ENVIRONMENTAL ASPECTS OF MINING

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Abstract

This report forms an integrated part of a larger feasibility study on Mining and Sustainable Development performed at Luleå University of Technology during 2014. The report comprises a literature review of previous and on-going activities related to mining and environmental sustainability, subdivided into the following three main topics: 1) national and international environmental objectives, directives and legislation, 2) national and international initiatives and 3) academic research. A major aim of the report is to identify gaps in knowledge that indicate important topics for a future research on mining and sustainable development. The report is limited to metal mining (excluding uranium mining), and includes environmental issues related to acid mine drainage, circumneutral mine waters, and aquatic–terrestrial linkages in areas affected by mining and dust/airborne emissions. The report focuses on water, soil, and air quality issues in the local–regional surroundings of mine sites. Thus, questions concerning for example mineral reserve management and issues of a more global nature such as energy consumption and climate effects are not included.

The report identifies research gaps judged as critical for improved environmental impact assessment of mining. There is a need for more in-depth case studies to clarify the biogeochemical and ecological footprint and environmental sustainability of mining. State–of–the–Art analytical techniques and modelling software should be used to study emissions, transport distances, attenuation mechanisms, and ecological effects in the receiving waters downstream of the mine. Studies of the environmental sustainability should be integrated with parallel studies of economic and social sustainability of mining in the same area.
Preface

Minerals are essential for human welfare. However, their extraction is associated with both opportunities and challenges. Historical concerns around work conditions and the competitiveness of the mining sector have been complemented by a growing number of other issues. Today, an overarching goal is to find ways by which the mining sector can promote sustainable development.

Sustainable development is often defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Furthermore, it is commonly agreed that this must incorporate economic, environmental and social concerns.

There is a growing literature that examines the relationship between extractive industries and sustainable development, yet much research is still conducted in a siloed fashion. For this reason, the Swedish state-owned iron ore mining company LKAB and Luleå University of Technology initiated a pre-study with the aim to establish a new multidisciplinary research programme on mining and sustainability.

The pre-study was conducted from January to October 2014. One part of the pre-study was to review existing research attempting to address mining and sustainable development – the current state-of-the-art – with focus on the past, present, and future situation in Sweden, but also to put the Swedish case into a broader perspective by comparing several international examples.

One of the outcomes of the pre-study is this report. It reviews previous and on-going initiatives and research that address environmental aspects of mining. This includes critical issues related to acid mine drainage, nutrient-rich mine waters, and water–land interactions in areas affected by dust.

The report highlights a number of future research needs. Notably, there is a need for more detailed information on the characteristics of emissions from mining, their effect in different environments and how they are transported. Also, further investigation is needed on their effect on fauna and flora.

Four other review reports have also been undertaken as a part of this pre-study.

- **Making Mining Sustainable: Overview of Private and Public Responses**, by Petter Hojem from Luleå University of Technology.
- **Environmental Regulation and Mining-Sector Competitiveness**, by Kristina Söderholm, Patrik Söderholm, Maria Pettersson, Nanna Svanh and Roine Viklund from Luleå University of Technology and Heidi Helenius from the University of Lapland.
- **Gender, Diversity and Work Conditions in Mining**, by Lena Abrahamsson, Eugenia Segerstedt, Magnus Nygren, Jan Johansson, Bo Johansson, Ida Edman and Amanda Åkerlund from Luleå University of Technology.
- **Mining, Regional Development and Benefit-Sharing**, by Patrik Söderholm and Nanna Svanh from Luleå University of Technology.

Together these reports provide a broad picture of the challenges and opportunities created by mining. The pre-study has been made possible through a generous contribution from LKAB. All errors and opinions expressed in this report belong solely to the authors.

Luleå and Uppsala, October 2014
Anders Widerlund, Frauke Ecke and Björn Öhlander

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1. Introduction

1.1 Objectives and Scope of work

According to the Brundtland Report (United Nations, 1987), sustainable development is defined as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This report comprises an overview of previous and on-going activities related to mining and environmental sustainability, subdivided into the following three main topics: 1) national and international environmental objectives, directives and legislation, 2) national and international initiatives and 3) academic research.

Regarding academic research on environmental issues, a major aim of this report is to identify gaps in knowledge that indicate important topics for a future research programme on Mining and Sustainable Development.

The report is limited to environmentally sustainable development related to metal mining (excluding uranium mining), and includes environmental issues related to acid mine drainage (AMD), circumneutral mine waters, and aquatic–terrestrial linkages in areas affected by mining and dust/airborne emissions. The report focuses on water, soil, and air quality issues in the local–regional surroundings of mine sites. Thus, questions concerning for example mineral reserve management and issues of a more global nature such as energy consumption and climate effects are not included.
2. General overview of previous and on-going activities related to mining and environmental sustainability

This section deals with the following three main topics: 1) national and international environmental objectives, directives and legislation, 2) national and international initiatives, and 3) academic research. The main emphasis is on academic research that has been performed on mining-related environmental issues during the last decades. Both basic research and applied research has been performed, and a similar combination of basic / applied research should be the goal also for future research.

