Environmental implications of acid mine drainage in the Middle Urals, Russia

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Abstract

The abandoned copper-pyrite mines of Levikha and Degtyarsk are located in the Ural fold mountains within the catchment areas of large water reservoirs. Acid mine waters have been discharged here for over 20 years. The AMD treatment systems of these mines are identical, involving neutralization and settling. However, the quality of the mine waters after treatment differs: in the area of the Degtyarsk mine almost all indicators at the point of discharge into the river network comply with regulatory requirements, whereas the discharge from the Levikha mine contains metal concentrations that exceed the standards by 2–3 orders of magnitude. The main factors that influence the water treatment efficiency at these mines are anthropogenic (mine water flow rate and acidity), natural (catchment area), and technological (amounts of reagent, volume of clarification ponds).

Keywords: Acid mine drainages, hydrosphere, copper-pyrite mines, clarifier pond, treatment, catchment area

Introduction

Acid mine drainage (AMD) occurs not only during the operation of mines but also after their closure. This is one of the leading environmental problems globally. The main cause of AMD is the presence of sulfide minerals in rocks. During the mining process, the structure of the rock mass is disrupted, which leads to sulfuric acid weathering of sulfide minerals in the course of interaction with water and air. Mine waters tend to have low pH values, thus further contributing to the dissolution of rocks and enrichment of the water with metals. Reaching landscapes and water bodies, these effluents cause significant harm to both the hydrosphere and the entire surrounding ecosystem.

In the Middle Urals (Russia), a large number of copper pyrite mines have been closed and flooded over the past decades. This has caused serious hydrogeoecological problems. The lack of groundwater resources in the Ural fold mountains accounts for the fact that the main, and sometimes the only source of water supply (especially for large cities) are water reservoirs. In terms of environmental impact on such reservoirs in the region, the Levikha and Degtyarsk copper pyrite deposits are considered to be the most dangerous ones.

The Degtyarsk deposit is located within the catchment area of the Volchikhinskoye reservoir, which supplies water to Yekaterinburg (population 1.5 million people). Following treatment, the AMD flows from the area of the Levikha deposit into the Lenevsky pond, which is used to supply water to the city of Nizhny Tagil (population 350 thousand people). To prevent emergencies from happening and ensure the proper quality of discharged mine water, work is being conducted at these mines at the expense of the regional budget to localize surface runoff, pump out mine water and neutralize it. These deposits are located in identical geological conditions and have a similar history of development using the same methods (open-pit mining and underground block caving methods, with the mining depth of about 600 m and the mining period of 80 years). After the cessation of drainage and filling of the cone of depression, localized AMD discharges formed at each of them in the lowest part of the mining landscape (in sinkholes). Although the overall AMD flow rate is now lower (by approximately 2 times) than during mine development and drainage, it can reach several thousand cubic meters per day. Without treatment, this AMD may cause degradation of the landscape and unacceptable pollution of the hydrosphere over large areas. The AMD is neutralized with lime milk, followed by settling in clarification ponds that were built in the middle of the last century (Fig. 1). However, the quality of the purified mine water at these two mines is fundamentally different: in the area of the Degtyarsk mine, almost all indicators at the point of discharge into the river network meet the regulatory requirements. At the Levikhinsky mine the treatment efficiency was lower both in period of deposit development and in period of flooding. Mg, Cu, Zn and Al content in water exceeded content standards 2-3 times. The first flush effect only made this situation worse (Rybnikova 2021).

The aim of this work is to assess the factors that determine the processes of AMD formation at the Degtyarsk and Levikha mines and identify the main natural and technological parameters that would allow better water quality indicators to be attained at the discharge into the water bodies.

