The importance of mine subsidence for environmental impact assessments of mine closure. Case study: Baia Sprie East mine, Baia Mare region (Romania)

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Abstract. In the following paper we discuss some aspects regarding the importance of mine subsidence in the mine closure and the environmental impact assessment of non-ferrous metal mines. Usually, for vein ore deposits, an impact assessment is focused on tailing ponds and tailing heaps, while mine subsidence tends to be neglected. This may lead to an incomplete impact evaluation. Using a complex methodology, subsidence zones and the associated risks at the Baia Sprie East mine from Baia Mare mining region (Romania) were determined. Based on the results, it is showed the importance of analyzing mine subsidence when it comes to carrying out a risk assessment in the mine closure process.

Key Words: mine closure, subsidence, mine water, vein deposit, environmental impact.

Introduction. In many Romanian regions and throughout the globe, mining remains one of the main causes of pollution. Mining related environmental problems occur in all three environmental mediums: air, water and soil. Pollution can be related directly to the mining activity, or to ore processing. It can appear in the form of heavy metals or other toxic substances, acid waters, airborne particles or toxic gases, tailing heaps, tailing ponds, radiation, etc.

In Romania, mining can be dated back as far as 15 thousand years, and after the Second World War it became one of the basic economic branches (Fodor 2005). Despite this fact, there weren't many measures taken regarding the protection of the environment. By the end of the 20th century, the Romanian government had to financially support most of the mines because they became non-productive. In the beginning of the 90's, the government started planning the closure of these mines. The mine closure processes started in 1999, and by the year 2007, all underground mines were closed, excepting some of the salt, coal and uranium mines.

Although there were many mine closure plans, these mines continue polluting. This could be related to multiple factors, but in the case of underground non-ferrous mines, which will be the main subject of this article, we can point out 2 main causes:

- poorly executed mine closures;
- usually, when we talk about environmental impact assessments, those are focused on tailing ponds and tailing heaps; in most of the cases, subsidence is neglected.

Not much research is done in mining subsidence and the impact over the environment (Hudson et al 1991). Although there are some researches in this field, most of them involve physical models, which are very expensive, site specific and inaccurate, because it's difficult to reproduce the exact replica of what's going on underground. Most of the research worldwide has been done on subsidence caused by coal mining (Blodgett & Kuipers 2002).

The aim of this paper is to illustrate the importance of mine subsidence, thus contributing to a more accurate environmental impact assessment in mine closures.

Mine closures in Romania. In Romania, a guideline to mine closure has been edited by the Ministry of Industry and Resources, i.e. Mine Closure Manual. According to this document, the main stages to be followed when talking about mine closures are:

- first stage: planning (plan for ceasing the mining activity, technical closure project of the mine);
- second stage: ceasing the mining activity;
- third stage: the contract of execution;
- fourth stage: implementation and monitoring of the "contract";

- fifth stage: land conveyance;
- sixth stage: post-closure monitoring.

Every stage is detailed and has its specific steps in its appendix. In the third part of the Mine Closure Manual we can find mine closure and conservation procedures. Section III.2.4.4. reffers to the stability of the terrain, in means that one has to identify the areas which can be affected by subsidence. We can even find a number of safety-measures which have to be taken on the affected area. However, at the moment we don't have a method that could predict or identify these areas, before the subsidence occurs. Furthermore, the environmental impact assessments usually focus on tailing ponds and tailing heaps. Due to lack of research in mine subsidence, this factor tends to be neglected. If related to, it is done based on former experiences and usually after the collapse occurred. The same thing happens in other parts of the world (Blodgett & Kuipers 2002; Hudson et al 1991; Goldbach 2009; Kruk & Ţîbulac 1994; Younger & Wolkersdorfer 2004). Due to lack of information and because there are no methods that could predict where subsidence will occur and at what extent, this sector remains uncovered.

