USE OF REMOTE SENSING AND GIS IN A RISK ASSESSMENT OF GOLD AND URANIUM MINE RESIDUE DEPOSITS AND IDENTIFICATION OF VULNERABLE LAND USE

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DECLARATION

I hereby declare that this research report is my own, unaided work, assisted by others only where duly acknowledged. It is being submitted for the Degree of Master of Science in Environmental Science from the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of candidate)

Signed on the ___**5th**___ day of _____**November**_______ 2012

M.W. Sutton carried out the literature review, designed the experiment, gathered the spatial data from various sources, compiled the GIS database, plotted features from aerial photographs, carried out the spatial analysis, performed the statistical tests, interpreted the results and wrote the research report. M.W. Sutton also wrote the three published papers together with his co-supervisor, I.M. Weiersbye. I.M. Weiersbye provided the study concept together with J.S. Galpin (co-supervisor). D. Heller, Bar-Kal Systems Engineering Ltd. was the service provider who supplied the thematic ASTER images for selected minerals and a vegetation index, and W. Luck, Department of Geography, University of Stellenbosch, orthorectified, georeferenced and mosaicked the 1938 aerial photographs. R. Stark, N. Margalit, I.M. Weiersbye and M.W. Sutton performed the spectral ground-truthing.

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ABSTRACT

Acid rock drainage (ARD) and dust are potential consequences of gold and uranium mine residue deposits (MRDs) on the Witwatersrand basin. Urbanisation has taken place around mines and, with the curtailing of mining activities and clearing of land previously covered by MRDs, there is pressure to use this land for residential, industrial and agricultural purposes. However, mining companies historically were not required to provide pollution control measures and there is evidence for contamination of land and water. Thus, there is a need to prioritise contamination sources for mitigation and to understand the extent of contamination and potential risks associated with different categories of land-use on mining land.

The aim of my study was to conduct a first-order risk assessment to aid in identifying vulnerable land use in the vicinity of gold and uranium mining, and prioritising MRDs, including footprints, for mitigation. To achieve this I constructed a Geographical Information System (GIS) using publicly available spatial data, and then tested the usefulness of historical aerial photographs and remote sensing imagery for mapping MRDs and impacts of MRD origin under Highveld conditions (i.e. a seasonal climate with summer rainfall and annual evapotranspiration of >2.5 times mean annual precipitation). The Ekurhuleni Metropolitan Municipality (EMM; 1923 km^2) is an area of extensive historical mining with major urbanisation, while retaining areas for agricultural land use; thus it was selected as a representative study site.

I used a numerical rating scheme, which combined a number of parameters in two separate stages to calculate a risk index. The first stage involved the classification of hazards associated with MRDs while the second involved an assessment of land use vulnerability based on exposure pathways and proximity. Historical aerial photographs (1938, 1964 and 2003) and the Chamber of Mines (CoM) Dump Indexes were used to identify and classify MRDs in terms of basic geotechnical properties, current status and historical failure. Multi-spectral data, acquired over two years (2002 and 2003) in two seasons (spring and summer) by the TERRA satellite's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, were used to compile thematic images, indicating potential contamination of surrounding land. It was intended that a zone of influence could be distinguished for each MRD enabling me to rate the hazard severity. The thematic images I selected included primary minerals (pyrophyllite and chlorite), secondary minerals (copiapite and jarosite), an indicator of uranium-bearing ore (referred to as mincrust) and the normalised difference vegetation index (NDVI). These minerals were chosen as potential indicators of different transport routes of contaminants and I tested their associations with different features and land use. I also tested for seasonal differences in the detection of these minerals, and used NDVI to examine the masking effect of active vegetation.

I found GIS to be well suited for combining the various forms of spatial data and providing information about MRDs, aqueous pathways, proximity to vulnerable land uses and impacted areas. However, I found that the potential severity of the hazards posed by each MRD, as indicated by a zone of influence, could not be determined from aerial photographs and ASTER alone. I therefore utilised the findings expressed in the literature survey to assign ratings for the different classes of MRDs. The vulnerability assessment was also supplemented by literature review to rate land uses based on human exposure pathways.

I determined that MRDs (including footprints) cover 4.1% of EMM, with slimes dams, totalling 3.5%, occupying the majority of this area. I found that 64% of slimes dams had failed prior to 2003 and I plotted a further 0.6% of EMM covered by visible mine residue spillage. Fifty three percent of MRDs were situated within 100 m of drainage lines or old wetlands, while 52% of these (i.e. 27% of the total) had been constructed in the watercourse. I also found that 15% were constructed on dolomites. Informal settlements were located on or bordering 6% of MRDs, with 41% of MRDs within 1 000 m. Eighty eight percent of MRDs were found within 1 000 m of formal residential areas, 71% within 500 m, and formal settlements were located on or bordering 5% of MRDs. Twenty three percent of MRDs were located within 500 m of agricultural land, while 35% were within 1 000 m; and industrial land use was on 9% of MRDs (footprints), with 40% of MRDs being within 500 m of industrial areas and 61% within 1 000 m

I found that chlorite did not provide a ‘signature’ of gold and uranium mine residue, whereas the other four minerals did. I also found that, of the two seasons examined (spring and summer), the best time to take an ASTER image to detect mineral signatures of gold and uranium mine contamination is after a few dry days following the first spring rains. For this reason, I used the ASTER taken in late October (spring) 2003 to examine associations with pathways and land use.

I found more pyrophyllite and copiapite on industrial and business land use than background, which I suggest is associated with the settling of windborne dust on large and flat roofs; although, in the case of copiapite this could be related to the oxidation of settled wind blown pyrite material. I found jarosite to be a reliable indicator of mine residue, which, together with mincrust, helped me identify contamination in former agricultural holdings, which are now a township. Although, chemically undefined, mincrust was a useful indicator of contamination, as I found it to be reliably detected on MRDs (including footprints), mine residue spillage, wetlands and other contaminated sites, and absent from known uncontaminated sites. Furthermore, it was not necessarily masked by active vegetation, whereas copiapite, jarosite and pyrophyllite were. Mincrust was also detected on irrigated agricultural land with an odds ratio of between 10 to 36 times greater than for rain-fed. Consequently, the most likely pathway for mincrust is the aqueous. The mincrust signature, together with historical aerial photographs, also assisted me to identify historical mining along Black Reef outcrops, through detection in a wetland upstream of known mining activities.

