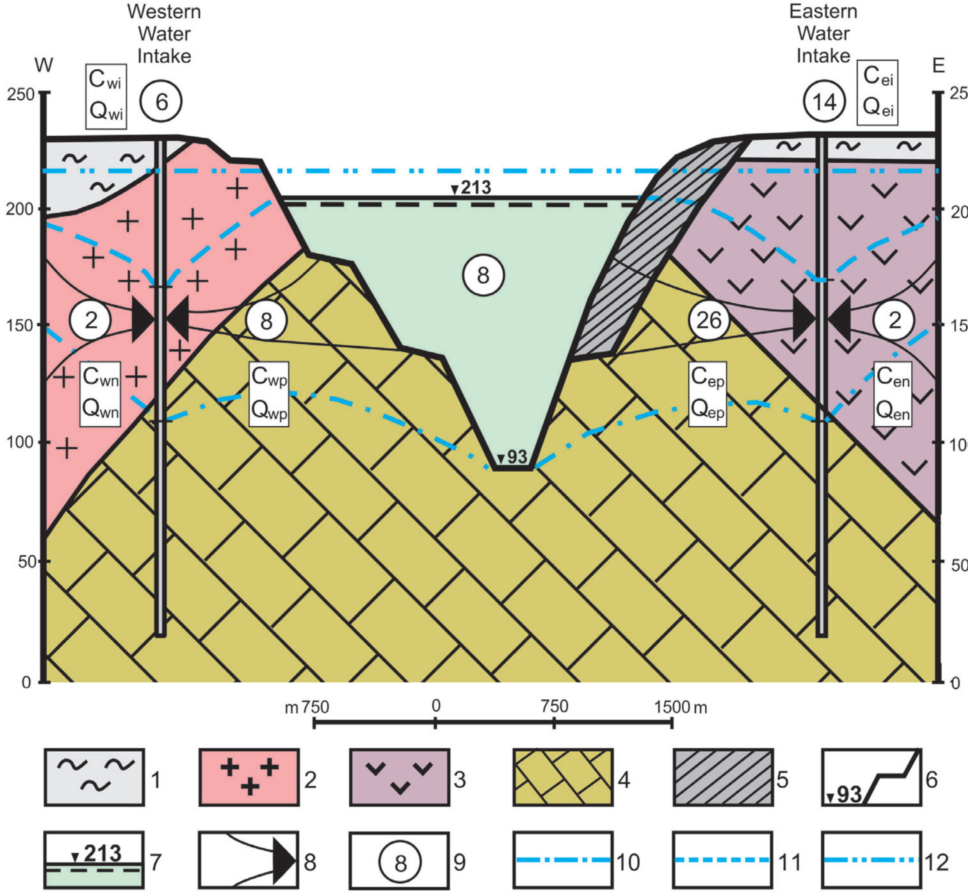

Figure 3 – *Hydrochemical model of the groundwater quality formation process at the Lipovsky deposit. The geological context is according to (Palkin and Palkin, 2003). Legends: 1 – argillaceous weathering crust; 2 – intrusive rock aquifer (granites); 3 –Riffean-Paleozoic metamorphic rock aquifer (schist, serpetinites, siliceous rocks); 4 –Paleozoic carbonate rock aquifer (marbles, limestones); 5 – internal dump of overburden rock and substandard ore, technogenic 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 coefficient (Kc –sulfate ion concentration coefficient, the ratio of component's actual content (C) to its background level (C_b), $K_c = C/C_b$, C_b = 10 mg/L); 10 – 12 groundwater level by phase, 11 – during mining; 12 – at the present time;13 – in natural conditions.*

technogenic aquifer within the filled part of the pit. A rise of the groundwater table in the technogenic aquifer to +150 m and higher (after 1994) with free access of oxygen has led to active geochemical weathering of the sulfide-containing minerals and dissolution of secondary sulfates, which accounts for the increased concentrations of sulfate, nickel and other components in the groundwater intake on the eastern edge of the pit. The technogenic aquifer has thus become a supplier of sulfate salts.

Conclusions

Thus, the recharge sources of the Lipovsky groundwater deposit have fundamentally changed. Two thirds of the discharge are formed at the expense of recharge from the open technogenic reservoir, whose water has a sulfate-ion concentration of Kc=8. In the process of groundwater quality formation at the eastern intake, the recharge water from the pit lake is additionally enriched in the course of filtration through the technogenic aquifer. The waters coming into the wells on the eastern edge of the pit have a sulfate-ion concentration coefficient of Kc=26. The main process by which the waters are enriched with sulfate, nickel, etc. is the dissolution of the secondary sulfates that formed as a result of chemical weathering of the sulfide minerals in the unmined ore and in the overburden and substandard ore used to fill the eastern part of the pit. Such processes have been observed at other mineral deposits as well (Appelo and Postma, 2005).

In recent years, the nickel content has been persistently higher than the permissible level: 20% higher at the western intake and 500% higher at the eastern one. The operation of this water intake facility continues since it is the only source of water supply for the town of Rezh.

Not denying the significance of hydrochemical activity in weathering crusts (particularly in karst sinkholes) for the formation of groundwater chemistry (Bizyaev, 2012), it should be pointed out that this factor apparently played the main role during the period when water drainage was operating, the technogenic aeration zone was forming, and oxidation processes were intensifying due to free oxygen access. As a result, the conditions in the pit were favorable for the development of soluble secondary sulfates. The pit lake and technogenic aquifer in the remediated part of the flooded pit became the main contaminant sources after 1991 at the operating water intake facility. Although some researchers believe that the basic processes of hydrogeochemical transformation at the Lipovsky geotechnogenic system are over (Palkin and Palkin, 2003; Bizyaev,2012), the hydrogeochemical situation is far from being stable, as demonstrated in fig. 2. Considering the limited supply of oxidized minerals within the technogenic aquifer, we may assume that in the future, the quality of the groundwater withdrawn by the intake wells will improve. This process, however, may take dozens or even hundreds of years (Rybnikova and Rybnikov, 2017).

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