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TECHNICAL COMMUNICATION

Post-mining of Chelyabinsk Coal Basin (Russia): The Effects of Mine Flooding

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Abstract

The closure of mining facilities, especially those with a long history of mining, often results in degradation of the environment. In particular, the development of mineral deposits is accompanied by drainage interventions, restructuring and rebalancing of surface and groundwater flows, and changes in the qualitative composition of the hydrosphere. Cave mining operations involve geomechanical processes that provoke surface subsidence and displacement accompanied by earth surface disturbance. The cessation of mining means stoppage of drainage, which leads to the gradual filling of the cone of depression, formation of flooded areas, and mine water discharges at the surface. Unstable rock in the walls of water-filled open pits can lead to potentially dangerous landslides. Given the fact that residential and industrial areas were often historically constructed close to the mines (sometimes within the mining allotment), the hydro-environmental problems of old industrial districts become particularly acute post-mining. Also, in many cases, it is difficult to determine which factors, natural (geological structure, geomorphological conditions, water content of the period) or human-induced (cessation of pumping), are responsible for area flooding, especially where these sites are located a considerable distance from the closed mine. This gives rise to speculations and irrational technical solutions. Using the Chelyabinsk Coal Basin as an example, we consider the eco-hydrogeological issues that arose after the completion of mining operations and cessation of drainage, and we propose measures to reduce their negative impact on the area's hydro-geoecological conditions.

Keywords Hydrogeological conditions · Geo-ecological problems · Drainage · Coal deposits · Mines · Open pits · Waterlogging · Landslide · Leakage · Water-carrying utilities · Hummock-and-hollow topography

Introduction

By now, many mineral deposits have been mined out around the world. Regardless of the state of the mining business, the challenging and growing problems of not only liquidating unprofitable enterprises and managing hazards in areas where mining is no longer conducted have to be addressed. In particular, it is important to prevent environmental risks in areas disturbed by long-term mining, which need remediation, flooding management, and monitoring (Domenique et al. 2022; Guman et al. 2001; Mironenko and Rumynin 1999; Norvatov and Petrova 2008; Rybnikova and Rybnikov 2019; Wolkersdorfer 2008; Wolkersdorfer et al. 2022).

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Following the abandonment of mining activities, the old industrial regions of Europe faced serious problems. Thus, in 1992, after 800 years of operation, mining was ceased in densely populated regions with numerous abandoned coal mines (e.g. Aachen, Germany and South-Limburg, the Netherlands), where cones of depression of about 400 km^2 filled with water over several years, and the groundwater level rose by 200–240 m (Kretshmann 2020).

In 2012, coal mining was stopped in Saarland, Germany, which had a 200-year history of mining. Mining also came to an end in the Ruhr coal basin, where coal had been mined since the twelfth century. Safe flooding of such underground workings and elimination of their negative impacts is financially challenging (Stemke and Wieber 2022).

Three hundred years of coal mining in the Durham Basin (UK) resulted in the dewatering of aquifers over a vast area. The termination of drainage and the filling of the cone of depression could have provoked numerous negative consequences, including contamination of drinking groundwater intakes, flooding of dump sites and settling ponds, their active leaching, etc. To maintain the level of mine waters below the Basal Permian Sands aquifer and prevent their discharge at the surface, these waters are pumped and treated at a specially constructed plant with a capacity of about 15,000 m^3/day (Younger et al. 2004).

In 1993–1994, Russia began restructuring its coal industry. As a result, 203 coal mining enterprises were liquidated, including 188 mines and 15 opencasts (Moiseenkov 2018). Contrary to the expected scenarios predicting the negative consequences of coal mine closure and flooding in various coal basins of Russia, many of these consequences have turned out to be more protracted and unstable. Significant areas in the Kuznetsk and Donetsk coal fields were waterlogged, drinking water intakes were contaminated and rendered inoperative; and gas emissions and surface subsidence were observed (Langolf et al. 2007; Morin and Barsukov 2012). The closure of the mines in the Kizel Coal Basin resulted in the formation of 19 outflows of acidic mine waters, which entered untreated into the Chusovaya, Kosva, Yaiva, and Vilva river basins, with the pollution traced as far as the Kama reservoir (Imaikin and Imaikin 2013; Menshikova et al. 2022; Rybnikov et al. 2020).

The deposits of the Chelyabinsk Coal Basin were discovered in 1832, and their commercial development began in 1907. Coal production peaked in the 1960s. In the late 1980s, mine closure began, and by now the operation of all mines and opencasts has been stopped. Currently, the most problematic areas in terms of environmental and hydrogeological impact are the sites of the former Krasnaya Gornyachka mine and the Kopeysk and Korkino open pits. Historically, the cities of Kopeysk (pop. 150,000) and Korkino (pop. 35,000) grew from the settlements located near the coal mines and opencasts, planned chaotically next to the mines. Currently, all coal mining enterprises are closed, but the miners' settlements have remained.

The total average annual drainage reached 2363 m^3/hour with a mining depth of up to 510 m. The cessation of drainage is leading to the gradual filling of the cones of depression and is accompanied by the flooding of collapse zones, rising water levels in the opencasts, and minor flooding of the settlements and infrastructure. The aim of this paper was to analyze and forecast the development of the hydrogeological situation within the Chelyabinsk Coal Basin after the abandonment of the mines and opencasts.

Site Background

The Chelyabinsk coal basin with an area of 1300 km^2 is located on the eastern slope of the Urals at the western edge of the West Siberian Lowland, stretching as a strip narrowing progressively to the south over a distance of more than 150 km (Fig. 1). The maximum width of its coal-bearing formation is 14 km, and the depth is up to 4 km (Hydrogeology 1972).

The maximum mining depth was up to 510 m at the Komsomolsk mine, which also featured the maximum drainage rate of 516 m^3/hour (Table 1). During mining, the mine waters were discharged to the lakes Kuraldy, Tretye, and Kurochkino, to the River Chumlyak, and to the Ulamovo bog. Over the period of 2005–2021, the average precipitation constituted 460 mm/year, with a minimum of 281 mm/year in 2021 and a maximum of 588 mm/year in 2014.

The topography of the region presents a slightly hilly forest-steppe plain, bordering on the peneplain of the Urals eastern slope in the west and gradually descending towards the regional drains. The plain is complicated by small mounds and saucer-shaped hollows, which gives the area a pit-and-mound character.

The area belongs to the Irtysh watershed district. The hydrography of the area features an extremely sparse river network and an abundance of closed lake basins ranging in area from fractions of a hectare to several tens of square kilometers (Fig. 2). There are two rivers in the basin: the River Miass flowing along its northern edge (an average annual discharge of 18 m^3/s), and the River Uvelka in the south (11 m^3/s). The rest are intermittent rivers, which disappear as they flow into swampy lake basins.

Tectonically, the area under study is located within the Eastern Urals syncline. The heavily metamorphosed and deformed Paleozoic rocks of this zone form a stepped system of faults and scarps submerged under the cover of deposits of the West Siberian Lowland.

In terms of geology, the Chelyabinsk Coal Basin is a Paleozoic graben filled with Lower Mesozoic coal-bearing deposits. The western flank is steep, almost vertical; the depth of the graben there ranges from 1700 to 3500 m. The eastern flank is less steep, with depths of 500–1500 m.

The coal-bearing formations are the deposits of the upper part of the Triassic system (1600–3500 m thick) and the lower part of the Jurassic system (450–770 m thick). At the base of the section of each of these suites, there are coal-free horizons, which are dominated by alluvial-proluvial sandstone-conglomerate deposits with a thickness of 100–400 m. Above them are the coal-bearing parts of the suites, which are dominated by marsh-lake facies containing coal seams of varying thickness. The common groundwaters of the area belong to either the Quaternary, Neogene, Paleogene, and Cretaceous cover deposits (sediments) or the fractured Jurassic and Upper Triassic coal-bearing strata.