The culmination of my study was a risk class and index for MRDs from which 'risk maps' were produced. These maps provide a guide to the level of risk posed by each MRD to the surrounding land use. Of the total 287 MRDs (including footprints) identified in the EMM, 50% were classified lower-risk; 40% medium-risk; 10% higher-risk and 0% as much higher risk. The lower-risk MRDs were predominantly rock dumps, whereas the higher-risk MRDs were slimes dams. The findings from my study will contribute to meaningful recommendations for future land use and enable mining companies, landowners, developers and government to allocate their resources judiciously (i.e. appropriate to the level of risk).

The results of this study have been published as:

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Sutton, M.W. and Weiersbye, I.M., 2007. South African legislation pertinent to gold mine closure and residual risk. In: A.B. Fourie, M. Tibbett and J. Wiertz (eds.), Mine Closure 2007: *Proceedings of the 2nd International Seminar on Mine Closure*, Santiago, ISBN: 978-0-9804185-0-7, pp. 89–102 (Appendix II).

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Abbreviations

ARD	Acid Rock Drainage also known as Acid Mine Drainage (AMD)
As	Arsenic
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CL	Confidence limits
Co	Cobalt
CoM	Chamber of Mines (of South Africa)
CSIR	Council for Scientific and Industrial Research
d	Day
df	Degrees of freedom
DEAT	Department of Environmental Affairs and Tourism
DEM	Digital elevation model
DME	Department of Minerals and Energy
DWAF	Department of Water Affairs and Forestry
EEA	European Environment Agency
Eh	Redox
EM	Electro-magnetic
EMM	Ekurhuleni Metropolitan Municipality
EMPR	Environmental Management Programme Report
EOS	Earth Observing System
ERA	Environmental Risk Assessment
ESRI	Environmental Systems Research Institute
EU	European Union
Fe	Iron
GDACE	Gauteng Department of Agriculture, Conservation and Environment
GIS	Geographic Information System
HSRS	Hyper-Spectral Remote Sensing
IAEA	International Atomic Energy Agency
ISCW	Institute for Soil, Climate and Water
IWQS	Institute of Water Quality Studies
km	Kilometres
l	Litre
m	Metre
mm	Millimetre
MCL	Maximum Contaminant Level
MPRDA	Mineral and Petroleum Resources Development Act
MRD	Mine Residue Deposit

NASA	National Aeronautical and Space Agency
NDA	National Department of Agriculture
NDVI	Normalized Difference Vegetation Index
NEA	Nuclear Energy Act
NEMA	National Environmental Management Act
Ni	Nickel
NIOSH	National Institute for Occupational Safety and Health
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act
NORM	Naturally Occurring Radioactive Material
NWA	National Water Act
Pb	Lead
RDP	Reconstruction and Development Programme
RS	Remote Sensing
S	Sulphur
SA	South Africa
SAS	Statistical Analysis System (SAS Institute, Cary, NC, USA).
SSA	Statistics South Africa
SWIR	Short-Wave Infra Red
t	Tonnes
TIR	Thermal Infra Red
TSF	Tailings storage facility
U	Uranium
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
VNIR	Visible and Near Infra Red
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
WRC	Water Research Commission

CHAPTER 1

1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Although its importance is declining, gold mining has been an important contributor to the South African economy for more than a century with over 50 000 t of gold having been produced from the Witwatersrand gold fields (G:ENESIS, 2007). However, as a result of all this mining it has been estimated that some 6 billion t of mine residue (Wymer, 2001) have been disposed of in hundreds of residue stockpiles and deposits, i.e. sites where mine waste has been stockpiled, stored, accumulated or disposed of and which are more commonly known as waste rock dumps, sand dumps and slimes dams (or tailings storage facilities, and which are collectively referred to in this study as mine residue deposits - MRDs). These sites cover a combined area of between 400 and 500 km^2 (Marsden, 1986). Gold deposits on the Witwatersrand basin co-occur with pyrite (Fe_2S) and uranium, as well as a number of other metals, metalloids and Naturally-Occurring Radioactive Materials (NORMs). In the mid-1970s gold recovery processes improved to allow gold, and in some cases pyrite and uranium to be recovered at a profit from MRDs and a number of dump reprocessing operations were initiated. Nevertheless, as a consequence of only intermittent recovery of pyrite and uranium it is estimated that MRDs still contain some 30 million t of sulphur (Witkowski and Weiersbye, 1998a) and between 430 000 and 500 000 t of low-grade uranium (Wilson and Anhaeusser, 1998; Wymer, 2001; Winde *et al*., 2004a).

There is increasing evidence that past and current disposal practices and sites for gold and uranium mine residue on the Witwatersrand basin pose a risk of harm to people and the environment (Wade *et al*., 2002; Coetzee *et al.*, 2004; Sutton *et al*., 2006; Sutton and Weiersbye, 2007). Pyrite can convert to sulphuric acid in the presence of air and water (Maree *et al.*, 1996); and uranium has a half-life of 4.5 billion years and is chemically toxic to the kidneys at elevated concentrations (Canadian Nuclear Safety Commission, 2009). It is well established that metals and NORMs such as uranium are being transported beyond mine boundaries and into watercourses and groundwater (Coetzee, 1995a; b; Coetzee *et al.*, 2006; Winde, 2001; 2004a; Tutu, 2005). Although these concentrations are generally lower than those found on base-metal mines or high-grade uranium mill sites (Jones *et al*., 1990) they exceed prescribed standards in some soils and wetland sediments (Rösner *et al*., 2001; Naicker *et al*., 2003; Joubert, 2007). There are a number of natural processes that can accumulate or sequestrate contaminants of concern in various ways (Coetzee *et al*., 2002; Winde, 2001; 2004a; Naicker *et al.*, 2003; Tutu, 2005; Tutu *et al*., 2008; Weiersbye *et al*., 1999; Weiersbye and Witkowski, 2003; Cukrowska *et al*., 2006; McCarthy and Venter, 2006) and these can either increase or decrease the risk of harm to people and the environment. Until recently, the focus of studies by the mining industry (Wymer, 2001) and regulators (Institute of Water Quality Studies (IWQS), 1999; 2000) has been on radiological risk. These studies have used methods (e.g. analyse only filtered water, exclude contaminants in sediments) and assumptions (e.g. slimes dam return water is not released) that fail to recognise and quantify the human health and environmental risks based on actual and potential pathways, the physical, chemical and biological accumulation of contaminants and their chemical, rather than radiological, toxicity.

