AN INVESTIGATION INTO THE RELATIVE IMPACT OF SMALL-SCALE MINING OPERATIONS ON THE CONTAMINATION OF WATER RESOURCES

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by

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ABSTRACT

While small-scale mining has socio-economic advantages like the reduction of unemployment, such operations, if not properly managed or controlled, have a potential to cause environmental damage, particularly with respect to the contamination of groundwater and water supplies that are not distant from where these mining activities take place. This project investigated the possible impact of small-scale mining on the contamination of surrounding water resources. Artisanal and small-scale gold, coal, clay, platinum group metal, diamond and sandstone operations were considered. Samples were collected from different mining sites in both wet and dry seasons. Results presented in Chapter 3 obtained confirmed contamination of the neighbouring water resources as evidenced by the presence of toxic metals, as a consequence of unregulated and unsafe mining practices.

It is suggested that a zonal, countrywide investigation into effects of mining on the contamination of water resources be conducted. This should constitute the basis of a much longer term project.

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LIST OF ABBREVIATIONS

AAS	Atomic absorption spectroscopy
AMD	Acid Mine Drainage
ASM	Artisanal small-scale Miners
CP	Cleaner Production
CY20S Agar	Czapek 20 Agar
CZ Agar	Czapek Agar
DWAF	Department of Water Affairs and Forestry
EIP	Environmental Impact Assessment
EMP	Environmental Management Plan
GCD	Ghanaian Consolidated Diamonds
HIV/AIDS	Human Immuno Virus/ Acquired Immuno Deficiency Syndrome
ICP	Inductively-Coupled Plasma
ICP-MS	Inductively-Coupled Plasma Mass Spectroscopy
ICP-OES	Inductively-Coupled Plasma Optical Emission Spectroscopy
ILO	International Labour Organisation
MEA	Malt Extract Agar
MPRDA	Minerals and Petroleum Resources Development Act
NIOH	National Institute for Occupational Health
NIOSH	National Institute of Occupational Safety and Health
OAESA	Ohio Agricultural Experimental Station Agar
ORP	Oxidation Reduction Potential
OSHA	Occupational Safety and Health Administration
PDA	Potato Dextrose Agar
PGM	Platinum Group Metal
PMC	Phalaborwa Mining Company
PPE	Personal Protective Equipment
SABS	South African Bureau of Standards
SANS	South African National Standards
SHEQ Codes	Safety Health Environmental and Quality Codes
SSM	Small-scale Mining
WHO	World Health Organisation
WRC	Water Research Commission
XRF	X-ray Fluorescence

CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT

Contamination from large mining operations is known to be a major cause of water pollution. Much of it is as a result of acid mine drainage (AMD). A largely unquantified potential threat to the quality of water resources arises from the widespread small-scale mining (SSM) operations. These escalating operations are, to a certain degree, driven by previously retrenched miners and unemployed matriculants/graduates who re-group (legally or illegally) to initiate SSM operations on shafts, dumps and deposits which may not be financially viable for the larger mining companies. While SSM has socio-economic advantages such as the reduction of unemployment, these operations, if not properly managed or controlled, have the potential to cause environmental damage, particularly with respect to the contamination of ground and surface water close to where these mining activities take place.

An area of primary concern is that some of these SSM operations are either illegal or do not adhere to documented mining protocols with respect to the mining process, the extraction procedures of the ores or raw product, and SHEQ (Safety, Health, Environment and Quality) codes and stipulations. This lack of adherence to best management practices may exacerbate the environmental consequences of SSM relative to those of larger operations. In many cases lack of knowledge, especially with the handling of some of the chemicals used in the extraction of the metals from their ores, and general ignorance of the end-to-end mining and metallurgical processes (including the use of inappropriate equipment for both processes) have resulted in the illegal disposal of potentially water-polluting mine waste and chemicals. For example, in the Ekurhuleni municipality, cyanide and mercury from gold mining operations were discovered in local water streams due to contamination of the groundwater table.

This project is a scoping study to assess the magnitude of the contamination caused by SSM activities. The main objective of this study is to quantitatively highlight the extent of contamination of the groundwater and nearby water supplies so that appropriate measures can be taken to reduce the pollution of water resources. The study was undertaken in the Free State, Gauteng and Northwest provinces where SSM activities occur in the mining of gold, coal, sandstones, clays, diamonds and platinum group metals (PGMs).

1.2 AIMS

The aims of the project were to:

1. Assess the magnitude of SSM activities associated with the mining of gold, coal, sandstone, clay, diamonds and PGMs.
2. Determine typical pollution levels related to SSM activities associated with the mining of these minerals.
3. Compare the pollution loads emanating from SSM activities relative to each of the above mineral commodities in different seasons.
4. Evaluate the need for further research into the impact of SSM activities on water quality.

1.3 METHODOLOGY

The following methodology was employed to address the aims of this project.

- **Assess the magnitude of SSM activities through visits to sites involving each of the aforementioned mining commodities**.
    - Study/ascertain current operations and techniques.
    - Obtain first order estimates of the magnitude of SSM operations (area affected, production, etc.).
    - Identify probable water polluting practices.

- **Evaluate/quantify pollution loads. (The sampling will be performed at the same sites during both dry and wet seasons for comparison purposes.)**
    - Sampling (soil, mine/operation water, solutions, gas effluents, etc.).
    - Sample existing (if any) pockets of groundwater.
    - Sampling from nearby water resources and streams.
    - Quantitatively analyse for the presence of mining generated pollutants in water using analytical techniques such as Atomic Absorption Spectroscopy (AAS), Inductively-Coupled Plasma (ICP) and X-ray Fluorescence (XRF).
    - Compare the results of the analysis with the minimum acceptable pollution loads.

- **Suggest remediation means**.
    - Based on the findings, environmentally friendly and water protecting small mining practices for mineral extraction will be recommended.
    - Remediation procedures of currently affected aquifer sites will be suggested.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Small-scale mining activities are mushrooming in South Africa, as in other developing countries, and the opening up of the government to local communities to share in the country's mineral wealth with a view to alleviating poverty has made it possible for artisanal miners of gold, platinum, diamonds, coal, clays and sandstones to participate in the mining economy. However, such opportunities have been accompanied by unsafe mining practices to the detriment of water resources. Effluents from these generally unregulated practices are often disposed of in neighbouring water resources. Here a literature review on water pollution as a result of mining operations is provided, and we also map out the magnitude of the impact of SSM activities (relative to big mining operations) for selected commodities in the South African mining terrain.

In many countries across the world, mining has made important socio-economic contributions (Hilson, 2002). For many years in Ghana and other African countries, this industry has provided thousands of people with employment and millions of dollars worth of products. These products have been produced and sold within the countries while raw materials have been exported (Hilson, 2002). According to Ghose (2008) SSM in particular, can make a significant contribution to a country's development though it is often overlooked. Contrary to large-scale mining, SSM requires minimum reserves, moderate skills and infrastructure, while the employment per unit output is high (Ghose, 2002). For example, in India the current contribution of SSM to global production is high in certain minerals such as antimony (45%), calcium (50%), chromites (75%), clays (75%), feldspar (80%), fluorspar (90%), gypsum (70%), tungsten (80%) and vermiculite (90%) (Ghose, 2002).

Other benefits from SSM according to Ghose (2008) are firstly, the ability to operate in remote areas with little infrastructure and a high degree of flexibility because of low overheads; secondly, SSM fits in well with the social structure, particularly if seasonal operations are required because of agricultural production in the same area. Another advantage of this type of mining is that it generates employment, income and entrepreneurial skills in the rural areas and this can act as a restraint to urban migration. More importantly, since SSM is locally owned it therefore provides a net gain to the community and to the national economy in contrast to larger foreign owned mines.

In spite of all the mentioned advantages mentioned, SSM can be a liability with poor working conditions, problems of safety and health and can cause harm to the environment. Environmentally, many countries in certain regions of Africa have fallen victim to excessive mercury pollution and incomplete reclamation of land. This has resulted in substantial damage to a number of landscapes. Policies and laws have been put in place to try and improve environmental conditions of the mining industry. However, up to now the overall impact of these activities has not been formally addressed.

In South Africa, mining operations, particularly SSM activities, contribute to the improvement of the socio-economic status of the communities. Despite these operations promoting the economic sustainability of communities (e.g., Ekurhuleni, Mpumalanga, Rustenburg), they do not meet accepted international environmentally stringent standards. It is documented that water resources present in the areas around the mining sites have been polluted and contaminated by effluents from the mining operations within their vicinity. For instance, drinking water quality in the natural springs around Chrissie Lake, in Mpumalanga Lake District and surrounding rivers (the Vaal, Komati, uMpuluzi and the Usutu) is compromised by illegal and unregulated SSM of coal. This causes pollution of the adjacent water resources, thus affecting the water quality.

2.2 BACKGROUND

Mining activities are generally categorised as full operations, medium operation, small-scale operations, and artisanal. The term ‘small-scale mining’, as used in this report, refers to artisanal operations.

Small-scale mining, an important subject in the mining fraternity, appeals to local communities due to the magnitude of the country’s mineral reserves and resources, the market prices of the final products produced and favourable exchange rates on mineral sales, as well as the need for cost curtailment in this highly competitive business. The drive by the South African mineral policies, as outlined in the Minerals and Petroleum Resources Development Act (MPRDA) seeks to extend the mining opportunities to the historically deprived South Africans to ensure equitable access to the country’s rich mineral wealth.

Portraying the use of rudimentary processes to extract valuable minerals from primary and secondary ore bodies, SSM activities in South Africa are characterised by the lack of long-term mine planning or control. They may be legal or illegal and in other cases either formal or informal. Such activities, for example, may come in the form of individual gold panning to medium scale operations employing thousands of people. In 1999, the International Labour Organisation (ILO) estimated that there were 13 million artisanal small-scale miners (ASMs) worldwide, of which 30% were female.

Hilson (2006) argued that SSM plays a pivotal role in alleviating poverty in the developing world and contributes significantly to the national revenues and foreign exchange earnings. However ASM has many variable hazards, including poor ground conditions leading to underground tunnel failure, methane or coal dust explosions from coal mines, flooding, machinery accidents, poor lighting and ventilation, explosives accidents and electrocution. Poor and lack of expertise in monitoring mine water from secondary deposits has led to serious health risks to be associated with mining operations with reference to water contamination. Mercury, lead, cyanide and other hazardous chemicals used as reagents for recovering and purifying gold and other precious metals often end up as water pollutants. This is largely an unquantified potential threat to the quality of water resources arising from the widespread small-scale mining operations.

In gold SSM, for example, primary or secondary mineral ores containing gold are ground to a fine sludge; liquid mercury is added to this mass and a small piece of amalgam containing approximately one part gold and three parts mercury is formed. To obtain the required gold, the amalgam is heated either with a blow torch or by laying it on open charcoal fires. Mercury evaporates at 500°C and gold is retained as the product. Since small-scale operators need no sophisticated technology the process is relatively easy. De Lacerda (2003) reported that approximately 30-50 million people collectively contribute to this water pollution with mercury.

There are currently as many definitions of SSM as there are authors on the topic. However, many researchers and organisations involved in the subject are *at idem* regarding the understanding of the subject as it generally refers to ‘small digging’. Castro and Sǎnchez (2003) and Kambani (2002) have proposed a generic definition for SSM, which is based on the following:

- Number of employees (1-99).
- Annual tonnage produced (1-249 999 tonnes).
- Annual turnover (R0-R9 999 000).
- Capital expenditure (R1 000-R4 999 000).

