Environmental impacts of metal mining

Vplivi kovinskih rudnikov na okolje

MATEJA GOSAR

Geological Survey of Slovenia, Dimičeva 14, 1000 Ljubljana;
E-mail: mateja.gosar@geo-zs.si

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Abstract: The impact of mining and processing of metal ores on the environment is described. Mines produce large amounts of waste, because ore is only a small fraction of the total volume of mined material. Mining is a process that begins with exploration for and discovery of mineral deposits and continues through ore extraction and processing to closure and remediation of exploitation sites. The potential environmental impacts that occur at all of these stages can be classified into physical and pollution impacts and occupation health impacts. The pollution impacts (acid mine drainage, soil/sediment pollution, etc.) are presented in detail. In the surroundings of abandoned mining and smelting locations environmental problems such as elevated metal concentrations in soils/sediments, dispersion of toxic metals in soil and water and ecological damage are observed. Some examples of past metal mining environmental impacts in Slovenia are presented.

Izvleček: Obravnavani so vplivi pridobivanja kovinskih rud in njihove predelave na okolje. Rudniki proizvajajo velike količine nevarnih in inertnih odpadkov, saj predstavlja ruda zelo majhen delež odkopanega materiala. Tako nastajajo pri pridobivanju kovin velike količine odpadkov, ki lahko vsebujejo težke kovine in/ali kemikalije, ki se uporabljajo v predelovalnem postopku, ali pa ne vsebujejo nevarnih snovi. Rudarjenje je proces, ki se začne s sledenjem rude in raziskavami rudnega nahajališča, sledi odkopavanje rude in njena predelava. Ko pridobivanje ni več rentabilno oz. ko poidejo zaloge rude, se rudnik strokovno zapre in rudniško območje sanira. Pri vseh naštetih fazah rudarjenja prihaja do neželenih vplivov na okolje. Na vplivnem območju opuščenih rudnikov in predelovalnih obratov rude so posledice rudarjenja večkrat zelo pereče. Vsebnosti težkih kovin v tleh, sedimentih in vodi so mnogokrat povišane, iz rudnikov lahko nenadzorovano odtekajo kisle rudniške odcedne vode itd. Na koncu prispevka so na kratko predstavljene nekatere ugotovljene posledice rudarjenja v Sloveniji.

Key words: mining impacts, mining waste, acid mine drainage, heavy metals, Slovenia**.**

Ključne besede: vplivi rudarjenja, rudniški odpadki, kisle rudniške odcedne vode, težke kovine, Slovenija.

INTRODUCTION

Metals are one of the foundations for the development of our present society. In addition, many metals are essential for life functions (SALOMONS, 1995). Since ancient times mining has had a large impact on society. Wars have been fought to acquire minerals. Slavery has been built around mining sites because a lot of labour force was needed for mining. Colonialism in many parts of the world was in part due to the need of Europe to acquire the metals to feed the factories of the industrial revolution.

Today, we are aware of the fact that mining and processing of metal ores can be important causes of environmental degradation. Mining is only one of the pathways by which metals enter the environment. The fate of metals from ore bodies in the Earth's crust to their final "resting place" on the surface of the Earth is shown in Fig. 1 (SALOMONS, 1995). Depending on the efficiency of the recycling of metals, metals initially released by mining activities end up after a number of years in the various compartments of the surface layer of the Earth. When they have been released through the atmosphere or into waters, they end up as diffuse pollutants in soils and sediments. Some of the metals is discarded with wastes and ends up in waste disposal sites (SALOMONS, 1995).

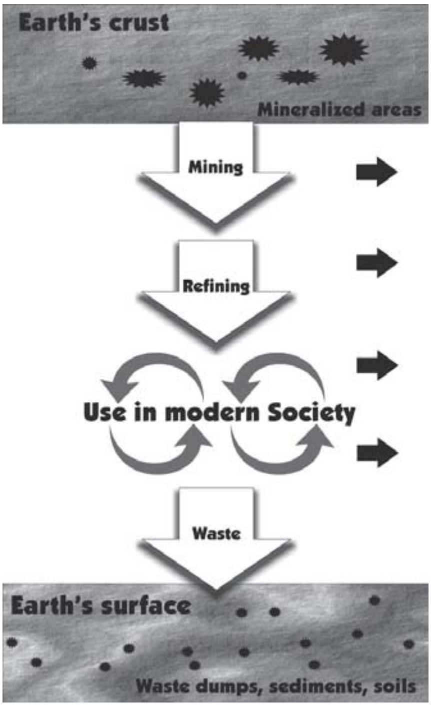

Figure 1. Pathways of metals from mineralised areas in the Earth's crust to their final "resting place" as diffuse pollutants in soil and sediments and stored in waste dumps (based on SALOMONS, 1995).
Slika 1. Pot kovin od orudenih območij v zemeljski skorji do njihove končne odložitve v tleh, sedimentih in na odlagališčih (po SALOMONSU, 1995).

