POLLUTION OF GROUNDWATER AND SURFACE WATER FROM THE MINING INDUSTRY

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ABSTRACT. The pollution of groundwater and surface waters from the mining industry is a very serious ecological problem worldwide. The article overview various examples from world practice, related to the research, monitoring and the applied measures to reduce this pollution. The causes and conditions, under which these environmental problems occur, are thoroughly analysed. Potential and real sources of pollution - landfills, and abandoned mines, specific mineralization in the sites, pollution from accumulated sediments and sludge, etc. are studied. The possibilities for assessment and predicting of this type of pollutions with the help of mathematical models are presented, and some typical examples of pollution areas around uranium mines in Bulgaria and Germany are overviewed. Pollution with heavy metals around mine in Morocco is another presented example.

Keywords: groundwater contamination, acid mine drainage, heavy metals, mass transport model and water quality.

ЗАМЪРСЯВАНЕ НА ПОДЗЕМНИТЕ И ПОВЪРХНОСТНИ ВОДИ ОТ МИННО-ДОБИВНАТА ДЕЙНОСТ

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РЕЗЮМЕ. Замърсяването на подземни и повърхностни води от минно-добивна дейност е много сериозен екологичен проблем в световен мащаб. В статията са разгледани различни примери от световната практика, свързани с изследването, мониторинга и прилагането на мерки за ограничаване на това замърсяване. Направен е обзорен анализ на причините и условията, при които възникват тези екологични проблеми. Разгледани са потенциалните и реални източници на замърсяване – отпадъкохранилища и изоставени минни, специфична минерализация в обектите, замърсявания от натрупани наноси и утайки и др. Представени са възможностите за оценка и прогнозиране на този тип замърсявания посредством математичеки модели и специализирани компютърни програми. Направен е преглед на някои типични примери на замърсяване на повърхностни и подземни води при добива на метални руди и естествен уран в Германия и България. Разгледан е и друг случай на замърсяване с тежки метали в района на мина в Мароко.

Ключови думи: замърсяване на подземните води, кисели руднично води, тежки метали, миграционен модел и качество на водите.

Introduction

The protection of the environment, the biosphere and the natural resources is connected with the sustainable progress. The surface and the interior of the Earth, the atmosphere and the water are basic natural resources, providing conditions for emerging, development and existence of organisms and humans. The presence of pollutants, in concentration over the regulated limits, could cause negative consequences for the whole food chain, the ecosystems and other natural resources. The environmental pollution directly affects the society, and is harmful for the people's health. It also has negative impact on tourism, fishing and agriculture. In addition to monitoring, analyzing and control of the surface water and groundwater condition is required.

Contamination of surface water and groundwater in result of ore mining operations is quite complex ecological problem worldwide. The analysis of a huge number of scientific publications shows, that the biggest impact over the nature and the peoples is from the toxic and radioactive type of pollutants (Casagrande et al., 2019; Arranz-González et al., 2016; Wang et al., 2019; Aleksander-Kwaterczak et al., 2016; Olías et al., 2019; Luo et al.,2020; Andonov et al., 2019; Stoyanov, 2019; and Stoyanov et al., 2018). The list of toxic pollutant is long - some of the most common are the metals Cd, Ni, Hg, Pb, As, Cr, Cu, Zn, Fe, Mn. The radioactive contaminants include radionuclides and products from fission of the uranium (isotopes of elements). The main sources of toxic pollution are related with mining activities and the processing of metal ore, tailing ponds, etc. Sources of radioactive contamination are the uranium mines, the processing of the uranium ore and the storage facilities. The negative impact continues after the the period of exploitation. The pollution could come from underground and open pit mines, extraction with reinjection, geotechnological and product enrichment facilities, temporary storage of hazardous materials, etc. In fact, the extraction of uranium ore is also connected with intensive pollution with various heavy metals, but also can cause long lasting contamination with a lot of others inorganic and organic contaminants as sulfates, chlorides, ammonium ions, oil products, cyanide, etc.

The text below includes some typical examples, with the results of the conducted research of the processes leading to pollution due to the mining of metal ores and uranium ore in Germany, Morocco and Bulgaria (Bain et al., 2001; Moye et al., 2017; Kolev and Hristov, 2019; Stoyanov et al., 2019).