Methods

At the Degtyarsk and Levikha deposits, water chemistry observations have been conducted both during the period of mining and after flooding. The observation points are confined to the areas where the water chemistry undergoes an essential change: AMD outlets (surface discharge), AMD neutralization, settling in the clarification ponds, and discharge into the river network (the mouths of the Yelchevka River at the Degtyarsk deposit and the Levikha River at the Levikha deposit). The main pollution indicators are

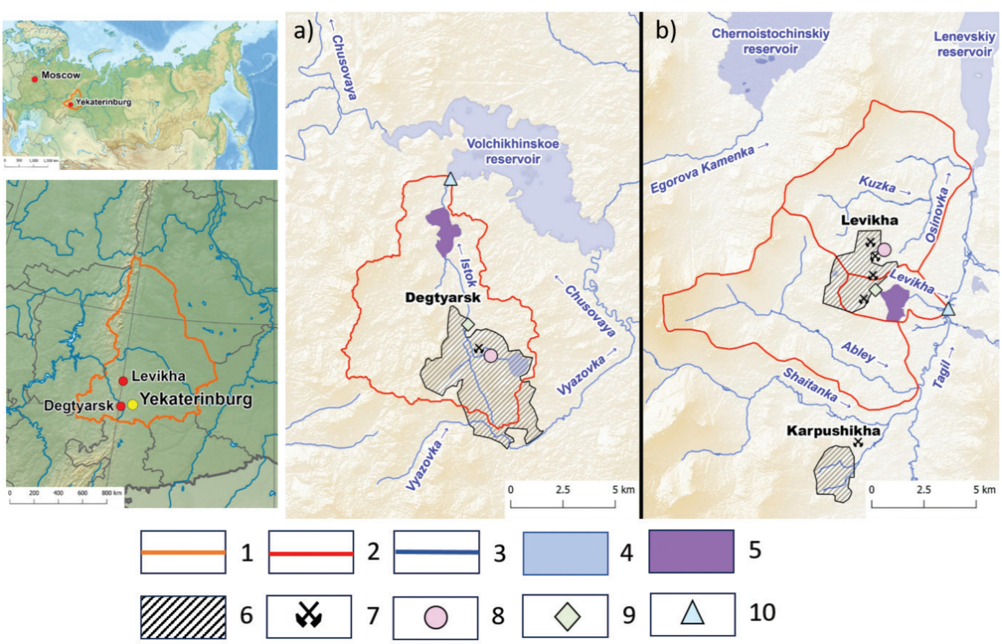


Figure 1 *Layout of the objects under study: a) Degtyarsk mine, b) Levikha mine. 1 – border of the Sverdlovsk region, 2 – local catchments, 3 – rivers, 4 – reservoirs a) Volchikhinskoye reservoir, b) Lenevskiy reservoir, 5 – clarification pond, 6 – towns, 7 – abandoned mines, 8 – AMD discharge zone, 9 – $Ca(OH)_2$ neutralization, 10 – the mouths of the Leivikha and Yelchevka rivers.*

determined on a monthly basis starting from the beginning of AMD discharge as follows: pH, Cu, Zn, Fe, Cl, SO4, Mn, As, suspended solids, total dissolved salts and oil products. In addition, we regularly carry out a detailed analysis of mine, underground and surface waters for an extended list of components.

Analysis for Na and K is carried out using flame emission spectrometry; Ca, Mg are determined by flame atomic absorption spectrometry; and Fe by atomic adsorption spectrometry. Inductively coupled plasma mass spectrometry is used for analysis for a wide range of elements, including: Al, Be, Cd, Co, Mn, Cu, As, Ni, Pb, Se and Zn. Nitrogen-containing substances (such as NO_2 and NO_3) are determined by ion-selective potentiometry. Gravimetric analysis is used to determine SO4, and argentometric titration to determine Cl. Measurements of t (°C), Eh (μV), pH, TDS are performed on site.

