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MINING AND THE ENVIRONMENT - UNDERSTANDING PROCESSES, ASSESSING IMPACTS AND DEVELOPING REMEDIATION

From chemical risk assessment to environmental resources management: the challenge for mining

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Abstract On top of significant improvements and progress made through science and engineering in the last century to increase efficiency and reduce impacts of mining to the environment, risk assessment has an important role to play in further reducing such impacts and preventing and mitigating risks. This paper reflects on how risk assessment can improve planning, monitoring and management in mining and mineral processing operations focusing on the importance of better understanding source–pathway–receptor linkages for all stages of mining. However, in light of the ever-growing consumption and demand for raw materials from mining, the need to manage environmental resources more sustainably is becoming increasingly important. The paper therefore assesses how mining can form an integral part of wider sustainable resources management, with the need for re-assessing the potential of mining in the context of sustainable management of natural capital, and with a renewed focus on its the role from a systems perspective. The need for understanding demand and pressure on resources, followed by appropriate pricing that is inclusive of all environmental costs, with new opportunities for mining in the wastes we generate, is also discussed. Findings demonstrate the need for a life cycle perspective in closing the loop between mining, production, consumption and waste generation as the way forward.

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Introduction

Mining is one of humanity's earliest activities, with archaeological remains of mining sites dating back to Palaeolithic times, and indeed the entire historical eras being named according to their use of metals, e.g. the bronze and iron ages (Pan et al. 2010). From prehistoric flint quarries, mining has evolved dramatically over history to the carefully and scientifically managed and often highly mechanised process it is today (Coyle 2010). As a result, mining has been of critical importance to industrialisation, urbanisation and modern society as a whole (Rajaram and Parameswaran 2005; Runge 1998). The raw materials provided by mining, together with agriculture, fisheries and forestry, are vital to virtually all human activities and sustain industries as diverse as ceramics, fossil fuels, construction, pharmaceuticals, jewellery and electronics, among many others (Azapagic 2004).

While its economic importance is clear, mining has also been the cause of many serious environmental and human health problems. Throughout all of its five life cycle stages, prospecting, exploration, mine development, exploitation and reclamation (Hartman and Mutmansky 2002), mining can cause numerous impacts ranging from soil or water contamination resulting from metalliferous mining and smelting to corruption of authorities in communities near mining corporate activities (Thornton 2012). Specific impacts can include habitat loss, soil contamination, contamination of ground and surface water, creation of voids or sinkholes and physical disturbance for the construction of roads and infrastructure, among others (Lottermoser 2010). Deforestation can also occur in the vicinity of mines to provide space for the storage of debris, soil and waste resulting from mining (Swenson et al. 2011), while natural hazards can present further environmental risks, such as mining in seismically active areas (Miranda et al. 2003). As well as causing environmental damage, chemical contamination caused by mining can affect the health of the local population (Ezekwe et al. 2012; Singh et al. 2011). In many countries, mining must adhere to environmental regulations, including for instance requirements for the reclamation and restoration of mine sites (Brown 2005). However, certain mining methods or poorly managed operations can have particularly adverse impacts on both the environment and public health (Kitula 2006). Mining and smelting are some of the largest sources of environmental pollution from heavy metals even today. For example, in China, one of the largest producers and consumers of lead and zinc, large amounts of these elements and others related ones, such as cadmium, have been released into the environment due to mineral processing activities and have impacted water resources, soils, vegetables and crops. In many areas, concentrations of pollutants such as lead (Pb) and cadmium (Cd) are associated with human health effects including high lead blood levels in children, arthralgia, osteomalacia and excessive cadmium in urine (Zhang et al. 2012).

On the other hand, often physical and economic causalities of mining are overestimated when included in life cycle assessments, as many mines have multiple functions and produce multiple metals. The ability to reflect changes in production and the economic value of metals is often a limitation in environmental studies related to metal mining (Tuusjärvi et al. 2012). Despite problems in some parts of the world, such as from artisanal mining in developing countries, modern mining to Western standards now generally utilises advanced technology combined with environmental monitoring, mitigation and remediation measures that aims to reduce environmental impacts (Pan et al. 2010). This has more recently been complemented by the increased use of more comprehensive environmental management and clean production approaches by mining companies (Hilson 2000). Recognition has grown that the possible environmental and social risks of mining expose not only mining companies directly but also financial institutions, insurance companies and metals product buyers who might be subject to consumer pressure (Miranda et al. 2003). In addition, the growing profile of sustainability and corporate social responsibility has led to at least some large mining companies to improve their reporting on social and environmental impacts, though still with no generally accepted international standards or consistency (Jenkins and Yakovleva 2006; Miranda et al. 2003). Even in China, there has recently been concern expressed about the decline of ecosystem services, calling for the need to integrate ecological and environmental impacts into decision making systems and the need for environmental management to decrease the harmful impact of mining and restore injured natural ecosystems (Chen et al. 2011).