Shen and Gunson (2004) define SSM as “the use of rudimentary processes to extract valuable minerals from primary and secondary ore bodies, and is characterised by the lack of long-term mine planning/control”. This rudimentary process lends itself to using basic tools such as picks and shovels, and occasionally, mechanised equipment.

Although several definitions have emerged, SSM is now considered as an all-encompassing label for the non-mechanised, labour intensive activities of the mining sector. What make it unique are its operations and management techniques. Unlike large-scale counterparts, which commonly feature state-of-the-art machinery and skilled workers, small-scale mines are usually rudimentary in design, and are characterised by highly manual processes.

Small-scale mining, largely a poverty-driven activity, is typically practised in the poorest and most remote areas of a country by a largely itinerant, poorly educated populace with few employment alternatives. Because of its rudimentary methods of exploitation, this activity can only exist where mineralisation occurs near the surface or, in the case of precious metals, within unconsolidated rocks.

According to Amankwah and Anim-Sackey (2004), the need to develop SSM in a sustainable manner cannot be overemphasized. While this industry's many benefits are clearly noticeable throughout Ghana where their study was focused, they equally took cognizance of the undesirable effects associated with this activity. It is for this reason, according to Amankwah and Anim-Sackey (2004), that there are ongoing discussions in Ghana by all stakeholders on the measures to mitigate the negative effects of SSM. Furthermore, as they proclaim, sustainable development of minerals and other natural resources is endorsed as a global management and development strategy and environmental, economic and social development are highlighted as the three pillars of sustainable development. They argue that the establishment of a legal framework for SSM, technical and financial support for the sector as well as the realisation and enhancement of socioeconomic significance of SSM are the strategies for sustainable development of small-scale gold and diamond mining industries in Ghana.

2.3 POLICY FRAMEWORK AND THE NEED FOR REGULATING SMALL-SCALE MINING

In India, SSM is more prevalent than large-scale mining, making a very significant contribution to the economy of India. However, because of significant variations in microclimates, the problems associated with SSM in India are varied and complex, requiring the design and implementation of site-specific solutions, as purported by Ghose (2002). Ghose (2002) argues that environmental conservation is generally a major barrier to the successful development of mines in areas considered to be ecologically sensitive and/or rich in bio-diversity and contends that Cleaner Production (CP) is a more desirable and progressive environmental management strategy, than reactionary pollution control, which focuses on the treatment of pollutants once released into the environment. Cleaner Production prevents pollution at the source, thus lending itself to being proactive in dealing with inherent and sometimes unavoidable problems of this mining practice, which will then lead to sustainable and profitable mining practices.

In its move towards CP, India implemented a number of policies and laws aimed at regulating the environmental aspects of the minerals industry, with emphasis on SSM. These included the *Industrial Policy* (1991), the *National Forest Policy* (1998) and *The National Forest Policy* of 1998. The most significant policy relevant to mining as stated by Ghose (2002) is the *Policy Statement for Abatement of Pollution and the National Conservation Strategy and Policy Statement on Environment and Development*, implemented in 1992.

The Policy Statement for Abatement of Pollution (1992), as summarised by Ghose (2002), has the following fundamental provisions regarding mining:

- Mining will not ordinarily be taken up in ecologically fragile areas.
- A mining plan shall accompany every mining project, which should include an Environmental Management Plan (EMP).
- The mining plan should also include a time bound reclamation programme for controlling environmental damage and restoring 'mined out' areas.

Ghose (2002) concludes the research work by recommending that the Indian state enters into an agreement with the entrepreneurs (small-scale miners), based on the principles that, among others:

- Opportunities be created for the development of small-scale ancillary industries.
- There should be easiness in processing and timely granting of a mining lease.
- An assurance should be obtained from the entrepreneur(s), through regional Environmental Impact Assessment (EIP) and EMP undertakings, that the development will not pose a threat of irreparable environmental damage.

2.4 BENEFITS IDENTIFIED FOR THE SMALL-SCALE MINING ACTIVITY

Small-scale mining has become an indispensable part of the socioeconomic fabric of the developing world. The industry has not only traditionally provided a wealth of employment opportunities to rural inhabitants, but has also contributed significantly to a number of countries' mineral export bases and foreign exchange earnings. Hilson (2002) stated that SSM employs approximately 11.5-13 million people worldwide, making this sector a significant contributor to worldwide employment.

Several researchers (Babut *et al.*, 2003; Moholo, 2001; Ghose, 2002; Amankwah and Anim-Sackey, 2004; Shen and Gunson, 2004) support the view that SSM is an indispensable industry in the developing world, offering the following benefits:

- Provides employment income to millions of rural inhabitants.
- Revenues accrued from activities contribute positively to the mineral export and foreign exchange earnings.
- The ability to operate in remote areas with minimal infrastructure, thus enabling the exploration of otherwise uneconomic resources.
- Transformation of unskilled labour into semi-skilled and skilled workers.
- High degree of flexibility due to low overheads.
- Provides entrepreneurial skills in rural areas, which can then restrain urbanisation.
- Provides tax revenue in remote rural regions with few economic alternatives.
- Plays a pivotal role in poverty alleviation in the developing world.
- Has the ability of the activity to be self financed, therefore does not require large investments in geological exploration, infrastructure, production and living facilities.

Considering the above benefits, it is abundantly clear that SSM plays a pivotal role in the welfare and well-being of a country, particularly a developing one. High unemployment level at Qwaqwa, Free State Province, is the reason why this area becomes so important in as far as SSM is concerned. The revival of Qwaqwa and its economic vibrancy can be achieved through strategic and well thought out SSM interventions and investments in this area.

2.5 SMALL-SCALE MINING SIZE

Small-scale mining is a common denominator in developing countries throughout the world (Hilson, 2002), possibly because rural people in such countries have found a survival strategy in this activity. The relationship between the number of small-scale miners and the price of precious minerals, especially gold, is directly proportional in that, as mineral prices have increased throughout the world in recent years, so have the number of small-scale mines.

About 85% of all the world's small-scale mines are situated in China and Indonesia – 65% and 20% respectively, according to a study by Shen and Gunson (2004). Considering the graphs in **Figures 2.1** and **2.2** one notices that small-scale mines in China (250 000), Indonesia (77 000), Burkina Faso (about 48), Haiti (50) and Zambia (200) have been excluded from the graph, because of the extremely high standard deviation, which would otherwise distort the Figures 2.1 and 2.2 if they were to be included. Figures 2.1 and 2.2 put the size of SSM into context. It should also be noted that the employment level estimates are based only on formal, legal or licensed operations. If informal, unlicensed and illegal miners (called galamsy in Ghana) were also to be included, the figures would rise by about 75%.

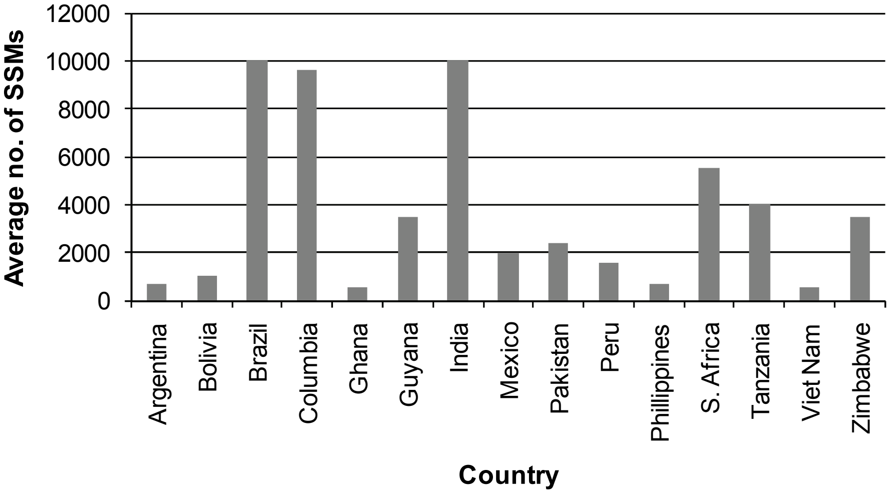

Figure 2.1: Average number of small-scale miners in developing countries: adapted from Hilson (2002)

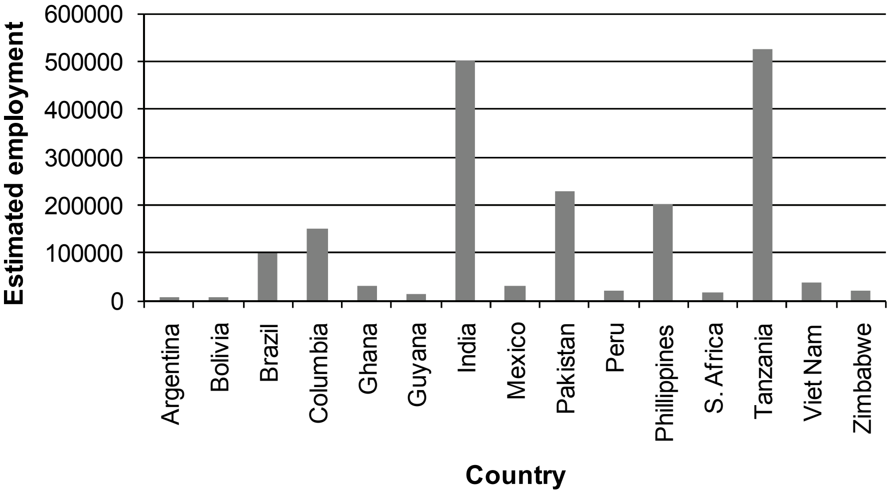

Figure 2.2: Estimated employment level in small-scale mining in developing countries: adapted from Hilson (2002)

2.6 PROBLEMS AND CHALLENGES ASSOCIATED WITH SMALL-SCALE MINING

The environmental degradation caused by SSM is a growing concern, as a result of intensification of mining activities. This environmental damage is mostly caused by infiltration of mineral processing chemical substances such as mercury, cyanide and hydrochloric acid, to mention a few. Common concerns expressed by many researchers (Babut *et al.*, 2003; Kligerman *et al.*, 2001; Aryee *et al.*, 2003; Castro and Sánchez, 2003; Crispin, 2002; Ghose, 2002; Kambani, 2002; Veiga *et al.*, 2004; Hilson, 2006; Hylander and Plath, 2006; Kelm *et al.*, 2003; McGill, 2005; Yelpaala and Ali, 2005) include water pollution, land degradation, health issues, safety issues and social impacts.

2.6.1 Water Pollution

Mining releases hazardous substances and environmentally unfriendly toxic species such as mercury and cyanide into the atmosphere, top soil and rivers, thus causing pollution. Mercury, for example has been found to have acute toxic effects on the neurological system. The recommended operational limit according to the South African National Standards (SANS) is < 1 µg/L for mercury and < 50 µg/L for cyanide. Up until 50 years ago, mercury was not utilised in artisanal gold extraction as professed by Babut *et al.* (2003). Mercury usage only began some 30 years ago when it became too difficult to extract gold from rocks. The optimal mercury to gold ratio (Hg:Au) is about 1:1, but, as inferred by Babut *et al.*, (2003), gold washers commonly add greater quantities of mercury to ensure that all available gold is amalgamated. The underlying reasons why mercury is so widely used by small-scale gold miners is that it is easy to use, readily available and inexpensive; but miners are not aware of, or choose to ignore, the health risks associated with this substance. The environmental and interrelated health impacts of mercury usage at SSM operations are well documented (Crispin, 2002; Amankwah and Anim-Sackey, 2004; Veiga *et al.*, 2004; Hilson, 2006).