The use of rivers, streams, and in some cases boreholes, as sources of water for drinking and cooking renders people vulnerable to illness and disease from poor quality water caused by, inter alia, industry, mining, agriculture and intermittently poor sewage treatment by municipalities (SRK, 2004). Furthermore, the use of rivers and streams by these same people for bathing and washing provides further opportunity for human exposure through accidental ingestion and skin absorption. An improved understanding of contamination pathways and receptors lead to the latest study on behalf of the National Nuclear Regulator (NNR), which still only considered the radiological risk but did include sediment/soil sampling, finding potential doses to members of the public above the regulatory limit (Joubert, 2007).

With the curtailing of mining activities and the opening up of mining land previously covered by MRDs through reprocessing, there is an ever-increasing demand from developers and the SA Government to put this land to use, especially for residential purposes (Coetzee, 1995a; Ekurhuleni Metropolitan Municipality (EMM), 2005). However, to protect public health, consideration needs to be given to restricted and soft land-uses after mining and waste disposal; where “soft land-uses” refers to uses that are low-risk and improve the environment, often by providing a cover of vegetation (Sutton and Weiersbye, 2007). Examples of soft post-mining land-use include public open space, forestry, non-edible crops, and carbon conservation or sequestration measures.

1.2 Overall study aim

The aim of my study was to conduct a first-order risk assessment to aid in identifying vulnerable land use in the vicinity of gold and uranium mining, and prioritising MRDs, including footprints, for mitigation. This required achievement of the following five objectives by answering the related key questions: firstly, to identify the environmental risks associated with gold and uranium MRDs; secondly, to assess the effectiveness of the policy and legislative framework for addressing land use vulnerabilities and the environmental risks posed by MRDs; thirdly, to identify land uses on gold and uranium MRD footprints and land surrounding MRDs and footprints that are more and less vulnerable to these risks; fourthly, to prioritise MRDs for mitigation and/or remedial measures; and finally, to assess the effectiveness of remote sensing (i.e. historical aerial photographs and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images) for identifying vulnerable land uses and prioritising MRDs for mitigation and/or remedial measures.

1.2.1 Objectives and associated key questions

(a) Identify the environmental risks associated with gold and uranium MRDs

i What are the environmental hazards, exposure pathways and land use vulnerabilities associated with gold and uranium MRDs?

ii Do the identified environmental risks vary for different classes (i.e. type and status) of MRDs?

(b) Assess the effectiveness of the policy and legislative framework for addressing land use vulnerabilities and the environmental risks posed by MRDs:

i What is the environmental policy and legislative framework related to mining?

ii Does the environmental policy and legislative framework adequately address land-use vulnerabilities and the environmental risks posed by MRDs, what are the gaps and how can these be rectified?

(c) Identify land uses on gold and uranium MRD footprints and land surrounding MRDs and footprints that are most and least vulnerable to these risks:

i What land uses are most and least vulnerable to impacts from gold and uranium MRDs?

(d) Prioritise MRDs for mitigation and/or remedial measures:

i Which MRDs are located in proximity (i.e. within the zone of influence) to vulnerable land uses?

ii Which MRDs are priorities for mitigation and/or remedial measures?

(e) Assess the effectiveness of remote sensing for identifying vulnerable land uses and prioritising MRDs for mitigation and/or remedial measures:

i Are historical aerial photographs useful for identifying, classifying, and quantifying the spatial extent of, MRD sites and mine residue spillage across different landscapes (despite possible subsequent changes in land use)?

ii Are thematic images for selected minerals derived from multi-spectral satellite-borne remote sensing (i.e. ASTER) useful for detecting indicators of mine residue and associated contamination?

These objectives are of value in demonstrating compliance, focussing mitigation and cleanup measures, and can assist in regional closure planning.

1.3 Gold and Uranium Mining on the Witwatersrand Basin

The discovery of gold in the Witwatersrand basin is generally attributed to an Australian prospector named George Harrison, who, in 1886, found economically exploitable gold in the Main Reef Leader conglomerates on the farm Langlaagte, which now falls within the present day City of Johannesburg, South Africa. Further prospecting led to the delineation of nine distinct ‘gold fields’ within the Witwatersrand basin, the world’s largest gold deposit (Robb and Robb, 1998). These nine gold fields are: Free State (Welkom gold field), Klerksdorp gold field, West Wits Line (Carletonville gold field), West Rand gold field, Central Rand gold field, East Rand gold field, South Rand gold field, Evander gold field and the Venterskroon (Vredefort gold field).

Although one gold mining company had been producing pyrite as a by-product for a number of years for the explosives and chemical industry (Stewart, 1957), the large scale flotation of pyrite from gold plant tailings only commenced in the 1950s with the need for sulphuric acid in uranium extraction. Thus, pyrite and uranium were disposed of as an integral part of the residue on all other MRDs prior to this time. The first full-scale uranium plant in South Africa was commissioned in September 1952. Five years later, 29 gold mining companies were providing slurry to a total of 17 uranium plants (Stewart, 1957). Uranium and pyrite were not only recovered from current tailings once the gold had been recovered; some of the mining companies reclaimed old gold plant MRDs by high pressure hydraulic monitoring for uranium extraction. However, by 1991, only four mines were producing uranium due to a collapse in the market (Handley, 2004), which reduced to one prior to the recent resurgence in the uranium price.