On top of significant improvements and progress made through science and engineering in the last century to increase efficiency and reduce impacts of mining to the environment, risk assessment has an important role to play in further reducing such impacts and preventing and mitigating risks. The paper reflects on how environmental risk assessment can improve planning, monitoring and management in mining and mineral processing operations in order to reduce pollution impacts. How risk assessment can improve planning, monitoring and management in mining and mineral processing operations is discussed, focusing on the importance of better understanding source–pathway–receptor linkages for all stages of mining. However, in light of ever-growing consumption and demand for raw materials from mining, the need to manage environmental resources more sustainably is becoming increasingly important. While there has been contentious debate surrounding the validity of the term 'sustainable mining' (Horowitz 2006; Rajaram and Parameswaran 2005; Whitmore 2006), the paper assesses how mining can form an integral part of a wider sustainable resources management. The need for reassessing the potential of mining in the context of sustainable management of natural capital is discussed and a renewed focus on the role of mining from a systems perspective is proposed.

Overview of chemical hazards in mining

Each of the life cycle stages of mining and smelting can act as a source for environmental pollution, natural capital loss and degradation, with subsequent impacts to human health and prosperity. For example, a serious arsenic (As) air pollution incident also occurred near a copper (Cu) smelter in Montana, USA, which released 16,884 kg per day of arsenic trioxide (Mandal and Suzuki 2002). Mercury (Hg) used in gold amalgamation is a major source of contamination in some developing countries, with levels of mercury pollution from gold mining around Grande Marsh in Northern Colombia, for example, permeating the food web, with levels in fish representing a serious concern for human health (Marrugo-Negrete et al. 2008). The first report of 'itai-itai' disease was from cadmium (Cd) contamination downstream from lead (Pb)–zinc (Zn) mining and processing in the Jinzu River basin in Toyama Prefecture, Japan (Uetani et al. 2007). Many environmental problems are associated with the vast amounts of mine tailings produced as waste, which amount to a quantity of approximately 18 billion m^3 per year globally, which is in the same magnitude of actual sediment discharge to the oceans (Förstner 1999).

Such waste is often associated with acid mine drainage, which is considered one of the single largest environmental issues facing the mining industry, being caused by the oxidation of sulphides (Paktunc 1999).

The degree of mining's impact on the environment varies according to factors such as minerals mined, other minerals present at the site, the mining methods utilised and the location, size and geographical features of the mining area. Therefore, in order to effectively predict and manage potential environmental problems, these various aspects of mining must be investigated and understood, including the possible sources, pathways and receptors of pollution. Only once this wider understanding of risk is achieved can best practice in mining design, engineering and management be used to minimise any potential environmental impacts (Pan et al. 2010).

Many of the environmental and human health impacts of mining are chemical related, so before conducting an environmental assessment, it is a prerequisite to understand the sources, behaviours and speciation of chemicals in mining environments. Generally speaking, chemicals from mining operation can be divided into three groups: pre-existing naturally occurring chemical substances (such as metals that occur in mineral deposits), chemicals added during mining operations to process the ore and finally chemicals generated during the mining, milling, smelting and refining processes (Pan 2009). Though not an exhaustive list, a brief overview of these chemical hazards is provided in Table 1.

In relation to such chemical hazards, it is important to note that given that the mining sector is heavily reliant on the use of chemicals in its operations, it is required to comply with specific legislation regulating the use and/or production of chemicals. Of particular importance is the European REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation (Regulation (EC) no. 1907/2006), which requires chemicals to be controlled more scientifically and systematically and shifts the burden ensuring the safety of substances from the local authority to industry. Any risk assessment procedure developed and used in the mining sector must be compliant with the relevant legislation, and although REACH legislation only applies within the European Union, a uniform risk assessment system that takes into account the relevant international chemical regulation, as discussed in detail by Singh et al. (2011), can be beneficial for multi-national mining operations.

Understanding risk in mining: source, pathway and receptor linkages

Given the difficulty in quantifying the relationship among mining, society, the economy and the environment, and also in determining the best balance between environmental protection and economic development, risk assessment can act as a key component in the appraisal of such complex problems and systems in order to inform more effective and sustainable policymaking and management. Its application in the mining sector has grown from being used in terms of workplace health and safety to encompass other issues such as environmental management and business and financial risk (Evans et al. 2007). It is a powerful and valuable tool to determine the nature, likelihood and acceptability of the risks of mining, allowing for potential risks/impacts to be prioritised and optimally managed. However, current challenges associated with risk assessment include inconsistency of data availability and quality as well as international variation in environmental regulations, meaning that risk assessment frameworks should be flexible enough to allow for such variations, able to utilise both qualitative and quantitative data and be part of an iterative process allowing for assessment findings and processes to be continuously reviewed and updated (Pan et al. 2010).