2.1 National and international environmental objectives, directives and legislation

In Sweden, permits for mineral exploration and mining are managed by the Mining Inspectorate (SGU, 2014). Permit applications are tried under the Swedish Minerals Act (Minerallagen). This Act aims to secure Sweden’s supply of metals and minerals. However, exploration and mining projects tried under the Swedish Minerals Act are not exempted from Swedish environmental legislation (SGU, 2013). There are several international legal documents on environmental issues that directly relate to mining operations. According to the Directive 2000/60/EC of 23 October 2000 on establishing a framework for Community action in the field of water policy (here called Water Framework Directive, WFD) (European Union, 2000), all natural recipients of mining effluents (including streams and lakes) must reach at least good ecological status. In Sweden, the WFD was implemented in 2007 (Naturvårdsverket, 2007; 2008). The assessment of ecological status is based on biological quality elements (diatoms, phytoplankton, macrophytes, macroinvertebrates and fish) (Naturvårdsverket, 2007). Since mining process water can be especially rich in different nitrogen species (Chlot, 2013) including highly toxic ammonia, also nationally and internationally approved threshold concentrations need to be considered (EIFAC 1970, SFS 2001). The operation and/or extension of mines might also be in conflict with the Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (here called Habitat Directive, HD) (European Union, 1992) including the previously approved so called Birds Directive (European Union, 1979). In addition to international directives, Sweden has approved 16 Environmental Objectives and related indicators of which several relate to mining operations (e.g. Natural Acidification Only, Zero Eutrophication, Thriving Wetlands, A Magnificent Mountain Landscape, A Rich Diversity of Plant and Animal Life, and Flourish Lakes and Streams) (Naturvårdsverket, 2012; 2013). However, only A magnificent Mountain Landscape refers directly to mining operations as a threat to fulfilling the Environmental Objective.
2.2 National and international initiatives

In the late nineties the global mining industry realised that it must address the concept of sustainable development rather than passively wait for new rules and expectations. Nine of the largest mining companies established a new initiative with the aim to change the way industry approached the concept of sustainable development, called the Global Mining Initiative. Through the World Business Council for Sustainable Development (WBCSD), they started the Mining, Minerals and Sustainable Development (MMSD) project and commissioned the International Institute of Environment and Development (IIED) to perform a scoping study. The final report of the study was published in 2002 (IIED, 2002), and a follow up-report was published in 2012 (Buxton 2012).

A set of global rules for best practice on sustainable development and minerals has been developed. The number of standards and best practice guidance, helping stakeholders to understand what sustainable development means, has increased. However, in a large number of cases, it is not clear how exactly these should be translated into basic environmental practices.

The scoping paper Mining and Metals in a Sustainable World was presented at World Economic Forum Annual Meeting, February 2014 (World Economic Forum, 2014). It was concluded that the definition of “sustainability” is unclear. It was considered important that the mining and metals sector should shape the agenda on this issue rather than react to it. With this background, the World Economic Forum introduced the new initiative “Mining and Metals in a Sustainable World 2050”. The suggested roadmap to a sustainable world identified actions that the sector needs to undertake. One of the most important was to invest in research and development: “Mining and metals enterprises must start developing the technologies to operate in a clean, affordable and safe environment in frontiers previously considered inaccessible”.

Formation of acid rock drainage (ARD) in sulphide-bearing mine waste (waste rock and tailings) is the major potential long-term environmental effect of mining, and can last for hundreds or even thousands of years in a waste deposit. The International Network for Acid Prevention (INAP) works collaboratively to address the ARD issue. INAP members presently are: Anglo American, Antofagasta Minerals, Barrick Gold, Freeport McMoRan, Kinross, Newcrest Mining Limited, Newmont Mining Corporation, Rio Tinto and Vale. All of these except Barrick and Kinross provide detailed information on their websites about how they relate to sustainable development. Barrick and Kinross instead give information about their environmental standards.

INAP has developed the GARD Guide (GARD Guide, 2014), which is intended as a state-of-the-art summary of the best practices and technology to assist mine operators and regulators to address issues related to sulphide mineral oxidation. Regarding sustainable development, the GARD Guide states:

“The economic benefit derived from mining is an essential contributor to sustainable development but the environmental and social consequences can offset this benefit unless managed appropriately”.

The above quote is also a good summary of what is stated on the home pages of the individual INAP members.

In a European perspective, Euromines is the common association of the European mining industry. Euromine’s members have set forth series of guidelines for sustainable development in the European mining sector.

The Mining Association of Canada established in 2004 a programme called Towards Sustainable Mining. Its main objective is to enable mining companies to meet society's needs for minerals, metals and energy products in the most socially, economically and environmentally responsible way. The programme is focused on best available technology rather than research.

A “Vision of growth for the Swedish mining industry” was published in September 2012 by the Swedish Mining Association (SveMin). The vision is that the Swedish Mining Industry will triple its production by 2025 (SveMin, 2012). Five important initiatives that must be taken to reach that goal are described. One of these is R&D including research on the efficient use of resources and sustainable development.

Several countries have developed national mineral strategies. Sweden’s mineral strategy, published
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in 2013, claims that Sweden should maintain and strengthen its position as Europe’s leading mining country (Sveriges regeringskansli, 2013). Mineral resources should be utilized in a sustainable manner. Here as well, five action points are described, one of which is research. However, environment and sustainable development are not emphasised.

Regarding the two major mining companies in Sweden, Boliden Mineral AB clearly addresses all three aspects of sustainable development (environmental, social, and economic) on its website, while LKAB focuses on the environmental aspects. However, both companies clearly state that they have high ambitions to leave as little impact as possible on the environment.

The Vision 2050 in Finland’s mineral strategy is that Finland is a global leader in the sustainable utilization of mineral resources, and the minerals sector is one of the key foundations of the Finnish national economy (GTK, 2014).