1.4 Environmental Risk Assessment

Priority decisions are often made in response to alarming events and perceived risks rather than actual risks. Decisions under these circumstances often result in wasted resources and unnecessary fears (Carpenter, 1995). With ever-increasing demands on the deployment of limited resources some form of decision-making tool is necessary. Risk assessments are attempts to quantitatively define the level of risk and can assist with determining priorities for action, selecting the least risky alternative or determining if the benefits outweigh the risks.

Environmental risk assessment (ERA) is the examination of risks that threaten the environment.

A risk-based approach tries to identify and assess the actual risks imposed by an environmental issue whereas a hazard-based approach examines potential hazards that may or may not result in harm (Fairman *et al*., 1998). For example, when considering contaminated land; a hazard-based approach would be to identify the contaminants in the soil and prescribe remediation measures that reduced the concentration to agreed standards. A risk-based approach would also begin with an identification of the contaminants but the level of clean-up required would depend on the probability of people being exposed to the contaminants and the likely effects of that concentration of exposure. The level of clean-up would therefore depend to a great extent on how the land is to be used and the risk posed by this land use. A risk-based approach has great value when faced with setting priorities for action or allocating scarce resources; however, a possible shortfall is the tendency to make inadequate provision for change (Fairman *et al*., 1998). Changes can include such things as changes in land use, in environmental conditions or human behaviour patterns. Thus polluted land may be low risk when used for mining or industrial purposes but if the same land is subsequently used for residential or agricultural purposes it can become high risk.

Determining the likelihood of adverse effects may range from qualitative judgments to quantitative probabilities. However, the gathering of empirical evidence can be very expensive and take many years. It also “makes no sense to prioritise all of one’s limited resources to the understanding of environmental systems at the expense of being able to design, implement and monitor solutions” (Gerrard, 1995, p. 314). Although it is preferable to include quantitative risk estimates, quantification of risks is not always possible; in such an event it is better to describe conclusions (and associated uncertainties) qualitatively than to ignore them because they are not easily understood or estimated (United States Environmental Protection Agency (US EPA), 1998).

When there is scientific uncertainty, two approaches are possible (Fairman *et al*., 1998). One approach would be to assume that substances or agents are harmless until scientifically proven to have harmful effects. The other approach would be to assume that they are harmful until proven otherwise. Gerrard (1994) calls for a conservative approach and the use of methods for estimating environmental effects that are biased towards caution. This “precautionary principle” is now fundamental to South Africa’s legal approach to environmental issues. Section 2(4)(a)(vii) of the National Environmental Management Act (NEMA) (Department of Environmental Affairs and Tourism (DEAT), 1998) requires “that a risk-averse and cautious approach is applied, which takes into account the limits of current knowledge about the consequences of decisions and actions”.

Whereas the traditional view of risk assessment was of a wholly scientific process, there is a growing acceptance that judgement and value form an integral part of the process; the characterisation of risk must therefore allow for divergent views of different interested and affected parties (Fairman *et al*., 1998). In some cases there may also be a need for fast examination techniques that allow some form of objective assessment of risk and vulnerability over large areas, which can inform local decision making, even though there may be only limited secondary data (Al-Adamat *et al.,* 2003).

A number of studies have been conducted using DRASTIC, which is a numerical rating scheme developed by the US EPA for evaluating the potential for groundwater contamination at a specific site given its hydrogeological setting (Knox *et al.*, 1993). In some of these studies, parameters were added or removed depending on the availability of data (Al-Adamat *et al.,* 2003). Determination of the DRASTIC index involved two separate stages, “Stage one involved an assessment of groundwater vulnerability, which is dependent on the physical conditions found in a specific environment and is essentially independent of the use to which the land is put. Stage two involved the addition of risk factors focusing on land use in the study area” (Al-Adamat *et al.,* 2003, p. 306).

1.5 Components of Environmental Risk for Mine Residue Deposits

In order for there to be risk of environmental harm there needs to be a potential source of harm (i.e. stressor or hazard), a means of causing harm (i.e. release mechanism and pathway), and some component of the environment that may be harmed (receptor).

1.5.1 Stressor sources and characteristics

(a) Background

A residue stockpile is defined in the Mineral and Petroleum Resources Development Act (MPRDA) as any debris, discard, tailings, slimes, screening, slurry, waste rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of, by the holder of a mining authorisation (Department of Minerals and Energy (DME), 2002). This definition recognises that the facility is potentially temporary, whereas a residue deposit is defined as a residue stockpile remaining at the termination, cancellation or expiry of a mining authorisation, which suggests more permanency. Even so, there is uncertainty regarding the duration of the facility in both cases based on such factors as mineral prices, recovery technology and usefulness of the material(s).

There are several ways in which mine residue can be classified, two of which are covered in this study. The first is a broad mineral classification, i.e. in terms of whether it is waste rock (also known as overburden in surface mining or gangue), which is dumped directly from the mine workings (and to which debris may be added), or comes from the ore, which is first processed to extract the valuable mineral (i.e. beneficiation plant waste) before the residue is disposed of and is commonly known as tailings, slimes or slurry. Another means of classifying MRDs is a geo-technical classification based on significant differences in texture or mean particle size (i.e. rock dumps, sand dumps and slimes dams).

(b) Ore

Gold in the Witwatersrand Basin occurs in conglomerates, which are sedimentary rocks consisting of muffin-shaped pebbles of quartz (approximately 80 percent by weight) in a fine-grained matrix of naturally cementing material (Anhaeusser *et al.*, 1987). In general the matrix consists of: micaceous minerals such as sericite, pyrophyllite, muscovite, chlorite and chloritoid (10-30 percent); pyrite (3-4 percent); other sulphides (e.g. pyrrhotite, chalcopyrite, pentlandite, galena, cobaltite, sphalerite, gersdorffite, linnacite and arsenopyrite) (1-2 percent); grains of primary minerals such as chromite, rutile, garnet, zircon, xenotime, ilmenite and tourmaline, alteration products such as goethite and leucoxene, and secondary minerals such as anatase and skutterudite (1-2 percent). Gold and uranium, the latter predominantly as uraninite (UO_2), are principally found in the matrix (Liebenberg, 1957).