Materials and methods

1. During the second half of the last century, significant quantities of uranium ore were mined in Bulgaria. In 1988 the extracted ore is 662 t (1,5% of the world total yield). The uranium reserves on the territory of Bulgaria in 2014 are about 35,374 tons.

One of the uranium ore sites is a mine called Druzhba, near Eleshnitsa village, in the southwest part of Bulgaria, operated in the period 1955 - 1992. After cessation of mining activities, the drainage pumps (with approximate pumping rate of 300 m^3/h) were shut down in December 1995, and since then the the discharged water flows directly into Zlataritsa river with initial rate of about 10 l/s. During the excavation work, three different confined aquifers (upper, medium and lower) were registered in the region of the deposit - respectively at approximate altitudes of 805, 730 and 630 m, recharged exclusively from infiltration of atmospheric precipitation. The filtration parameters of the massif are adopted by archive data as follows: cumulative thickness of the aquifers 146 m; hydraulic conductivity k = 0,5 m/d, water yield coefficient μ = 0,005. The galleries volume is respectively 980000 m^3 between 520 and 620 m height, equivalent radius 56 m; 1150000 m^3 between 620 and 712 m height, equivalent radius 56 m; 325000 m^3 between 712 and 738 m height, equivalent radius 63 m.

Fig.1. Photo of the area of Druzhba mine (Google Earth, 2020)

The tailing pond collecting the wastewaters from the mining activities is located 2,6 km southeast of Eleshnitsa village, and is used since 1969 (Fig.1). The height of the dam is 74 m, and the total area of the tailing pond is 250000 m^2. The pond contains about 9000000 t of wastes, 730 t of them uranium, with total radioactivity = $1,5.10^{15}$ Bq . Rehabilitation of the pond was conducted from 2003 to 2005 (project PHARE). Since then a water treatment plant downstream from the tailings pond collects all the drainage water and treats it for possible uranium pollution (Kolev and Hristov, 2018).

2. Another area in Bulgaria impacted by pollution with metals is the Madjarovo ore field. The mining operations began in 1958 and finished in 1997. The ore field includes the mines Arda, Harman kaya, Momina skala and Brousevtsi (Fig.2). The parts of the rock massif that are affected by mining activities are characterized by very high water permeability and play the role of complex drainage systems. Data from the system monitoring, as well as hydro-chemical studies carried out in 2015, revealed increased contents of Fe, Mn, Zn, Pb, Cd, As, Ni, and other heavy metals in the mine and in the surface waters in the region. The main pollution is caused by zinc, lead, cadmium and nickel. The harmful effects of the pollutants are health disorders, such as damage to body cells, kidney damage, cancer, skin inflammation, negative impact on plants and animals.

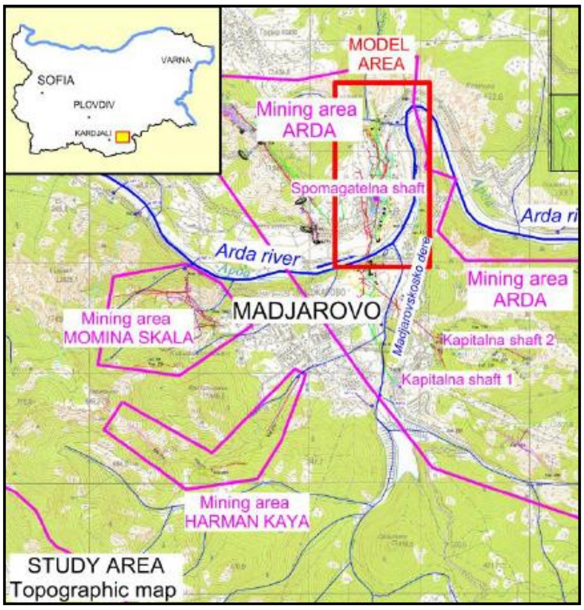

Fig.2. Map of the area of the Madjarovo ore field (Stoyanov et al., 2019).