Mercury amalgamation results in the discharge of an estimated 1 000 tonnes of mercury per annum into the ecosystem of developing countries (Spiegel and Veiga, 2005). Studies have shown that 70-80% of metallic mercury (Hg) is lost into the atmosphere during processing and about 20-30% is lost to tailings, soils, streams, sediments and water (Serfor-Armah *et al.*, 2004). Due to inefficient techniques in regions such as Latin America and Africa, an estimated 2 g of mercury is released into the environment for each gram of gold produced (Spiegel and Veiga, 2005). All the mercury released finds its way into the environment. In the aquatic environment, Hg undergoes biological methylation into methylmercury (Me-Hg) and accumulates via the food chain (Serfor-Armah *et al.*, 2004; Spiegel and Veiga, 2005). People in communities who rely on carnivorous fish as their food source are mostly exposed to Me-Hg. The health effects range from neurological damage (such as ataxia, tremor and coordination problems), kidney problems and thyroid problems to sterility. Pregnant women can also pass Me-Hg to their unborn foetus and this can cause spontaneous abortion or neurological problems for the child. Mercury in the terrestrial environment can also bioaccumulate in plant vegetation or crops; it binds to the plant cells and eventually finds its way to humans through ingestion of those crops/plants. Mercury vapour has been found to undergo mercury methylation and this has been a problem in mining sites in countries such as Zimbabwe, Brazil and Indonesia, and has also led to neurological problems for people living around those areas (Spiegel and Veiga, 2005).

Cyanide is another highly toxic chemical used in the refining and recovery of gold. Normally the gold is recovered in good yield but the cyanide remains in the waste slurry and ends up in tailings dams (Ashton *et al.*, 2001).

Tailings from SSM bring about siltation, the process whereby fine particles build up on the bed of a river, resulting in excessive piles and suspended solids in the river. The problem is that these tailings are quite unstable and are therefore blown away by winds when dry and also eroded by heavy rains. This subsequently introduces these suspended particles in the nearby river systems (Ashton *et al.*, 2001). Some of these tailings are polluted with mercury and cyanide used in the extraction of gold.

Artisan gold miners process alluvial sands and residues from old tailings dams using gravity concentration techniques. A highly extended practice is the use of the artisanal mill called a trapiche, which is employed for ore grinding and, at the same time, to amalgamate coarse gold particles with mercury. Usually, trapiche tailings are subjected to conventional flotation.

Other changes brought about by mining activities in water systems are AMD and the release of metals. Acid mine drainage affects the speciation of metals, since the solubility, mobility and bio-availability of metals are generally increased by the acidification of water. This generally causes harmful effects to animals and humans using the water since toxic metals like cadmium, chromium and mercury become more soluble in an acidic medium after being released into the water system (Ashton *et al.*, 2001).

A wide variety of technical processing routes is found in the SSM sector. Small-scale installations (usually with production capacities up to 50 tonnes per day), featuring mineral processing activities such as crushing, grinding and flotation, are used to produce gold, silver, copper and diamonds, and silver, copper and gold concentrates. Flotation is applied to copper tailings slurries discharged from large and medium scale enterprises. Simple installations, where cascade flotation is coupled with conventional flotation, are employed. Additionally, if sulphuric acid leaching of oxidised copper ores is carried out, cement of copper is produced by the reduction of copper ions by iron.

2.6.2 Land Degradation

Land degradation leads to deforestation, loss of fertile soil, decrease of agricultural productivity and development of dangerous pits and trenches near homesteads, which also destroy the scenery and prime land for future development. Mining scars, sometimes of great stretch and depth, are problematic in urban areas such as is the case in and around Johannesburg at present. Deforestation reduces plant and animal biodiversity, resulting in a decrease in the availability of medicinal plants used by local herbalists for treatment of a variety of ailments. Moreover a large problem, since most African people depend on subsistence farming for their basic nutritional needs, is the special loss of fertile land to these mining activities, as well as associated pollution and soil erosion. Also, the blasting vibrations from mines can cause damage to land and housing structures. In South Africa the Department of Minerals and Energy is inundated with blasting and vibration related complaints by communities located near quarries.

2.6.3 Health Issues

The digging of land to excavate minerals leaves large pits which later become filled with water during the rainy season. This standing water provides a breeding ground for *Anopheles* mosquitoes which are vector transmitters for malaria in African countries. Malaria cases have been reported to be one of the leading causes of outpatient cases in Ghana (Yelpaala and Ali, 2005). Although it is well established that standing water is a cause for malaria contamination nothing has been done by the larger mining companies to drain water out of the pits (Yelpaala and Ali, 2005).

Abandoned tailings dams pose a serious environmental problem in SSM, because of a threat of contamination, particularly when located in close proximity to urban zones. In S.A., this problem is very common in the East Rand and West Rand, where shacks are built literally on the tailings dams. Many people in these silica pregnant areas suffer from a condition called silicosis or pneumoconiosis (a lung disease caused by prolonged inhalation of dust containing silica, and marked by the development of fibrous tissue in the lungs resulting in chronic shortness of breath. Silicosis is a disabling, non-reversible and sometimes fatal lung disease caused by overexposure to respirable crystalline silica. Silica is the second most common mineral in the earth's crust, and is a major component of sand, rock and mineral ores. There is no cure for silicosis but it is largely preventable if employers, workers, enforcement agencies and health professionals work together to reduce exposures.

Mercury, as mentioned earlier, is a common problem associated with SSM with respect to health. Mercury is a poisonous, heavy silver-white metallic chemical element that is liquid at room temperature. In many instances, small-scale miners use no safety precautions when using this chemical substance. Miners typically handle mercury carelessly, and often inhale toxic mercury vapours whilst distilling gold amalgam. This mercury toxicity remains one of the most pervasive environmental impacts in the SSM sector. Due to the health effects of mercury exposure, industrial and commercial uses are regulated in many countries. The World Health Organisation (WHO), Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) all treat mercury as an occupational hazard. These organisations have established specific occupational exposure limits, for example the WHO specific occupational limit for water is 1 μg/L and air is 1 $\mu g/m^3$ (per annum), and the NIOH limit is 0.1 mg/m^3. Unfortunately, small-scale miners are not aware of these exposure limits and thus fall prey to the devastating consequences of overexposure. In many instances, no personal protective equipment (PPE) in the form of gloves, masks or even overalls are provided and used. Harmful dust and blasting fumes also pose a health risk to communities living around the mining areas.

2.6.4 Safety Issues

The dangerous pits and trenches are normally not filled and these become death traps since vegetation grows over them and are invisible to people living around that area. Safety is a state of mind upon which a person, with reasonable justification, believes and feels secure from any physical harm. It is a situation in which any possibility of harm is negligibly small or literally nonexistent. Safety is one aspect of SSM which is neglected by participants in SSM activities. The following situations are very common in SSM.

a) Diggings made for the removal of the precious minerals sought are usually operated without support. People just crawl in and out of these dangerous excavations characterised by unstable walls, quite often to their detriment.

b) Equipment maintenance is virtually non-existent. Because of a lack of funds, operators usually work with unserviced equipment until such equipment fails beyond repair. By the time it reaches these levels, many operators would have been maimed or even killed by such equipment.

c) Abandoned excavations that have not been barricaded or closed off often become a serious threat to human and animal life, as there is a risk of falling into these excavations (Limpitlaw *et al.*, 2005).

2.6.5 Social Impacts

A wide range of social impacts, such as prostitution and migratory labour, at mines in African countries such as South Africa have been identified as factors responsible for the spread of HIV/AIDS. The negative social impact of mining on women has also been identified as a challenge in India. Women in India are responsible for nurturing the family, collecting forest products, agricultural and livestock management (Ghose, 2008). However, mining in India has brought about displacement and loss of land. Women displaced as a result of mining lose the ability to cultivate traditional crops due to deforestation, and are unable to collect forest produce for sale and consumption (Ghose, 2008). This eventually leads to women being exploited as maidservants, construction labourers and prostitutes, which is socially humiliating (Ghose, 2008).

2.7 BARRIERS AND PROPOSED SOLUTIONS IN THE IMPLEMENTATION OF SOUND ENVIRONMENTAL PRACTICES

The findings of Moholo (2001) on matters of concern pertaining to SSM are shared by Tyler (1997), who adds that access to mineral rights, capital, skills and the existence of bureaucracy plus environmental issues are the greatest obstacles facing SSM. Tyler (1997) insists that a concerted and unified effort by the government, mining houses and the entrepreneur is required in order to overcome the above-mentioned obstacles.

Shen and Gunson (2004) successfully argued that contributions of SSM in China may outweigh their negative impacts, especially if the central government of China makes a concerted effort to regulate, guide and encourage the development of this industry as well as create a sound environment for its operators. Proponents of SSM in China see a well-regulated SSM industry as the cornerstone of future rural economic development, particularly for disadvantaged communities in poor regions.

In their strategies for improving environmental performance in SSM, Aryee *et al.* (2003) proposed a number of policy options to address the environmental impacts in this industry. These are discussed in the subsequent sections.

2.7.1 Finance

Aryee *et al.* (2003) identified a number of factors that inhibit implementation of improved environmental practices in the Ghanaian SSM sector. Firstly, a lack of self-generated funding as well as difficulties in securing credit facilities are inhibiting miners from implementing sound environmental management options. This acute shortage of finances in turn leads to reliance on cheap, haphazard and environmentally unfriendly operational methods. For example in Ghana, the Ghanaian Consolidated Diamonds (GCD) Ltd began to sell licenses to small-scale miners declaring that it would care for the safety of the environment. However there have been reports that GCDs financial resources were too limited to fully rehabilitate all the mined out places in Akwaitia (Yelpaala and Ali, 2005). This has resulted in a negative impact on the land such as deforestation.

Some of the solutions to the financial problems would be the manipulation of market forces to ensure that funding is made available to meet the cost of environmental sustainability. Raising such funds or determining who bears the burden of cost may be addressed through direct taxes or levies to be charged to the producer. Investment in SSM should be such that the activity provides assistance to small-scale miners to improve their operations.

2.7.2 Technical Factors

A number of technical factors have also been identified by Aryee *et al.* (2003) as inhibitors to environmental improvement in the SSM industry. Many SSM operations do not follow any systematic exploration in areas where SSM takes place. As a result, due to inadequate geological information concerning mineralised areas within their concessions, small-scale miners operate on a ‘trial and error’ basis; a practice that again impacts negatively on the environment.

This problem can be curbed by providing information and educating the small-scale miners. Moral persuasion, which should include using education, publicity and social pressure, could bring about a positive change in behaviour and a major challenge to SSM, especially in South Africa where there is a high level of illiteracy. Research on the management and regulation of SSM in South Africa, particularly at Osizweni (Newcastle, KwaZulu-Natal), was conducted by Moholo (2001), who reported that the low level of education among small-scale miners is an inhibiting factor in the development of this sector from being a mere survivalist business concern to being an efficiently run business enterprise. Moholo (2001) contends that the success of the SSM sector is dependent on the development of coherent strategic structures for basic skills development, exposure to valuable resources and training on business skills and regulations governing the industry in general. In the mining area of India's Himalayan deposits, Ghose (2002) concludes the study by arguing that whilst the system of preparing an EMP for clearance from the government of India prior to the implementation of a mining project is a positive step towards minimising the negative impacts, a weak regulatory regime inhibits progress in this area. Ghose further calls for the promotion of environmental research at university level as key to delivering improved environmental results in future.