Uranium concentrations in the Witwatersrand Basin range from 50 g/t in the east to 640 g/t in the west (Funke, 1990). The underlying and overlying country-rock, which is sometimes included in the ore, consists mainly of quartzite and some shale (Liebenberg, 1957).

(c) Residue from ore processing

The two main residues from processing gold ore are sand and slime:

i Sand

Sand (approximately 200 micron mean diameter) is the residue from the gold extraction process used at the advent of gold mining on the Witwatersrand, when stamp mills were used to break up the ore in order to liberate the gold (Stanley, 1987b). Similarly to waste rock, sand was deposited mechanically using coco-pans (Thomas, 1968). The introduction of cylindrical or tube mills from Australia in 1904 enabled the ore to be reduced to a much finer size, thereby further liberating the gold and this technology gradually phased out the stamp mills (Funke, 1990).

ii Slime

Slime is the fine slurry (approximately 70 micron mean diameter) from cylindrical milling. The disposal of this fine material presaged the start of hydraulic deposition and the construction of MRDs (i.e. slimes dams) via paddock systems (Funke, 1990). At the time of deposition slimes is alkaline (i.e. pH above 8) but becomes acidic (with a pH between 2 -4) within a few months as the pyrite oxidises (Bradshaw and Chadwick, 1980). Slimes dams are of particular concern because of their large size, hydraulic properties and the contaminants that they hold (Coetzee *et al.*, 2006).

(d) Waste rock

Waste rock is generally considered to be inert (DME, 2005); although a better definition is material that at the time of extraction was considered to have insufficient mineralization to be economically extracted (Hinde *et al.* 1986). As previously mentioned the underlying and overlying country-rock consists mainly of quartzite and some shale. In order to access and exploit the ore body, tunnels are made through this country-rock by drilling and blasting, known as off-reef development, and the waste rock from this source is transported to surface and mechanically tipped onto a waste rock dump.

The waste rock is dumped mechanically in proximity to the rock hoisting shaft to minimise transport costs. A common practice, purportedly to assist with dump stabilisation by causing the rock to slump more readily, was to discharge "low grade" water onto the dump at the tipping point (Funke, 1990). This water could be mine process water, i.e. water used underground for dust suppression, drilling, and cleaning of the working places. Although underground process water is neutralised with lime at the settlers before being pumped to surface it contains high concentrations of sulphates. This low grade water percolates through the waste rock and, particularly in cases where there is no washing plant, through pyrites and other sulphates associated with the gold-bearing fines.

(e) Mine residue deposit footprints

Where MRDs are removed, the secondary sources of contaminants that remain in the underlying soil are either ignored by mining companies, because it is assumed that removal of the MRD removes all potential for pollution (Pulles *et al*., 2005), or lime is added to lower the pH and immobilise metals (Tutu *et al*., 2008). Rösner and van Schalkwyk (2000) showed that the soil exposed after reclamation of MRDs did have elevated concentrations of heavy metals, notably Co, Ni and Zn. Although most of these metals were not mobile forms, it was predicted that they would eventually be leached into the ground water. Furthermore, Tutu *et al*. (2003; 2005), showed that there was significant remobilisation of uranium in the footprints left behind after MRDs had been reclaimed.

1.5.2 Contaminants of particular concern

As mentioned earlier, gold deposits on the Witwatersrand Basin co-occur with pyrite and uraninite, although the grades (i.e. concentrations) vary considerably. In cases where only the gold is extracted, the pyrite and uraninite are disposed of in the residue. Although this applies to only some of the slimes dams it is likely to apply to most sand dumps because uranium recovery only commenced in 1952 (Stewart, 1957) and the last sand dumps were probably deposited in the early 1960s (Funke, 1990).

Other heavy elements that are used in the gold, pyrite and uranium recovery processes, thus they are often present in MRDs, are manganese, zinc and vanadium (Mphephu, 2001). Slimes dams have occasionally been used as mine, municipal or industrial waste disposal sites and may also contain, *inter alia*, chemical and organic waste including sewage and abattoir waste (Muir *et al.*, 2005).

(a) Sulphur

Acid rock drainage (ARD) is a commonly occurring impact of many mines, where sulphide minerals (e.g. pyrite) are oxidized through exposure to oxygen (air) and water (Maree *et al.*, 1996). In the presence of bacteria such as *Thiobacillus ferrooxidans,* which use sulphur as an energy source as opposed to carbon (Singh and Doulati Ardejani, 2003), the sulphide minerals on the surface of tailings dams (and spilled mine residue material) become oxidised, forming iron crusts and efflorescence yielding sulphates and metal cations. Secondary minerals formed in this manner on the Witwatersrand basin gold fields include jarosite, copiapite, gypsum and melanterite (Naicker *et al.*, 2003).

The mobility of elements is strongly affected by changes in soil and water pH and redox (Eh) (Evangelou, 1998). In low pH environments some metals are soluble and therefore mobile, whereas at high pH this mobility is decreased and they tend to precipitate as hydroxides (Plate 1). Only a few elements, for example, the alkali metals (e.g. Na and K), alkaline earths (Ca and Mg), some elements that form acid radicals (such as nitrogen and chlorine) and some heavy metals such as uranium, are normally soluble throughout the entire pH range (Tutu, 2005). Heavy metals do not degrade and may be concentrated or dispersed in the environment through geo-morphological, geochemical and biological processes (United States Geological Survey (USGS), 2003).

Plate 1 Iron hydroxides 'yellow boy', which have precipitated from gold and uranium mine residue seepage and/or metallurgical plant effluent, coating a stream bed

(b) Uranium

Uranium accumulated together with gold under a non-oxidising atmosphere and has remained relatively intact in the ore body; however, under oxidising conditions, such as our current atmosphere, uranium is highly soluble and readily mobilised (Coetzee, 1995a). Many contaminant pathways are therefore indicated by elevated radioactivity from uranium series radionuclides (Coetzee, 2008). A Tier-1 risk assessment by Wade *et al.* (2002), of a stream flowing through gold mining properties on the West and Far West Rand, identified chromium (Cr), cobalt (Co), nickel (Ni), copper (Cu), arsenic (As), cadmium (Cd) and uranium (U) as contaminants of potential concern, with U and Cd potentially having the highest environmental impact. From a Tier-2 risk assessment, Coetzee *et al.* (2006) found that several tens of tons of uranium per annum were entering the stream via controlled and uncontrolled point discharges, and large-scale diffuse discharges. Although it was found that much of the metal contamination was bound to the sediment in the river system it was also indicated that this immobilisation is not irreversible. Overall the study indicated that uranium poses a hazard to water users in the catchment because of its chemical toxicity rather than its radioactivity.