Applying the Modflow and MT3D-MS computer programs (McDonald and Harbaugh, 2000), (Zheng and Wang, 1998), several 3D numerical models are composed. The studied area is divided in five hydrogeological units:

I - parts of the rock complex affected by the mining activities – galleries, shafts, shattered zones, pillars (hydraulic conductivity k = 3 m/d; volumetric mass = 1850 kg/m^3; longitudinal dispersion 3 m; coefficient of molecular diffusion $D_M = 5.10^{-4}$);

II - tectonic zones (hydraulic conductivity k = 4,5 m/d; volumetric mass = 1850 kg/m^3; longitudinal dispersion 4,5 m; coefficient of molecular diffusion $D_M = 5.10^{-4}$);

III - regionally fractured and secondary altered parts of the rock complex down to elevation 110 m (hydraulic conductivity k = 0,35 m/d; volumetric mass = 2150 kg/m^3; longitudinal dispersion 10 m; coefficient of molecular diffusion $D_M = 7.10^{-4}$);

IV - weakly affected by secondary changes parts of the rock complex (hydraulic conductivity k = 0,02 m/d; volumetric mass = 2150 kg/m^3; longitudinal dispersion 10 m; coefficient of molecular diffusion $D_M = 7.10^{-4}$);

V - river terrace - cobblestones, gravels, and sands (hydraulic conductivity k = 100 m/d; volumetric mass = 2100 kg/m^3; longitudinal dispersion 5,5 m; coefficient of molecular diffusion D_M = 3.10^{-4}).

The 3D mass transport model simulates the movement of the main pollutants, and follows the prepared filtration model of the studied area. Convection, reversible elimination, dispersion, diffusion and mixing are taken into account. The transverse dispersion is 1/10 of the value of the longitudinal dispersion. The vertical dispersion is 1/100 of the longitudinal dispersion. The simulated period is from 1995 to 2030 (Stoyanov N. et al., 2019).

3. The uranium mine Koenigstein is located in the Saxony Region of eastern Germany near the River Elbe, about 20 km south of the City of Dresden. The ore is not very rich - about 0,03 % (mass), mainly as UO_2. The study area consists of a series of sandstone aquifers separated by clay. The ore body is located in a lower sandstone layer, designated as the fourth aquifer. This aquifer has about 10 m average thickness. The overlying aquifer is used as a potable water supply. From 1950 through to the end of 1990, uranium ore was extracted at this mine by means of an underground in situ leaching process, which involved passing a sulfuric acid leaching solution through isolated blocks of the ore body. Since closure of the mine in 1990, the level of the underground waters has been maintained at low level.

The groundwater flow system for complex multi-aquifer system has been modeled by WASY software and FEFLOW software. The two profiles (sections), showing the uranium transportation, are presented on Fig. 3. The longer is 5 km and the short is 1 km long. The flowing direction of the underground waters is N - NE. A simplified model of a one-dimensional profile parallel to the direction of groundwater is used. The choice for 1D model is appropriate because the ratio between length and thickness of the fourth aquifer (1000 - 5000 m in length, 10 m thick).

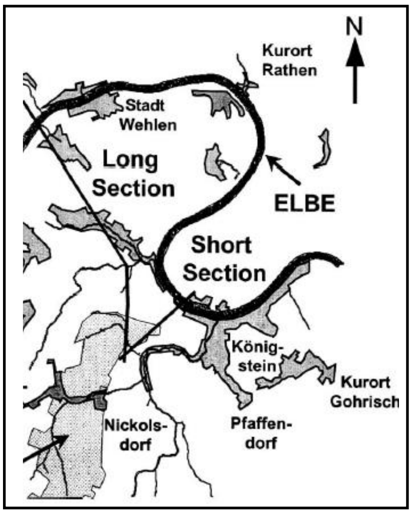

Fig.3. Two sections (Long Section и Short Section), oriented accordingly to the underground flow direction (Bain J. et al., 2001)

The filtration parameters of the lowest aquifer are: hydraulic conductivity 0,86 m/d; porosity 0,19; volumetric mass = 2100 kg/m^3; coefficient of molecular diffusion D_M = 9.10^{-5} m^2/d).

In 1993, an experiment was carried out in which the pumping of groundwater was stopped and the mine was flooded. Water samples from the site were taken after 190 days from the beginning of the flooding. The predicted period for the long section is 50 years, and 100 years for the shorter section. The studied data is for the following contaminants: Fe, U, Pb, Ni, Cd, Cr и Zn and sulfates (Bain J. et al., 2001).

4. Ketara mine is located nearby Ketara village, 35 km northwest from Marrakech city, in Morocco (Fig.4). The mine extracted sulfide minerals from pyrrhotite ore, and currently the mining operations are ceased. The area around the mine is polluted with Mn, Fe, Zn, As, etc., which affect the quality of groundwater.