By estimating the probability and severity for a given harm occurring through such linkages, measures can be identified to prevent and minimise potential risks, with associated benefits established. With mining activities represented as risk sources, thematically evaluated through the five stages of mining (which are in turn dependent the type of mining, in terms of substances present and processes used), risk assessment subsequently relies upon the identification of potential pathways and receptors. In the broadest sense, this can cover a myriad of potential social, environmental and economic risks, many of which are closely interrelated. While the emphasis of this paper is primarily on environmental risks rather than economic and social ones, Fig. 1 provides a conceptual framework for understanding such source–pathway–receptor linkages in determining overall risk. The framework aims to show both the number and the diversity of source–pathway–receptor linkages, with the different patterns and colours of lines indicating the plethora of possible 'exposure' routes, ways in which mining, throughout its life cycle and through a range of diverse social, environmental and economic pathways, can have an impact to our environment, society and economy as receptors. The pathways listed are included as examples, but are not intended to comprise an exhaustive and fully representative representation of all possible pathways that can also be indirect or interrelated.

This process of assessing source–pathway–receptor linkages ensures that all risks are identified and understood through a clear and structured approach so that they can be appropriately managed. For example, the release of naturally occurring arsenic during the exploitation stage (source) into groundwater (pathway) could have obvious direct impacts on human health or ecosystem health (receptors), but

Table 1 Main types of mining chemical hazards

Pre-existing chemicals	
Pre-existing chemicals such as arsenic, cadmium, mercury lead and thallium all occur naturally in rocks and soils and tend to be especially concentrated in mineral deposits. They are released into the environment both naturally and through human activities (Pan 2009). Heavy metal exposure can affect human health both directly or indirectly by disrupting ecological systems in rivers, lake, oceans, streams, wetlands, estuaries and other ecosystems (Dokmeci et al. 2009).	
Arsenic	Arsenic is relatively abundant in the Earth's crust, occurring mainly in sulphide and sulpharsenide minerals, and is also sourced anthropogenically from pesticides, coal combustion and sulphide ore roasting and smelting (Kang et al. 2011; Pan 2009). Acute human exposure to arsenic can lead to gastrointestinal effects, nausea, vomiting, neural effects, coma, increased risk of cancer and death due to fluid loss and circulatory collapse (Bundschuh et al. 2012; Cullen et al. 1995)
Cadmium	Cadmium can be highly toxic to humans, has been identified as a carcinogen, can cause severe damage to a variety of organs, including the lungs, liver and kidneys, and is responsible for itai-itai disease (Dokmeci et al. 2009). Cadmium is particularly concentrated in sulphide minerals and is usually associated with zinc in mineral deposits, and can contaminate the environment anthropogenically through atmospheric deposition (most often directly resulting from Cd and Zn production), phosphate fertilisers and sewage sludge (Pan 2009).
Mercury	Globally, the main anthropogenic sources of mercury include coal combustion, waste incinerators, mining and chlor-alkali production (Walters et al. 2011). It is often concentrated in coal and oil, is highly toxic to most forms of life and is readily absorbed by aquatic organisms and prone to biomagnifications up aquatic food chains (Pan 2009).
Lead	Lead is commonly mined from ores including galena (PbS), anglesite ($PbSO_4$) and cerussite ($PbCO_3$), and is also widely found in trace amounts in a wide range of other minerals. It is also sourced anthropogenically from Pb mining, refining and smelting, agrochemicals, sewage sludge, coal fly ash and vehicle emissions (Pan 2009; Zhang et al. 2012), though the latter has declined massively in recent decades due to regulation (Pacyna et al. 2007). Being highly toxic, lead can affect all human organs but is most well known for its effects on the nervous system (Gai and Yu 2010; Pusapukdepob et al. 2007).
Thallium	Thallium is more toxic to humans than mercury, cadmium, lead, copper or zinc and can present substantial local risk to both the environment and human health (Peter and Viraraghavan 2005). Thallium is rare but found widely in minerals, being most concentrated in sulphur-containing ores and K minerals, and can contaminate sediments and soil as a result of mining and smelting sulphide ores (Pan 2009).
Chemicals used in mining and milling	
Mining explosives	Explosives used for mining and quarrying fall into four main classes: gelatines, semi-gelatines, nitroglycerine powder and non-nitroglycerine explosives (Pan 2009). While the use of explosives was the most important advance in mining in the nineteenth century, they can present a great potential hazard to mine workers and the immediate environment due to the gases (e.g. ammonia, CO_2 and NOx) and dusts (respirable particulates) generated after explosion, and require intensive ventilation (Pan 2009).
Cyanide leaching	Cyanide is commonly used to recover gold (Au) but can lead to significant environmental risks. While the toxicity of different cyanide species varies widely, free cyanide concentrations greater than 0.2 mg/kg can kill sensitive species in fresh water or the marine environment (Bartlett 1998). Residual cyanide found in mine tailings has additionally been shown to cause the release of toxic metals including mercury and arsenic into the environment (Al et al. 2006; Bartlett 1998; Velásquez-López et al. 2011).
Acid leaching	Acid leaching of ores and concentrates is the most common method used in hydrometallurgy to dissolve and concentrate metals, and is widely used for the abstraction of copper, gold, silver and uranium from low-grade ores (Bartlett 1998; Padilla et al. 2008). The main environmental concern with regard to solution mining is with the toxic metals and metalloids present as well as the leaching chemicals used (Pan 2009).
Reagents in flotation	Flotation reagents are chemicals used for forth flotation, a common processing technique to recover sulphides from minerals (Lottermoser 2010). The kinds of reagents used in flotation are generally interfacial surface tension modifiers, surface chemistry modifiers and/or flocculants (Pan 2009).
Chemicals generated in mining, milling and smelting	
Acid generation and AMD	Mining of metallic ore deposits, phosphate ores, coal seams, oil shales and mineral sands has the potential to cause acid mine drainage (AMD), which results from the oxidation of sulphide minerals (Lottermoser 2010). Being potentially difficult to control and having the potential to contaminate surface and groundwater both during mining and for many years after (Lottermoser 2010), acid drainage results from the exposure of some sulphide minerals to water and air, causing elevated acidity and concentrations of metals and sulphate (Johnson and Hallberg 2003, 2005).
Emissions from smelting and refining	Smelting and refining emissions can also present major environmental and human health risks (Pan 2009). Such emissions can include aerosols, greenhouse gases, acid-forming gas (such as SO_2) as well as respirable particles containing heavy metals (Pan 2009; Schaider et al. 2007).