On the university level there are several initiatives. For example the Australian Centre for Sustainable Mining Practices (ACSMP) has been established at School of Mining Engineering at University of New South Wales in Australia. They define themselves as an “active research organization focused on new mining practices, and development and application of technologies and systems for sustainable mining initiatives”. In other words, it has a purely technical focus. Also the Sustainable Minerals Institute (SMI) at the University of Queensland, Australia, has a technical focus. However, this university also has a Centre for Social Responsibility in Mining (CSRM). At Lakehead University in Northern Ontario, Canada, the Centre of Excellence for Sustainable Mining & Exploration (CESME) has been established with the goal to encourage and support research, education and outreach activities regarding the nature and impacts of mineral resource exploration and extraction particularly in Northern Ontario. The large mining universities in Canada such as University of BC, McGill University, University of Western Ontario and University of Waterloo all have strong research on mining and the environment, but have no programmes or centres for mining and sustainable development. The Center for Environmentally Sustainable Mining (CESM) at University of Arizona in USA has a clear focus on methods to decrease the environmental impact of mining. Colorado School of Mines has no particular emphasis on neither environment nor sustainability. Camborne School of Mines Research in the UK has a research theme involving environmental protection and corporate social responsibility. University of the Witwatersrand, Johannesburg, South Africa, has a Centre for Sustainability in Mining and Industry (CSMI).

Thus, the importance of sustainability in mining is clearly recognized by government agencies, universities and the mining industry. In reality, research and development is in most cases focused on decreasing the environmental impact of mining. It appears that the industry, to a higher degree than government agencies and universities, includes and assesses the importance mining has for economy and development of a sustainable society.
Most funding agencies for mining related research, including national programmes, act like research councils. It is open to anyone to apply for funding. The result in most cases is a number of projects of good quality, but without mutual coordination. To tackle such a big issue as sustainable mining including the environmental, social and economic footprint of mining, there is an obvious need for a coherent research initiatives focusing on mining and sustainable development.

2.3 Academic research

During the last decades a considerable amount of academic research has been performed on mining-related environmental issues. This research has been carried out both within the framework of large, coordinated research programmes such as the Canadian MEND programme (Mine Environment Neutral Drainage) (MEND, 2014) as well as a large number of separate studies. In addition, mining-related environmental research is performed by organizations such as the US Geological Survey (USGS, 2014a).

In previous mining-related environmental research, biogeochemical and ecological effects of mining activities have to a large extent been studied separately. Only a limited number of studies have attempted to provide a synthesis of inorganic geochemical and biological/ecological effects on systems receiving mine effluents. Thus, for practical reasons, previous geochemical and ecological studies of mining-influenced systems are reviewed separately in this Section 2.3. In Section 3.3, the importance of integrating biogeochemical and ecological effects is emphasized, with the aim of linking ecological effects to levels of emissions in water, sediments and air.

2.3.1 Biogeochemical studies

The term “biogeochemical” is defined here as reactions involving the flow of chemical elements and compounds between living organisms and the physical environment. The term thus includes biological uptake of nutrient elements such as phosphorus and nitrogen, and redox reactions mediated by bacteria, e.g. bacterially catalysed precipitation of iron hydroxides. The term does not include the ecological topics of distribution, abundance and interaction of living organisms.

Acid Mine Drainage (AMD)

Overall the main focus of previous geochemical research on mine waste has been on acid mine drainage (AMD), with particular emphasis on prevention and remediation measures. This research has been described in textbooks (e.g. Lottermoser, 2003) as well as various reports from major research programmes such as Passive In-Situ Remediation of Acid Mine/Industrial Drainage (PIRAMID), Mitigation of the Environmental Impact from Mining Waste (MiMi), and Mine Environment Neutral Drainage (MEND) (PIRAMID, 2003; Höglund and Herbert, 2004; MEND, 2014). The International Network for Acid Prevention (INAP) with the support of the Global Alliance sponsored the development of the Global Acid Rock Drainage (GARD) Guide (GARD Guide, 2014). This guide deals with the prediction, prevention and management of drainage produced from sulphide mineral oxidation, and also addresses metal leaching caused by sulphide mineral oxidation. The GARD Guide is intended as a state-of-practice summary of the best practices and technology to assist mine operators, excavators, and regulators to address issues related to sulphide mineral oxidation.

Compared to work related to AMD prevention and remediation measures, considerably less work appears to have been performed regarding the effects of mine water effluents on receiving waters downstream of mine sites. In some cases, effects on receiving waters have been addressed within the framework of research programmes mainly focusing on prevention and remediation (e.g. Sjöblom, 2003; MEND, 2009). Nordstrom (2011) reviewed selected US Geological Survey research on hydrogeochemical processes governing trace element mobilization, dispersion and attenuation from mineralized areas during transport in surface waters. It was concluded that the mobility of contaminants (metals) from mining operations depends on 1) occurrence: is the mineral source of the contaminant present? 2) abundance: is the mineral present in quantities to be important as a source? 3) reactivity: what are the reaction rates relative to the water flow rate? 4) hydrology: what are the main flow paths for contaminated water? Nordstrom (2011) also suggested a number of approaches that can be used to study the fate of mining-related metals in surface waters.
Relatively few studies have attempted to integrate studies of biogeochemical effects (e.g. metal concentrations in waters and sediments) with studies of any corresponding biological/ecological effects. Niyogi et al. (2002) proposed a hypothesis that related biodiversity, community biomass, and ecosystem function to a gradient of stress related to AMD. Interactions between trace metals and aquatic organisms were also compiled in a literature and review report published within the MEND programme (MEND, 2009). This report describes the development and application of tools to predict the effects of transition metals in sediment, water and aquatic food. These tools can be used to assess the potential for metal toxicity in sediments and to derive site-specific water quality guidelines.