Unwanted mining by-products pose a problem not just because of their volume, but because they are often chemically reactive substances (Ripley et al., 1995). There are two conflicting objectives with respect to mining:

- desire for a continued stream of benefits, combined with
- a dislike of mining due to the potential for environmental damage.

On one hand, mining generates wealth for companies, communities and countries. Metals and other mined materials are an integral part of human life on this planet. On the other hand, mining generates huge amounts of waste and pollution, disrupts indigenous livelihood, local economies and communities (sociological impact), destroys natural habitat and it can leave a toxic legacy - acid mine drainage and other negative environmental impacts - that persist for hundreds of years (Hoskin et al., 2000).

Environmental impacts of metal mining

A working definition of mining could simply be "the extraction of minerals from the Earth". Mining can also be seen as a process that begins with exploration for and discovery of mineral deposits and continues through ore extraction and processing to closure and remediation of worked out sites. Environmental impacts occur at all of these stages. The environmental concern in mining areas is primarily related to mechanical damage of the landscape and acid mine drainage (AMD) (Dudka & Adriano, 1997). The potential environmental impacts of mining can be classified to physical impacts, pollution impacts and occupation health impacts, and are presented in Table 1.

Metal ores are **extracted** by mining, which involves removal of rock from the ground (Dudka & Adriano, 1997). There are two ways of doing this: open pit mining and underground mining. An open pit is a surface excavation, usually conical in shape, dug for the purpose of extracting near-surface ore bodies. Most mines today are surface excavations. Underground mining is economical only for high-grade ore bodies (Hoskin et al., 2000).

Metallic ores **processing** may involve a number of chemical and physical separation steps that can have serious implication for the environment. The first step in processing most often consists of crushing or grinding. Beneficiation is called the entire process of crushing, grinding, sizing, and separation of ore into waste and value. In this way the mineral grains are liberated (Hoskin et al., 2000).

Mining and beneficiation processes generate four categories of **large-volume waste** (Salomons & Förstner, 1988a, b):

- mine waste (overburden, barren rocks),
- tailings,
- dump heap leach,
- mine water.

Mines produce large amounts of waste because the ore is only a small fraction of the total volume of the mined material (Dudka & Adriano, 1997). Surface mining generates more waste than underground mining (USEPA, 1982). In surface mining, the amount of waste ranges from 2 to 10 times the total volume of crude ore (Minerals Yearbook, 1992). Tailings are produced from ore beneficiation. The crushed ores are concentrated to release ore particles (value) from the matrix of less valuable rock (KESLER, 1994). Dump leaching, heap leaching and *in situ* leaching are the processes used to extract metals from low-grade ore. Dump leach piles often cover hundreds of square meters, which become waste after the process is finished. Heap leaching operations are much smaller than dump leach operations and last over a period of months rather than years. The mine water is water that infiltrates into a mine and must be removed to facilitate mining (USEPA, 1985).

After beneficiation the mineral grains have to be physically separated using one of several methods: magnetic separation, gravimetric methods or chemical methods. The magnetic separation and gravimetric methods do not present environmental hazard, but the chemical methods do. The most common chemical methods are flotation, cyanidation, amalgamation and heap leaching. This methods use large amounts of organic compounds, cyanide, mercury and acids. All of them need to be properly handled and are frequently found in the tailings (environmental problems) (HOSKIN ET AL., 2000).

Table 1. Potential environmental impacts of metal mining (HOSKIN ET AL., 2000).
Tabela 1. Možni vplivi rudarjena kovin na okolje (HOSKIN ET AL., 2000).

Potential Environmental Impacts of Metal Mining

Physical Impacts	**Pollution Impacts**	**Occupation Health Impacts:**
• Destruction of natural habitat at mining site and waste disposal sites • Destruction of natural habitat as a result of emissions and discharges • Changes in river regime and ecology due to flow modification • Changes in landforms • Land degradation due to inadequate rehabilitation after closure • Land instability / Land subsidence • Danger from failure of structures and dams • Abandoned equipment, plant and buildings	• Drainage from mining site (AD –acid drainage) • Sediment run-off from mining site • Pollution from mining in riverbeds • Effluent from minerals processing operations • Soil contamination • Leaching of pollutants from tailings, disposal areas and contaminated soils • Air emissions from minerals processing operations and ventilation on mines • Dust emissions (Vegetation destruction)	• Dust inhalation • Handling of chemicals, residues, products • Fugitive emissions within the plant • Exposure to toxic materials used on-site • Air emissions in confined spaces from transport, blasting, combustion • Exposure to heat, noise, vibration, radiation • Physical risks at a plant or at the site