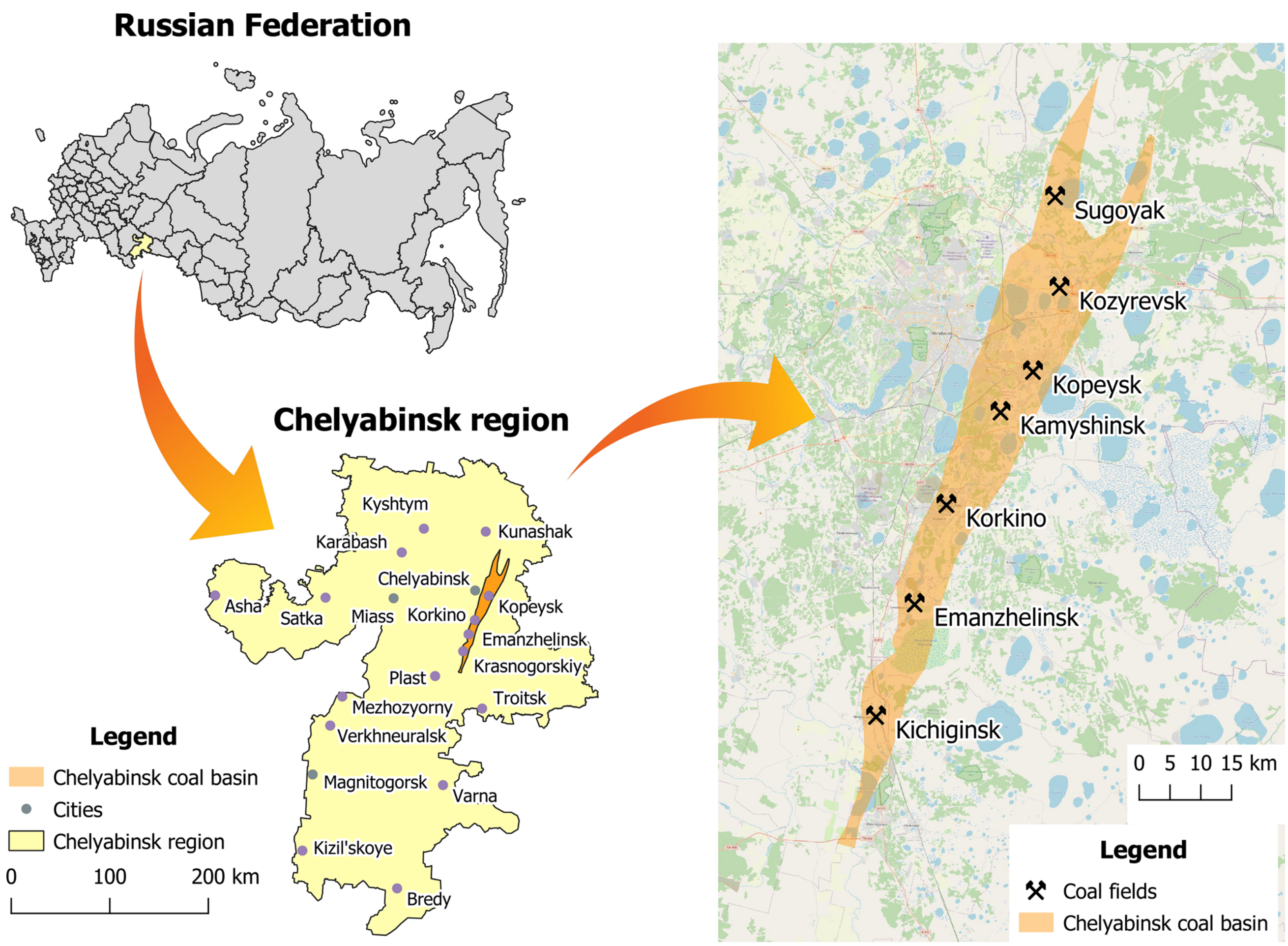


Fig. 1 Location map of deposits in Chelyabinsk Coal Basin

Table 1 Mining depths and drainage rates

Shaft, opencast	Mining depth, m	Water inflow rates from–to/ average, m^3/hour	Water inflow coefficient, m^3/t	Operation period, years
Krasnaya Gornyachka shaft	400	282–405/350	5.7	1930–2003
Tsentralnaya shaft	475	181–234/203	2.8	1932–2006
Kopeysk opencast	75–130	35–90/63	1.0	1981–2004
Kapitalnaya shaft	460	120–137/131	1.0	1942–2009
Komsomolsk shaft	510	248–516/368	6.6	1952–2008
Oktyabrsk shaft	265	160–238/187	8.3	1958–1996
Kalachevsk shaft	100	96–175/114	6.0	1953–2002
Korkino opencast	480	71–145/109	1.4	1947–2013
Korkino shaft	453	85–137/99	0.5	1934–2017
Baturinsk opencast	240	210–261/236	5.3	1941–1997
Baturinsk shaft	153–189	315–468/416	6.9	1941–2001
Kullyarsk shaft	330	50–147/91	3.8	1955–1997

Over the period of 2005–2021, average precipitation constituted 460 mm/year, with a minimum of 281 mm/year in 2021 and a maximum of 588 mm/year in 2014

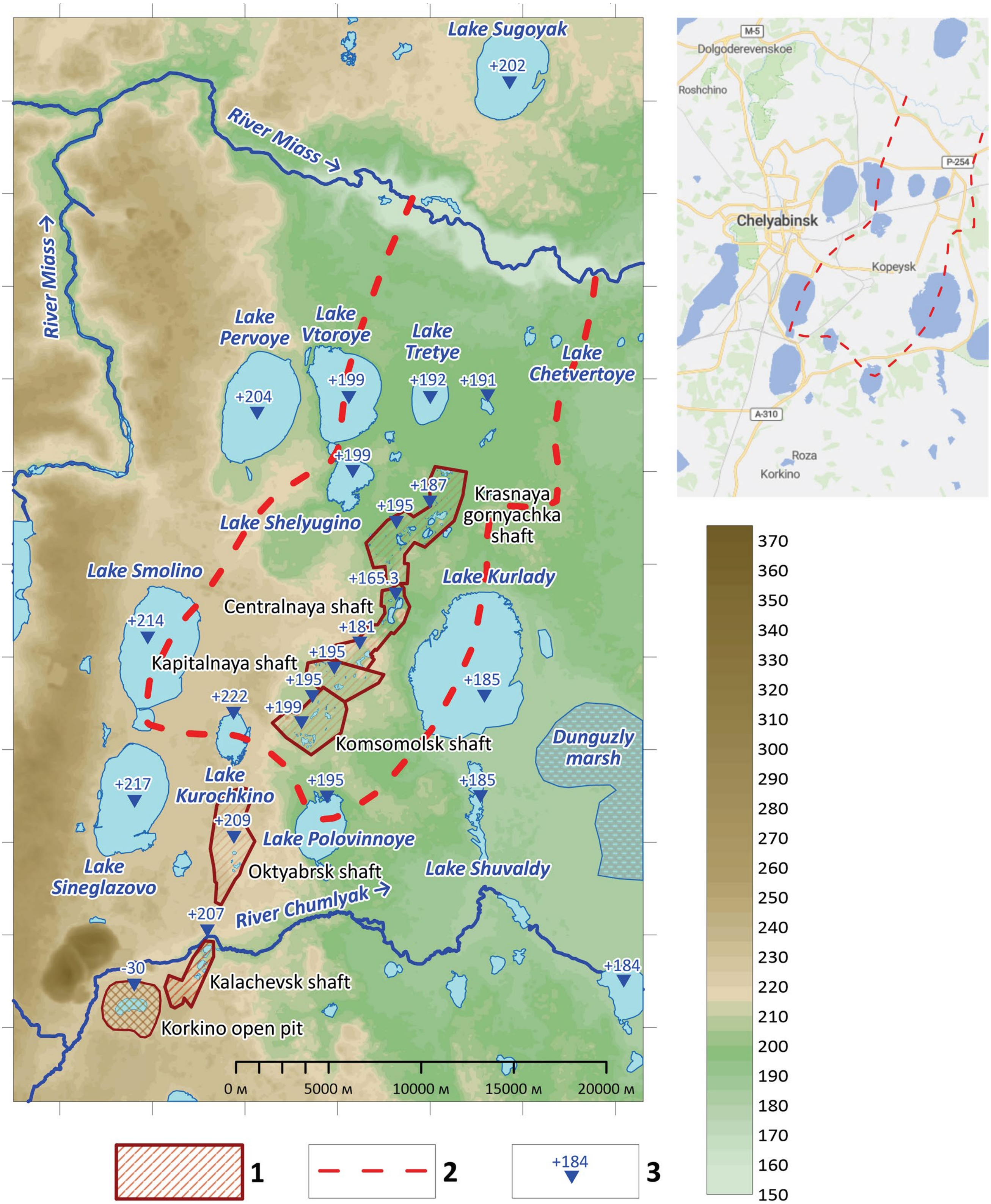


Fig. 2 Minefield location map and hydrographic network of the region. 1—mining allotment; 2—mine catchment area boundary in the northern part of the Chelyabinsk Coal Basin (boundary of the geofiltration model); 3—reservoir water level mark

Sampling and Methods

The surface and ground waters in the area has been monitored since 2004, along with observations of surface deformations and displacements. The monitoring network includes surface water bodies (9 stations); seepage zones (7 stations); and wells (9 stations with a depth of 10–50 m). The monitoring schedule for water level and temperature measurements is once a month, while chemical analysis is conducted once a year. So, in one year, we performed 122 measurements of surface and underground waters, collected 27 samples of surface and ground waters for chemical analysis, along with three samples of the bottom sediments.