In Sweden, biogeochemical effects in aquatic systems receiving AMD have been studied by e.g. Sjöblom (2003). Sjöblom (2003) discussed various aspects of environmental sustainability in wetland systems receiving metal-rich AMD from the Kristineberg mine site, and concluded that correctly constructed wetlands can treat certain kinds of drainage to compliance with discharge requirements. Sjöblom (2003) also studied metal immobilization in natural wetlands as a complement to other treatment methods. The overall conclusion was that the investigated natural system had a limited influence on the attenuation of trace metals such as cadmium, copper, lead, and zinc. Consequently, these metals to a large extent were transported further downstream in the system.

In addition to environmental monitoring based on present-day lake and stream water data, several studies have focused on historical changes of the environmental situation in aquatic systems downstream of mine sites. Dated lake sediment cores have successfully been used to monitor historical variations in biogeochemical processes such as metal pollution and eutrophication such systems. Although annually laminated sediments are best suited for this type of investigations (O’Sullivan, 1983; Renberg, 1986), studies can be performed in any undisturbed sediment that can be dated, e.g. by the 210Pb method (Turner and Delorme, 1996). In Sweden, monitoring of environmental effects of mining based on dated sediment cores have been performed e.g. at the abandoned Laisvall lead mine (Widerlund et al., 2002) and in the Rakkurijoki system receiving water from the Kiruna iron mine (Widerlund et al., 2014). In addition, studies of bioindicators such as diatom frustules in dated sediment cores can reveal pre-industrial conditions in lakes as well as mining-related environmental effects (e.g. Peinerud et al., 2001).

Wolkersdorfer and Bowell (2005) presented a review of mine water studies in 21 European countries. The case studies described addressed environmental issues both at mine sites and consequences of mining on receiving waters, and included abandoned as well as active mines. At Swedish mine sites, limited ground-water quality data were considered as a major gap in Swedish water quality monitoring and management. The review also pointed out that no Swedish institution has the responsibility for coordinated monitoring, supervision, and management of diffuse water pollution sources over the wide scale of spatial–temporal scales associated with mine water pollution (Wolkersdorfer and Bowell, 2005).

**Pit lakes**

Production of acid mine drainage (AMD) with pH values below 3 and high dissolved concentrations of sulphate and metals is a common problem in sulphide mine pit lakes. Thus, pit lake water quality is one of the most significant environmental issues facing the global mining industry today. Decreasing ore grades and more efficient, open pit mining methods will result in an increasing number of large pit lakes, and hydrological, chemical and ecological conditions downstream of the lakes will be affected by overflow and groundwater seepage from the lakes. Globally, open pit mines and pit lakes are located in all major mining districts, with the highest numbers in North America, Australia and South America (Castendyke and Eary, 2009). In the Skellefte Field alone, about 20 small- to medium-sized pit lakes exist today. In other Swedish mining districts, several large pit lakes will start to form when existing and future open pit mines are closing within the next two to three decades.

In Sweden, the Udden and Rävlidmyran pit lakes in the Skellefte Field have been studied, and datasets exist for these two lakes (Ramstedt et al., 2003; Lu, 2004). However, no hydrological, physical limnological or ecological modelling of the lakes has been performed.
Nutrients and eutrophication

The mining industry is a major consumer of ammonium-nitrate-based explosives worldwide. In 2011, approximately 2.6 million tonnes of these explosives were used in mining operations in the USA (USGS, 2013), and in 2010, around 11 500 tonnes of ammonium nitrate emulsion explosives were used at the Kiruna iron ore mine in Sweden. Previous studies show that up to 28% of the N contained in explosives may be discharged into receiving waters as dissolved nitrate, ammonium, and nitrite (Morin and Hutt, 2009). Nitrogen leaching from mine sites depends on many site-specific factors, but explosives that remain undetonated appear to be a major issue. In addition to ammonium-nitrate-based explosives, sodium cyanide (NaCN) is a major N source at mine sites where this chemical is used in gold extraction (Logsdon et al., 1999; Lottermoser, 2003). It is becoming evident that eutrophication is an emerging problem in aquatic systems receiving circumneutral, nutrient-rich mine waters, particularly if P originating from apatite or mineral processing (flotation) chemicals such as dithiophosphate is also present (Fig. 1; Chlot, 2013; Widerlund et al., 2014).

Few case studies have been published regarding N leaching from mine sites (Morin and Hutt, 2009). Thus, considering the worldwide use of ammonium nitrate blasting agents in mining operations, eutrophication of receiving waters close to mine sites may be more common than previously realized. Recently, the environmental relevance of N-releases from mining has been acknowledged by VINNOVA, Boliden Mineral AB and LKAB, resulting in a 27 MSEK research project running 2013–2016 which focuses on reducing N-discharges in mining processes and mitigation of their environmental impact.

Chlot (2013) studied nitrogen and phosphorus interactions and transformations in two aquatic systems receiving mine waters from the Boliden and Kiruna mine sites. This work focused on speciation and transformation processes of nitrogen and phosphorus, and the natural nitrogen removal capacity of these systems. The question of limiting nutrient was also addressed, and this study emphasized that phytoplankton and macrophytes may be limited by different nutrients (nitrogen or phosphorus). These aspects have implications for assessing the environmental influence of nutrient-rich mine effluents. A study of historical changes related to nutrient-rich effluents from the Kiruna mine showed that phytoplankton and macrophyte detritus have increased in lake sediments in the Rakkurijoki system downstream of the Kiruna mine since around 1950, when nutrient-rich mine waters began to reach the system (Fig. 2).
Saline waters

Pristine, natural surface waters draining Precambrian rocks in Scandinavia are typically low-ionic strength waters with specific conductivities below 100 µS/cm. In contrast, specific conductivities of effluents from major Swedish mine sites may exceed 2000 µS/cm. In addition to this salinity increase by a factor of approximately 20, the water composition generally changes from typical Ca–HCO₃-dominated freshwaters to Ca–SO₄–Cl–NO₃-dominated mine waters. Basic studies of ecological effects of salinity have shown that the relative proportions of major cations and the ratios of monovalent/divalent cations can influence the metabolism of algae and submersed macrophytes as much as the absolute concentrations do (Wetzel, 2001).