In an effort to mitigate the undesired effects of mercury in SSM, Hylander and Plath (2006) propose increased awareness among gold miners about health and environmental damages caused by mercury. They argue for the introduction of environmental tax or fees in mining operations where gold is recovered using mercury or cyanide; the proceeds would then be used to reclaim and rehabilitate contaminated sites. Although the environmental costs should ideally be included in the market price, present conditions may make it less difficult to reduce environmental costs from gold mining by adding a premium to gold extracted using environmentally benign methods to appeal to the altruistic. Further, gold purchasers should not be the ones deciding which gold miners should be paid at a higher premium for the gold they produce. Hylander and Plath (2006) call for the introduction of certification criteria for clean gold or fair trade gold for the end users of gold. The end users should therefore be willing to pay more for the gold that is mined in an environmentally less harmful manner and less for the one mined through environmentally unfavourable methods.

2.7.3 Illegal Mining

Finally, illegal small-scale miners operating on the concessions of large-scale mining companies also cause a significant amount of environmental damage. For instance, a number of large-scale mining companies, after acquiring prospecting licenses, find themselves in an awkward position of not being able to prospect for some time due to financial constraints or other technical hindrances. In these instances, as inferred by Aryee *et al.* (2003), the concessions are left at the mercy of illegal miners since no security measures are in place to prevent encroachment. According to the observations by Aryee *et al.* (2003) even mining areas where concessions have been granted and are actively operated by large-scale mining companies, and areas not being immediately worked on as yet, have been known to be under siege by small-scale miners, including illegal operators.

Illegal mining can also be brought about by the unpredictability in the revenues that the small-scale miners earn. It has been reported by Yelpaala and Ali (2005) that miners' earnings in Ghana (Akwaita) vary significantly. The total revenue earned from one day of mining ranged from \$0 to \$80 with four out of ten teams not earning anything. Therefore SSM miners resorted to illicit mining outside areas set for legal mining. This posed danger to the environment since miners would mine in places not allocated to them, hence compromising the environment (Yelpaala and Ali, 2005). Providing other alternative sources of revenue could curb problems of illegal mining.

2.7.4 Intense Mining

Another factor that acts as a barrier is that large mining companies encourage intense mining, i.e. mining of land that has already been mined before. For example in Akwaita, Ghana small-scale miners dig licensed plots as deep as three to four metres to reach the diamond zone that has already been mined by the large-scale miners (GCD Ltd) (Yelpaala and Ali, 2005). This intensity in mining leads to a double burden on the environment since the land is mined twice. Policy and regulation could be a solution to some of these problems, mainly through the enforcement of legal requirements of monitoring and policing. However, due to the size of illegal small-scale mines as well as the inadequacy of penalties to serve as a deterrent, Aryee *et al.* (2003) concede that this approach may be an *ad hoc* measure.

2.8 TYPES OF MINERALS INVOLVED IN SMALL-SCALE MINING WORLDWIDE

Small-scale mining emphasises the extraction of a wide range of metals, precious stones, and industrial minerals, and accounts for a significant portion of the world's mineral and energy production. It has been reported that more than 30 different mineral substances are extracted by SSM worldwide. The prominent minerals include gold, diamonds, platinum group metals (PGMs), copper, lead, zinc, bauxite, tin, pyrite, iron one, sulphur, antimony, dimension stones, coal, silver, chromite, manganese ore, asbestos, clay, quartz, dolomite and silica sand. This typical spread in mineral extraction, together results in environmental degradation.

In China, SSM has greatly mitigated the shortage of energy and minerals caused by the country's booming economy, and has saved large amounts of capital investment in the formal state-owned mining industry. On average, 43% of the total coal production in China is produced by SSM, making China the number one coal producer.

South Africa has a wide spread of minerals extracted by small-scale miners. Mineral exploitation on a small-scale basis – especially for clay (for brick works), aggregate and sand – is carried out in all the provinces. On the contrary, major commodities like gold (Mpumalanga, Gauteng, Free State and North West), coal (Eastern Cape and KwaZulu-Natal), alluvial diamonds (Northern Cape and North West), kaolin (KwaZulu-Natal), are exploited in selected provinces with a known geology profile of mineralisation.

2.9 MINING METHODS

The type of mineral, its particle size, depth below surface and the surrounding geology of the area have a great influence on the choice of mining and extraction methods. However, due to the rudimentary nature of SSM, the literacy level and the absence of large capital investment in the activity, SSM employs itself to pick-and-shovels, pick-axes, chisel and hammer mining methods.

The methods used in SSM of precious minerals in South Africa and many parts of the African continent can be categorised into the following three groups:

- shallow alluvial mining,
- deep alluvial mining and
- hard rock (lode) mining.

2.9.1 Shallow Alluvial Mining

Shallow alluvial mining techniques, which are popularly called ‘dig and wash’, are used to mine shallow alluvial deposits usually found in valleys or low lying areas. In the case of diamond mining in South Africa, SSM activity is predominant along the Orange River banks, as well as along the west coast of the African continent.

In the case of gold mining, an elementary mining approach is adopted. These deposits have depths of up to three metres. Vegetation is usually cleared and the soil excavated until the gold-rich layer is reached. The mineralised material is removed and processed in small rotary mills, concentrated using mercury and then heated using cutting torches or other heating processes to recover the gold. Alternatively, the mineralised material is removed and transported to nearby streams for sluicing to recover the gold. It should be noted that in view of the relative ease of reaching these deposits and treating such ores, a significant proportion of the industry’s operations are of this type of mining. For similar reasons, illegal workings fall predominantly into this category. Areas where this type of mining practice is very common include Barberton, Messina, Pilgrims Rest, Welkom, the East and West Rand in Gauteng, as well as Klerksdorp in the North West province.

2.9.2 Deep Alluvial Mining

This technique is used to mine deep alluvial deposits found along the banks of major rivers in Ghana such as Ankobra, Tano, Offin and certain older river courses (Aryee *et al.*, 2003). The method involves excavating a pit and digging until the gold bearing gravel horizon, which is typically located at depths of 7-12 metres, is reached. Terraces or benches are constructed along the sides of pits to prevent collapse. The gold bearing gravel is then removed and sluiced to recover the gold.

2.9.3 Hard Rock (Lode) Mining

This method is adapted in mining gold bearing reefs, which are located close to the surface or deep-seated. Holes are drilled to intercept the reefs and when accomplished, the reefs are worked along the strike. Where such reefs are weathered, small-scale miners use chisel and hammer methods to break the ore. In instances where the ore is hard, explosives may be used.

2.10 ORE PROCESSING

Ore processing by SSM follows very basic and sometimes inefficient processing methods, because of lack of knowledge or lack of capital to invest in state-of-the art technology. The traditional ore processing methods are used where alluvial deposits are involved. These methods, which usually yield a recovery efficiency of approximately 60%, involve the sluicing of mined material in a sluice box to obtain the gold concentrate. Mercury is then added to the concentrate and mixed to form gold amalgam, which is then heated to separate the gold. A schematic flow sheet for semi-mechanised hard rock processing is shown in **Figure 2.3**. In the case of diamonds, the mined material is transferred onto a jig and washed with clean water. As washing progresses, the diamonds are then handpicked.

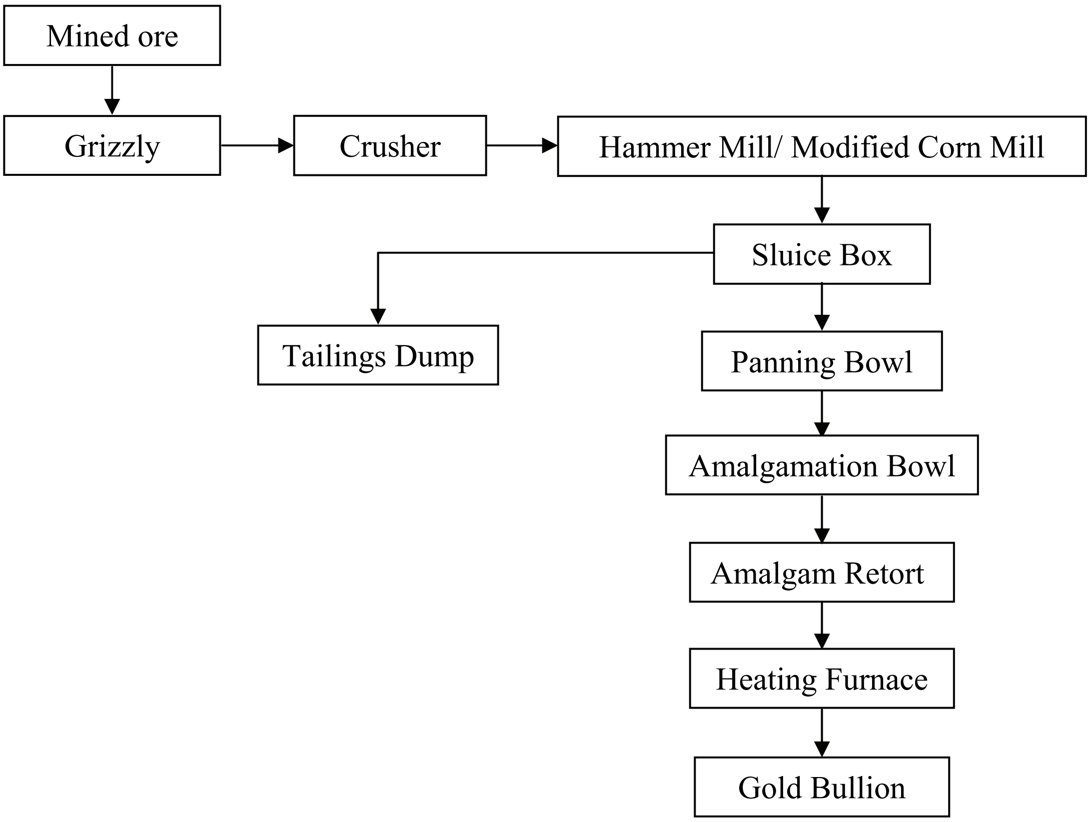

Figure 2.3: Gravity concentration gold recovery process

2.11 COAL MINING

The environmental impacts especially on water resources due to poorly managed SSM activities in South Africa have been documented. Coal mining requires the disturbance of large areas since surface mining is predominantly practised and this raises a number of environmental challenges such as water pollution. Acid mine drainage is one of the major problems which results from uncontrolled discharge of contaminated water from abandoned mines. This type of water pollution is characterised by a low pH, high salinity levels, elevated levels of sulphate, iron, manganese and aluminium. Raised levels of heavy metals such as cadmium, cobalt, copper, molybdenum and zinc and possibly radionuclides are characteristic of AMD (Oelofse, 2008). Basically, AMD is metal rich water formed from chemical reaction between water and rocks containing sulphur bearing material. The water run off is acidic and comes from areas where ore or coal mining activities have exposed rocks containing pyrite; this pyrite reacts with air to form sulphuric acid. The acidic run off dissolves heavy metals such as copper, lead and mercury. These metals – especially – mercury can have adverse effects on aquatic and human life when present in water systems.

In South Africa AMD pollution occurs mainly in the West Rand of the Gauteng Province. Its origins are from closed underground mine workings and this was uncovered in 2002. The AMD is a result of seepage through various mine shafts to the surface, via the natural water course. This natural water course flows northward through a game reserve and eventually towards the Cradle of Humankind World Heritage Site (Oelofse, 2008).