The laboratory analyses of the waters include the determination of the following chemical components: pH, dry residue, bicarbonate ions, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen, chloride ions, sulfate ions, permanganate index, total hardness, calcium, magnesium, potassium, sodium, aluminum, total iron, boron, cadmium, cobalt, silicon, lithium, manganese, arsenic, nickel, lead, selenium, zinc, beryllium, copper, total chromium, barium, total phosphorus, silicic acid, and carbonate ions.

Research Results and Discussion

The Krasnaya Gornyachka Shaft

The area within the boundaries of the Krasnaya Gornyachka mining allotment is partially built up with private housing and is occupied by residential development in Kopeysk's northeastern part. North of the mine, there is the Kopeysk-Vakhrushevo motor road and the South Ural railway pass (Fig. 3).

Drainage from the Krasnaya Gornyachka shaft was discontinued in July 2003. To prevent flooding of the area, a number of measures were undertaken in 2004–2008, including the construction of a 1.65 km ditch connecting the Tretye and Chetvertoye Lakes, a drainage collector from Lake Chetvertoye to the River Miass (diameter 820 mm, length 5 km), and the development of a system of drainage ditches to divert water from the flooded areas into the water body of the VIII-2 and 3 open pits (the lowest part of the mining allotment), from which it is pumped further on into Lake Tretye (Fig. 3).

The flooding problems of the northern part of the Kopeysk district, including the motor road and the railway, were associated with a rise of the water level in the lakes Tretye and Chetvertoye. Mine waters had been discharged into Lake Tretye for decades (more than 3 million m^3 a year). The maximum water levels in these lakes (194.2 m above mean sea level) were observed in 2002, when the lakes joined together.

By 2007, the water level in the lakes had dropped to an elevation of 193 m, and the problem of motor road and railway flooding was thus resolved. In 2021, the water level in Lake Tretye was at 190.9 m (design level 192.6 m), and 191.6 m in Lake Chetvertoye (design level 193.2 m) (Fig. 4). The water levels in the lakes are 1.6–1.7 m still lower than the design values, and there is no discharge of water from Lake Tretye to Lake Chetvertoye. The areas of the lakes have significantly decreased and the quality of the water in them has deteriorated significantly.

To ensure the filling of the lakes Tretye and Chetvertoye, the water level in the lakes must be raised to the design levels. This will require 8.9 million m^3 of water (2.8 million m^3 for Lake Tretye, and 6.1 million m^3 for Lake Chetvertoye). Currently, 600,000 m^3 are pumped out during the warm season, so dewatering of the lakes will continue.

The water level in the VIII-2.3 pit reached its maximum (189.6 m) in the spring of 2019, resulting in the flooding of the recreation and fishing camp located on the shore of the water body. In June 2019, the pumping station started pumping the water from there through a conduit to Lake Tretye. By November 2019, the level had dropped by 3.5 m (to 186.1 m). With water being pumped out of the VIII-2.3 pit, the cone of depression is small; the observation wells at a distance of 1 km or more show that the groundwater level does not respond to the pumping and reflects the natural groundwater regime (Fig. 5).

The steady-state water level in the VIII-2.3 pit with the pumping continued in summertime is 187.5 m (seasonal fluctuations ± 1.0 m). Without such pumping, the level would stabilize at about 189.5 m, and the surrounding area would be flooded. The steady-state water level in the flooded sinkholes and open pits ranges from 192.2 m in the sinkhole of shaft no. 23 to 195.1 m in open pit X (Fig. 5).

In the central and southern parts of the mining allotment, the cone of depression has actually been filled up (Fig. 6). The depth of the groundwater table ranges from 1.7 m in well 9-gn (on the northern outskirts of Novostroyka village) to 12.7 m in well 7-gn between the YIII-1.2 pit lakes and Lake Lesnoy.

The hydrogeological situation in the central and southern parts remains stable. There is no need to set up new drainage systems to maintain it, as proper maintenance of the current drainage system is all that is needed to prevent surface flooding.

The combination of a number of factors, such as the geological structure (the presence of low-permeability strata at the surface), geomorphological conditions (hummock-and-hollow depression-type topography), and increased water content of the period (snowmelt, heavy precipitation) has

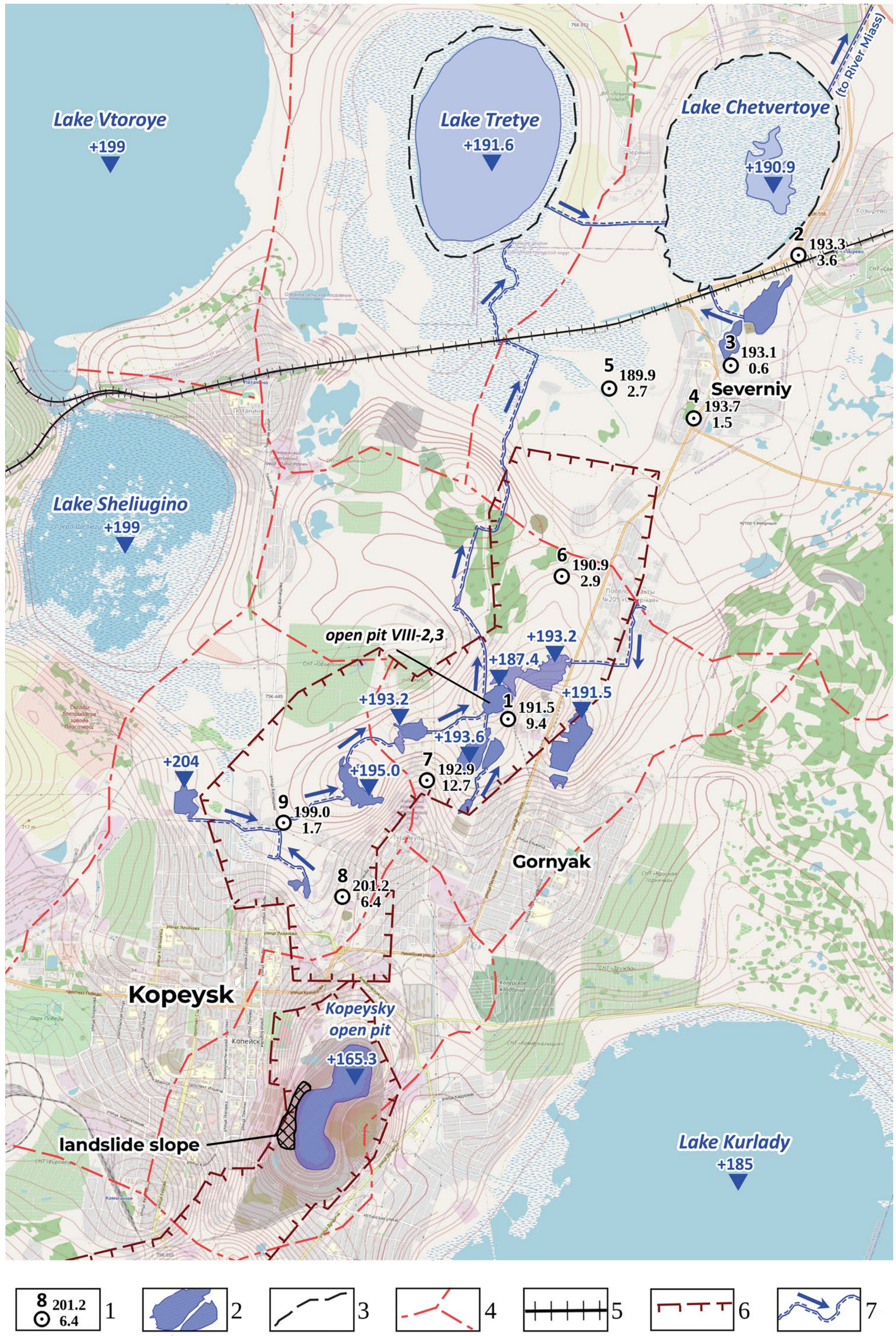


Fig. 3 Site plan and location of man-made objects in the area of Krasnaya Gornyachka mine. 1—observation borehole, numbered at the top; top right: absolute water level elevation; bottom right: depth to water table; 2—flooded pits and sinkholes; 3—lake contours as of 2003; 4—minor catchment area boundaries; 5—railway line; 6—mining allotment boundary; 7—drainage ditches and water flow direction

led to the formation of wetlands, including within the settlement areas. The size of these depressions ranges from several tens to several hundreds of meters in diameter, with depths from 1–3 m to 5–6 m. The hummock-and-hollow landscape accumulates the entire volume of melt water and atmospheric precipitation and almost completely prevents their surface runoff. Thus, for example, on the eastern outskirts of Kopeysk, in the area of the Gornyak settlement, natural depressions include flooded sites within the watershed spaces, outside the mining allotment. They existed even when the drainage system was operating (Fig. 7). Local people erroneously associate this flooding with inadequate mine closure work, although such phenomena occurred regularly during the operation of the mines. At that time, water was