If voids are taken into account, it's usually because of mine water, but without considering the changes in underground conditions (water volume, acidity, heavy metals, etc.) which occur after the mine collapses. It is impossible to know for sure what the link is between the severity of mine subsidence and these changes.

Importance of predicting the subsidence affected areas. Subsidence is an inevitable consequence of underground mining. It can be local, or can extend on large areas, with immediate or long-term effects (Blodgett & Kuipers 2002).

Knowing the affected area can be very important in the mine closure process, subsidence can radically change the mine's impact on the environment, because after the collapse, there are a number of serious changes in different factors that can alter the environment. Some of these negative effects are: injury of wild animals, domestic animals and humans, surface degradation, destruction of vegetation, it can affect the infrastructure and populated areas (depending on where the mine was built), and it can affect the hydrology of the area. Also, subsidence can have a direct and indirect impact on the quality and flow of mine water.

There are a series of parameters that can influence the intensity and extent of subsidence: ore thickness and depth (Blodgett & Kuipers 2002; Kruk et al 2003); multiple ore zones; dip of ore zone; the geological, chemical, physical and mechanical characteristics of the surrounding lairs; nature of overburden; surface and near-surface geology; geologic discontinuities; degree of extraction; surface topography; groundwater; water level and fluctuations; mining method; backfilling; time. These factors and their influence on subsidence are explained in the mentioned and in relating literature.

Possible injuries on animals and humans. Subsidence can form a link between the surface and underground voids. This can conclude in animal or human injuries. Throughout the years there were many reported cases of such injuries in mining areas from the northern part of Romania. For example, the injury of wild and domesticated animals in the Socea perimeter – Satu Mare county, Tyuzoşa, Borzaş – Maramureş county, or the Valea Roşie, Dealul Crucii perimeter from Maramureş county, Baia Mare mining region, where even people suffered injuries from falling in holes caused by mining subsidence.

Here we can also mention the impact on aquatic species, by affecting the levels of surface and underground waters and their chemistry. The evaluation of the impact can be easy, if we measure the loss of a certain species. But, as in an ecosystem „everything is linked"; evaluating the exact impact can be really hard. For example, if one species of aquatic insect is threatened by mining, and that particular insect is the food source of any mammalian wildlife, mining will have an indirect impact on them (Blodgett & Kuipers 2002).

In order to prevent similar injuries, according to (Kruk & Ţîbulac 1994) we have to:

- point out the areas where such phenomenon could or already occurred;
- restrict access on these areas;
- backfilling (if possible);
- prevention of subsidence by designing pillars, or backfilling the void.

These measures can be taken while the mine is operational, or, excepting the pillars, they can be done during the closure or the conservation state. But, initially we need a study that describes the evolution of the subsidence (Labonde 1996).

The impact on the surface, land use and vegetation. The fact that subsidence will or will not affect the surface is strongly influenced by the depth of the mine. Mining at any depth can result in subsidence, and the affected surface area is generally larger than the extraction area (Blodgett & Kuipers 2002). The intense ground movements and voids resulted from mine subsidence can affect areas up to tenth of hectares. On these surfaces, beyond affecting the landscape, subsidence can also affect the flora of the area and land-use.

Subsidence can affect agricultural land. In this case the estimation of the impact is easier, measured in partial or total loss of productivity. Additional consideration is required where lands are intended to support threatened or endangered wildlife species or in wilderness areas that are intended to retain certain undisturbed or natural characteristics (Blodgett & Kuipers 2002). In the case of estimating the impact on lands used for public recreation or where the land is covered in wild flora, it is harder to make a precise impact and it becomes subjective.

The impact of subsidence on land-use and vegetation can be direct (cracks, voids, slope modification etc.), or indirect, by modifying the flow and quality of the area's hydrology, etc. If the impacts on the surface are not on an extended area, and land movements are stabilized, as a mitigation variant we can fill up the voids and cracks. Because of the existing volumes, this procedure is rather expensive and rarely applied. Prevention is more advisable in this case too (Labonde 1996).