Further reports have emerged on the contamination of water sources by AMD at the Loskop Dam, Randfontein and Wonderfontein Spruit areas. In Mpumalanga an estimated 10 000 km^2 of hydraulically interlinked coal mines have been left un-rehabilitated and ownerless leading to their closure (Limpitlaw *et al.*, 2005). These deserted mines have been a threat to the Western Witwatersrand Basin. Mine water decanting from the 44 926 778 km^3 mined out has flowed into the head waters of Tweelopiespruit. This water then flows through the Krugersdorp Game Reserve and, after investigation by chemists, was found to be unfit for animal and human consumption. The Tweelopies River is considered hazardous and it has been reported that the people living along this river do not have access to piped water thus rely on the river as a water source. People mainly affected are Sterkfontein informal settlement and Krugersdorp Brickworks hostel dwellers (Limpitlaw *et al.*, 2005).

2.12 URANIUM MINING

Uranium mining has also caused serious pollution in water sources in places such as Wonderfonteinspruit which has been identified as a hot spot for radioactive contamination due to mining activities. Also, about 12 tonnes of uranium was reported to have entered the water system in 1991 coming from this area; more than 10 000 tonnes of uranium was also found in the tailings deposits. The mine water entering the water system around the area had much higher levels of uranium than those stipulated by South African drinking water guidelines. These levels were reported to be 10 times more than the South African water standards maximum limits level for drinking water and 70 times more than the levels prescribed for irrigation purposes. Furthermore, the far West Rand is also another potential source of uranium water pollution. About 24 tonnes of dissolved uranium found in the tailings deposits are released to the neighbouring water sources (Lieferink, 2007).

Uranium is a carcinogen and remains radioactive over many years, and extended exposure to the metal could have numerous health effects. These effects range from infertility and birth defects to neurological damage and cancer. The set limit for uranium in fresh water is 0.0004 mg/L and at Wonderfonteinspruit area the uranium levels were found to be 1 000 times above this limit. It was also noted that the amount of uranium in sediments exceeded those set by the National Nuclear regulator (Lieferink, 2007). People mostly affected in this area were those with already weak immune systems which were further compromised by poor nutrition or HIV/AIDS. The identified areas which were affected by uranium pollution include Khutsong, Bekkersdal, Kagiso, Rietvallei, Toekomsrus, Carletonville, Fochville, Westonaria, Potchefstroom and Welverdiend (Lieferink, 2007). The carcinogenic risk quotient estimate of the surface water in Wonderfonteinspruit area is 2.22 and the chemical risk for this water is 6.67 (Lieferink, 2007).

2.13 GOLD MINING

Gold mining introduces cyanide and mercury into the water system. Cyanide and mercury are often used to extract gold from ores (Morna and Clarke, 2008). Cyanide bearing solutions are utilised in mining because they react with gold and with other metals such as Cu, Zn and Co. Weak cyanide complexes are then formed and these normally dissociate in solution to produce high concentrations of free cyanide (Morna and Clarke, 2008). Biological oxidation also decomposes free cyanide into cyanate (CNO^-) and then to HCO_3^- and NH_3. Further biological nitrification of these degradation products leads to the formation of NO_2^- and NO_3^-. Nitrification in the water systems over-stimulates the growth of aquatic plants and algae. This consequently prevents light penetration into the deeper waters which is necessary for the well-being of aquatic animals. Cyanide ingestion results in acute poisoning in humans and animals. This contaminant can also remove trace elements and hence disturb their balance in the environment (Morna and Clarke, 2008). Other impacts of cyanide in the water system are extinction of some fish species in neighbouring contaminated water. Water birds and other carnivorous animals that feed on these contaminated fish usually die after them (Morna and Clarke, 2008).

Presently Hg emissions from gold mining emanate from SSM, labour intensive peasantry or artisanal mining (de Lacerda, 2003). Mercury amalgamation is simple and inexpensive hence it is used in SSM (Spiegel and Veiga, 2005). Mercury amalgamation results in the discharge of 1 000 tonnes of mercury per annum into the ecosystem in developing countries (Spiegel and Veiga, 2005). Washing of the gold ore and amalgamation with mercury is often carried out along river banks or near domestic water wells and ponds (Inkigura *et al.*, 1997). This inevitably causes direct contamination of the water by the Hg spilled from gold pans during the extraction of gold. Also, some mercury remains in the tailings (about 30%) and is leached and finds its way to the environment (Inkigura *et al.*, 1997). People living near gold mines are exposed to two forms of mercury; these are inorganic mercury and methylmercury (Serfor-Armah *et al.*, 2004). When metallic mercury gets into the water systems it is transformed to methylmercury and becomes biomagnified in the aquatic systems (Spiegel and Veiga, 2005). Fish in the Amazon have been found to contain about 70-98% of methyl-Hg (de Lacerda, 2003). In the Hartbeespoort dam (South Africa) it was found that Hg concentration was 2-5 times higher in birds than in fish and this was due to the bioaccumulation of Hg in the food chain (Inkigura *et al.*, 1997). The Hartbeespoort dam is generally used as a reservoir for industrial and municipal waters of Johannesburg. Communities relying on fish are particularly exposed to high levels of methylmercury. The ingested methylmercury can cause sterility, neurological damage and spontaneous abortion in pregnant women. In China's Dexing Province where SSM of gold mining occurs, extremely high concentrations of Hg have been reported in environmental samples, human blood and hair samples (de Lacerda, 2003).

The Witwatersrand region of South Africa has also had incidents of AMD due to gold mining activities. Mine dumps that have been abandoned for more than a decade have contributed to AMD. The dumps have been exposed to oxygenated rain water (Naicker *et al.*, 2003). This in turn has resulted in the oxidation of the pyrite and other sulphide material in the mine dumps. According to Naicker *et al.* (2003), the oxidation of the pyrites acidifies the water that percolates through the mine dumps and then enters the groundwater and eventually the streams along the Witwatersrand. Contamination of water by AMD has been discussed earlier in this document for other parts of South Africa.

2.14 PLATINUM GROUP METALS MINING

Platinum group metals (PGMs) are currently mined in South Africa (Bushveld mineral complex), Siberia and Sudbury, Ontario and the production of these elements has been increasing since the 1970s (Rao and Reddi, 2000; Ravindra *et al.*, 2004). South Africa is the leading country in the production of PGEs with 85% of the world's production and has 82% of the world's economic resources (Rao and Reddi, 2000). It produces 3 820 × 10^3 oz of Pt, 5 000 × 10^3 oz of Pd and 394 × 10^3 oz of Rh (Rao and Reddi, 2000). The Bushveld mineral complex in South Africa stretches to 400 km from the North West province across Limpopo Province to Mpumalanga (Curtis, 2008).

The mining of the PGMs such as Rh, Pd and Pt poses a great environmental challenge. These metals have been found to be increasing in the water ecosystem such as in rainwater, drinking water and seawater. It has been reported by Ravindra *et al.* (2004) that the presence of the metals in these matrices is attributed to the vehicle exhaust catalyst and may as well result from mining activities. When released in elevated levels in the environment via water sources they are taken up by plants and then enter the food chain (Rao and Reddi, 2000). Exposure to platinum based compounds can cause 'platinosis'. Platinum group metals have also been associated with asthma, nausea, increased loss of hair and spontaneous abortion (Rao and Reddi, 2000). Platinum complexes have been reported to bind to N and S in proteins, causing a reduction in enzymatic activity (Ravindra *et al.*, 2004).

Two communities in the Limpopo region have previously complained about Anglo Platinum mining activities around that area. A fact finding assessment was carried out and it was found that the water contained high nutrient levels; however this was not attributed to the mining activities around that area according to findings by Anglo Platinum. Although Anglo Platinum made approximately US$1.75 billion profit in 2007 alone, communities around the mining areas continue to be disadvantaged with respect to accessing decent water supplies (Curtis, 2008). Residents of Ga-Pila in Makopane were relocated from their former settlement to a place where there were no clean water supplies. There were four reservoirs but waste from the mines was dumped in all four reservoirs (Curtis, 2008). Residents have not been able to use this water because of its potential health hazard. While every citizen has a right to have access to adequate and pure water this has not been the case for people living around the Anglo Platinum mining area. Water sampling around this area commissioned by Action Aid revealed water pollution at four different sites (Curtis, 2008) and this was attributed to the mining activities around those places.

2.15 DIAMOND MINING

The mining of gemstones such as diamonds throughout southern Africa is widespread (Ashton *et al.*, 2001). Small-scale mining of such minerals in the SADC region is often illegal because most small-scale miners do not have licences. The major problem with diamond mining is that it enhances soil erosion and therefore increases sedimentation in nearby watercourses (Ashton *et al.*, 2001). This results in excessive loads of solid particle building up on beds of rivers and lakes (Ashton *et al.*, 2001).

In South Africa, SSM and processing of diamonds is performed using the ‘dig and wash’ technique whereby the mined material is transferred onto a jig and washed with clean water. As washing is in process, the diamonds are then handpicked. This technique is mainly found on the banks of the Orange River while the screening followed by the hand sorting is conducted on materials collected from diamonds tailings dumps from Kimberley. In addition to soil erosion by water, liquid effluents from the diamond processing, containing aluminosilicate metal companions emanating from kimberlitic rock mineralisation are transported to the surrounding and neighbouring water resources. Silicon iron manganese, magnesium and aluminium are regular pollutants commonly found therein.

2.16 CLAY AND SANDSTONE MINING

Apart from the medium sized companies like Sandstone City, activities on sandstone SSM in South Africa are mainly in the rural areas of Free State province (Qwaqwa, Bloemfontein) and in the Limpopo province. In addition to the metal contents of the aluminosilicate mineral structure of the sandstone emanating from its mineralisation process, which constitutes a tremendous water pollution threat to resources nearby, the radioactive uranium contained in the uraniferous sandstone from the Waterval, Damsfontein/Bloemfontein and Rietkuil areas increases the water resources’ contamination risk. According to SRK Consulting, 5% to 10% of the areas underlain by uraniferous sandstone may be mineralised which brings about radioactive contamination of water resources through infiltration and erosion.

Clay mining has been reported to make the lives of thousands of people miserable. Clay mining can cause skin problems and is leading to a steady decrease in water resources (www.minesandcommunities.org). Residents around clay mining areas have complained that children sometimes experience difficulty in breathing. Sandstone mining in the Brazos River requires the stripping of the sandstone, therefore exposing marine shales to celeritous erosion. This erosion introduces silts and clay particles, hence clogging the river which mainly affects the river flow and vegetation (Traylor, 2004).

2.17 PROBABLE WATER POLLUTING PRACTICES

Abandoned, inactive or orphaned mines can be defined as sites where advanced exploration, mining or mine production has ceased without rehabilitation or where it was not completed (MMSD, 2002). As is the case in Nigel, these mines are characterised by the presence of mountains of tailings dumps surrounding an old building with many spots of dams and streams flowing from underground, as well as unprotected big holes. In South Africa, the law regulating mine closure was implemented only in 1956 under the Water Act 54 (MMSD, 2002); most of the existing owners of old mines were not required to manage the waste produced. According to law, management of abandoned mines existing before the implementation of the Water Act 54 was the responsibility of the state (Limpitlaw *et al.* 2005). Proper rehabilitation of these mines to mitigate pollution could include (MMSD, 2002) removal of risks to health and safety, stabilisation of the site and the reduction or removal of impact of erosion and mass movement. Where feasible, a return of the biological diversity of species in the vicinity to pre-mining levels, and removal or amelioration of sources of site contamination, are essential.