Fig. 4 Water level variation in the lakes Tretye and Chetvertoye, and in well No. 5

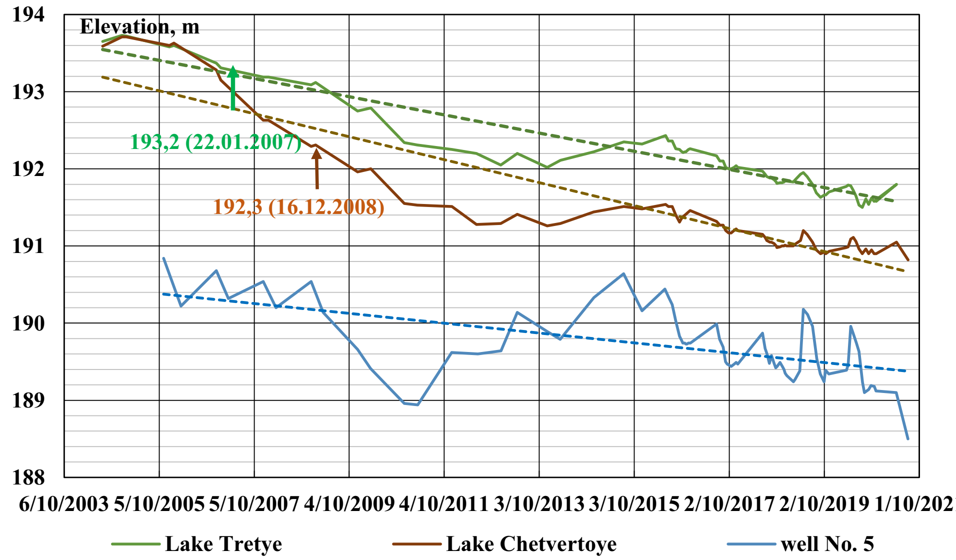


Fig. 5 Water level variation in pits and subsidences

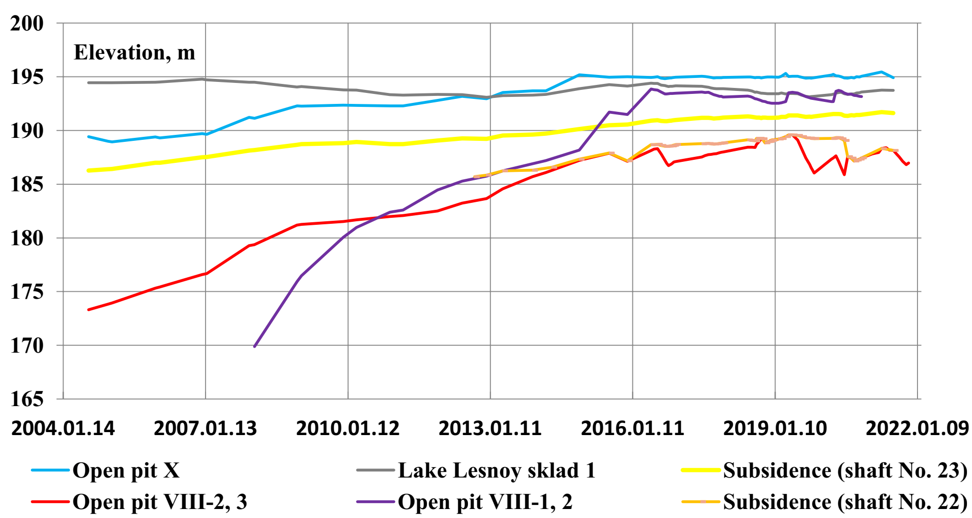
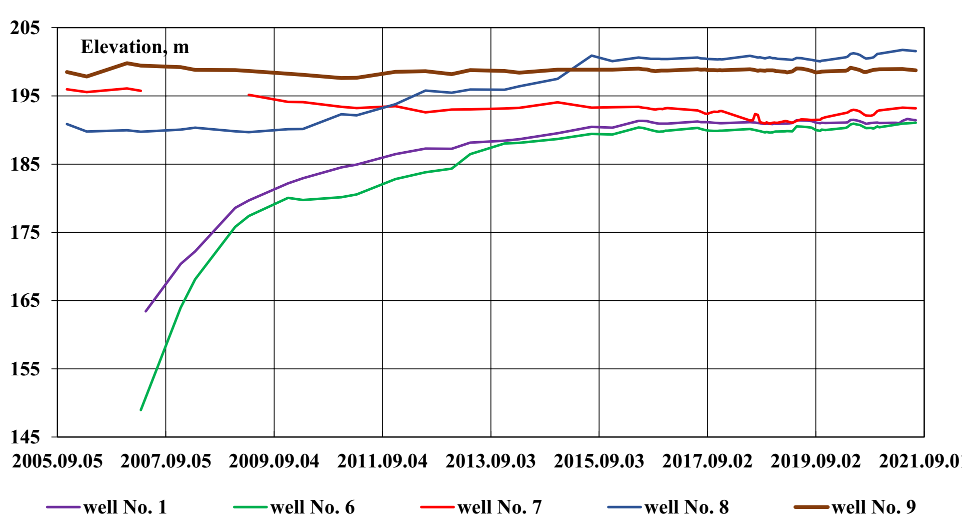


Fig. 6 Water level variation in the boreholes in the central (1, 6) and southern (7, 8, 9) parts of Krasnaya Gornyachka minefield



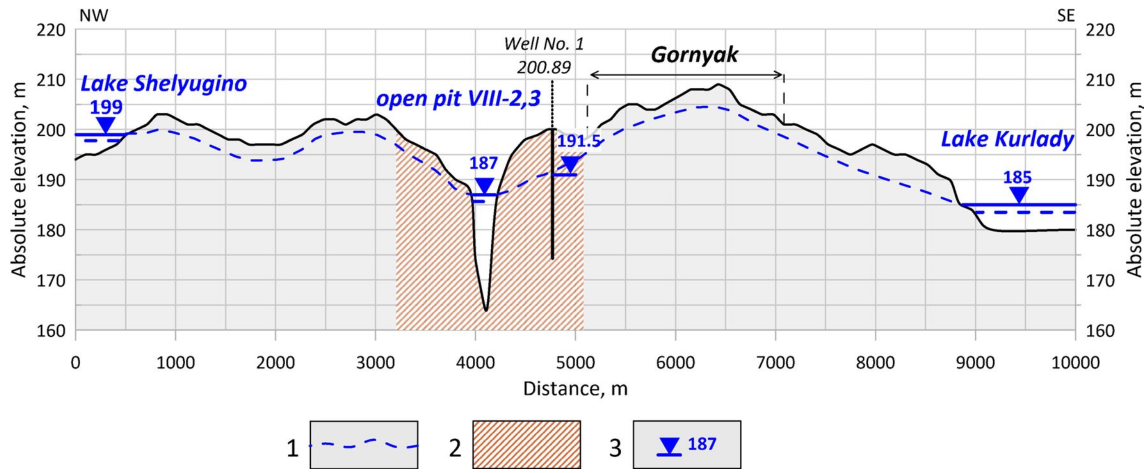


Fig. 7 Schematic cross-section along the line Lake Shelyugino—Lake Kurlady through the lake of pit YIII-2, 3. 1—groundwater level; 2—mining allotment for the shaft Krasnaya Gornyachka; 3—absolute water-level elevation

regularly pumped to Lake Kurlady during the period of snowmelt and heavy precipitation.