All isotopes and compounds of uranium can be chemotoxic and radiotoxic (Zajic, 1999). Although no information could be found on the concentrations of uranium in windborne dust from gold and uranium mine residue, the chemical toxicity of ingested uranium from such a source is significantly higher than the radiotoxicity (Coetzee, 2008). Soluble uranyl complexes are readily available and therefore toxic (Miller *et al*., 1998) and the secondary mineral phases of uranium are potential toxicants in that when conditions favour their dissolution they become remobilized and rendered toxic (Tutu, 2005). This toxicity can be lethal. In less than lethal doses toxicity is limited primarily to recoverable kidney damage. Uranium dissolves in the body fluids and reacts with the biological molecules. Uranium retained by the body deposits in bones, lungs, liver, kidney, fat and muscle. The toxic effects include: nephritis (i.e. inflammation) and cellular necrosis (death of cells) in the kidney and atrophy in the tubular walls of the kidney resulting in a decreased ability to filter impurities from the blood (Miller *et al*., 1998). In South Africa the DWAF do not provide a water quality guideline for uranium although a concentration of 70 µg l^{-1} is considered the drinking water limit (IWQS, 1999).

1.5.3 Contaminant release mechanisms from mine residue deposits

Many MRDs were constructed with little or no pollution control measures and were often placed in environmentally unsuitable locations, e.g. in wetlands, drainage lines (Plate 2) or on top of dolomitic aquifers (Sutton, 1994; Sutton *et al.,* 2006).

Plate 2 Mine residue deposit (slimes dam) built across a watercourse

MRDs may remain active as ARD sources for many decades (Kontopoulos *et al*., 1996; Blowes *et al*., 1998; Tutu, 2005). Even when mine residue has a high buffering capacity because of liming, the system still has the potential to generate more acid from self-sustaining and acid-producing reactions (Tutu, 2005; Tutu *et al.,* 2008). This means that buffering provides only temporary immobilisation and metal pollutants will eventually be released. The main mechanisms, by which contaminants can be released, include the following:

(a) Seepage

Groundwater within the vicinity of MRDs (including return water dams) and unlined evaporation dams is heavily contaminated and acidified as a result of oxidation of pyrite and has elevated concentrations of heavy metals (Funke, 1990; Naicker *et al.*, 2003; Mphephu *et al*., 2004; Coetzee *et al.*, 2006; Sibilski and Okonkwo, 2007; Tutu *et al.*, 2008). Placing MRDs on top of dolomites allowed easy drainage, thereby improving stability of the dump, but promoted contamination of the dolomitic aquifer (Sutton, 1994; Hodgson *et al*., 2001). Indeed, the absence of impermeable subsurface clay strata was one of a large mining house's requirements for an ideal MRD site (Ruhmer, 1974). Hodgson *et al.* (2001) found that increased salinity and lowered pH of ARD will increase the water's ability to dissolve dolomite. The two major implications of this are: a) Significant widening of preferred pathways causing greater overall transmissivity in the dolomites and greater storage volumes; and b) Possible stability problems, should excessive karstification result (Plate 3). Coetzee *et al.* (2003), question the ability of the dolomite to continue neutralising ARD because the precipitation of ferric hydroxide armours the surfaces where the neutralization could take place.

Plate 3 A sinkhole on a gold mine, which resulted in the deaths of 29 workers when a 3-storey crusher plant collapsed / fell down the hole (Swart *et al*., 2003)

(b) Erosion by wind and water

Besides direct contamination of aquifers through seepage, wind and rain erode the MRDs over the years and transport the contaminants, including dissolved metals and NORMs, across wide areas (Stromberg *et al*., 1998, Panichayapichet *et al*., 2007) as dust and slimes run-off, before depositing it on surrounding soils and vegetation, or as sediment in watercourses. Tutu *et al*. (2008) found that streams near MRDs on the Central Rand had low pH (typically <4), high conductivity and elevated concentrations of some metals (Al, Co, Cu, Mn, Ni, U and Zn). Conversely, they found that dams and lakes in the area had neutral pH and low conductivity, which they ascribed to a combination of dilution by rainfall and the functioning of wetlands around the mouths of the inlet streams.

Near horizontal surfaces suffer relatively little erosion but slopes of between 30-35°, which is a common slope for slimes dams in South Africa, suffer maximum erosion (Blight, 2007). Grassing, particularly of slimes dams, has also failed to prevent erosion in anything more than the short-term (Weiersbye and Witkowski, 1998; Witkowski and Weiersbye, 1998b). Thus, even though the depth of oxidation in a MRD, hence the generation of ARD, is limited to the depth of oxygenated water penetration, this does not remain static. Earlier studies found the depth of oxidation to be between 2 and 3 m in slimes and between 5 and 10 m in the coarser grained sand deposits (Kempe, 1983; Marsden, 1986), and from these Wells *et al*. (1996, p 356), incorrectly concluded that "after this outer layer has oxidized, acid production stops". Tutu (2005) quite correctly states that any disturbance of the dumps that allows penetration of oxygenated water, for example reworking of the dump or erosion, creates a potential pollution problem. According to Blight (1989), erosion from slimes dams can be up to 500 t/ha/annum, predominantly from the side walls (Blight, 2007), which equates to between 27 - 45 mm per annum or 2,7 – 4,5 m over a hundred years. Consequently, unless erosion is effectively addressed the oxygen-front will continually move towards the centre of the dump, thereby generating ARD, even if the depth of penetration remains constant.