AMD acidity (AC) and the amount of alkaline reagent needed for AMD neutralization (RE) were determined by the formula (Hedin 1994):

$$AC = 50 \times \left(\frac{2Fe^{2+}}{56} + \frac{3Fe^{3+}}{56} + \frac{2Mn^{2+}}{55} + \frac{3Al^{3+}}{27} + \frac{2Cu^{2+}}{64} + \frac{2Zn^{2+}}{65} + 1000 \times (10^{-pH})\right),$$

where the estimated acidity AC is expressed in mg/L of $CaCO_3$; Fe^{2+}, Fe^{3+}, Al^{3+}, Mn^{2+}, Cu^{2+}, Zn^{2+} are metal concentrations in the solution, mg/L; 50 is a coefficient for conversion of acidity in mg-eq into mg/L $CaCO_3$.

Required amount of reagent (RE) was estimated by the formula (Taylor 2005):

$$RE = Q \times AC \times 0.0864,$$

where the estimated RE is expressed in kg $CaCO_3$/day; Q is the flow rate, L/s; AC is the acidity, mg/L of $CaCO_3$; 0.0864 is the conversion factor.

Treatment efficiency (TE) was estimated by the formula:

$$TE = \frac{C_{in} - C_{out}}{C_{in}} \times 100\%,$$

where C_{in}, C_{out} are the concentrations of pollutants in the AMD discharge zone and in the effluent at the mouths of the rivers Yelchevka and Levikha, respectively, mg/L.

For the cumulative assessment of water pollution, we used the total pollution index (Zc):

$$Z_c = \sum_{i=1}^{n} \frac{C_i}{C_{MAC}} - (n-1)$$

where C_i is the actual concentration of a substance in water, mg/L; C_{MAC} is the maximum allowable concentration (MAC) for a pollutant in fishery water bodies, mg/L; n is the number of substances determined.

Results and Discussion

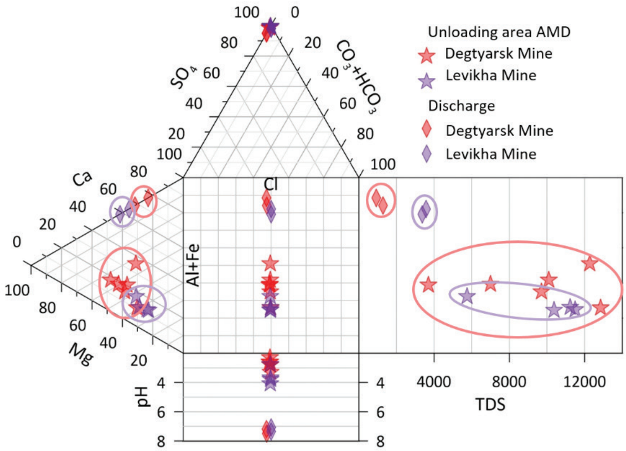
When the acidic waters reached the surface, they were found to have high concentrations of all components. In recent years, these concentrations have shown a slow gradual decrease. This process is called 'first flush' and is observed in many abandoned mines (Younger 1997, Gzyl 2007, Wolkersdorfer 2022, Rybnikova 2019).

The AMD from the Degtyarsk mine (the caved area of the «Kolchedannaya» shaft) are sulfate, the predominant cations being calcium, or magnesium, or iron, pH=2.3-3.3, mineralization ranges from 3.7 to 16 g/L. At the mouth of the river Yelchevka, the mine waters are characterized as sulfated magnesium-calcium, pH = 7.2-7.5 (neutral medium). Mineralization is from 0.9 to 1.2 g/L (Fig. 2).

At the Levikha mine, in the discharge zone (the collapse area of the Levikha II shaft), the mine waters are sulfate magnesium-iron-aluminum (the ratio of cations can vary). The water is less acidic (pH = 3.6-3.9), with a higher mineralization from 14.2 to 20.0 g/L. At the mouth of the Levikha River, water after treatment is characterized as sulfated magnesium-calcium, pH = 6.6-7.6. Mineralization is from 0.5 to 9.2 g/L (Fig. 2).