Smelting and refining processes produce gaseous and particulate matter emissions, waste waters, and solid wastes (slag). These are emitted into ambient air, discharged into water systems or disposed on land (Fig. 2). The most noticeable form of contamination from the metal production industry is the discharge of emissions into the atmosphere. Tall stacks discharge pollutants at such heights that the emissions are sufficiently diluted when dispersed into the lower atmosphere to meet air quality requirements (Dudka & Adriano, 1997). The major solid wastes generated by smelting and refining, which may constitute hazardous waste, include: process wastes, residuals from air pollution control, and waste from water treatment systems (Kesler, 1994).

Mining itself affects relatively small areas. It is the tailings and waste rock deposits close to the mining area, which are the source of the metals (Salomons, 1995). When these deposits contain sulphides (pyrite) and there is an access of oxygen, acid mine drainage (AMD) results (Salomons, 1995). A sequence of chemical reactions leads to oxidation of pyrite and production of acids:

$$2\ FeS_2 + 15/2\ O_2 + 7\ H_2O = 2\ Fe(OH)_3 + 4\ H_2SO_4 \qquad (1)$$

The oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) cations is usually accelerated by the presence of *Thiobaccillus ferroxidans* bacteria. The amount of acidity produced by FeS_2 is a function of many variables - temperature, oxy-

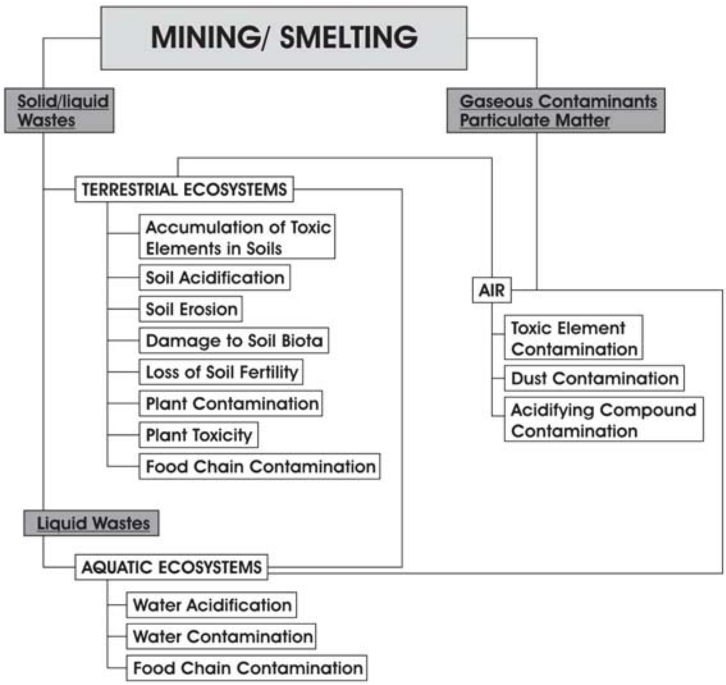

Figure 2. Shematic diagram of potential environmental impacts of mining/smelting industries (based on Dudka & Adriano, 1997).
Slika 2. Shema možnih vplivov rudarjenja kovin in metalurške dejavnosti na okolje (po Dudki & Adrianu, 1997).

gen supply, concentration of sulphides, initial pH of the surroundings, total Fe concentrations, and bacteria presence. Formation of H_2SO_4 decreases the pH of the tailing environment and adjacent soils, which usually results in increased mobility of metals that are present there (DUDKA & ADRIANO, 1997).

In general, many economically important mineral ores occur as metal sulphides, which cause SO_2, a contributor to acid deposition, to be released into the atmosphere in smelting operations. In this way emissions of SO_2 from smelters contribute to the soil acidification. For example, the main concern related to Cu production is emission of SO_2 into the atmosphere due to the sulphidic nature of these ores (DUDKA & ADRIANO, 1997).

Depending on the nature of the waste rock and tailings deposits, the AMD contains elevated levels of metals. When these leachates reach rivers, a wider dispersion of the metals both in solution and (after adsorption) in particulate form is possible. Erosion of waste rock deposits or the direct discharge of tailings in rivers results in the introduction of metals in particulate form into aquatic ecosystems. Smelting of ore concentrates results in the release of metals to the atmosphere and may, in fact, be higher compared with the mining activities themselves (NRIAGU & PACYNA, 1988; NRIAGU, 1990). Manufacturing is the next step in the release of metals to the environment (SALOMONS, 1995).