Damage of the infrastructure and populated areas. In most cases, mining sites are established far from habited areas. However, in some cases, because we don't know the extent on which subsidence will affect the surface, it is possible for urban or inhabited areas to be directly affected by subsidence.

When it comes to the direct influence on surface structures, in the majority of the cases we can talk about affecting the annex mine establishments, like roads, gas lines, electrical power lines, electrical substations, or other buildings, like in the case of the Baia Sprie West mine (Galiceanu et al 1984), or even sterile deposits, In such cases, the impact assessment can be done considering material loss and rehabilitation costs. The evaluation becomes more complex, when there are human deaths are involved, or the estimation of social impact, when relocation is necessary. It is difficult to evaluate the loss, due to the subjectivity of the situation, when archaeological sites are involved, or the involved loss belongs to a community or is a part of the country's patrimony.

Usually, exploitations don't go beyond the "safety zone" (where populated areas or annex mine buildings can be harmed). This illustrates the importance of defining the affected area. Because there are some severe consequences, preventive measures should be taken.

The impact on the area's hydrology. The biggest impact generated by mine subsidence is on the area's hydrology. Whereas, in previous cases, the impact is felt only on the affected area, when we talk about hydrology, the effects of subsidence can be felt way beyond the affected area. Subsidence can have a direct impact on water quality and flow, and it can also impact aquatic life forms (Blodgett & Kuipers 2002).

Vein deposits are the result of the hydrothermal phase of the eruption, so usually we can find them in mountain areas. In Romania, annual precipitations are around 900-1200 mm in these areas, and the surface is studded with seasonal and year round streams. As a direct result of subsidence, voids and cracks can appear on the surface.

The streams and rivers from the affected area, along with meteoric water will flow in these cracks and voids. The meteoric water from above the affected area, when not collected by a different water course, which does not pass through the affected area, will be swallowed by these openings.

Groundwater can be affected by mine subsidence in various ways, including lowering of groundwater levels, changes in flow rates, and impacts to water quality. Lowering of groundwater levels may decrease the groundwater supply and result in the decrease or loss of well water, and decreased surface transmission to springs, seeps and other surface water sources (streams, lakes etc.) as well as decreased evapo-transpiration. Alteration of water quality is caused by changes in the chemical reactions and reaction rates with the minerals or surrounding strata (Blodgett & Kuipers 2002).

If subsidence occurs during the active life of the mine or in the conservation period, surplus water will be evacuated along with existing water quantities. This could lead to changes is the capacity of the water pumps. When closing the mine, the calculations regarding mine-water will be done considering the new values. However, when subsidence occurs after the mine was closed, it is much harder to manage these new values in water flow, because dimensioning for evacuation and water treatment plants were already done. In this case there is a possibility that the pumps or treatment plants will not be able to handle the mine water flow rate.

The long-term impact of mine water is analyzed by Younger (2003). The author comes to the conclusion that, mine voids have a bigger role in generating acid mine waters, than tailing heaps and tailing ponds. Pillar failure induced by flooding is also discussed by Goldbach (2009).

Case study: Baia Sprie East Mine, Baia Mare mining area, Maramureş county. As a case study it was chosen the Baia Sprie East Mine within the Mining Area Baia Mare. The mine has been chosen because the natural sustaining pillars were modeled on dry mine conditions. A calculus study has already been done for the measure in which subsidence in will affect the surface but this study was done for conditions of dry mine (Kruk & Ţîbulac 1994; Kruk et al 1995; Kruk et al 2003). As consequence of closing the mine, it will be flooded, fact that will lead to the alteration of sustaining rocks so the initial conditions are changed. This study focuses on the mine taking into account the new conditions created.

Description of the area. Baia Sprie area is located in north-western part of Romania, at around 15 km distance to Baia Mare, on DN 18 road Baia Mare – Sighetul Marmaţiei. Unwritten testimonies regarding the exploit activity in the area are known since the year 1329 (Feştilă et al 1972). The Baia Sprie deposit is a base metals and precious metals vein deposit (Pb, Zn, Cu, Au, Ag). The mine has two perimeters, Baia Sprie West, between pits 1 and 4 and Baia Sprie East, between pits 4 and 6. The mining activity has been ceased in 1999 in the western perimeter, and in 2006 in the eastern perimeter.