Cold climate and climate change

The Canadian MEND programme presented a report on issues, strategies, and research requirements for disposing of potentially acid-generating mine waste in permafrost environments (MEND, 1996). Similar aspects, although in non-permafrost cold conditions, were addressed in the Swedish research programme Mitigation of the Environmental Impact from Mining Waste (MiMi) (Höglund and Herbert, 2004). Sjöblom (2003) and Chlot (2013) studied various aspects of natural attenuation of metals and nutrients in receiving waters downstream of cold-climate mine sites. Both studies indicated that high spring-flow water discharge and low temperatures reduce the overall efficiency of natural attenuation processes in wetlands and lakes.

Expected future changes in climate will present challenges to environmental management and mitigation with, for example, heavier rainfall increasing the risk of tailings dam failures and discharge of contaminated waters into aquatic systems (Nelson and Schuchard, 2014). A report by the David Suzuki Foundation (2009) described the vulnerability of the Canadian mining industry to climate change, and opportunities for adaptation.

Airborne emissions

Airborne emissions are generated during all stages of mining operations, i.e. during exploration, development, construction, mining, and mineral processing. Emissions occur in two principally different forms: gas emissions of mainly CO, CO₂, SO₂, and NOₓ, and particulate matter (dust and aerosols) (Fig. 3). Three main types of sources of airborne emissions can be identified: 1) mobile sources including all types of vehicles used in mining operations, 2) stationary sources including combustion of fuels in power generation plants and mineral processing operations (drying, roasting and smelting), and 3) fugitive emissions defined as emissions that could not reasonably pass through a stack, chimney, vent or other equivalent opening (EIA, 2014). Fugitive emissions include for example gases from ore blasting and dust
from storage and handling of materials, construction activities, roadways, tailings ponds and waste rock piles. EIA (2014) concluded that airborne emissions are difficult to predict and calculate, but should be considered since they are a potentially significant source of hazardous pollutants.

Csavina et al. (2012) presented a review on the importance of metals and metalloids in atmospheric dust and aerosols from mining operations. The review summarizes the results of 34 case studies performed from the mid 1970 up to the present, focusing on
1) the environmental fate and transport of metals and metalloids, 2) current methods used to study contaminant concentrations and particulate emissions, and 3) the potential health and environmental risks associated with airborne mining-related contaminants. The review also points out future research priorities (reported in Section 3.1.2), and concludes that mining activities play an important but underestimated role in the generation of atmospheric dust and aerosols.

Dust and aerosol dispersion is best investigated through integration of field data, physical approaches and computer modelling (Csavina et al., 2012). The Dust Regional Atmospheric Model (DREAM) can provide forecasts in both time and space of the emission, transport and deposition of dust and aerosols (Nikovic et al., 2001). However, to date only few attempts have been made to model atmospheric particulate emissions from mine tailings. One such model was presented by Kon et al. (2007).

It is often assumed that air pollution in remote areas is a recent problem related to modern industrial activities. However, a study of Swedish lake sediments showed that pre-industrial airborne emissions resulted in lead concentrations that exceeded previous background concentrations by a factor of 20–30 as early as 1000 to 2000 years ago. These emissions appear to have been derived from lead production by Greek and Roman cultures in continental Europe (Renberg et al., 1994). This example of pre-industrial, airborne emissions emphasizes the importance of determining accurate pre-mining background concentrations in mining areas, but also the difficulties involved in this determination.

Environmental monitoring programmes at mining companies

Today mining companies are required to carry out environmental monitoring programmes where discharges and emissions are quantified in terms of chemical composition and discharge rates. The Metals Mining Sector of the Acid Drainage Technology Initiative (ADTI–MMS) is developing a handbook describing the best scientific and engineering practices for the design of such programmes (McLemore et al., 2009). An important aspect of such a programme is that sample and data quality should be acceptable for modelling and prediction studies.

During the last two to three decades, Swedish mining companies have systematically collected and analysed samples of water, biota and airborne particulate mater-
ter close to mine sites. In general, both the quantity and the quality of the data have improved over time. These long-term datasets provide important information on historical variations of emissions, and should be used in future studies of mining-related environmental effects and sustainability.

In contrast to Swedish authorities, Environment Canada has developed guidelines for monitoring environmental effects of metal mining (Environment Canada, 2012).

**Biogeochemical and ecological modelling**

A large number of biogeochemical and ecological numerical models are now available. Although these models in most cases were not specifically developed for studies of mining-related environmental issues, many of these models can be applied to study various biogeochemical and ecological aspects related to the dispersion of chemical compounds in waters receiving mine effluents. Fundamentals of ecological modelling are described in Jorgensen and Bendoricchio (2001), and a large number of studies have been published (e.g. Asaeda et al., 2001). Five different computer softwares/models are briefly described below.

**HYPE** simulates water flow and substances on their way from precipitation through soil, river and lakes to a river outlet. The model also simulates concentrations and river transport of the nutrients nitrogen and phosphorus (Lindström et al., 2010).

**PHREEQC** is a computer programme designed to perform a variety of aqueous geochemical calculations (PHREEQC, 2014). The programme has capabilities for speciation and saturation-index calculations, one-dimensional transport calculations etc., and has been used extensively to model mine water compositions.

**AQUATOX** is a simulation model for aquatic systems, and predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates and aquatic plants (Fig. 4, AQUATOX, 2014a).