Although mines are classified on the basis of their predominant product, they may produce large quantities of other metals as by-products. As a result, metal ore processing usually leads to the multi-elemental contamination of the environment (DUDKA & ADRIANO, 1997).

ABANDONED MINING IMPACTS

Past evidences have shown that uncontrolled mining can have a large and lasting impact on the environment (SALOMONS, 1995). Today, because of the efficiency of mining operations, the loss of metals to the environment, based on complete pathways of the metals, is low. Nevertheless, localized impacts can be highly visible and if containment has not been practiced, as occurred often in the past, dispersion can occur over hundreds of kilometres (MOORE & LUOMA, 1990; SALOMONS, 1995; GOSAR & ŠAJN, 2001; GOSAR & ŠAJN, 2003).

In many areas worldwide present and historical mining and smelting activities are causing a variety of environmental problems such as elevated metal concentrations in soils/sediments, dispersion of toxic metals in soil and water and ecological damage caused by extensive metal pollution (MALM ET AL., 1990; LI & THORNTON, 1994; SOUVENT, 1994; SALOMONS, 1995; GOSAR ET AL., 1997B; BONI ET AL., 1999; DURN ET AL., 1999; ŠAJN ET AL., 2000; ASTROM & NYLUND, 2000; VREČA ET AL., 2001; ŠAJN, 2002; GEMICI & OYMAN, 2003; HORVAT ET AL., 2003). Physical remobilisation of abandoned tailings, waste piles, channel beds and heavy metal-contaminated floodplains (formed during historic mining activity) provide large amounts of metal contaminants to rivers (GOSAR ET AL., 1997B; BIESTER ET AL., 2000; HUDSON-EDWARDS, 2003). Because mining necessarily involves disturbing of previously stable formations, and may involve exposing large quantities of material to weathering processes, the environmental effects of mining activities can continue long after operations have ceased.

Some examples of past metal mining environmental impacts in Slovenia

The early period of mining and smelting in Slovenia began very early, probably in the Bronze Age at Pohorje and Kozjak, where polymetallic sulphide vein occurrences were mined (Tržan, 1989). During the Roman times ore bearing veins (Pb, Hg) of Carboniferous age in Litija and Knapovže were under exploitation (Češmiga, 1959).

From the times of the Romans to present 49 mines were opened in Slovenia; four of them were large (Budkovič et al., 2003). There were also 25 ore processing plants and smelters, which were operating mostly in the vicinity of larger mines. Large metallurgical objects were built in the vicinity of mines (Mežica, Idrija, Litija, Žirovski vrh; Fig. 3) mostly simultaneously with the mines. The only exceptions are the zinc ore smelter in Celje (in which mostly imported ore was processed), and the Kidričevo plant (in which aluminium is being produced out of imported bauxite) (Budkovič et al., 2003).

In all previous periods of mining very little attention was paid to the environmental impacts of metal mining, with the exception of the Žirovski vrh uranium mine, which was built according to very rigorous environmental standards.

At present, no active metal mines exist in Slovenia. At this moment closure activities in three metal mines (Idrija, Mežica, Žirovski vrh) are taking place. A program of closure has been prepared for each of these mines (Bajželj, 2001).