Due to the fact that the mine workings in the eastern perimeter are localized underground below the road DN 18 and the Săsar River, a protection pillar has been sized in order to protect the road and the river. The protection pillar was sized for conditions of “dry mine” and by this we understand the stop of the infiltrations from the surface and the evacuation of the technological water and possible volumes resulted from underground sources (Kruk et al 1995). After the interruption of the activity in the eastern perimeter no more closing works were done in order to collect the surface waters and the evacuation of the mine water from the underground ceased, so today the lower levels are flooded (level XV and level XIV). Due to the change of the underground conditions, the mine is becoming humid, so it became opportune to verify the influence of the exploit on the surface because it would be possible that the protection pillars sized for dried conditions are not efficient, fact that could alter the surface, the national road and the river.

Around the area of caving in it is formed the area of intense movements, that manifests by the leaking and fracture of the rock. The cracks so formed vary from millimeters to tens of centimeters (there are more intense as we go closer to the void).

The delimitation of the area of intense movements is possible after the delimitation of the area of caving in, the extension of the area of movements depending on the size of the caving in area.

***Possible consequences**.* In the case of intense movements, one can not predict exactly the extent in which the surface will degrade. The area of intense movements may be manifested by unevenness, compaction or cracks by size of millimeters up to tens of centimeters. The only way to prognostic where the effects will be more intense is to follow which are the sections where the area of caving in reaches the closest to the surface. The unevenness and cracks will be more intense as close to the area of caving in we are. But also in this zone, exceptions may appear, due to the number of factors that may influence mine subsidence. For this reason, the maximum possible consequences are taken into account.

Concerning the time period in which the consequences will be sensed, there is a big incertitude because it is not known exactly which are the conditions of alteration and the speed of alteration of the rocks in those conditions. To this factor it is added the fact that we can not predict exactly the speed of propagation of the caving in towards the surface. If the present conditions do not change, the effects of subsidence may appear in 2-5 years and may last up to 10 years until their attenuation. Practically we know that the effects of subsidence will be resented cyclically at the surface until the wholes will enter in an equilibrium state. That is why it is proposed a continuous monitoring and remedy of the elements that may be affected.

The area affected by the intense movements is located in a mountain area with intense road circulation, close enough to the town Baia Sprie, so the presence of the fauna is reduced enough, mostly concerning mammals. So the influence of intense movements on the fauna will be much reduced. On the other side, the influence on the flora will be stronger. The most affected will be probably the trees, their stability being reduced due to the cracks formed in the area of intense movements, the result being their fall because of their own weight or because of the winds which are strong and frequent in this area.

The direct impact over the other plants will be smaller, still being the greater risk of the indirect impact, because the cracks reduce the capacity of the soil to retain water and decrease the level of the groundwater. So, all the plants in the area could be affected. Among the indirect effects we may also remember the mine waters. Due to caving in the infiltrations will increase so the flow rate of mine waters will increase. The caving in has also as affect the increase of oxygen inlet, fact that will lead to the intensification of oxidation processes in the mine. This leads to the increase of the acidity of the water, which may have negative effects on the flora in the area and downstream.

The area of the surface possibly affected by the intense movements is crossed by the DN 18 road, which is intensively circulated, being the main link between Baia Mare and the historical Maramureş. The road (Figure 1) is possible to be affected in two places: before the cross roads to Şuior (approximately nearby the pit 5), on a length of around 200 m and in the area of the first curve after the crossroads, on a length of around 600 m. The effect of the influence of intense movements will be materialized by the apparition of some unevenness and cracks in the road side having the amplitude of centimeters up to tens of centimeters. Although these effects represent serious risks, they may be only temporarily remedied. The measures will be cyclical until the extinguishment of the movements, and then the final remedy may be started. In the area of the first curve, beside the deterioration of the road side, there is the risk that the support walls are affected or even destroyed. The destruction of the walls leads to the cleavage of a part of the road side. From the point of view of measures, it is acted as in the previous case.