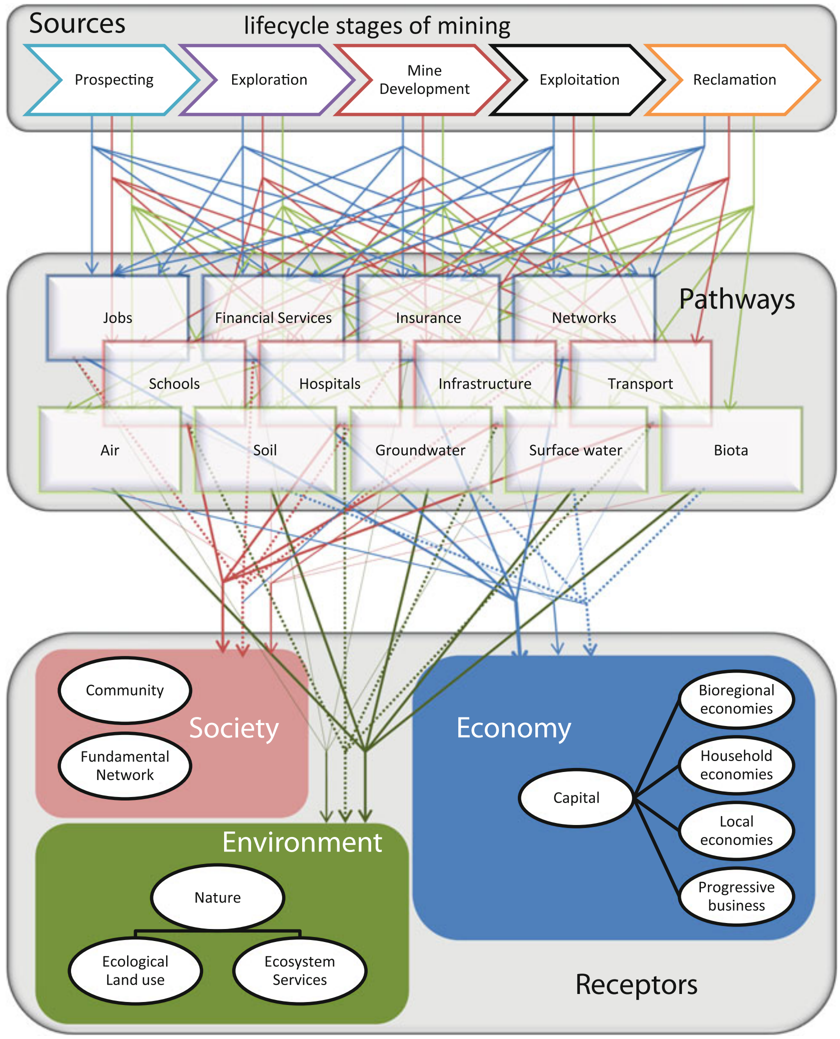

Fig. 1 Conceptual framework for source–pathway–receptor linkages for mining risks

other impacts could also occur as a result of a variety of more complex or indirect pathways, such as business profitability (receptor) being impacted by community activism and legal action (pathway), or the local community (receptor) being more severely impacted due to weak governance or national environmental regulation (pathway). In more extreme cases, such as that of the BP Deepwater Horizon oil spill, mining incidents, which could be prevented through effective risk management practices, can result in much wider economic and political impacts, including changes in national policy and knock-on effects on stock markets (Sabet et al. 2012).