Treatment efficiency at the Degtyarsk mine reaches 99%, and the maximum allowable concentration (MAC) excess factor ranges from 10 (for Cu, Zn) to 20 (for Mn). At the Levikha mine, a similar scheme leads to worse results: treatment efficiency varies from 59% (for Mn) to 93% (for Fe, Cu). As a result, pollutant concentrations at the mouth of the Levikha River at the point of discharge into the Tagil River exceed the MAC 11 thousand times for Zn; 1.4 thousand times for Mn; and hundreds of times for Cu.

As a result, the total pollution index demonstrates that the degree of purification at the Degtyarsk mine is 300 times higher than at the Levikha mine, whereas it is only two times higher in the AMD discharge zone.



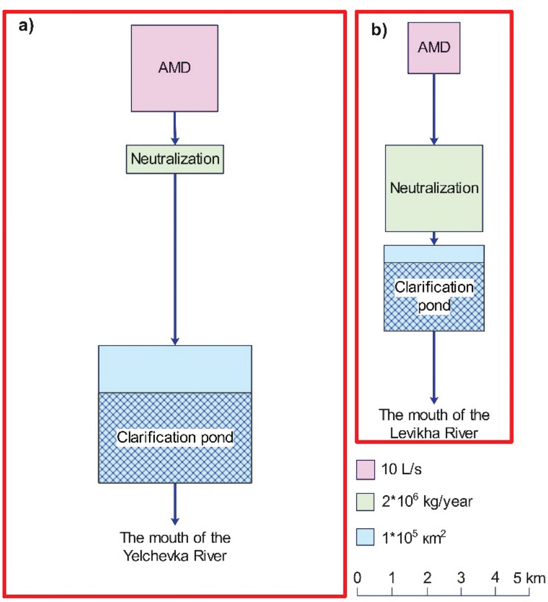
Parameter	Unloading area		Discharge	
	Degtyarsk Mine	Levikha Mine	Degtyarsk Mine	Levikha Mine
pH	2.6	3.8	7.4	7.2
Fe, mg/L	899	1 455	0.1	95
Mn, mg/L	39	82	0.2	34
Cu, mg/L	11	19	0.01	1.0
Zn, mg/L	121	280	0.1	107
SO_4, mg/L	7 110	7 493	704	2 133
∑M, mg/L	11 188	16 534	628	4 557

***Figure 2** Chart showing the chemical composition of water in the AMD discharge zone and after treatment, %-eq/L.*

We have identified the following reasons for this discrepancy.

Water acidity and amount of reagent used

At the Degtyarsk mine, the pH values are lower, but the water acidity is 5 times lower (the all metals content is lower). Therefore, it takes 1.58*10^6 kg/year of $Ca(OH)_2$ to neutralize 50 L/s of mine water from the Degtyarsk mine, whereas the Levikha mine needs 3,5 times more of $Ca(OH)_2$ to neutralize 32 L/s, or 5.46*10^6 kg/year (Fig. 3).



Location	Parameter	Degtyarsk Mine	Levikha Mine
AMD	**pH**	2.6	3.7
	Zc	36 057	64 821
	Q, L/s	50	32
Neutralization	**AC**, mg/L $CaCO_3$	1 003	5 413
	RE, kg/year	1.58*10^6	5.46*10^6
Clarification pond	**F**, km^2	2.2	1.42
	Vpr, million m^3	9.34	3.30
	Vfr, million m^3	2.43	0.23
Discharge	**pH**	7.4	7.0
	Zc	44	15 967
Catchment	**TE**, %	99	75
	F, km^2	100	14

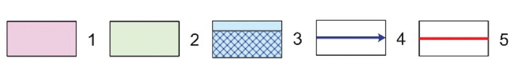


***Figure 3** AMD purification chart and parameters: a) Degtyarsk mine, b) Levikha mine. 1 – AMD discharge zone, 2 – $Ca(OH)_2$ neutralization, 3 – clarification pond (shading – volume of bottom sediments, blue – free volume), 4 – surface streams, 5 – catchment area of the Yelchevka and Levikha rivers. Q – flow rate, F – area, Vpr – project volume, Vfr – free volume, AC – estimated acidity, RE – required amount of reagent, Zc –total pollution index, TE – treatment efficiency.*