Being no danger that the area of caving reaches the surface, maybe it will not be necessary to close the road, only restrictions regarding the circulation, but it is imposed to monitor the area of intense movements by topographic measures until the extinguishment of the movements. As alternative road it is proposed the county road DJ 184, Baia Sprie – Cavnic – Budeşti. On June 29, 2011 a water pipe of almost 100 years old brooked. The pipe under crossed road DN 18 within the affected area. Water washed the foundation of the road that led to the collapse of the sustaining walls. It was necessary to stop circulation on the affected segment until the remediation of the situation and the above-mentioned alternative route was used. In the case the caving affect the respective pipe under the segment of road, a similar scenario may be expected. The water pipe supplies water to around 5000 inhabitants in the town of Baia Sprie.

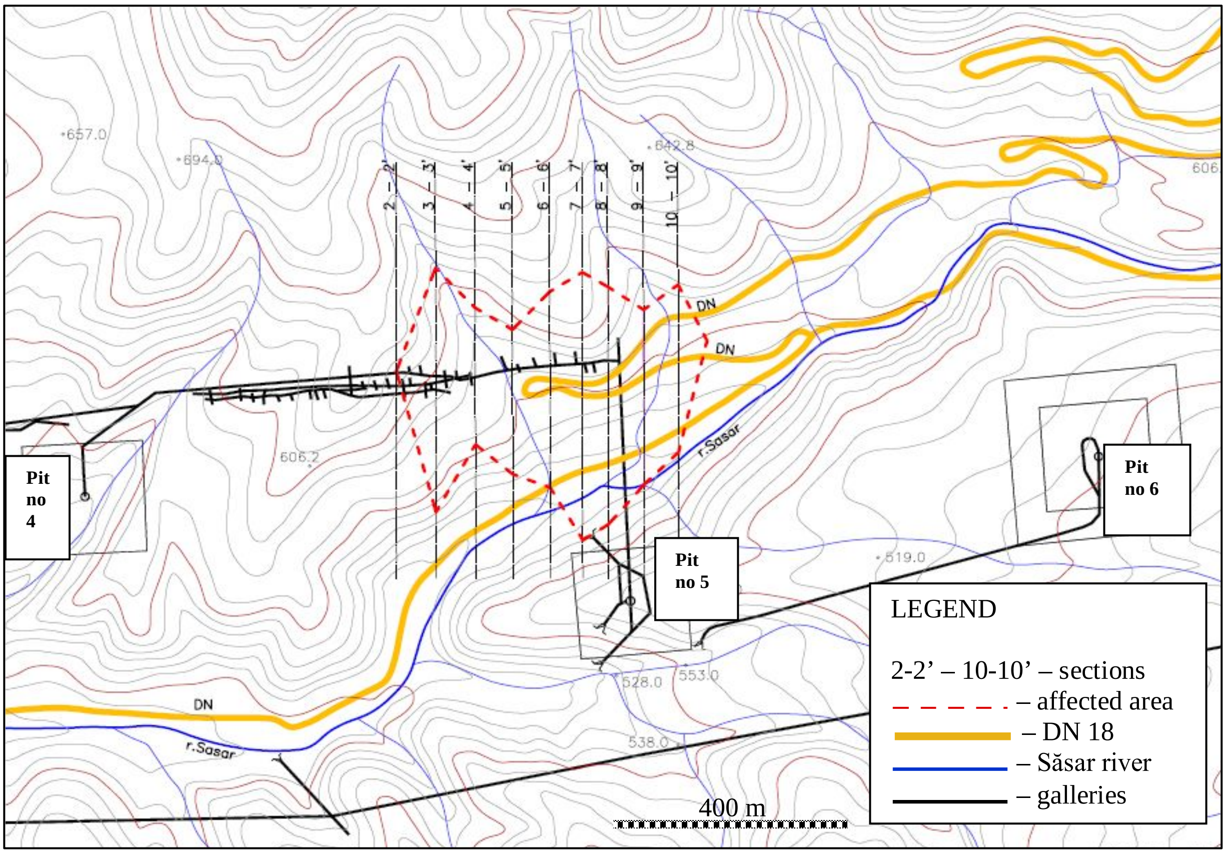

Figure 1. Location of the mining subsidence affected area.

Parallel to DN 18, between Săsar river and the road there is a high voltage line (110 kW), which supplies the historical Maramureş. The pillars belong to a "loop" of high voltage lines that begins in Baia Mare and crosses all Maramureş (Figure 2). In the case a serious damage occurs to a pillar, the consequences would be the followings: the town Baia Sprie there would be a power shortage for approx. 10 minutes, the other part of the "loop" would become very charged because it should overtake all the supply of current in the county.