As part of risk assessment, several approaches to hazard identification and assessment have been developed, such as hazards and operability analysis, failure modes and effects analysis and hierarchical holographic modelling (HHM) (Burgman 2005). These models aim to generate a comprehensive list of sources of risk and help in understanding the complexity of the systems under consideration. HHM for example is often adopted to improve risk identification, used as a contemporary system decomposition method based on different perspectives on the system in terms of its organisational and functional hierarchical structures; various time horizons; the multiple decision makers, stakeholders and users of the system; and the host of institutional, legal and other socioeconomic conditions that require consideration (Haimes 1991) to ensure that no risks are overlooked (Kaplan et al. 2001). Figure 2 provides an example of utilising HHM for general mining risk identification, with the risks of individual subsystems contributing to and determining wider system risks (Kaplan et al. 2001). It provides a generic representation of different perspectives on the system rather than an exhaustive list of all relevant aspects and is intended to demonstrate how establishing system dimensions and boundaries can help define the problem and facilitate the calculation of associated risks. In particular, the ability to model the complex relationships among the various sub-systems and to account for all relevant and important elements of risk and uncertainty makes the modelling process better and the risk assessment process more representative and encompassing of the system studied (Haimes et al. 2002).

Risk assessment and management is an iterative process consisting well-defined sequential steps supporting decision making, with the flow of information between identified steps and monitoring review able to provide feedback at any stage (Power and McCarty 1998). Many jurisdictions possess formalised risk assessment tools available through their local standards organisations, and these may be suitable for use within the risk assessment process (IAEA 2009).

Current challenges associated with risk assessment, however, include inconsistency of data availability and quality as well as international variation in environmental regulations, meaning that risk assessment frameworks should be flexible enough to allow for such variations and be part of an iterative process allowing for assessment findings and processes to be continuously reviewed and updated (Pan et al. 2010). Being very data demanding, risk assessment is heavily dependent on the quantity and quality of data available; sensitivity analyses are therefore increasingly used to guide the decision making process and help evaluate the impact different types of data have on the process's outcome, thereby allowing the examination of how robust an alternative is to changes in the information or assumption used in the analysis (IAEA 2009).

In addition, stakeholder consultation helps to identify issues of significance and focus social components of baseline data collection, with recognition and response to stakeholder concerns and expectations being shown to minimise the potential for conflict and be mutually beneficial to both communities and operators (IAEA 2009). As the functions of risk analysis and risk treatment cannot be separated, those who treat risk must be involved in the formulation and analysis stages of an assessment (Jones 2001). It is therefore essential that stakeholders participate in and have direct inputs to environmental decision making; with regard to risk assessment and management, stakeholder involvement in its broadest sense should be applied to shape problem definition, scope, conduct and output (Eduljee 2000).

The process of assessing risks is almost more important than its outputs because by gaining an understanding of source, pathway and receptor linkages, potential solutions can be derived by blocking, reducing or avoiding such linkages. For example, it can help find options to manage the large amount of solid and liquid wastes produced by mines and mills each year. This can be minimised by alternative disposal methods like paste and dry stack, as well as new emerging techniques such as environmental desulphurization, covers built with sulphide-free tailings, co-disposal of tailings and waste rocks, geotextile tube dewatering and use of tailings in cement production and road construction for both industrial and environmental purposes (Yilmaz 2011). The assessment will facilitate approaches for efficient waste treatment and disposal, on top of energy and water use and reduction of emissions from mining in general. Increasingly strict environmental legislation and cost competitiveness also dictate the utilisation of technically suitable, economically viable, environmentally acceptable and socially responsible techniques.

The role of mining in the context of natural capital

While it has been often accepted that it is the responsibility of governments to impose solutions upon resource users in the form of regulation in order to achieve sustainable resource use, some government policies have been shown to accelerate resource destruction, and conversely some resource users have seen the benefit in making the investment needed for increased sustainability (Ostrom 2009). Achieving this sustainability, however, requires our many ecological/environmental, economic and social issues to be accounted for (Fig. 3). A better understanding of demand and pressure on resources is needed, followed by appropriate pricing that is inclusive of all environmental costs, with new opportunities for mining in the wastes we generate.