The number and the areas of the wetlands that formed in the natural landscape depressions have not changed since the mine drainage stopped. To prevent the waterlogging of the settlements during snowmelt and heavy precipitation periods, it is essential to pump out melt and rainwater from these low areas.

The Kopeysk Open Pit and Tsnetralnaya Shaft

The Kopeysk open pit is being flooded since 2004, while water discharge from the Tsentralnaya shaft was discontinued in 2006. On the western flank of the open pit, there is an industrial site, the Kopeysk machine-building plant, and the residential area of Kopeysk itself. In the process of flooding, several landslides occurred on the western wall of the pit, the one in 2015 being the largest, after which the ground surface near the area of the Kopeysk machine-building plant sank 15 m. In the spring of 2019, the slope of the landslide area was stabilized by backfilling. Currently, the area is being geomechanically monitored, which has not revealed any movement of the ground benchmarks.

The water level in the open pit is rising much slower than in the near edge strip and the Tsentralnaya mine shaft, since the amount of evaporation exceeds the amount of precipitation. The ground surface elevations in the plant's area rise from 203 m at the edge of the wall to 210 m. The depth of the water level in the middle of 2021 ranged from 15.8 to 20.7 m, settling at 183.4–186.1 m. The groundwater has risen 4.0 m since April 2017. During the same period, the water level in the open pit rose by 10.3 m, from 158.5 (Dec. 7, 2017) to 166.3 (Jan. 5, 2021) (Fig. 8).

To estimate the flooding rate of the Kopeysk open pit, we developed a groundwater flow model of its affected area. The boundaries of the model were determined in accordance with the location of the natural watercourses and water bodies: Lake Smolino in the west, Lake Kurlady in the east, and the River Miass in the north (Fig. 2). The model included the mine fields of Krasnaya Gornyachka, Tsentralnaya, Kapitalnaya, and Komsomolsk. The number of blocks is 700 along the axis X, and 500 along the axis Y, the block size being 50×50 m. The area of the model is 440 km^2. Groundwater modeling was performed using the Processing ModFlow software (Anderson et al. 2015).

The model has two layers: the top layer is associated with sediments (the Eocene-Upper Cretaceous aquifer) and the bottom one is confined to Triassic-Jurassic deposits. The thickness of the first layer is 50 m, and that of the second is 100 m. Hydraulic conductivities vary from 0.2 to 1 m/day for the top layer; and from 0.05 to 0.15 m/day for the bottom layer. To correctly set the hypsometry of the aquifer surfaces, we used a digital topography model. The recharge modulus can be taken as 1.25 L/s per 1 km^2 based on the estimation of available groundwater resources for the population of the Chelyabinsk Oblast, which was then extrapolated to the territory of the Ural Federal District and the Russian Federation (Borevsky et al. 2012).

The model is calibrated with reference to the mining period of stable mine water inflows (steady-state solution). To calibrate the storage coefficients that determine the course of the transient process of pit flooding, we imitated the flooding period from 2010 to 2021 in the model.

Forecasting was aimed at assessing the flooding rate in the Kopeyskiy open pit for three scenarios: (1) without taking any measures; (2) taking measures to stabilize the western wall of the open pit (backfilling the open pit to

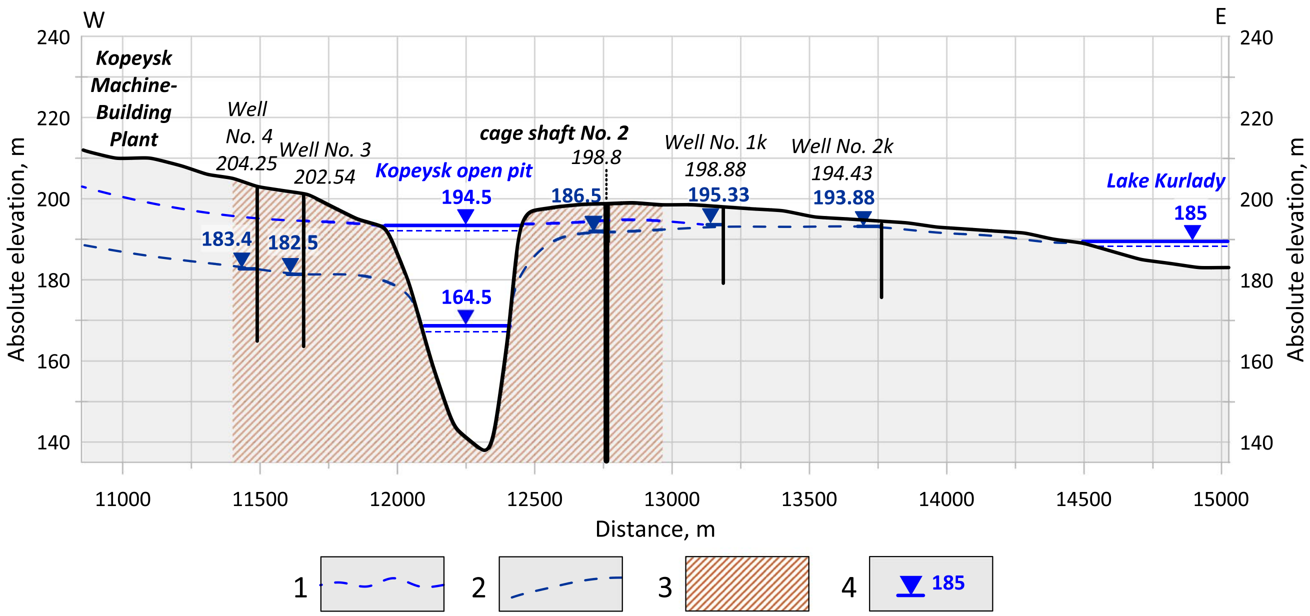


Fig. 8 Schematic cross section along the line Kopeysk Machine-Building Plant—Kopeysk open pit—Lake Kuraldy. 1—current groundwater level; 2—predicted groundwater level; 3—mining allotment for the shaft Tsentralnaya; 4—absolute water-level elevation

half storage); and (3) complete backfilling of the open pit (Fig. 9a). To determine the impact of the period's water content, we considered three scenarios (based on the half-filled open-pit option): (1) 10 years of increased water content; (2) normal water content over the entire flooding period; and (3) 10 years of low water content (Fig. 9b).

The ultimate flooding level for all scenarios was the same: 194.5 m. The flooding time counted off from 2021 would constitute 70 years without any measures taken, and five years with the open pit fully backfilled. With the pit's western wall stabilized (50% backfilling of the mined-out space), the elevation of 194.5 m would be reached in the Kopeysk open pit in 25 years. With several years of high precipitation,

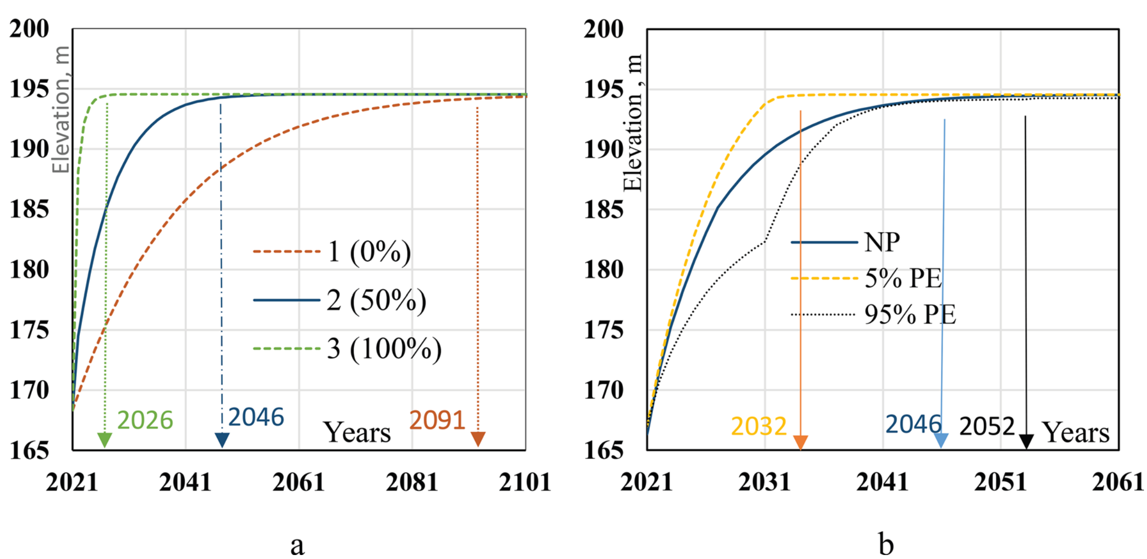


Fig. 9 Prediction of Kopeysk open pit flooding for different scenarios allowing for: **a** degree of pit backfilling (1—without backfilling, 2—with 50% backfilling, 3—with 100% backfilling); **b** variation in natural water recharge (1—normal period (NP), 2—water-rich period with 5% probability of excess for 10 years (5% PE), 3—water-short period with 95% probability of excess for 10 years (95% PE). The number at the arrow means the year of peak water mark

this elevation would be reached in six years. In the case of a series of very low water years (for instance, like the year 2021), flooding would continue for 31 years.