In the moment of ceasing the mining activity in the mine Baia Sprie East, level XII was avtive. Up to this level there was no intercepted groundwater. At level XV there is a major fracture that links to the old mine (Baia Sprie West) where the mine workings intercepted groundwater. In order to maintain the mine in dry status, the water infiltrated in the eastern perimeter before ceasing the mining activity was pumped out at around 1200 m^3 water/day, meaning 13.9 l/s. Due the interruption of the evacuation the level of the water started to increase, in present being between levels XIV and XIII, representing a sure source that has to be taken in calculus when elaborating the documentations for closure.

After the intense movements will reach the surface, meteoric waters that reach the underground would have to be taken in calculus. Generally, the area of intense movements acts as a draining system that may significantly reduce the volume of groundwater that it crosses. In our case, in the analyzed area was not noticed the presence of groundwater. So the system of cracks will affect only the quantity of water stored in the soil and will drain the water resulting from precipitations in the underground wholes.

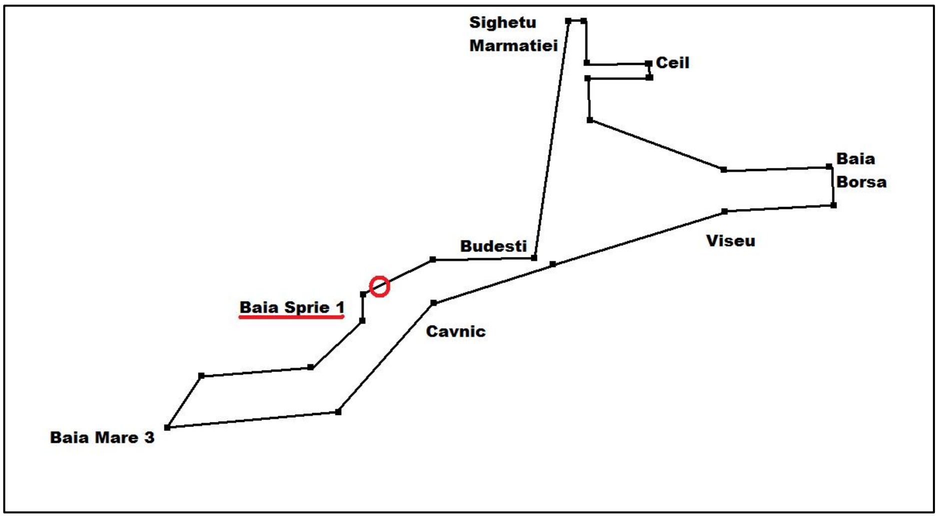

Figure 2. Schematic representation of the main power lines in the North-Eastern region of Maramures county

The surface directly affected by the intense movements is around 20 hectares, the surface on which the waters will be drained being of around 50 ha, taking into account the upstream surfaces, where from the waters resulting from precipitations are collected by two seasonal rivers crossed by the area of intense movements. It is possible that the area of intense movements include the Săsar River on a length of around 200 m (Figure 1), segment where the average width of the water mirror is of around 1.50 m.