There is a need for more appropriate pricing that is inclusive of all environmental costs and for environmental externalities to be better accounted for in decision and policymaking in relation to the mining sector. The carrying capacity of the natural environment is an unpriced input to resource production, and it is increasingly accepted that resource users should be made to pay for the environmental impacts they cause (Slade 1992). While several methods for the monetary valuation of environmental impacts have been developed (Damigos 2006), the internalisation of environmental costs have yet to be fully mainstreamed in practice (Dalal-Clayton and Bass 2009). In addition, the World Bank has continued support for the expansion of mining activities in resource-rich countries, maintaining its mantra on the sector's potential economic benefits for developing countries, though slowly in recent years also increasingly acknowledging the importance of poverty reduction and environmental sustainability (often justifying the need for the World Bank to maintain its active involvement in the sector). Although in many cases this new socio-environmental narrative has helped influence a wave of new mining regimes that include multilateral social and environmental safeguards, often these along with the highly political role played by the World Bank in the mining sector of its client-countries have been criticised to be more for circumscribing the risks faced by industry, rather than by local populations (Hatcher 2012). This partly positive influence has also been a barrier to more integrated systems for resource management.

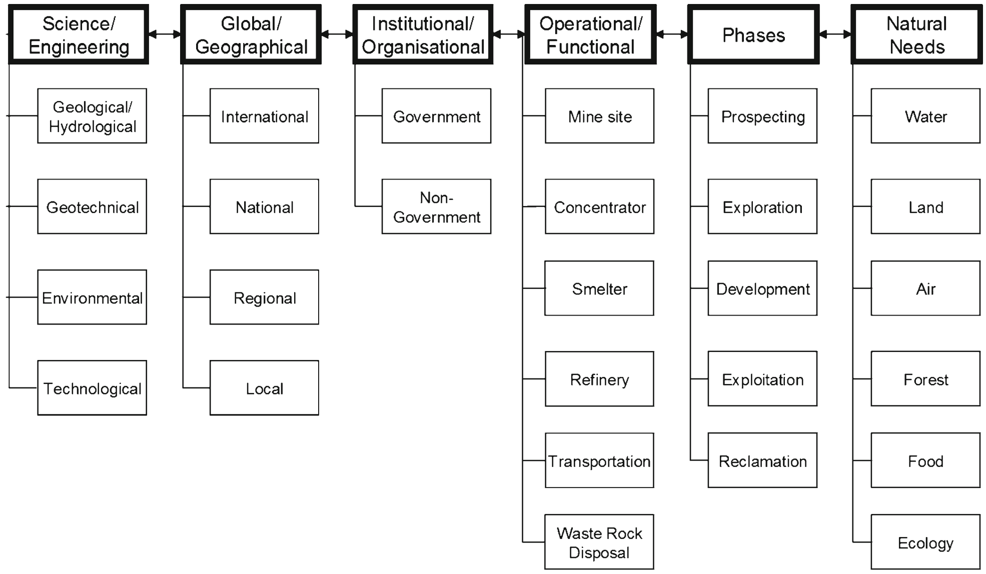

Fig. 2 HHM framework for general mining environmental risk identification. Source: (Kaplan et al. 2001)

In addition, in light of increasing concerns of material security, shortages and environmental pollution, realistic frameworks have emerged for processing mining waste as a resource in many parts of the world (Brunori et al. 2005; Castro-Gomes et al. 2012; Jellali et al. 2010; Yellishetty et al. 2008). Mining and mineral-processing wastes are one of the world's most significant and chronic waste concerns. When properly evaluated, potential reuse options for mining waste include to reextract minerals, provide additional fuel for power plants, supply construction materials and repair surface and subsurface land structures altered by mining activities themselves. Determining which uses are most appropriate and economically feasible depends on the chemical composition and geotechnical properties of the source rock (Bian et al. 2012). More broadly, waste reclamation and reuse can provide a viable opportunity to augment traditional resource supplies, at the same time reducing the need for waste disposal (Iranpour et al. 1999).

In the traditional modern industrialised economy, natural resources are mined and extracted, turned into products in manufacturing systems driven by heavy industrial growth and resource-intensive infrastructure and finally discarded after consumption or use. Perhaps an economically effective approach in generating profit, this fundamentally open, linear system is highly inefficient, particularly when the larger costs of production, most often seen as externalities (e.g. wastewater discharge, air emissions, depleted soils, razed forests) are included. Rather than releasing high quality