According to the United Nations (1972), SSM is any single unit mining operation having an annual production of unprocessed materials of 50,000 tonnes, or less as measured at the entrance of the mine. Mining types considered to be SSM operations in South Africa include, diamond diggings, sand winning (dry-pit mining, wet pit mining, bar skimming of pits on adjacent floodplains or river terraces), coal mining, gold mining/panning and alluvial gold deposits, clay mining and peat extraction (Heath, 2005).

Despite huge efforts by the government to educate small-scale miners through workshops, seminars and provision of consultants, mining and minerals processing activities in this sector are still inappropriately performed and the risks of accidents as well as the discharge of dangerous wastes into surrounding water resources is getting even more serious. While pyro-metallurgy is artisanal and conducted with torching of amalgamate, released toxic gases eventually dissolve into water resources.

2.18 IMPACT OF ABANDONED MINES AND UNCONTROLLED SMALL-SCALE MINING ON THE SURROUNDING WATER RESOURCES.

In theory there should be no mining operations in abandoned mines. However, wastes left unattended, assisted by the morphology of the ground and percolation of water from underground, are prone to negatively impacting the quality of the already scarce water resources.

Tailings dumps which are fine-grained mineral wastes are easily transported by wind as dust to surrounding rivers, increasing the turbidity of water and so making processing difficult at the treatment plant. When exposed to atmospheric oxygen and water, tailings dumps can be oxidised resulting in AMD and dangerous heavy metals (lead, uranium, zinc, cadmium, nickel, etc.) and chemicals (cyanide, etc.) being found in surface and ground waters (Younger and Wolkersdorfer, 2004). The introduction of these toxic species into water systems can destabilise the aquatic ecosystem causing the poisoning and killing of fish. Further, the contaminants may compromise the quality of drinking water thus causing health risks to humans (Bell *et al.*, 2001; Feng *et al.*, 2004). Water percolating from the ground in abandoned mines brings pyrite to the surface. As mentioned earlier, pyrite is a sulphide mineral that is associated with AMD, especially after its oxidation (Edwards *et al.* 2000). The amount of mining waste produced in Gauteng is not yet determined but according to the Department of Water Affairs and Forestry (DWAF, 1997), gold mining produces the highest amount of waste in the province.

The considerable amount (90% of the gold mines) of cyanide used for the treatment of gold containing ore most likely ends up in effluent water. It is estimated that approximately 0.05% of this cyanide is deposited in dams and ponds (Korte *et al.*, 2000). Residual cyanide therefore accumulates over the years and constitutes a serious threat to the quality of surrounding water resources. Cyanide is a potentially toxic compound that affects human and animal health after ingestion or inhalation. Both types of exposure can contribute to systemic effects, namely immunological and lymphoreticular, neurological, reproductive, developmental and cancer, eventually leading to death (Uitti *et al.*, 1985; Carella *et al.*, 1988; Grandas *et al.*, 1989; Rosenberg *et al.*, 1989; Feldman and Feldman, 1990; Rosenow *et al.*, 1995; Chin and Calderon, 2000; Rachinger *et al.*, 2002; WHO, 2004b). According to Akcil (2002), the maximum acceptable concentration limits for cyanide in potable water are 0.2 ppm (for United States Environmental Protection Agency) and 0.07 ppm (for WHO). Cyanide is therefore considered a serious hazard and should be dealt with according to international regulation norms.

2.19 POSSIBLE REMEDIATION OF WATER POLLUTION DUE TO SMALL-SCALE MINING ACTIVITIES

Pollution of water resources associated with mining activities poses major concerns among surrounding communities and local government as these impact negatively on aquatic biolife and degrade the quality of available water resources in the region.

Remediation of polluted water resources has always been a cumbersome task, given the high cost and effort required. Conventional methods, principally based on physico-chemical principles, include reverse osmosis, electro-dialysis, ultrafiltration, ion-exchange and precipitation, to mention a few. Very often these techniques are inappropriate because of their high cost, ineffectiveness and possible generation of large volume of toxic sludge (Ibeanusi and Wilde, 1998). The suitable approach which has now been identified as the biological method (Vieira and Volesky, 2000; Alluri *et al.*, 2007) consist among others the exploitation of the capabilities of microorganisms (fungi, yeast, bacteria, algae, etc.) and plants (wetland system) to remove metals as well as biodegrade complex toxic compounds from water and/or soils. Additionally, EJODEC Minerals and Process use the naturally occurring South African zeolite such as clinoptilolite to remove metals from water and aqueous solutions.

Microorganisms' capacities to remove metals from solution are either passive or active. The two mechanisms called biosorption and bioaccumulation can occur simultaneously or individually depending on the type of microorganism and the metals involved. Biosorption is a passive method and depends on the structure of the microbial cell membrane and on the affinity for a particular metal (Langley and Beveridge, 1999). On the other hand, bioaccumulation is an active transport of metals into the cell system of microorganisms and this can adversely affect the microorganism growth. Fungi and yeast such as *Aspergillus* spp. and *Saccharomyces cerevisiae* have been used in the removal of metals such as cadmium and mercury respectively (Barros *et al.*, 2003; Madrid *et al.*, 1995). However, bacteria are frequently used in bioremediation as they are easy to handle and grow. They offer the possibility of metal recovery and can also degrade toxic compounds such as cyanide. *Bacillus* spp. (Kaewchai and Prasertsan, 2002; Kim *et al.*, 2007) and *Pseudomonas* spp. (Muraleedharan *et al.*, 1991) have been successfully used at removing metals such as Cd, Cu, Ni and Co from the environment.

While the zeolite, clinoptilolite, requires prior activation, the major drawback in the use of microorganisms is metals' intoxication of bacteria and acidity of mine water, which inhibit the microorganisms' activity. Indigenous microorganisms, which can tolerate harsh environmental conditions, are often preferred for remediation processes. To optimise metals removal using microorganisms, biomasses are sometimes pre-treated by processes that involve detergent washing, exposure to heat, and the use of acid, alkalis and enzymes (Gadd *et al.*, 1988; Ting and Teo, 1994; Kapoor and Viraraghavan, 1998; Yan and Viraraghavan, 2000). Alternatively, heterogenous microorganisms can be genetically modified to increase their tolerance to high concentration of metals *in situ* as well as create a biodegradative pathway necessary for bioremediation. For example, Ahmad *et al.* (1991) successfully transferred the biphenyl degradative genes (bphBCD) from *Comamonas testosteroni* B-356 into *Pseudomonas putida*.

Cyanide may be treated and removed from water and the environment using several techniques such as breakpoint chlorination, natural attenuation, cyanide recovery, granular activated carbon and biological treatments (Akcil and Mudder, 2003). Chemical and physical methods are considered expensive and complex to operate, while the biological methods using indigenous bacteria can be less costly (Akcil, 2003). Both types of method, however, are based on the principle of degrading cyanide into benign species through oxidation reactions.

2.20 CONCLUSIONS

Small-scale mining is an important economic activity for any developing country, South Africa included. However, government support in terms of funds, manpower resources and development is a crucial ingredient for the success of this activity. A tripartite strategy monitoring government structures, donor bodies and the entrepreneurs in this activity should be encouraged and promoted. Increased attention to skills provision, training, environmental sustainability, occupational health and safety issues (including the responsible use of cyanide, mercury and other chemicals) and financial services support will help to ensure the success of SSM wherever this is practised. This would assist in reducing the extent to which water resources (and the environment in general) are polluted. Ongoing work in this project involves sampling of water in areas where commodities such as gold, platinum, coal, diamonds, sandstones and clays are being exploited by small-scale miners. Results obtained thus far confirm that there is contamination of these water resources as evidenced by the presence of toxic metals and other species already mentioned in this report, which are a result of unregulated and unsafe mining practices by small-scale miners, natural causes leading to AMD and the run-off erosion of pollutants into water systems.

CHAPTER 3: PRESENTATION OF FINDINGS

3.1 QUANTITATIVE ANALYSIS OF WATER POLLUTION BY SMALL-SCALE MINERS DURING DRY SEASONS

3.1.1 Introduction

Small-scale mining activities are on the rise in South Africa, typical of many developing countries, and as a result of the government's policies that encourage local communities to share in the country's mineral wealth in order to alleviate poverty. This has made it possible for artisanal miners of gold, platinum, diamonds, coal, clay and sandstone to participate in the mining economy.

However, such opportunities have been accompanied by unsafe mining practices to the detriment of water resources. Effluents from these generally unregulated practices are often disposed off to neighbouring water resources. Here, we report on the contamination of water resources during the dry season in selected areas where gold, coal, diamonds, clay, sandstone and PGMs are mined by small-scale mine operators.

3.1.2 Background

Quantitative analysis of water polluted by gold, coal, clay/sandstone, diamonds and PGM SSM operations during the dry season is presented and discussed in this section of the report.

3.1.3 Sampling and Analysis

Soil and water samples were collected during the dry season from gold, coal clay/sandstone, diamonds and platinum mines at operations in Ekurhuleni-Gauteng, Mpumalanga, Qwaqwa (Free State), Ventersdorp (North West) and Ekurhuleni-Gauteng respectively. Physico-chemical measurements of collected water samples (i.e. pH, conductivity, turbidity, oxidation reduction potential (ORP) were measured on site. Contaminants (cations as well as anions) were measured using either AAS or the Inductively-Coupled Plasma Optical Emission Spectroscopy (ICP-OES) depending on the concentration of the analytes in the water samples.

3.1.4 Results and Discussion

3.1.4.1 Gold Operations

Table 3.1 presents the results of the physico-chemical analysis of collected water samples from gold operation during the dry period while **Table 3.2** shows contaminants that were found.

Table 3.1: Physico-chemical quality of water around mine areas

Sampling sites	pH	Temp (°C)	ORP	Conductivity (µS)	Turbidity (NTU)
Big dam Nigel	6.32	25	12.2	988	5.04
River Nigel (A) site1	5.45	25	61.6	1103	9.61
Site 2	5.45	25	61.6	1103	9.61
Site 3	5.45	25	61.6	1103	9.61
River Nigel (B) site 2	5.05	25	74.4	1114	52.5
Shaft C	7.28	25	44.7	252	4.94
Piet's farm (A)	6.85	25	5.2	808	2.95
Piet's farm (B)	7.28	25	34.8	–	–
Piet's farm (C)	7.98	25	82.8	669	13.1
Piet's farm (D)	7.5	25	41.6	1161	5.94
Piet's farm (E)	7.95	25	73.7	721	3.63
Piet's farm sludge	7.76	27.6	124	2957	37.4

Table 3.2: Quantitative analysis of contaminants in waters collected near a gold operation during the dry season

	Limit (mg/l)	River town	Shaft C	Piet's Farm 1	Piet's Farm 2	Big Dam
Ag	0.1	**0.116**	**0.258**	**0.152**	**0.190**	**0.223**
Ni	0.15	-	-	**9.295**	**0.257**	-
Mn	1	0.901	0.108	0.624	0.446	0.630
Fe	< 0.2	**0.205**	-	-	**1.559**	-
Cr	< 0.5	0.023	0.140	0.034	0.042	0.045
Zn	< 5	0.012	0.293	1.343	0.077	-
Cu	< 1	0.004	0.006	0.291	0.019	-
Nitrate	< 10	2.43	2.07	3.41	0.75	3.28
Sulphate	< 400	315.23	286.20	**727.94**	**552.15**	242.48
Bromide	< 200	136.83	29.10	33.97	110.09	130.77
Fluoride	< 1	0.32	-	0.71	0.26	0.94
Chloride	< 200	-	-	-	-	1.04

Sites 2, 3, and River Nigel sites 1 and 2 were found to have a higher acidity level as the pH of water collected was around 5. This could be caused by AMD generated by the exposure of pyrrhotite minerals present in this tailings dumps site to the atmospheric oxygen and water.