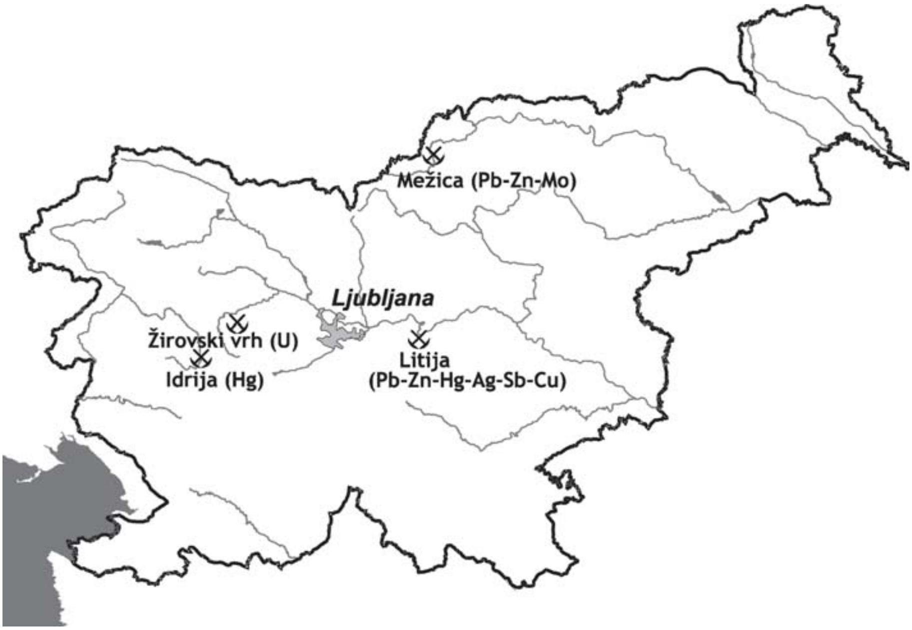

Figure 3. Locations of four most important metal mines in Slovenia.
Slika 3. Lega štirih najpomembnejših kovinskih rudnikov v Sloveniji.

THE IDRIJA MERCURY MINE

Five hundred years of intensive mercury mining activities in Idrija left a legacy of highly polluted soils and sediments (BYRNE & KOSTA, 1970; KOSTA ET AL., 1974; HESS, 1993; PALINKAŠ ET AL., 1995; GOSAR, 1997; GOSAR ET AL., 1997A, GOSAR ET AL., 1997B; BIESTER ET AL., 1999; BIESTER ET AL., 2000, GNAMUŠ ET AL., 2000; GOSAR & ŠAJN, 2001, GOSAR & ŠAJN, 2003; HORVAT ET AL., 2003). Besides soil pollution by atmospherically derived Hg°, considerable amounts of mercury bearing ore residues were spilled into the river Idrijca, and used in road construction or otherwise. Hg pollution in the Gulf of Trieste was reported to be related to the influx of sediments of the rivers Idrijca and Soča draining the mining area (HORVAT ET AL., 1999; BIESTER ET AL. 1999; COVELLI ET AL., 2001; HORVAT ET AL., 2003). Sampling of soil in years 2000-2001 over the area of 160 km^2 around the Idrija mercury mine has shown established that mercury contents in soil exceed the critical values for soil (10 mg/kg - Uradni list, 1996) on 19 km^2 (GOSAR & ŠAJN, 2003). The weighted mercury mean for the studied area is 1.3 mg/kg. Spatial distribution of mercury in soil depends very much upon the morphology of the terrain. High values occur in the Idrijca river valley and at the base of slopes, while lower values prevail at higher elevations and tend to decrease with distance from Idrija (GOSAR & ŠAJN, 2003). Smelting process produced gaseous and particulate matter emissions, which were the major cause of creating this huge geochemical anomaly around the Idrija mercury mine.

In the mining area land subsidence and sliding of the terrain were noticed. Suitable research supported with modelling proved that the consequences of the shifting of the surface are connected with non-compressed back-fills in the mine. Intensive and consistent filling of all open mine spaces and the consolidation of the old ones was needed. A program of closure of the Idrija mine comprises all necessary measures for stabilizing the whole mine structure. The task is technically very demanding because of the very complicated geology of the mine, and because of the unsuitable position of the Idrija town being built exactly above the deposit (BAJŽELJ, 2001).

THE MEŽICA LEAD AND ZINC MINE

The lead and zinc mine in Mežica has been operating for over 300 years; today it is in the closure stage. Agricola mentioned the smelters in this area in his book "De Re Metallica". The production of lead increased after 1827. Zinc production started in 1874. Ore was processed in a smelter situated at the mine. From 1947 on molybdenum was also extracted. The most extensive development period was after the Second World War.

Long lasting mining and smelting had many negative consequences on the environment:

- multi-elemental contamination of the environment (Pb, Zn, Cd, As, Ag, Mo) (SOUVENT, 1994; ŠAJN ET AL., 2000; VREČA, 2001; ŠAJN, 2002)
- mine waste deposits, flotation tailings
- SO_2 gas emissions from smelter destroyed vegetation cover in the vicinity of the smelter
- increased water erosion at barren slopes in the vicinity of the smelter.

The mine waste and flotation tailings are deposited at various locations. According to the closure program, stability and possibility of erosion at each deposit were checked and necessary protection measures and recultivation of the deposits were planned (Bajželj, 2001).

Conclusion

Active and past mining can be an important cause of environmental degradation. The main issue in metal mining is the control of acid mine drainage and of the erosion of waste rock and tailings deposits during and after the closure of a mine.

Studies in the area of the Idrija mercury mine and Mežica Pb-Zn mine have proved important environmental impacts of mining and processing of metal ores on the researched areas.

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