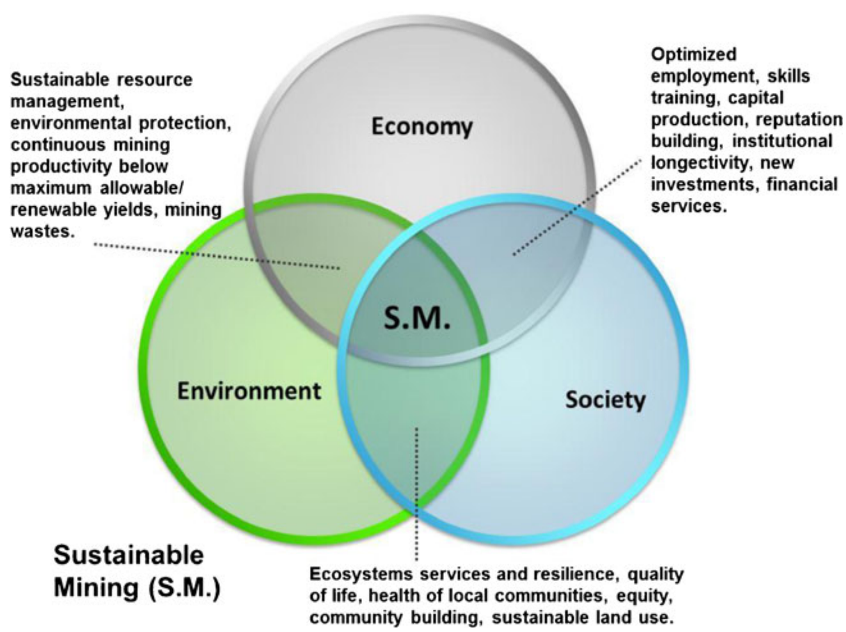

Fig. 3 Sustainable mining (S.M.), as optimised in the nexus of the economic, environmental and social dimensions of mining

wastes back into the environment while paying to extract it as minerals through traditional mining, it is more sustainable and energy efficient to close the loop (Fig. 4). As a result, resource reuse can help to close the loop between supply and waste disposal, providing a sustainable alternative to mining of virgin stocks. Achieving more from less by closing resource loops is paramount given the twofold need of protecting the environment and recognising the importance of natural capital while at the same time enhancing our economic prosperity and improving living standards of developing countries and the world's poor.

Properly accounting for natural capital in resources management first requires a more comprehensive understanding of how materials and their waste by-products, including those produced through mining activities, are used and discarded (Wagner 2002). Economies are largely dependent on linear systems where resources are extracted from virgin stocks before ending up as discarded waste after proceeding through a supply chain which itself produces waste at every stage (Hicks et al. 2004). While the debate surrounding 'peak minerals' and the potential threat posed by resource scarcity is ongoing (Bridge and Wood 2010; Gordon et al. 2006, 2007; Steen 2006; Tilton and Lagos 2007), it is regardless essential to address inefficiencies of this system, especially when social and environmental constraints are taken into account in addition to physical ones (Prior et al. 2012). At the same time, mined materials (such as platinum group elements) are increasingly used in a range of environmentally related technologies, for example chemical process catalysts, catalytic converters for vehicle exhaust control, hydrogen fuel cells, electronic components and a variety of specialty medical uses, among others, a growth

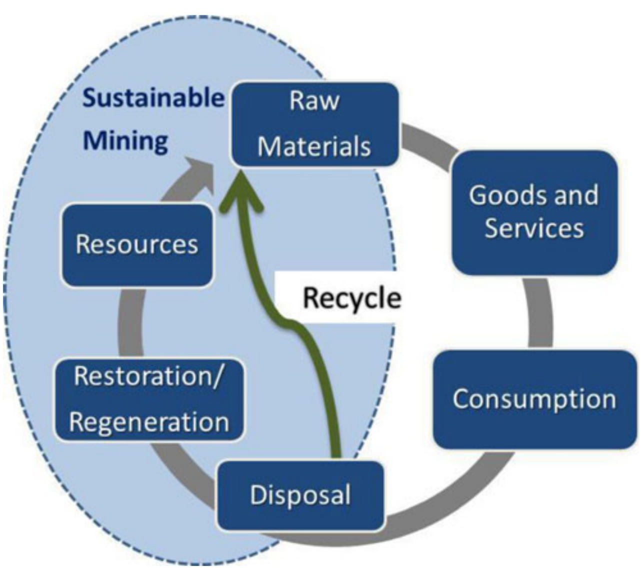

Fig. 4 Closing the loop: mining in the context of sustainable resources management

trend which is expected to continue in light of environmental and technological challenges. Despite arguments by some on the case of abundant geologic resources, it will still be necessary to manage environmental impacts associated with any increases in production (Mudd 2012).

Though technological advancements and the changing economic climate are likely to make the exploitation of new virgin stocks viable, opportunities found in alternative non-virgin stocks such as waste must be better taken advantage of. Information on the scale and distribution of such stocks is limited, however, with individual components of the supply chain too often viewed in isolation (van Beers and Graedel 2007). Material flow analysis is one tool that can be utilised to address this, providing insight into how an economic system interacts with natural resource and material flows, thereby informing environmental policy (Kovanda and Weinzettel 2013).