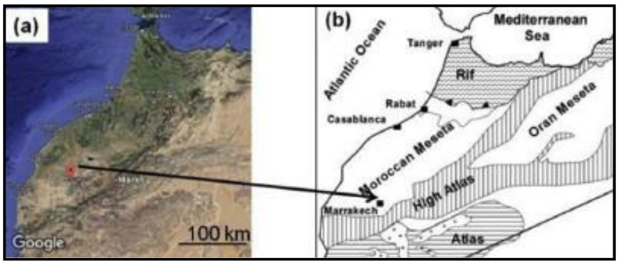

Fig.4. Location of Ketara mine, Morocco (a - photo; b - map)

Two aquifers have been established on the territory of the site - one in the Sarhlef shale, and one in the granite rocks called Bamega. The study is focused on the aquifer in the shale with hydraulic conductivity 78 m/d and storage coefficient 5.10^{-2}.

After collecting the necessary data, models for the underground water levels and electrical conductivity were created using the computer program Golden software. The concentrations of contaminants from the water samples are presented in Table 1 (Moye et al., 2017).

Table1. *Concentration of contaminants*

Pollutant	Concentration min-max (ppb)	Average concentration (ppb)	Standart deviation
As	0,25 - 22,12	3,35	6,52
Fe	43,5 - 668	168,71	189,35
Mn	5,36 - 1184,5	88,8	302,28
Zn	5,92 - 29,54	-	-

Results and discussion

1. The concentration of the pollutant in water samples taken from gallery №9 (point 34 of the monitoring) in the period from 2012 to 2016 is shown in Fig.5. Gallery №9 is the lowest exit of the mine at level 738 m and is discharging the flow (10 l/s) in Zlataritsa river.

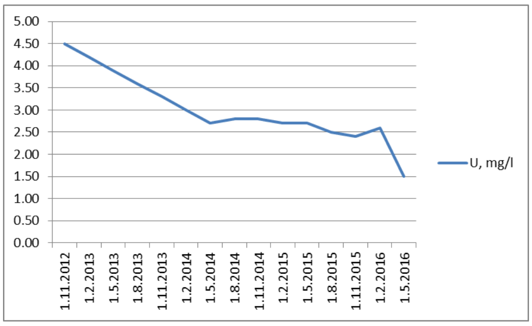

Fig.5. Concentration of the uranium (mg/l) in the waters from gallery №9 (Kolev and Hristov, 2018)

At this flow rate, the amount of uranium poured into the Zlataritsa river for the period 2012 - 2018 is about 5 tons, with average concentration of 2,8 mg/l. Over time, concentrations decrease, due to flooding of the mine, leading to limited contact with oxygen and reduced mobility of the pollutant.

2. The model of pollution in the Madzharovo ore field is based on a filtration model, which determines the spatial distribution of pressures, gradients and velocities. The problematic pollutants are Zn, Pb, Cd, and Ni. The range of the pollution is determined with 3D mass transport model. The largest contamination by area is caused by the element nickel (Fig.6), but the zinc has the strongest exceeding of the permissible norms (Fig.7).

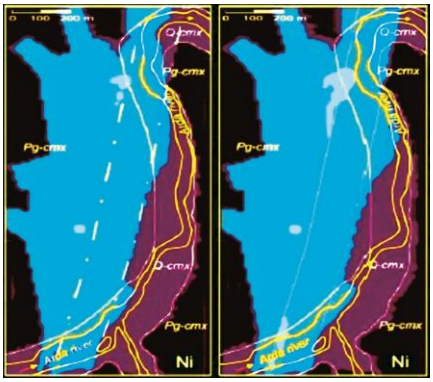

Fig.6. Nickel pollution for period of 15 and 30 years (Stoyanov et al., 2019). Concentration (mg/l):

0,004 - 0,015	0,015 - 0,02	0,02 - 0,075	0,075 - 0,2

The results show a significant impact on the area between the town of Madzharovo and the large meander of river Arda. The wastewater flow is significant (about 40 l/s), and the pollution covers an area of the river terrace with a length of over 1 km (Stoyanov et al., 2019).