Conductivity was very high compared to the recommended limits, especially those for drinking water. This suggests the presence in high amounts of anions and cations as well as organic pollutants. The sites that showed high turbidity could be as a result of dust particles or algal bloom around mine dumps. Nigel River receives seepages from most of these sites and thus the turbidity and conductivity of its water are raised and the pH is at 5.05. The fact that the river's physical parameters are not significantly high compared to the feeding sites could be attributed to the filtration process that occurs as the water percolates the earth towards the river and the fact that river water is continuously flowing.

Sulphate was significantly higher (727.94 and 552.15) in Piet's farm sites; this could be as a result of run-off from agricultural activities where fertilisers containing sulphates might have been used. It could also have originated from the weathering of iron sulphide contained in the ore. The excess of Ni could come from the lateritic soil hosting the gold while Fe derives from the pyrrhotite and the resulting pyrite. The presence of silver is as normally expected in Witwatersrand gold deposits.

During the dry period it was noticed that the tailings dumps produced in the gold mining were blown away by winds when dry, producing a respiratory problem.

3.1.4.2 Coal Operations

Table 3.3 gives the physico-chemical measurements of water collected near a coal mining operation. The sites were opposite the mine, separated by a busy highway (N12). Relatively neutral pH values (7-8) were observed, showing that this coal operation has a limited impact on the acidity of this water reserve.

Table 3.3: Physical parameters of water samples collected next to a coal mine

Parameters	**Sample names**				
	A1	**A1 (standing)**	**A2**	**A2 (standing)**	**Witbank dam**
Temperature (°C)	25	25.5	25.2	25.4	25
Conductivity (µS)	517	357	253	256	379
ORP	-37.2	-22.8	-36.2	-35.2	-35.6
Turbidity (NTU)	7.8	9.2	9.8	9.9	2.08
pH	8.2	7.3	7.3	7.3	7.25

The distance between site A1 and site A2 is approximately 500 metres
A1: water flowing from coal mining operation towards a small wetland pond A1
A1 (standing): Standing water of small wetland pond A1
A2: water flowing from coal mining operation to a small wetland pond A2
A2 (standing): Standing water of small wetland pond A2
Witbank dam: A large dam located about 25 km from the coal mine

Normally a low pH, high salinity levels and elevated levels of sulphate, iron, manganese and aluminium should have been expected but it was noticed that water samples collected around the coal mine were generally neutral as the pH was approximately 7 (**Table 3.3**). The conductivity and the ORP were not indicative of major ionic interaction; the conductivity of all the samples was found to be within the acceptable range according to the South African Bureau of Standard (SABS) guideline (SANS, 2005).

Table 3.4: Quantitative analysis of contaminants in waters collected near a coal mine during the dry season

	Limit (mg/l)	**A2**	**A2 (Standing)**
Ag	0.1	**0.498**#	**0.557**#
Ni	0.15	-	-
Mn	1	-	-
Fe	< 0.2	**2.351**#	**3.802**#
Cr	< 0.5	0.173	0.192
Zn	< 5	-	-
Cu	< 1	-	-
Nitrate	< 10	-	-
Sulphate	< 400	4.88	6.33
Bromide	< 200	15.70	12.79
Fluoride	< 1		
Chloride	< 200	-	-

Bold indicates amount above the acceptable limits

Iron and silver were found at a relatively higher concentration than the accepted value. While the silver content is unusual, higher iron content is only representative of the pyrrhotite, pyritic and sulphate content of the processed coal. While iron finds itself in the coal structure as iron sulphides and sulphates, the separation by the use of a heavy medium where magnetite is dispersed into water for the washability of coal may also add to the observed high iron content.

Table 3.5: Additional metal content

	Limit (mg/l)	A2	A2 (Standing)
Be	2.00	-	< 0.088
Cd	0.005	-	**0.031**[#]
Co	0.01	**0.443**[#]	**0.367**[#]
Pb	< 0.05	**9.650**[#]	**10.169**[#]
As	0.05		0.034

The relatively higher amount of chromium (0.17 and 0.19 mg/l) and iron (2.35 and 3.80 mg/l) poses a potential risk to the water resources (**Table 3.4**). While iron could come from the structural sulphides and sulphates, the presence of chromium, cobalt and cadmium may only be explained by their availability in the coal deposit geological formation. The absence of guidelines for some metals (e.g. silver) should not be taken as an indication that their presence is no cause for concern. The higher amount of lead observed could come from vehicle exhaust emissions as the sampling sites were next to the N12 highway.

3.1.4.3 Clay Operations

Water samples from clay operations were collected at a mining site for the manufacture of bricks. The sampling site is located in Qwaqwa, next to an internal road; it should be noted that the Monapo Hospital is near the river side. Samples were collected at the processing site (Q1D) and from the nearby river (Q3D).

Table 3.6: Quantitative analysis of contaminants in waters collected near a clay operation during the dry season

	Limit (mg/l)	Q1D	Q3D
Ag	0.1	< 0.068	-
Ni	0.15	0.032	**3.731**
Mn	1	0.209	0.130
Fe	< 0.2		
Cr	< 0.5	-	0.065
Zn	< 5	-	-
Cu	< 1	0.228	0.247
Nitrate	< 10	0.73	0.1
Sulphate	< 400	36.08	7.99
Phosphate		-	0.49
Bromide	< 200	-	-
Fluoride	< 1	**4.41**	**4.57**
Chloride	< 200	8.84	-

Q1D: River side Monapo Hospital, process water for brick making
Q3D: River side Monapo Hospital, running water from the stream near the brickmaking site

Table 3.7: Additional metal content

	Limit (mg/l)	Q1D	Q3D
Be	2.00	< 0.024	< 0.042
Cd	0.005	< 0.075	< 0.077
Co	0.01	-	**0.233**
Pb	< 0.05	-	**6.420**
As	0.05	< 0.097	< 0.071

Q1D: River side Monapo Hospital, process water for brick making
Q3D: River side Monapo Hospital, running water from the stream near the brickmaking site

Nickel, fluoride and lead contents were found to be unusually high. This reveals that the clay is lateritic in nature; the lead could come from vehicle exhaust emissions; nickel could come from the lateritic clay.

3.1.4.4 Diamond Operations

An alluvial diamond site in Ventersdorp was visited. As for kimberlotic reserves, diamonds are processed by dense medium separation (DMS). Samples were collected at relevant sites.

In South Africa, SSM and processing of diamonds are performed using the ‘dig and wash’ technique where the mined material is transferred onto a jig and washed with clean water. During washing, the diamonds are handpicked. This practice is predominant on the Orange River banks and the screening followed by the hand sorting is conducted on materials collected from diamonds tailings dumps at Kimberley. In addition to soil erosion by water, liquid effluents from diamond processing, containing aluminosilicate metal companions emanating from kimberlitic rock mineralisation, are transported to the surrounding and neighbouring water resources.

The Ventersdorp diamond mining operation is on an alluvial deposit. As shown in **Table 3.8**, fluoride and iron were found in excessive amounts. Iron emanated from the ferrosilicon dense medium separation process used to concentrate the alluvial diamonds.

Table 3.8: Quantitative analysis of contaminants in waters collected near a diamond operation during the dry season

	Limit (mg/l)	Aquelle	RWT
Ag	0.1	0.026	0.021
Ni	0.15	-	-
Mn	1	-	0.384
Fe	< 0.2	**0.350**	**21.97**
Cr	< 0.5	-	-
Zn	< 5	-	-
Cu	< 1	-	-
Nitrate	< 10	0.99	0.62
Sulphate	< 400	6.83	8.72
Phosphate		-	0.61
Bromine	< 200	17.79	23.17
Fluoride	< 1	**4.90**	**5.01**
Chlorine	< 200	-	9.11

3.1.4.5 PGM Operations

Although mainly mined in the Bushveld mineral complex, we sampled at a PGM mining operation in the East Rand area of Gauteng.

Table 3.9: Quantitative analysis of contaminants in waters collected near a PGM mine during the dry season

	Limit (mg/l)	Pimville shacks 3	Ni-Pd near shaft 1	Ni-Pd near road
Ag	0.1	**0.336**	**0.360**	**0.381**
Ni	0.15	**2.868**	0.147	-
Mn	1	**1.249**	0.274	0.478
Fe	< 0.2	**1.650**	**0.996**	**0.630**
Cr	< 0.5	0.210	0.206	0.211
Zn	< 5	0.061	1.457	-
Cu	< 1	0.0064	0.155	0.122
Nitrate	< 10	0.31	1.95	0.89
Sulphate	< 400	**1577.12**	**1115.69**	136.31
Phosphate		-	-	-
Bromine	< 200	181.11	141.79	19.36
Fluorine	< 1	0.02	0.17	0.04
Chlorine	< 200	-	-	-

3.2 QUANTITATIVE ANALYSIS OF WATER POLLUTION BY SMALL-SCALE MINERS DURING WET SEASONS

3.2.1 Introduction

Quantitative analysis of water pollution from gold, coal, clay/sandstone, diamond and PGM SSM operations during the wet season is presented and discussed in this section.

3.2.2 Sampling and Analysis

Soil and water samples were collected during the rainy season from gold, coal clay, sandstone, diamond and platinum mines at operations in Ekurhuleni-Gauteng, Mpumalanga, Qwaqwa (Free State), Ventersdorp (North West) and Gauteng respectively. Water samples were collected in sterile glass bottles at sixteen points in soils, dams and streams around old mines in Nigel-Johannesburg, at operation sites in Qwaqwa, and at the DMS and tailings dumps at Ventersdorp. They were preserved at 8°C in cooler boxes and transported to the laboratory for analyses. Physico-chemical measurements of collected water samples (i.e. pH, temperature, conductivity, ORP were taken on site using the portable Eutech Instruments Cyberscan (made in Singapore), while the turbidity was measured in the laboratory using the Nephla turbidity meter (Dr Lange GmbH-Berlin). Contaminants (cations as well as anions) were measured using either AAS or ICP-OES depending on their amounts of their occurrence.

3.2.3 Results and Discussion

3.2.3.1 Gold Operations

Due to AMD, water from the small dam at the mine site owned by HVH gold mining company had a pH averaging approximately 3 (**Table 3.10**). Considering the SABS (SANS, 2005) and World Health Organisation (WHO, 2004) guidelines, the level of 3.09 was unacceptable, indicating a probability of high metal sulphate pollution.

Although the sites sampled during the rainy season were not identical to the sites sampled during the dry season, they were within a radius of 50 metres from each other. Accessing exactly the same sites proved rather difficult because of destruction due to overflows after huge downpours. The values for conductivity and turbidity were comparable to the values quoted in the dry season.

Table 3.10: Physico-chemical quality of water around mine areas

Sampling sites	pH	Temp (°C)	ORP	Conductivity (μS)	Turbidity (NTU)
Big dam Nigel	6.32	25	12.2	988	5.04
River Nigel (A) Side1	5.45	25	61.6	1103	9.61
Side 2	5.45	25	61.6	1103	9.61
Side 3	5.45	25	61.6	1103	9.61
River Nigel (B)	5.05	25	74.4	1114	52.5
Stream next to River Nigel	6.55	25	61.6	3640	424
Nigel 169 (artisanal)	6.52	25	0.6	3616	45.4
Small dam (HVH)	3.09	25	183.7	3999	7.01
Stream (HVH)					
Shaft C	7.28	25	44.7	252	4.94

In **Table 3.11**, it can be seen that the Fe content was generally above the recommended limit. This could be due to the predominant presence of pyrite in the gold mining area. However, the relatively low sulphate content compared to the dry season may be as a result of dilution due to the heavy rains. The same inference can be made with respect to the other analytes measured which were generally below the maximum allowable limits.