Besides the consistent increase of the flow rate from the underground, the infiltration waters will also lead to the change of the chemistry of the underground water. No study is being done regarding the solubility of the minerals in the Baia Sprie East deposit, with the existence of factors that facilitate the process (bacteria, oxygen inlet, increase of the contact surface, relatively high temperature, etc.) so we do not know how the chemistry of the water will evolve after the area of intense movements will reach the surface.

An analysis on the waters coming from the major fracture at level XV with the collection point at the Pumping Station (Analysis Bulletin no. 71/1510÷18.10.2007 – S.C. I.C.P.M. SA Laboratory, Baia Mare), indicates a reduced acidity (Table 1). That peculiarity is due to the flow on the same routes since many years, the presence of oxygen and the contact surface being relatively reduced. In order to have an idea on the evolution of the water chemistry there were taken the results of the analysis from Baia Sprie West (Table 1), where the minerals are similar to that from Baia Sprie East and the effect of subsidence reached the surface since the year 1984 (Galiceanu et al 1984). Comparing with the water coming from Baia Sprie East, the water from Baia Sprie West has a lower pH and a higher content of metallic ions.

If we take into account that compared to the situation in the eastern area where we have fresh contact surfaces, the mine water analyzed already has well fixed ways, washed for years and years (even the infiltration waters wash the rock since around 25 years), in the eastern area we can expect to more acid waters (pH < 3), with higher contents of metal ions, especially during the first years after the apparition of movements at surface.

Table 1

Mine water analysis from Baia Sprie

No	*Parameter*	*Measurement unit*	*Level XV, Baia Sprie East*	*Level IV, Baia Sprie West*
1	pH	-	6.37	4.00
2	Residuum filtered at 105°C	mg/dm^3	11,600.00	6,500.00
3	Sulfates	mg/dm^3	6,661.36	3,086.25
4	Copper	mg/dm^3	< 0.05	0.5
5	Lead	mg/dm^3	<0.10	1.80
6	Zinc	mg/dm^3	1.70	2.48
7	Manganese	mg/dm^3	35.00	172.00
8	Total ionic iron	mg/dm^3	20.00	100.00
9	Magnesium	mg/dm^3	268.75	225.00

Conclusions. Baia Sprie East mine is a very good example that illustrates the need to know in detail the phenomenon of subsidence. Knowing the surface that will be affected by caving in, we may significantly contribute to the estimation of the impact of a closed mine. Because of mine subsidence, the water flow calculated when the mine was closed will increase because of the infiltrations. Changes will also occur in the chemical properties of the water.

Without technical solutions that would solve the management of mine waters in the Baia Sprie East area, it is proposed to abandon the alternatives of flooding the mine. If the mine would be flooded, the movement of the rocks would still take place (the flooding being done on long term), after which it would be possible the apparition of some uncontrolled leakages of mine water that could pollute significant surfaces. These leakages could be continuous or in the happiest case cyclical, because the infiltration waters would contribute to the maintenance of a constant level of waters. In the same time there is the risk of groundwater pollution whose flow rate and positioning are not known. By flooding the mine, the superior level of the water will be positioned much above the opened levels (due to infiltrations), creating a considerable pressure.

We may notice that in some cases the caving in may lead to drastic change of the initial parameters of the mine, as mine waters, and they create new risks that have to be taken into account. By further study of these phenomena we could estimate the impact of underground mines with a higher accuracy, so we could elaborate strategies for reducing or even preventing the effects.

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Received: 01 December 2014. Accepted: 29 December 2014. Published online: 30 December 2014.
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How to cite this article:
Kruk Z., Costin D., 2014 The importance of mine subsidence for environmental impact assessments of mine closure. Case study: Baia Sprie East mine, Baia Mare region (Romania). Ecoterra 11(4):40-48.