**MODFLOW** is the USGS’s three-dimensional finite-difference groundwater model, considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions (USGS, 2014b).

**AERMOD Modeling System** is a steady-state plume model recommended by the US EPA for modelling of atmospheric dispersion of aerosols. The model incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain (AERMOD, 2014).

In addition to the more general modelling software mentioned above, models have also been developed more specifically for mining-influenced waters. For example, Chapra and Whitehead (2009) simulated the transport and fate of cyanide in a Romanian river, but the model is of general nature and it would be possible to apply the model to any pollutant with first-order decay kinetics. Chlot et al. (2011) modelled nitrogen transformations in waters receiving mine effluents from the Boliden sulphide ore concentrator.

During the last 10–20 years, significant progress has been made in the field of predictive modelling of pit lake water quality (Castendyk and Eary, 2009). However, in 2009 only one study had been published on prediction of physical limnological conditions in a pit lake that did not exist at the time of prediction. Depending on pit lake volume, the time perspec-
tive relevant to lake formation and biogeochemical development ranges from years to decades. This implies that global climate change must be taken into account in predictive modelling of the development of future as well as existing pit lakes. Predictive modelling is an important tool in the development of site closure plans and post-mining rehabilitation of pit lakes. Today modern software engineering techniques are employed to couple different models together so that various hydrological–biogeochemical aspects of pit lake processes can be addressed (Hydrocomputing, 2014).

2.3.2 Ecological studies and biodiversity

Ecological effects of mining can derive from mainly mine water effluents and airborne emissions exposing organisms to the environmental conditions at mine sites. The effects can be detected in both aquatic and terrestrial systems and at small and large spatial scales, respectively. Effect types range from elevated concentrations in biota, via physiological to behavioural effects at the level of specimens, populations, communities and even whole ecosystems. Ultimately, effects on biodiversity may be evident. So far, most ecological studies have focused on the impact of mining process water and drainage on aquatic organisms. Nitrogen rich effluents generally result in increased biomass of different organism groups including phytoplankton and fish (Holopainen et al., 2003), which risks violating the demands set out by the WFD. Trace elements in mining-affected waters can, in addition to population densities (De Jonge et al., 2008), also affect morphological traits and can even result in deformations in the affected species (Ferreira da Silva et al., 2009). Ecological effects of trace elements in relation to the WFD are however difficult to assess since most environmental quality criteria are developed in relation to nutrients (Mestre, 2009).

There are only few studies that have assessed the impact of mining process water on riparian, wetland or even terrestrial systems. A food chain risk analysis in a mining-affected wetland in Montana, USA, did not reveal any mining-related increased bioavailability of several trace elements (Pascoe et al., 1994). In contrast, Husson et al. (2014a) revealed high concentrations of Cu, Cd and Zn in riparian and wetland vegetation along Vornbäcken, the recipient of mine effluents from the Kristineberg mining area, Northern Sweden. The concentrations of the trace elements varied along the spatial gradient from the mine site as well as among plant species, with willow species (Salix spp.) having the highest concentrations (Husson et al., 2014a). The concentrations of Cd in Salix spp. were so high that they could potentially constitute a health risk for humans if they eat moose that has predominately browsed on willows from that area (Göran Ericsson, personal communication).

Small mammals are keystone species in many ecosystems due to their role as herbivores, dispersers of fungi and viruses and prey for many predators. Therefore, their study enables inferences of the whole-ecosystem effects of mining. In addition, small mammals (voles, lemmings and shrews) generally have a small home range, which makes them highly suitable study organisms to investigate mining related impacts (see also Rodushkin et al., 2011). Airborne emissions from smelters affect trace element concentrations in different organs of small mammals (Johnson et al., 1978) as well as densities and community structure of small mammals (Kataev et al., 1994). At mine sites, trace elements even affect the genetic structure of small mammals (Mussali-Galante et al., 2013). During the last two decades there has been an increasing interest in biodiversity and the need for expressing the health of ecosystems and their integrity in terms of e.g. ecosystem functioning (syn. ecosystem processes) and provided ecosystem services (Karr, 1993; Costanza et al., 1997; Haines-Young and Potschin, 2013). Indices of stress (related to e.g. concentrations of the hormone cortisol or incidence of stress-related diseases) are increasingly used as a tool to assess ecosystem integrity (Amiard et al., 2000). Direct assessments of stress in biota (especially higher up in the food chain) related to mining are to our knowledge missing. Lee and Bukaveckas (2002) showed that leaf litter decomposition as a measure of ecosystem functioning was lower in mining impacted sites compared to reference sites. Generally, there is however a lack in studies assessing ecosystem functioning at mining affected areas, especially in those using multi-functional approaches.
3. Gaps in knowledge

A major aim of this report is to identify gaps in knowledge that will indicate important topics for a future research on mining and sustainable development. This overview of gaps in knowledge is organized into three sections dealing with 1) characterization of different types of emissions from mining activities, 2) the dispersion of these emissions into terrestrial and aquatic systems and the atmosphere, and 3) biogeochemical and ecological effects of these emissions.

3.1 Characterization of emissions

Characterization of mine waste and emissions is important for several reasons, and is normally included as a first step in studies of environmental effects of mining operations. Solid mine wastes such as tailings and waste rocks are characterized in terms of grain size, mineralogy, chemical composition and acid-generation to determine their potential as a source of contamination. Emissions such as mine water effluents and airborne emissions are also characterized with respect to the same properties to provide information on their potential effects on terrestrial and aquatic ecosystems.