Area and volumes of clarification ponds

To settle the water after neutralization, clarification ponds were built in the 1950s. They have been in operation without cleaning for several decades. After neutralization of highly mineralized acidic mine waters, hydrates and oxides are precipitated in the form of a finely dispersed silt-like suspension of a brick-orange color. These sediments have filled the southern part of the Yelchevka clarification pond (design area 2.2 km^2, total volume 9.34 million m^3) and formed a beach with dried sludge in the western part of the Levikha pond (design area 1.42 km^2, total volume 3.2 million m^3) (Fyodorova 2014, Rybnikova 2023). The clarification ponds are filled to 74 and 93%, respectively. The free volume is 2.43 million m^3 at the Degtyarsk mine and only 0.23 million m3 at Levikha (Fig. 3). As a result, the available free volume of the Levikha clarification pond is 10 times less than that of Yelchevka.

It is obvious that this volume of the Levikha clarification pond is not enough for settling the water after neutralization and ensuring interaction of pollutants with reagents. At the discharge from the pond, we observe increased concentrations of Zn (107 mg/L), Fe (95 mg/L), Mn (34 mg/L), and Cu (1 mg/L) (Fig. 2).

Passive purification and dilution

The passive purification stage involves settling the water after neutralization in streams and dilution with surface and groundwater in the catchment area. The catchment area of the river basin where the Yelchevka clarification pond is situated is about 100 km^2, with the AMD discharge zone located in the upper part of the catchment. The river network is long and has relatively high flow rates, which ensures a good degree of effluent dilution. The catchment area of the Levikha River where the Levikha clarification pond is built, is as small as 14 km^2. The AMD discharge zone here is located in the neighboring private catchment area of the Kuzka River (also a tributary of the Tagil River), from where the acidic waters are pumped across the local watershed into the Levikha River valley. In fact, the flow rate of the Levikha River is increased 3 times due to the inflow of acidic waters, whereas the possibility of diluting the purified effluent in the catchment area is very low. At the mouth of the river Yelchevka, the total pollution index is over 350 times lower than that at the mouth of Levikha (44 and $1.6*10^4$, respectively).

For the Degtyarsk mine, the current two-stage system is quite effective. To improve the treatment efficiency at the Levikha mine, it is necessary to switch to a more advanced scheme of three-stage purification, for example: 1 – treatment facilities with aerators, 2 – radial settling tanks, 3 - a cascade of ponds (Rybnikova 2024).

Conclusion

At the Degryatsk and Levikha mines, now depleted and abandoned, AMD is being discharged to surface streams. The waters are sulfate, and calcium, magnesium, iron or aluminium may dominate among the cations.

AMD treatment at both sites is carried out in two stages: neutralization with lime milk and settling in clarification ponds. However, the treatment efficiencies are different. At the Degtyarsk mine, it reaches 99%, while at the Levikha mine it varies from 59% to 93%. Accordingly, the quality of the water discharged into the Tagil river system does not meet the standards: the concentrations of manganese, copper, zinc, and aluminum exceed the standards hundreds and thousands of times.

The main factors influencing the efficiency of the treatment system are as follows: anthropogenic (mine water flow rate and acidity), natural (dilution with clean water in the catchment areas), and technological (amount of reagent used for neutralization, volume of the clarification ponds).

Acknowledgements

This work was supported by State Assignment of The Institute of Mining, Ural Branch of the Russian Academy of Sciences 075-00410-25-00 PR. Theme 2 (2025-2027) “Geoinformation support for systemic assessment of environmental conservation strategies in the development of subsoil resources” (FUWE-2025-0002) s. r. 1022040300092-1-1.5.1.

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