To exclude any minor flooding of surface facilities at absolute elevations of 193.0–195.0 m on the shore of Lake Kurlady, it is necessary to maintain the water level in the flooded open pit no higher than the absolute elevation of 190.0 m. To this end, it is necessary to pump out about 1 million m^3 of water per year, implementing one of two options: (1) a floating pumping station with a capacity of 220 m^3/hour when the lake surface is not frozen; (2) a submersible dewatering complex with a capacity of 130 m^3/hour (note that the discharge flow rate from the shaft and open pit was 266 m^3/hour).

Provided that leakage from the water-carrying lines is eliminated and water discharge to the landslide slope is stopped, there is no threat of flooding the machine engineering plant area at present and in the future. The territory of the city of Kopeysk is located at even higher elevations, so the flooding of the city is in no way connected with the flooding of the open pit but is caused by technology-related leaks from the water-carrying lines. The total volume of water supply to the Kopeysk urban agglomeration is 15.2 million m^3/year. Losses in the water supply system reach 5.8 million m^3 (38%), which exceeds the total discharge from the Krasnaya Gornyachka and Tsentralnaya shafts. This large amount of water loss is caused by the old age of the water supply lines, worn out to more than 80%.

Korkino Open Pit

Korkino was the deepest opencast coal mine in Eurasia with a depth of 493 m, a surface length exceeding 3 km, and a width greater than 2.5 km. Over the 70-year period of mining, about 250 million tons of coal and 1.5 billion tons of soil were extracted, and the coal output amounted to about 3 billion m^3. This open-pit mine was abandoned in 2017 (its development began in 1934). In addition to open-pit mining, underground work was also conducted in the Korkino deposit. In 2005, the commercial coal reserves, estimated to a depth of 630 m, amounted to 33 million tons, which could enable the mine to keep running for 23 years. To do this, it would have been necessary to expand the walls of the opencast, relocate the residents, and move out the industrial facilities. However, when the walls of the pit started to move (the first major landslide on the northwestern side occurred in 1945), the shafts of the Korkino mine were recognized to be dangerous, and buildings began to collapse. It was decided to phase out the mine and relocate some of the residents of the town of Rosa and the city of Korkino. Endogenous fires were regularly recorded in the walls of the open pit, which affected not only the environmental situation in the city of Korkino, but also the entire region, including the city of Chelyabinsk, which suffered from smog and the pungent smell of burning when winds were blowing from the open pit (Fig. 10).

To reclaim the Korkino open pit, the Russian Copper Company (RCC) developed a project to backfill the mine workings and eliminate spontaneous combustion zones using tailings of the Tominsk processing plant. The material is being delivered to the open pit by a 14 km long pipeline (Sokolovsky et al. 2018). The company is mining the Tominsk porphyry copper ore deposit (with a copper content of 0.46%), which is one of the 50 largest copper deposits in the world, with estimated ore reserves of 660 million metric tons. Over five years, 556,000 m^2 of spontaneous combustion zones were sealed. As a result, emissions decreased from 950 tons in 2017 to 36 tons in 2021.

The plan provides for completely filling the mined-out workings with tailings material by 2045. By that time, at a water level of + 155 m, the open pit will contain 479 million m^3 of backfill mixture and 212 million m^3 of water (Fig. 11). The ultimate flooding elevation in the Korkino open pit will be no more than + 210 m (judging by the Kalachevsk shaft

a b

Fig. 10 Korkino open pit (**a**), spontaneous fires on pit walls (**b**)

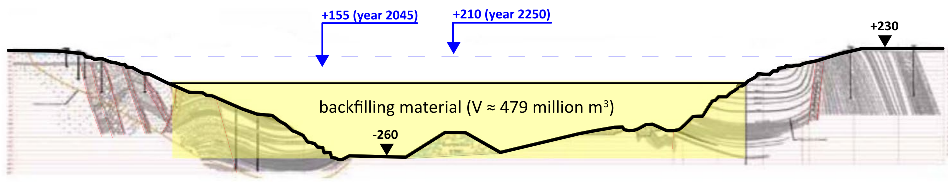


Fig. 11 Korkino open pit space in the course of reclamation

located to the northwest). With groundwater inflows of about 200 m^3/hour (Table 1), the pit flooding time from an elevation of + 155 m (a water surface area of 4.7 km^2) to an elevation + 220 m (an area of 7.4 km^2) is estimated to be at least 200 years.

Forecast of the Hydrogeochemical Situation

Based on an analysis of trends in the mineralization and component composition of the groundwaters within the mining allotments, we conclude that the chemical composition is gradually stabilizing: the maximum values will not exceed 3.0–3.7 g/dm^3 for groundwater mineralization, 1.5–2.0 g/dm^3 for sulfate ions, and 30 mg eq/dm^3 for total hardness (Tables 2 and 3). The expected values of the indicators for the surface waters of the flooded sinkholes, opencasts, and the Kopeysk open pit are as follows: mineralization = 3.2–4.8 g/dm^3, sulfate ion concentration = 1.3–3.0 g/dm^3, and chloride ion concentration = up to 0.5 g/dm^3. The waters will remain very hard (total hardness up to 40 mg eq/dm^3) and neutral or slightly alkaline (Fig. 12).

The most difficult hydrochemical situation has developed in the lakes Tretye and Chetvertoye, which were fed mine drainage waters. The waters of the lakes are very highly mineralized (up to 50 g/dm^3) with NaCl-type water. There are fairly clear trends towards increased mineralization, sulfates, chlorides, sodium, magnesium, boron, and lithium, while in Lake Chetvertoye, lead, barium, aluminum, iron and a number of other micro-components are also increasing. With evaporation continuing, the waters will be concentrating further, and this process will be accompanied by salt precipitation.

No significant changes have been observed in the chemical composition of the drinking water intakes, which indicates that the mine water in the closed shafts has not affected the groundwater. We do not expect the Korkino open pit flooding to impact the groundwater intakes either. The forecast for the water level in the Korkino open pit after its reclamation over the next three centuries indicates that elevations will not exceed + 210 m, and the cone of depression around the open pit will remain the same. This will completely exclude the inflow of water from the artificial water body of the Korkino open pit into the aquifers and its flow towards the underground water intakes.

Conclusions

1. To prevent swamping processes in the northern part of the city of Kopeysk and nearby settlements in the early 2000s, a unique drainage system was built, which has no analogues in Russia. The water that accumulates in areas disturbed by mining is pumped by a pumping station through a 20 km system of ditches and settling ponds to the River Miass. With proper maintenance of the drainage system and the water level in the VIII-2.3 open pit lake at 180 m (in accordance with the design project for the liquidation of the Krasnaya Gornyachka mine), there is no risk of flooding due to drainage cessation.
2. The Kopeysk open pit will be flooded up to the ultimate elevation of + 194.5 m in 2091. To prevent the flooding of the facilities on its eastern flank, it is advisable to maintain the water level in the flooded open pit no higher than the absolute elevation of 190.0 m. There is no risk of the Kopeysk machine-building plant being flooded, provided that leakage is stopped, and water is no longer discharged onto the unstable slope. The territory of the city of Kopeysk is located at even higher elevations; therefore the flooding of the city is in no way associated with the flooding of the open pit but is caused by leaks from the water-carrying lines.
3. Reclamation of the Korkino open pit, the largest in Eurasia, is being carried out by backfilling the mined-out workings with tailings from the Tominsk processing plant, which are being delivered to the open pit by a 14 km long pipeline. The plan provides for the complete filling of the mined-out space by 2045 at a water level of + 155 m. Final flooding to an elevation of + 210 m will occur no earlier than 2250.
4. The combination of the geological structure with the geomorphological conditions, hydrometeorological factors, and mining methods has led to the post-mining emergence of new hydrogeoecological conditions. On the one hand, the filling of the cone of depression has caused the formation of artificial reservoirs, flooding of areas, and the development of landslide processes; on the other hand, this has caused dewatering of the lakes, which existed at the expense of mine drainage, and the radical deterioration of their water quality.