(c) Mine residue deposit side wall failure

Historically, many "breakaways" from sand dumps and slimes dams occurred, especially during heavy rainfall events, resulting in the silting up of watercourses with sand and slime for many kilometres (Thomas, 1968 – Plate 4). Side wall failures are often recognisable long after the spillages have been removed or masked (e.g. grown over or developed on) and provide indirect evidence of the earlier release of mine residue and associated water.

Plate 4 Spillage of gold and uranium mine residue into a watercourse

1.5.4 Alternative release mechanisms for gold and uranium mining contamination

(a) Mine dewatering

Many of the underground workings of the gold mines across the Witwatersrand are linked. This means that fissure and other ingress water rises equally across interconnected mines (van Tonder *et al*., 2008). Chemical pollution of this water, especially by heavy metals, is of particular concern (International Atomic Energy Agency (IAEA), 2003). Decant of underground water can occur after pumping ceases and the mining void floods, as was demonstrated a few years ago with the first occurrence of decant on the West Rand (Coetzee *et al*., 2003). This discharge had “a devastating impact on the ecology of downstream areas and local groundwater quality” (van Tonder *et al*., 2008, p. 92). In addition to elevated concentrations of uranium, this decant had high levels of iron, magnesium, aluminium, manganese, lead, nickel, cadmium, arsenic and zinc, some of which are elevated to potentially toxic and eco-toxic levels (Coetzee *et al*., 2003).

(b) Spillage from metallurgical plants

Metallurgical plants are potentially major sources for pollution of soil, surface and ground water by metals and NORMs (IAEA, 2003). Papers written about gold recovery from soils in the vicinity of gold plants can be used as an indication of the extent of pollution from spillage:

- During clean-up operations at a mine between 1983 and 1986 some 348 kg Au was recovered from soil beneath and around the old crusher plant, 80 kg from soil around the 4 shaft headgear bin and 302 kg from soil in and around the old mill and filter plants (Futcher and Morris, 1987).

- At another mine where the clean-up was completed in May 1952, some 122 kg Au was recovered from soil from plant surroundings and slightly over 3 kg Au from soil from the scrap yard (Britten, 1954).
- At another mine the clean-up took place from 1969 to 1971 and 404 kg Au was recovered from surface soil (Futcher and Morris, 1987).
- At a further mine the clean-up took place from 1977 to 1979 and 951 kg Au was recovered from surface soil, concrete and fill (Futcher and Morris, 1987).

(c) Spillage of mine residue

Spillage from mine residue pipelines is another source of ARD and associated contamination (Sibilski and Okonkwo, 2007; Tutu *et al*., 2008). A spill that results from a MRD failure, such as at Merriespruit in 1994, receives media, public and regulatory attention probably because of the loss of life. Smaller incidents, with no apparent immediate threat, tend to go largely unnoticed. However, in their research, Mphephu *et al.,* (2003), also considered mine residue spillage and found that they affect surrounding soils, which become highly acidic and sterile for other uses.

Mine residue pipelines amount to several hundreds of kilometres in length, and in most instances in South Africa do not have any effective secondary containment. In the event of failure, large volumes of slimes can be released. Although the associated water will most probably have a high alkalinity level from the addition of lime in the gold recovery process, it will also contain high levels of TDS. Furthermore, the spilt tailings are normally left to dry before being heaped and then loaded. This process can take anything between 2 weeks and several years, allowing oxidation of the pyrite in the tailings and the generation of ARD during rainfall. Once the spillage has been allowed to settle and starts to oxidise, further leaching takes place into the soils (time taken not known). There is a distinct possibility that removal of the visible spillage after leaching will be mainly aesthetic, as most mobile contaminants will have already leached into the soils.

1.5.5 Impacts of mine residue deposits related to human health

(a) Impacts of acid rock drainage

Even though a large number of the world's rivers are contaminated by heavy metals released from present-day and historic mining operations, relatively little is known about the effects on communities that live beside and rely on these rivers for food and livelihood (Taylor and Hudson-Edwards, 2007). One complication is that the toxicity of many metals is a function of such conditions as redox, pH and water hardness (US EPA, 1986).

On a global scale, studies of soils near urban areas, metalliferous mines and major road systems have found anomalously high concentrations of Pb, Cd, Hg, As and other heavy metals (Alloway, 1990a). The mining and smelting of non-ferrous metals has caused soil pollution for centuries, with metals dispersed in dusts, effluents and seepage water (Alloway, 1990b).

In a study to identify the nature and extent of contamination from unsaturated and saturated zones underneath reclaimed MRDs on the Witwatersrand basin, Rösner *et al.* (2001) and Tutu *et al.* (2008), found that groundwater quality beneath, and in proximity to, the investigated gold mining MRDs in the Gauteng region indicated acidic seepage. In addition, high TDS (up to 8 000 mg l^{-1}) values occurred in some groundwater samples, mainly as a result of high salt loads (SO_4^{2-} and Cl^-). In some boreholes this groundwater was characterised by elevated trace elements (e.g. As, Cd, Co, Fe, Mn and Ni) and total CN concentrations, exceeding drinking water standards. Rösner *et al.* (2001) found that most of their groundwater samples had pH values that were fairly neutral due to the acid neutralisation capacity of the dolomitic rock aquifer. Tutu *et al*. (2008) only sampled near-surface groundwater, close to seepage sites, which they considered representative of water entering the surficial environment, and their samples had low pH.

A two-year survey of 12 000 hectares of soils surrounding 56 MRDs on the Witwatersrand basin found that contamination of soil was severe, could extend for hundreds of metres from the MRDs, and had resulted in significant increases in soil acidity, salinity and heavy metal availability to plants, and impairment of nutrient cycling. Overall, the authors estimated that 6 000 km^2 of soils are significantly impacted by gold mining in this region (Witkowski and Weiersbye, 1998b; Weiersbye *et al*., 2006b).