Table 3.11: Quantitative analysis of contaminants in waters collected near a gold operation during the rainy season

	Limit (mg/l)	Shaft 2 (C)	River Nigel town	Big Dam Nigel	HVH Gold A (small dam)	HVH Gold B (stream)
Ag	0.1	-	-	-	-	-
Ni	0.15	0.01139	0.00724	0.003070	**0.2691**	0.00644
Mn	1	0.009876	0.09435	0.001808	0.1593	0.1023
Fe	< 0.2	**3.270**	**0.2954**	**0.2340**	**9.172**	**8.660**
Cr	< 0.5	0.064	0.0156	0.070	0.0168	0.00238
Zn	< 5	0.01353	0.00392	0.001285	0.1714	0.005846
Cu	< 1	0.06900	0.875	0.1960	0.1059	0.02355
Nitrate	< 10	4.70	0.440	8.64	1.67	**12.10**
Sulphate	< 400	226.2	335.51	8.31	332.1	338.2
Phosphate		-	-	-	-	-
Bromide	< 200	57.66	107.59	121	106.69	352.2
Fluoride	< 1	-	0.84	-	-	-
Chloride	< 200	-	-	-	-	-

It was decided to sample at additional sites within the gold mining operation at Nigel. Although the high bromide content in the Nigel 169 site could not be explained, there was a nitrate concentration at least three times beyond the acceptable limits; as Nigel 169 was next to agricultural land, it is likely that the nitrates were deposited into the adjacent waters due to rain wash-off of fertilisers.

Table 3.12: Quantitative analysis of contaminants in further water samples collected near a gold operation during the rainy season

	Limit (mg/l)	**Site E**	**Site C**	**Nigel 169**	**Site A**	**Site D**
Ag	**0.1**	-	-	-	-	-
Ni	**0.15**	-	-	-	**0.2335**	-
Mn	**1**	0.005547	-	0.1331	0.3742	-
Fe	**< 0.2**	0.008783	0.01033	-	0.01349	-
Cr	**< 0.5**	-	-	-	-	-
Zn	**< 5**	-	-	0.01404	0.01628	0.05032
Cu	**< 1**	0.01215	0.01507	0.007162	0.01081	0.009045
Nitrate	**< 10**	**35.26**	**49.61**	**32.12**	-	17.25
Sulphate	**< 400**	157.06	60.70	**526.58**	275.38	145.2
Phosphate		-	-	-	-	-
Bromide	**< 200**	**236.59**	107	**1639.35**	24.58	194.62
Fluoride	**< 1**	0.86	0.83	0.79	0.81	0.80
Chloride	**< 200**	-	-	-	-	-

3.2.3.2 Coal Operations

Table 3.13: Quantitative analysis of contaminants in waters collected near a coal mine during the rainy season

	Limit (mg/l)	**A1**	**A1 PRIME**
Ag	0.1	**0.439**	**0.375**
Ni	0.15	-	-
Mn	1	-	-
Fe	< 0.2	**3.597**	**1.384**
Cr	< 0.5	0.160	0.080
Zn	< 5	-	-
Cu	< 1	-	-
Nitrate	< 10	-	-
Sulphate	< 400	7.50	5.64
Bromide	< 200	19.70	21.02
Fluoride	< 1		
Chloride	< 200	-	-
Be	2.00	-	-
Cd	0.005	**0.031**	**0.030**
Co	0.01	**0.566**	**0.531**
Pb	< 0.05	**10.302**	**10.054**
As	0.05	0.040	0.034

Bold indicates amounts above the acceptable limits

3.2.3.3 Clay Operations

Water samples from clay operations were collected at a mining site for the brick manufacture in Qwaqwa. The Qwaqwa sites were located next to an internal road and the Monapo hospital at the river side, samples were collected at the processing site (Q2R) from the cover as it rained, as overflow from the rain after filling mining pits where clay has been dug from the river nearby (Q4R).

Table 3.14 Quantitative analysis of contaminants in waters collected near a clay operation during the rainy season

	Limit (mg/l)	Q2R	Q4R
Ag	0.1	< 0.053	< 0.042
Ni	0.15	-	**6.277**
Mn	1	0.076	0.214
Fe	< 0.2		
Cr	< 0.5	-	0.335
Zn	< 5	-	-
Cu	< 1	0.198	0.324
Nitrate	< 10	1.86	0.07
Sulphate	< 400	9.28	5.66
Bromide	< 200	17.07	4.81
Fluoride	< 1	**4.50**	**4.60**
Chloride	< 200	-	

Q2R: River side Monapo Hospital, rain water on the brick making site, collected from the covers
Q4R: River side Monapo Hospital, overflow from the rain after filling mining holes from which clay has been dug

Table 3.15 Analysis of metal ions in water

	Limit (mg/l)	Q2R	Q4R
Be	2.00	-	0.093
Cd	0.005	< 0.019	0.188
Co	0.01	-	**0.811**
Pb	< 0.05	-	**10.672**
As	0.05	-	0.194

Q2R: River side Monapo Hospital, rain water on the brick making site, collected from the covers
Q4R: River side Monapo Hospital, overflow from the rain after filling mining holes from which clay has been dug

Metal contents of the aluminosilicate mineral structure of the sandstone emanate from its mineralisation process, which constitutes a tremendous water pollution threat to resources nearby.

As advanced by Traylor (2004), we noted that during the rainy season in Qwaqwa the soil was eroded. Indeed, this erosion introduced silts and clay particles which clogs the river, mainly affecting the river flow and vegetation.

3.2.3.4 Diamond Operations

A diamond mine in Ventersdorp area was visited. Water samples were collected at the tailings dumps, DMS and the concentration process plant.

Due to the levels of dilution, the analytes around the diamond operation were found to be reasonably within expectations. The fluoride content was four times higher than the maximum limits. The geological formation of the deposits explains the slightly high value of chromium in the water sampled at the diamond operation.

Table 3.16 Quantitative analysis of contaminants in waters collected near a diamonds operation during rainy season

	Limit (mg/l)	**DMS Plant stream 2**
Ag	0.1	-
Ni	0.15	0.1353
Mn	1	0.7072
Fe	< 0.2	0.1694
Cr	< 0.5	**0.6086**
Zn	< 5	2.656
Cu	< 1	-
Nitrate	< 10	0.52
Sulphate	< 400	5.79
Bromide	< 200	-
Fluoride	< 1	**4.91**
Chloride	< 200	-

3.2.3.5 PGM Operations

The same reasons advanced in the section on gold operations may be used here to explain the high sulphate concentration. The lateritic soil could probably account for the high nickel content in the water samples while the Fe concentration at Pimville shack 1 was high due to the presence of pyrite.

Table 3.17: Quantitative analysis of contaminants in water samples collected near a PGMs mine during the rainy season

	Limit (mg/l)	**Pimville shacks 1**	**Pimville shacks 2**
Ag	0.1	**0.305**	**0.314**
Ni	0.15	**1.932**	**2.261**
Mn	1	0.699	0.826
Fe	< 0.2	**3.212**	-
Cr	< 0.5	0.1690	0.175
Zn	< 5	0.079	0.090
Cu	< 1	0.074	0.0026
Nitrate	< 10	0.44	0.34
Sulphate	< 400	**1320.01**	**1364.74**
Bromine	< 200	160.78	157.71
Fluoride	< 1	0.03	-
Chlorine	< 200	-	-

3.3 CONCLUSIONS

This project involved the sampling of water in areas where commodities such as gold, platinum, coal, diamond, sandstone and clay are being exploited by small-scale miners. Results obtained confirmed that there was contamination of these water resources as evidenced by the presence of toxic metals and other species already mentioned in this report which are a result of unregulated and unsafe mining practices by small-scale miners, natural causes leading to AMD and the run-off erosion of pollutants into water systems. The Nigel river water near the gold operation was found to be acidic and the HVH gold mine site constituted a potential contributor of the acidification of source water, as the pH of this site was drastically low (3.09). This could have been expected since a recently abandoned mining site can have acidic water.

The digging of land to excavate minerals leaves large pits which later become filled with water during the rainy season as was observed in Qwaqwa. In the East Rand area of Gauteng (gold operation) some of these pits were covered by vegetation causing them to be shrouded and not easy to notice.

Fine particles collected from the dumps found their way into the nearby water resources hence increasing their contamination levels. The effect of AMD was evident as reflected by low pH values in water samples collected, particularly from the gold and clay operations.

The disappearance (dryness) of some previous water sources was characteristic for the dry season. A relatively higher amount of contaminants was observed during the dry season, probably due to the sampling sites being dried, preventing any possible dilution that one would encounter in the raining season. Contamination of water by toxic metals was noticed. In addition to the fine contaminants blown by wind during the dry season, dangerous pits were found, especially in the Gauteng area (gold) and in Qwaqwa (clay).

CHAPTER 4: GENERAL CONCLUSIONS

Artisanal and SSM are important economic activities for many developing countries, including South Africa. However, government support in terms of funds and manpower resources and development is a crucial ingredient for the success of this activity. A tripartite strategy monitoring government structures, donor bodies and the entrepreneurs in this activity should be encouraged and promoted. Increased attention to skills provision, training, environmental sustainability, occupational health and safety issues (including the responsible use of cyanide, mercury and other chemicals) and financial services support will help to ensure the success of SSM wherever it is practised. This would assist in reducing the extent to which water resources (and the environment in general) are polluted.

This preliminary work involved sampling of water in areas where commodities such as gold, platinum, coal, diamond, sandstone and clay are being exploited by small-scale miners. Results obtained thus far confirm that there is contamination of these water resources as evidenced by the presence of toxic metals and other species already mentioned in this report which are a result of unregulated and unsafe mining practices by small-scale miners, natural causes leading to AMD and the run-off erosion of pollutants into water systems.

The Nigel river water near the gold operation was found to be acidic, and the HVH gold mine site constituted a potential contributor of the acidification of source water, as the pH of this site was drastically low (3.09). The digging of land to excavate minerals leaves large pits which later become filled with water during the rainy season as was observed in Qwaqwa. In the East Rand area of Gauteng (gold operation) some of these pits were covered by vegetation causing them to be shrouded and not easy to notice. Fine particles collected from the dumps were deposited into the nearby water resources, increasing their contamination levels. The effects of AMD were evident as reflected by low pH values in water samples collected, particularly from the gold and clay operations. The disappearance (dryness) of some previous water sources was characteristic for the dry season. A relatively high amount of contaminants was observed during the dry season, probably because the sampling sites were dried out, preventing any possible dilution that one would encounter in the raining season. Contamination of water by toxic metals was noticed.

Both clinoptilolite and bacteria were capable of removing Cu^{2+}, Co^{2+}, Fe^{2+}, Mn^{2+}, As^{3+} and Au from solution. The 0.02 M HCl-activated clinoptilolite also demonstrated good metal removal capabilities. Environment friendly bio-methods to reduce water contamination and soil pollution were studied. Fungal strains such *Aspergillus niger* and *Aspergillus fumigatus*, commonly found in soils surrounding mining areas, were used and were found to be contributing to environmental detoxification by absorbing metals as a nutrient source. It is suggested that country-wide mining zonal effects on the contamination of water resources be investigated. This should constitute the basis of a much longer term project.

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