Table 2 Average value and interval (min–max) for TDS, pH, concentration of major ions in surface and groundwaters

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)
SW1—open pit X (n = 14)								
Average	3599	8.2	177.2	261.1	599.2	709.7	1312.3	340.5
Min	2042	8.0	149.0	201.0	502.9	570.4	715.0	281.0
Max	4160	8.4	212.3	327.0	722.0	890.0	2047.0	399.6
SW2—Lake Lesnoy sklad 1 (n = 18)								
Average	3017	8.3	185.2	244.9	411.0	337.3	1505.8	313.7
Min	2064	7.9	136.0	175.0	246.5	289.0	970.0	206.0
Max	3630	8.6	294.3	312.4	527.0	388.0	2372.0	383.7
SW3—Lake Lesnoy sklad 2 (n = 14)								
Average	2532	8.0	226.0	207.6	283.6	297.4	1298.9	183.1
Min	31	7.6	166.0	139.0	201.0	254.0	795.0	130.0
Max	3210	8.2	286.0	262.5	369.5	430.0	1740.0	326.0
SW4—Subsidence (shaft no. 23) (n = 9)								
Average	3542	8.0	321.5	198.6	462.6	216.2	1607.8	233.5
Min	3160	7.5	280.0	170.6	419.4	190.0	1045.0	216.0
Max	3860	8.4	377.9	230.0	543.5	246.7	1330.0	246.0
SW5—open pit VIII-2, 3 (n = 14)								
Average	3814	8.0	320.4	233.2	482.8	321.5	1750.1	324.1
Min	3230	7.5	245.4	178.3	372.1	254.5	866.0	286.0
Max	4802	8.3	419.2	280.0	619.0	450.0	2903.0	387.4
SW6—open pit VIII-1, 2 (n = 5)								
Average	3253	8.3	135.9	196.4	505.1	976.8	1194.4	334.0
Min	2858	8.1	115.0	160.0	408.0	508.0	1080.0	295.0
Max	4410	8.5	160.3	241.0	582.0	2 680.0	1407.0	394.0
SW7—Lake Tretye (n = 14)								
Average	22,705	8.1	474.4	1453.5	5 186.1	10 083.0	3805.2	578.9
Min	2402	7.5	111.9	375.7	1 334.0	4 397.0	1569.0	105.0
Max	61,070	9.0	1050.0	3248.0	11 244.0	22 398.0	12,260.0	4 319.0
SW8—Lake Chetvertoye (n = 14)								
Average	28,236	7.9	534.7	1903.2	6497.4	12 355.1	4763.7	351.4
Min	11,483	7.3	309.7	928.8	3095.0	5 467.0	1871.0	182.0
Max	65,380	8.4	1 020.0	3770.0	12,202.0	24 790.0	12,600.0	574.0
SW9—River Miass (background point) (n = 14)								
Average	544	7.6	56.9	27.7	77.4	85.7	133.2	188.9
Min	400	6.9	47.1	21.7	58.5	55.0	72.0	158.0
Max	722	8.0	75.6	36.0	111.0	139.0	220.0	205.0
SW10—River Miass (n = 13)								
Average	502	7.7	52.3	25.4	74.1	71.8	122.5	211.0
Min	390	7.0	19.0	20.0	58.9	53.0	82.0	163.0
Max	586	8.3	70.7	30.1	107.0	93.0	180.0	482.6
SW11—Site no. 4 (main) (n = 14)								
Average	6159	8.2	236.4	319.4	1434.2	1999.9	1864.8	423.4
Min	3946	7.8	148.0	223.0	697.8	730.0	1170.0	322.0
Max	8116	8.4	349.7	452.6	2107.0	4180.0	2813.0	549.0
SW12—site no. 4 (south) (n = 14)								
Average	4765	8.0	259.9	280.3	1061.5	1259.5	1576.5	369.7
Min	3490	7.4	175.0	182.0	618.0	781.0	768.0	270.0
Max	7180	8.3	580.2	527.4	2020.0	2960.0	2355.0	445.0

Table 2 (continued)

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)
GW1—observation well no. 1 (n = 8)								
Average	638	7.1	187.9	171.9	199.8	100.9	1008.3	189.7
Min	1205	6.5	47.7	98.8	152.2	46.0	159.0	31.0
Max	2800	7.9	308.9	218.5	343.9	211.0	1550.0	878.4
GW2—observation well no. 2 (n = 9)								
Average	212	8.8	15.5	43.3	266.6	100.9	187.2	485.7
Min	505	7.6	4.2	10.0	159.0	30.0	47.0	235.0
Max	1210	10.0	38.8	65.8	430.0	280.0	345.0	775.0
GW3—observation well no. 3 (n = 9)								
Average	567	7.6	88.3	148.0	334.9	752.8	354.1	184.1
Min	1330	5.9	3.5	98.2	253.6	620.0	10.0	16.0
Max	3042	9.3	365.4	227.9	419.5	892.0	811.0	708.0
GW4—observation well no. 4 (n = 9)								
Average	277	8.0	60.3	65.1	187.3	278.9	291.2	138.0
Min	150	5.5	10.9	5.6	25.2	20.0	26.0	10.0
Max	3360	9.2	217.7	243.3	632.4	1 142.0	1072.0	306.0
GW5—observation well no. 5 (n = 9)								
Average	1304	7.3	291.1	344.6	661.5	1 315.5	1166.0	213.4
Min	520	6.4	17.3	16.6	25.6	59.0	140.0	75.0
Max	7986	8.6	593.1	627.7	1065.0	2 601.2	1836.0	511.0
GW6—observation well no. 6 (n = 8)								
Average	816	7.2	373.8	216.7	571.9	464.3	1309.1	335.3
Min	2570	7.0	250.0	168.7	225.3	300.0	778.0	82.0
Max	3686	7.4	549.2	250.9	2613.8	709.0	1820.0	544.2
GW7—observation well no. 7 (n = 6)								
Average	2729	7.1	135.2	131.7	790.0	265.3	1032.7	925.5
Min	2009	6.8	120.5	110.9	643.9	217.0	676.0	871.0
Max	3380	7.3	143.9	160.0	874.7	320.0	1460.0	988.8
GW8—observation well no. 8 (n = 9)								
Average	623	7.3	151.0	105.5	423.8	468.4	828.2	602.0
Min	1532	6.8	101.8	70.7	300.0	141.0	412.0	491.0
Max	4690	7.8	216.8	161.0	746.1	2580.0	1300.0	1 185.0
GW9—observation well no. 9 (n = 9)								
Average	1085	6.9	206.4	246.1	669.3	1 251.1	1313.1	101.2
Min	2000	5.0	34.4	159.3	355.5	620.0	560.0	10.0
Max	5345	8.9	574.1	437.6	1 127.0	2 870.0	2451.0	258.0
GW10—groundwater intake (n = 3)								
Average	128	6.4	74.2	32.5	47.2	62.4	235.9	77.2
Min	518	6.1	68.4	29.9	45.4	54.4	224.0	70.0
Max	585	6.8	78.4	36.5	49.1	68.7	255.6	82.4

Table 3 Average value and interval (min–max) for trace elements in surface and groundwaters