3.1.1 Mine water effluents

Mine waters are normally classified according to a scheme based on pH, with the following four classes of waters: a) extremely acid, b) acid, c) neutral to alkaline, and d) saline (Morin and Hutt, 1997). Below follows a discussion of major gaps in knowledge and recommendations for future studies related to these four classes of waters. Classes a) extremely acid and b) acid are considered together due to the general similarity of these two waters (low pH and high metal concentrations).
3. GAPS IN KNOWLEDGE

Extremely acid and acid waters (AMD)

- Regardless of the type of effluent studied, a general recommendation is that screening analyses should be performed in the initial stage of a study aiming to characterize mining-related emissions. In a screening analysis, all elements that technically can be determined with a particular analytical method are included in the analysis. With a multi-element method such as the Inductively Coupled Plasma technique, up to approximately 70 elements can be determined in a screening analysis. This approach enables detection of less well-known, potentially hazardous elements that may be present in effluents.

- Predictive modelling of biogeochemical conditions in pit lakes has been performed in relatively few existing lakes, and predictive, coupled hydrodynamic–physical limnological–geochemical–ecological models for future lakes are still generally lacking.

- A major data gap regarding sustainable development of pit lakes is the general lack of long-term field data required to compare and validate model predictions.

Neutral to alkaline waters

Provided that concentrations of pollutants toxic to biota are low to moderately high (Niyogi et al., 2002), natural waters receiving neutral to alkaline, nutrient-rich mine waters may be sensitive to eutrophication. The following data gaps are identified regarding this type of mine water effluent:

- Speciation data for N (total N, dissolved NO$_3^-$, NO$_2^-$, NH$_4^+$) and P (total P, suspended P, dissolved orthophosphate) is needed as input data for biogeochemical and ecological models.

- The N isotopic composition of mining-related N sources (mainly ammonium-nitrate-based explosives and sodium cyanide) should be determined. This will enable the use of N isotopes in studies of N transforming reactions in receiving waters downstream of mine sites.

Saline waters

- Previous studies of mine waters have usually focused on toxic trace metals. A major gap in knowledge regarding saline mine waters is that the potential effects on freshwater biota of increased concentrations and/or varying relative proportions of major ions not normally considered to be toxic (e.g. Ca$^{2+}$ and SO$_4^{2-}$) are poorly known.

3.1.2 Airborne emissions

The review by Csavina et al. (2012) suggested the following research priorities regarding characterization of dust and aerosol emissions from mining operations:

- Size-resolved chemical analyses of dust/aerosol emissions from mining operations are needed. Earlier studies based on bulk collection of dust/aerosols do not fully show the related environmental health hazards.

- Very few studies take a holistic approach at understanding dust from mining operations, including source identification.

- Understanding the fine particle size fraction in dust/aerosols should be prioritized in future research.

3.2 Dispersion of emissions

A study of the biogeochemical and ecological footprint of mining emissions requires knowledge of transport distances and attenuation mechanisms of these emissions in the receiving waters downstream and/or downwind of mine sites. The following major gaps in knowledge have been identified regarding transport distances and attenuation mechanisms responsible for the dispersion of mining-related water effluents and airborne emissions.

3.2.1 Surface and ground waters

- At many mine sites a large amount of biogeochemical and partly also biological data has been collected in environmental monitoring programmes performed by mining companies. There is a general need for an increased application of this data in numerical models that can be used to identify major transport pathways and attenuation mechanisms in clarification ponds and receiving waters downstream of mine sites, as well as ecological impacts.

- Tracer techniques based on mining-related elements (e.g. Cl at LKAB mines) have been used, but should be developed further (e.g. Nordstrom, 2011). Isotope tracer techniques that can be used to determine sources and transport distances of mining-related elements should be developed (e.g. isotopes of Cl, N, S, and other elements).

- The quantitative importance of natural attenuation of N emissions through biogeochemical transformation reactions such as denitrification and anammox should be determined.

- At Swedish mine sites, limited groundwater quality data is considered as a major gap in Swedish water quality monitoring and management (Wolkersdorfer and Bowell, 2005).
In Sweden, the assessment of water quality in relation to the WFD is mainly focussed on eutrophication in general and phosphorous in particular (Naturvårdsverket 2007). The assessment of ecological status at mine sites affected by trace elements using these quality criteria is therefore not meaningful. In addition, the existing criteria in relation to eutrophication are not developed for water bodies with such skewed N/P ratios as can be found in recipients affected by mining effluents. There is a need for new quality criteria that are developed to assess ecological status at mine sites.

There is a strong need to assess ecosystem functioning and ecosystem services in mining-affected recipients since diversity per se has been shown to be a misleading indicator of ecological integrity.

3.2.2 Aquatic-terrestrial linkages along longitudinal and lateral gradients

The environmental fate of nutrients and trace metals transported laterally, i.e. from water bodies via wetlands and riparian zones into terrestrial systems including their respective biota is largely unknown. This concerns especially the spatial and temporal scale of the processes. Such knowledge is crucial for the whole ecosystem impact assessment of mining.

Lateral processes not only occur from water bodies to terrestrial systems but also vice versa (e.g. via transport of dust deposition and leaching), which also needs to be investigated.

The spatial-temporal extent of aquatic-terrestrial linkages needs to be assessed. Over which spatial scales are these linkages of ecological relevance (e.g. with respect to ecosystem functioning and ecosystem integrity) and for how long do they last?

Determination of the ecological impact of dust and other emissions from mine sites in relation to food chain responses and trophic cascades in aquatic and terrestrial systems, i.e. from primary producers (vegetation) via detritivores (e.g. invertebrates), herbivores (voles, lemmings, hares), consumers (fish) to predators (e.g. shrews). The severity of the ecological impact needs to be assessed. Are the effects limited to elevated concentrations of environmentally relevant compounds in biota, are they expressed in physiological or behavioural changes or even toxic reactions? Do potential adverse effects in biota put a public health problem?