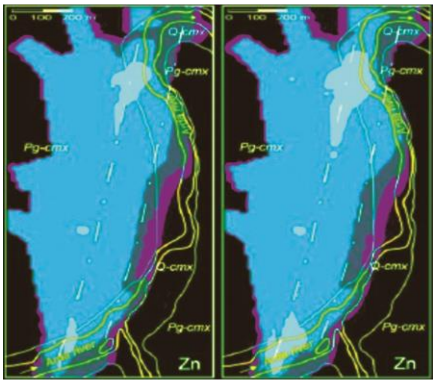

Fig.7. Zinc pollution for period of 15 and 30 years (Stoyanov et al., 2019). Concentration (mg/l):

0,015 - 0,075	0,075 - 0,1	0,1 - 35	35 - 70	70 - 100

3. Koenigstein mine in Germany - the prediction data for the two profiles are in Fig.8 and Fig.9. For the "Short Section" are presented data which take into account the reactions between the pollutant and the aquifer, and data calculated without the influence of the reactions with the underground aquifers (conservative model).

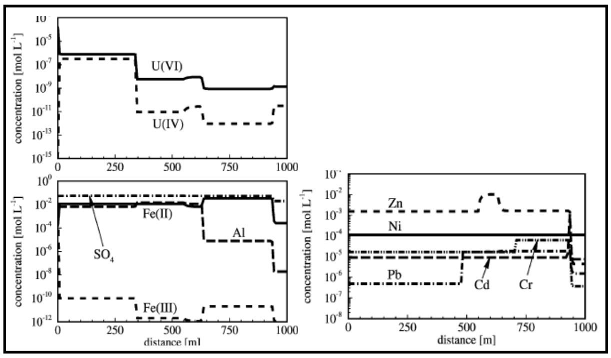

Fig.8. "Long Section" profile concentrations for 50 year period (Bain et al., 2001)

The predicted concentrations for the short profile (Fig.9) are for point located at 1000 m from the pollution source (Bain et al., 2001).

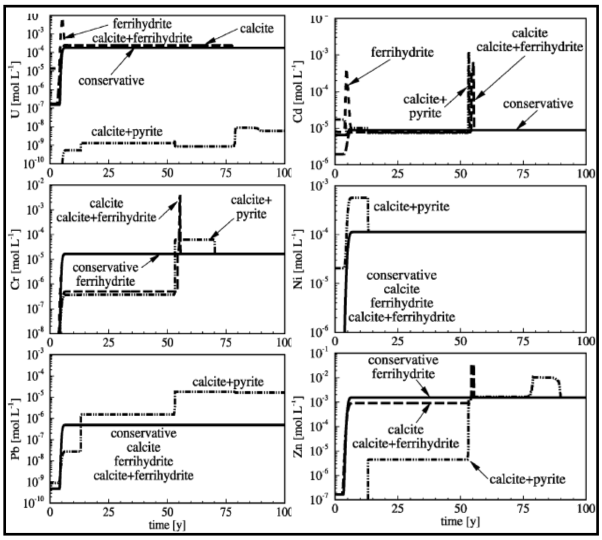

Fig.9. "Short Section" profile concentrations for point at 1000 m distance of the contaminant source. Prediction period - 100 year (Bain et al., 2001)

4. The analysis of data from the Ketara mine site was used to determine the concentrations of pollutants that may affect the quality of groundwater.

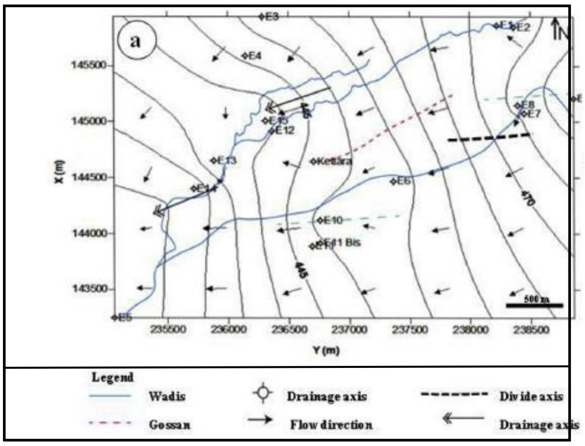

Fig.10. Piezometric levels in the area of the mine (Moye et al., 2017)