Water samples ID (see Fig. 4), sampling site and number of samples	Al (mg/L)	B (mg/L)	Fe_{tot} (mg/L)	Li (mg/L)	Mn (mg/L)	Ni (mg/L)	SiO_2 (mg/L)	Zn (mg/L)
SW1—open pit X (n = 14)								
Average	0.08	0.23	0.13	0.14	0.14	0.00	0.94	0.01
Min	0.01	0.12	0.05	0.07	0.02	0.00	0.01	0.01
Max	0.38	0.38	0.48	0.19	0.38	0.01	1.65	0.02
SW2—Lake Lesnoy sklad 1 (n = 14)								
Average	0.07	0.55	0.10	0.15	0.14	0.00	2.34	0.01
Min	0.01	0.32	0.05	0.08	0.02	0.00	0.15	0.00
Max	0.44	0.84	0.23	0.22	0.37	0.01	5.29	0.01
SW3—Lake Lesnoy sklad 2 (n = 14)								
Average	0.04	0.40	0.09	0.14	0.06	0.00	0.62	0.01
Min	0.00	0.29	0.05	0.08	0.01	0.00	0.09	0.00
Max	0.011	0.60	0.21	0.25	0.23	0.01	1.52	0.01
SW4—subsidence (shaft no. 23) (n = 14)								
Average	0.07	0.58	0.15	0.24	0.27	0.01	0.98	0.01
Min	0.02	0.32	0.05	0.12	0.02	0.01	0.35	0.01
Max	0.14	0.90	0.92	0.35	0.68	0.02	1.99	0.01
SW5—open pit VIII-2, 3 (n = 14)								
Average	0.07	0.41	0.16	0.22	0.28	0.03	6.81	0.01
Min	0.01	0.12	0.05	0.11	0.03	0.01	3.81	0.01
Max	0.16	0.61	0.40	0.31	0.81	0.05	10.54	0.01
SW6—open pit VIII-1, 2 (n = 10)								
Average	0.05	0.28	0.08	0.16	0.20	0.01	2.15	0.01
Min	0.01	0.14	0.05	0.11	0.01	0.00	0.35	0.01
Max	0.10	0.45	0.15	0.29	0.55	0.05	5.48	0.01
SW7—Lake Tretye (n = 14)								
Average	0.14	1.63	0.13	0.63	0.06	0.00	0.82	0.01
Min	0.01	0.68	0.05	0.14	0.00	0.00	0.07	0.01
Max	0.42	3.70	0.44	1.30	0.036	0.01	5.60	0.03
SW8—Lake Chetvertoye (n = 13)								
Average	0.13	1.25	0.26	0.75	0.12	0.00	1.35	0.01
Min	0.01	0.62	0.05	0.17	0.00	0.00	0.05	0.00
Max	0.50	3.30	0.64	1.80	0.34	0.01	6.80	0.04
SW9—River Miass (background point) (n = 13)								
Average	0.30	0.10	0.40	0.01	0.07	0.01	3.16	0.06
Min	0.04	0.07	0.07	0.01	0.01	0.00	1.99	0.01
Max	0.82	0.15	1.12	0.01	0.16	0.01	4.87	0.16
SW10—River Miass (n = 15)								
Average	0.23	0.09	0.38	0.01	0.07	0.01	3.05	0.06
Min	0.04	0.03	0.11	0.01	0.01	0.01	2.01	0.01
Max	0.60	0.14	0.72	0.01	0.17	0.02	4.86	0.16
SW11—site no. 4 (main) (n = 14)								
Average	0.06	0.46	0.11	0.11	0.05	0.01	4.50	0.01
Min	0.01	0.33	0.01	0.06	0.00	0.01	1.10	0.00
Max	0.22	0.64	0.40	0.15	0.18	0.03	12.04	0.02
SW12—site no. 4 (south) (n = 14)								
Average	0.05	0.52	0.07	0.12	0.19	0.05	4.55	0.01
Min	0.01	0.33	0.02	0.07	0.01	0.02	3.00	0.01
Max	0.10	0.67	0.19	0.18	0.56	0.10	7.39	0.03

Table 3 (continued)

Water samples ID (see Fig. 4), sampling site and number of samples	Al (mg/L)	B (mg/L)	Fe_{tot} (mg/L)	Li (mg/L)	Mn (mg/L)	Ni (mg/L)	SiO_2 (mg/L)	Zn (mg/L)
GW1—observation well no. 1 (n = 8)								
Average	0.03	0.27	11.08	0.10	1.50	0.00	3.75	0.02
Min	0.01	0.18	0.09	0.06	0.15	0.00	0.33	0.01
Max	0.06	0.62	46.36	0.13	7.55	0.01	15.08	0.03
GW2—observation well no. 2 (n = 9)								
Average	0.04	0.16	2.52	0.02	0.12	0.00	0.78	0.01
Min	0.01	0.09	0.35	0.01	0.01	0.00	0.24	0.01
Max	0.08	0.32	11.53	0.3	0.31	0.03	1.56	0.02
GW3—observation well no. 3 (n = 9)								
Average	0.02	0.13	20.58	0.08	0.63	0.00	2.99	0.02
Min	0.01	0.06	0.07	0.04	0.02	0.00	0.05	0.01
Max	0.05	0.26	96.16	0.11	1.79	0.01	24.60	0.06
GW4—observation well no. 4 (n = 9)								
Average	0.03	0.07	9.43	0.06	0.51	0.00	2.63	0.02
Min	0.01	0.03	0.45	0.01	0.04	0.00	0.51	0.01
Max	0.10	0.14	37.67	0.22	2.20	0.01	16.23	0.07
GW5—observation well no. 5 (n = 9)								
Average	0.03	0.22	17.37	0.11	0.93	0.00	5.06	0.02
Min	0.01	0.03	0.05	0.01	0.02	0.00	0.28	0.01
Max	0.06	0.53	68.89	0.17	2.74	0.01	29.03	0.08
GW6—observation well no. 6 (n = 8)								
Average	0.04	0.23	15.14	0.08	1.13	0.01	5.90	0.03
Min	0.01	0.15	8.52	0.06	0.52	0.00	1.48	0.01
Max	0.08	0.50	21.20	0.11	2.84	0.03	13.22	0.07
GW7—observation well no. 7 (n = 8)								
Average	0.09	0.25	13.11	0.10	0.58	0.01	7.18	0.03
Min	0.01	0.11	1.62	0.07	0.35	0.00	5.10	0.01
Max	0.16	0.39	31.54	0.13	0.78	0.04	8.85	0.11
GW8—observation well no. 8 (n = 9)								
Average	0.07	0.23	12.28	0.06	0.52	0.02	7.58	0.03
Min	0.01	0.10	1.38	0.04	0.24	0.00	2.66	0.01
Max	0.20	0.41	52.87	0.09	0.82	0.05	11.11	0.08
GW9—observation well no. 9 (n = 9)								
Average	0.04	0.08	34.13	0.07	1.90	0.00	2.67	0.02
Min	0.1	0.04	0.96	0.04	0.36	0.00	0.08	0.01
Max	0.07	0.17	83.97	0.11	4.36	0.01	22.39	0.06
GW10—groundwater intake (n = 3)								
Average	0.013	0.08	3.68	0.04	0.35	0.01	16.09	0.00
Min	0.01	0.05	2.83	0.04	0.34	0.01	0.01	0.00
Max	0.31	0.09	4.36	0.05	0.38	0.02	28.84	0.01

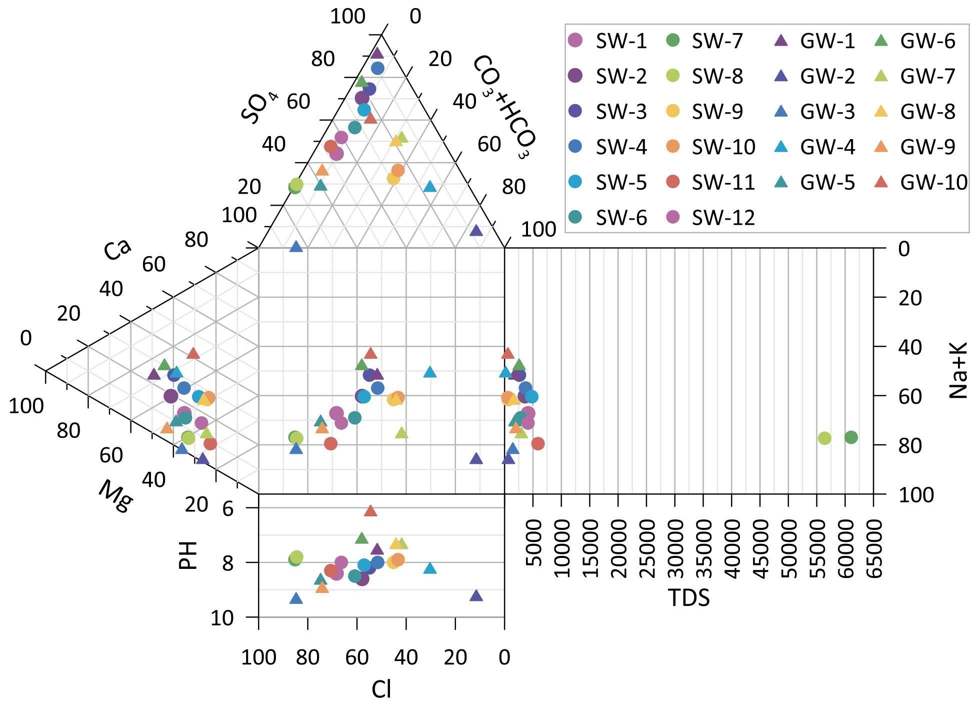


Fig. 12 Durov plot. *SW* surface water samples, *GW* ground water samples. For water sample. IDs, see Tables 1, 2

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Data availability All data is available via open sources.

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