3.2.3 Airborne emissions

The review by Csavina et al. (2012) suggested the following research priority regarding dispersion of airborne emissions from mining operations:

- Computer modelling should be used to study atmospheric particulate emissions from mine sites. Emissions from mine tailings piles have been modelled (Kon et al., 2007), but this type of modelling should also be applied at Swedish mine sites and be integrated with field studies.

3.3 Biogeochemical and ecological effects

The term biogeochemical effects is used here to describe the effects and fate of mining-related chemicals during and after transport from a mine site (e.g. Nordstrom, 2011). Biogeochemical effects thus involve speciation, bioavailability, sedimentation, permanent/non-permanent removal, and remobilization of chemical compounds in receiving waters. The resulting concentrations of these compounds in water, sediments and biota are also included. The following major gaps in knowledge have been identified regarding the biogeochemical effects of mining operations in aquatic systems located downstream of mine sites.

- Screening analyses should be performed of waters and lake sediments in aquatic systems downstream of mine sites, with the aim of detecting less well-known, potentially hazardous elements that may be present downstream of mine sites.

- Water and sediment concentrations of mining-related compounds should be determined and compared to normal background (pre-mining) concentrations of these compounds. In cases where quantitative data on pre-mining conditions is limited or lacking, the use of natural analogues and modelling should be considered (Alpers and Nordstrom, 2000). The geographical extent of elevated concentrations from mine sites should also be determined.

- The bioavailability of mining-related compounds dissolved in water as well as the extent of remobilization of compounds from lake sediments should be determined. For metals, future research should aim towards an improved assessment of the metal speciation in the exposure media, and a better understanding of the physiological effects in biota and biotas’ adaptation to trace metals.

- The question of limiting nutrient has important implications for mitigation of eutrophication in aquatic systems receiving nutrient-rich mine waters, and should be investigated further.
4. Suggestions for future work

Future research focusing on the biogeochemical and ecological footprint of mining should be performed at a mine site suitable for studies of combined biogeochemical and ecological effects of mining. A number of criteria can be set up for the choice of a site suitable for such a study:

- Mining operations should have been performed during a long period of time, so that any potential mining-related effects have developed to a measurable level.
- The mine site should be located in an otherwise relatively pristine area, with few other industries complicating the interpretation of the environmental record.
- Environmental monitoring data and previous environmental studies should be available dating back a considerable period of time from the present.

Based on these criteria, the Kiruna mine site and its surroundings is an example of an appropriate as a case study for an environmental impact assessment of mining (EIA, 2014). Mining operations began in 1890, when the Kiruna area can be considered to have been entirely pristine, with practically no local anthropogenic influence. In addition, environmental monitoring data collected by the LKAB mining company is available during the last three to four decades. A number of environmental studies have also been performed in the Kiruna area during the last decades (e.g. Chlot, 2013; Husson et al., 2014b).

Future research should focus on the identified research gaps judged as critical for a biogeochemical and ecological impact assessment of mining operations. State-of-the Art analytical techniques and modelling software should be used to characterize emissions from the Kiruna mine and to model transport distances and attenuation mechanisms of these emissions in the receiving waters downstream of the mine. Biogeochemical and ecological data should be combined to study possible connections between biogeochemical and ecological environmental effects in the study area. To obtain a broad perspective of the biogeochemical and ecological footprint of mining, the overall strategy of the project should be to combine and, as far as possible, integrate three principally different approaches: 1) field sampling/field data, 2) laboratory and field experiments, and 3) computer simulations (Fig. 5).

![Figure 5. Three principally different approaches to be used in a study of the biogeochemical and ecological footprint of mining.](image-url)
5. Conclusions

National and international environmental objectives, directives and legislation

There are several international legal documents on environmental issues that are directly related to mining operations. Two important Directives are the Water Framework Directive (WFD) (European Union, 2000) and the Habitat Directive (HD) (European Union, 1992). The WFD states that natural waters receiving mine effluents should reach at least good ecological status, while the HD deals with the conservation of natural habitats and wild flora and fauna.

National and international initiatives

The importance of sustainability in mining is clearly recognized by government agencies, the mining industry and universities. Several countries have developed national mineral strategies. Sweden’s mineral strategy, published in 2013, describes five action points, one of which is research. In both Sweden and Finland the national mineral strategies are matched by mining research programmes.

To tackle such a big issue as sustainable mining including the environmental, social and economic footprint of mining, there is an obvious need for a coherent research programme focusing on mining and sustainable development.

Academic research

During the last decades a considerable amount of academic research has been performed on mining-related environmental issues. This research has been carried out both within the framework of large, coordinated research programmes such as the Canadian MEND programme (Mine Environment Neutral Drainage) (MEND, 2014) as well as a large number of separate studies. In addition, mining-related environmental research is performed by organizations such as the US Geological Survey (USGS, 2014a). Regarding academic research on environmental issues, a number of gaps in knowledge have been indicated (summarized in Section 3).

Future work

Future research should focus on research gaps judged as critical for an environmental impact assessment (EIA, 2014). The Kiruna mine site and its surroundings is an example of an appropriate study site to assess the biogeochemical and ecological footprint and environmental sustainability of mining. State-of-the Art analytical techniques and modelling software should be used to study emissions, transport distances, attenuation mechanisms, and ecological effects in the receiving waters and their riparian zones downstream of the mine.
6. References


MEND. 1996. Acid mine drainage in permafrost regions: issues, control strategies and research requirements. MEND Project 1.61.2.