Discussion

Identifying and building sustainable resource management systems is one of the most critical issues that today's society is trying to address. Recent trends with regard to mineral resources have presented many new challenges for resource management, including mining. Operations research is becoming increasingly prevalent in the natural resource sector, specifically in agriculture, fisheries, forestry and mining. While there are similar research questions in these areas, e.g. how to harvest and/or extract the resources and how to account for environmental impacts, there are also differences, e.g. the length of time associated with a growth and harvesting or extraction cycle, and whether or not the resource is renewable. Research in all four areas is at different levels of advancement in terms of the methodology currently developed and the acceptance of implementable plans and policies (Bjørndal et al. 2012). Owing to population growth and rises in incomes, per capita resource use has been increasing sharply (ICMM 2012). At the same time, there is a need to achieve more with less by improving the living standards of the poor while improving the sustainability of resource use and shrinking our ecological footprint. While technological advancements and clean production approaches have vastly improved environmental management and material and energy efficiency in mining (Altham and Guerin 2005), these new challenges threaten to overwhelm our capacity to adapt through technological improvements alone.

The alumina industry worldwide has reduced the volume of waste produced by about 50 %, with valuable raw materials being recovered and the risk of storage failure significantly reduced. For example, dry disposal produces a paste for stacking and drying instead of a water-like suspension to be stored in a dam or pond and other options, demonstrating improvements in waste management practices driven by several factors, such as public perception, water recovery, the necessity to earn the right to operate and even by common sense accounting (Jones and Boger 2012). Similarly in the case of copper, there have been efforts to mitigate some of the negative effects of increased copper use and copper mining. Recent progress in microbiological and biotechnological aspects of microorganisms in contact with copper could lead to more thermo-tolerant, copper ion-resistant microorganisms that could improve copper leaching and lessen copper groundwater contamination, and copper ion-resistant bacteria associated with plants might be useful in biostabilisation and phytoremediation of copper-contaminated environments (Elguindi et al. 2011).

Owing to legislation such as REACH and other drivers such as corporate social responsibility, in mining, the focus has already grown from being primarily on economic and health and safety concerns to more broadly encompass a full range of environmental, social and economic impacts. However, the emergence of new threats such as climate change and resource scarcity will drive further changes in management. Growing unpredictability in the climate will need to be more adequately accounted for, as will potential increases in water scarcity or energy costs for mining.

Sustainability necessitates a more integrated and interdisciplinary approach to mining and resources management that takes into account interrelationships between resources, people and the environment. Our current understanding of the wider processes that govern natural resources is still limited because scientific disciplines use different concepts and languages to describe and explain complex ecological systems (Ostrom 2009). This problematic focus on individual components rather than wider systems has hindered the development of more effective and integrated solutions to managing environmental, and indeed economic and social, problems associated with mining (Voulvoulis 2012). Because of the current limited understanding of wider processes, advancements in individual fields and disciplines have not been matched with major improvements in understanding the complex interrelationships among them. Achieving such a ‘systems mindset’ with an emphasis on interdisciplinary and holistic thinking is a prerequisite to addressing resource management challenges and solving the environmental problems of mining.

The nexus of water, energy and materials is slowly becoming recognised as a system that needs to be examined, but solutions have so far not been nearly integrated enough to deliver overall benefits across the sectors, especially in light of the many emerging challenges facing resources management. Rising global demand for mining commodities will increase the sector’s impact on water resources, a trend exacerbated by the fact that mining activities are increasingly taking place in water scarce regions, that climate change presents further challenges in terms of water scarcity, and that globally declining ore grades for many major commodities are likely to increase water demands for most future mines (Miranda and Sauer 2010). Meeting the growing demand for commodities will of course also bring additional demand for energy used in extraction, processing and transport, while it is additionally evident that material constraints could have an impact on the sustained growth of the renewable energy sector (Andersson et al. 1998; Kleijn and van der Voet 2010; Wadia et al. 2009).

Again it comes down to systems thinking. Systems thinking, for any kind of system, natural, scientific, engineered, human, or conceptual, provides a very useful framework for really solving problems rather than just taking decisions. It is the complexity of natural systems that create the real challenge for environmental problem solving, and the reason why for example further research on system analysis tools could provide further opportunities for interdisciplinary, integrated and holistic solutions to resources management that will shape the future of mining operations. The last few years have seen a shift from policy in reaction to high profile events, then to control of releases to single environmental media, and to the present position of moving toward integrated management of all environmental media. This development has moved away from classical chemical risk assessment toward environmental holism, including recognition of the ecological value of these media and resources management in the whole life cycle (Bone et al. 2010). Challenges for environmental policy will increase in the future and the role of mining will be central to any discussions. The question remains if mining will be perceived as part of the problem or part of the solution for a sustainable future. Before that, mining companies might soon face the choice between two roles: that of exploiters of natural resources or that of managers of natural resources cycles.

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