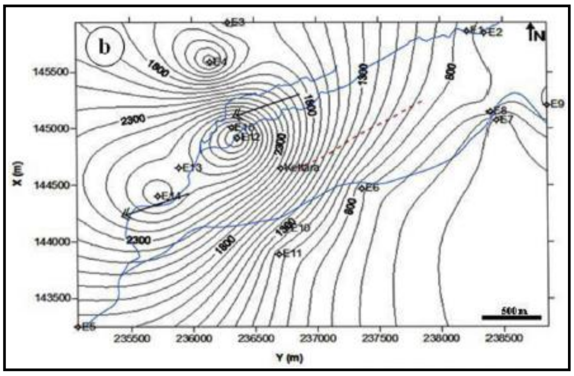

Fig.11. Electrical conductivity in the area of the mine (Moye et al., 2017)

The results of the model for the filtration field and the calculated electrical conductivity are presented in Fig.10 and Fig.11. The concentrations of the pollutants are in Fig.12 and Fig.13.

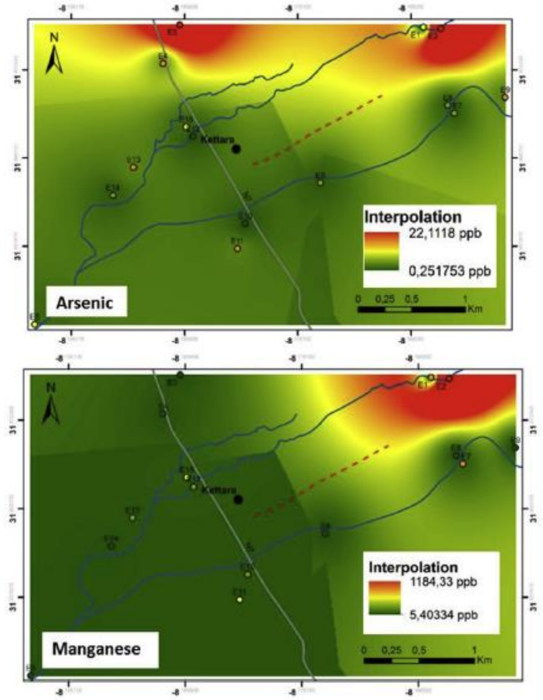

Fig.12. Pollutant concentration in the area around Ketara mine (Moye et al., 2017)

The major problem in the area around the mine is caused by arsenic. The high levels of pollution are most likely due to the presence of a regional fault, the high values of evaporation in the area and possibly to reaction with organic substance or iron oxide (Moye et al., 2017).

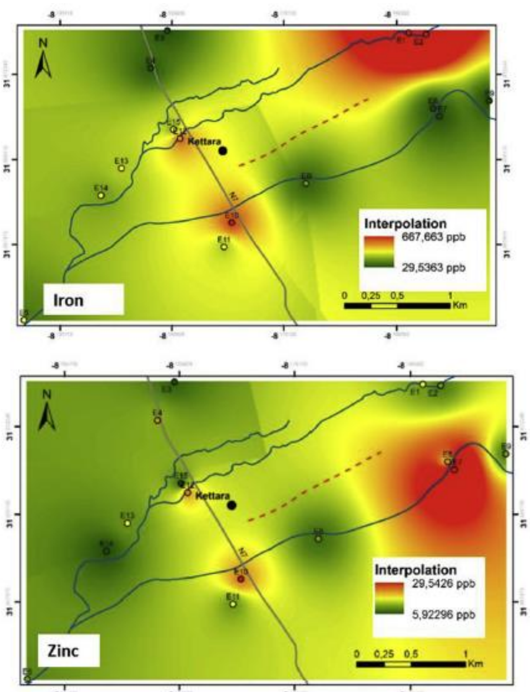

Fig.13. Pollutant concentration in the area around Ketara mine (Moye et al., 2017)

Conclusion

The presented examples above clearly show that mining activities are very often the cause of long-term, large-scale and very intense pollution with toxic, radioactive and other pollutants of groundwater and surface water. Solving the problem requires a very detailed scientific hydro-geoecological study of each specific site. The study should involve a set of field, laboratory, and study models. The main purpose of this study is long-term forecast and quantitative assessment of the negative processes related to the pollution with metals, and the identification of appropriate recovery measures. Undoubtedly, such a study must precede any investments in mining and mineral processing activities.

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