On the Witwatersrand basin region, evapotranspiration exceeds precipitation by >2 times, hence there is insufficient rainfall to flush out mineral salts, which consequently accumulate in the upper 200 mm of the soil profile through capillary rise and evaporation (Naicker *et al*., 2003) (Plate 5). On both MRDs and in soils overlying shallow contaminated seepage this results in mineral efflorescence containing gypsum and other salts (containing 2 000-5 000 mg kg^{-1} of several metals including Co, Ni and Zn) (Witkowski and Weiersbye, 1998a). During the rainy season this crust is partially dissolved and releases low pH solution into the soil profile (Naicker *et al*., 2003; Tutu *et al.*, 2008).

Plate 5 Mineral efflorescence resulting from the evaporation of gold and uranium mine water, which has decanted from an unsealed shaft

Solubility, adsorption and desorption (all affected by pH – Eh), exchangeability and salt level in the soil are factors that affect the concentration of ions in the soil solution (Barber, 1995). Whereas some heavy metals are biologically essential elements (e.g. Co, Cu, Mn, Se and Zn) others, such as Pb, Cd, Hg, As and U, are non-essential and toxic; although even essential elements are toxic at elevated concentrations (Alloway, 1990c). There is evidence for uptake of elements from mine polluted groundwater and impaired growth and regeneration in a range of plant species (Witkowski and Weiersbye, 1998b; Weiersbye and Witkowski, 2003; Cukrowska and Weiersbye, 2010). Food plants that tolerate relatively high concentrations of potentially harmful metals are more of a health risk because an elevated concentration in soil may be transmitted, through plant uptake, into the food chain (Plate 6). This can lead to detrimental health effects in animals, including humans, by affecting the central nervous system, causing reproductive failure or birth defects and acting as cofactors in many other diseases (Alloway, 1990c; Li *et al.*, 2004).

Plate 6 **Crops grown in the flood plain downstream of gold and uranium mine residue deposits. Some crops (e.g. sunflower) are accumulators of uranium, making this a high-risk land use**

Tutu *et al.* (2005) showed that the uranium mobilized from exposed MRD footprints is either in bio-available forms or where it is in secondary mineral phases it is potentially available. Winde *et al*. (2004a), found salt crusts containing very high concentrations (>1 000 mg kg^{-1}) uranium that were readily accessible to cattle (Plate 7).

Elevated tissue metal concentrations were detected in the organs of wildfowl from EMM (Van Eeden and Schoonbee, 1992), but this could not be directly attributed to mining emissions. Weiersbye *et al.* (1999), Weiersbye and Witkowski (2003) and Dye *et al*. (2008), have demonstrated the uptake of uranium and other potentially toxic metals from MRD-polluted substrata into plants, and McIntyre *et al*. (2008), have shown heavy metal accumulation in invertebrates: beetles and spiders, which are eaten by predators such as lizards. In the case of the latter study, the Sungazer lizard, *Cordylus giganteus*, was found to exhibit similarly impaired body condition on both over-grazed rangelands and gold and uranium mine contaminated sites. This was despite animals and prey items having elevated tissue metal burdens only on the latter sites. Causality has, however, been demonstrated under laboratory conditions in a dose-dependent fashion by Haywood *et al.* (2004) for frog larval mortality in response to ARD and metal bioavailability.

Plate 7 Cattle have access to decanting gold and uranium mine water from unsealed shafts and mineral efflorescence

(b) Impacts of mine residue dust

Both wind and water are major agents in eroding the slopes of MRDs (Blight, 1989; 2007). Wind-blown dust from MRDs can be of concern up till 3 km from the site boundary and communities neighbouring poorly controlled MRDs may be severely impacted by such dust (DEAT, 2006 – Plate 8).

Plate 8 Dust from the uncovered slopes and berms of a mine residue deposit (slimes dam)

It was previously believed that gold mine residue dust was predominantly a nuisance (Annegarn *et al.*, 1991) but there is a more recent awareness that this depends on the respirable and thoracic fractions, which had not been reported for gold mine sand and slimes (Ojelede *et al.*, 2008). Despite reports of gold mine residue dust having been associated with hospitalisation for respiratory or cardiovascular diseases and exacerbation of respiratory diseases, such as asthma (CoM, 2001; DEAT, 2006), this appears to be based more on anecdotal evidence than on epidemiologic studies. Nevertheless, Ojelede *et al.* (2008) found that the respirable and thoracic fractions in sand dump and slimes dam dust do warrant concern.

Extended inhalation of siliceous (crystalline quartz) dust particles smaller than 10 microns is highly likely to produce a diseased condition of the lung known as silicosis (Stanley, 1987a). Silicosis is a potentially fatal respiratory disease and sufferers are also at a high risk of contracting tuberculosis (National Institute for Occupational Safety and Health (NIOSH), 2002). According to the NIOSH (2002), several recent epidemiologic studies indicate that current occupational standards do not prevent the occurrence of chronic silicosis among workers. The effect of silica quartz nanoparticles in the lungs is also not properly understood (Hoet *et al*., 2004); therefore, it is plausible that persons (and animals) regularly exposed to low levels of dust from MRDs may also contract chronic silicosis.

Health effects from exposure to particulate matter depend not only on particle size but also elemental composition. Ojelede *et al.* (2008) found that the elemental composition of gold mine residue dust approximates the composition of bulk mine residue (sand and slime) and suggest that pyrite is present.

1.5.6 Vulnerability

Vulnerability can be defined as “The propensity of social or ecological systems to suffer harm from external stresses and perturbations” (Kasperson *et al.*, 1995). Central to the concept of vulnerability is how different individuals or groups both respond to and recover from such stresses (De Fur *et al.,* 2007). Thus, if the likelihood of exposure to environmental pollution is high but the likelihood of an adverse response is low or the likelihood of recovery is also high then vulnerability is low. When considering social systems, the consequences of environmental stresses vary for different people, places and times (Leary *et al*., 2007). As a group, children are particularly vulnerable to environmental pollution because they drink more water, eat more food and breathe more air than adults in relation to their body weight and they also have more time to develop chronic diseases as a consequence of early exposure (EEA, 2002). Their absorption rates are also greater, with infants absorbing up to 50% of Pb in food while adults absorb only 10% (Ryu *et al*., 1983).

Another group, the poor, are usually ill-equipped to cope with adverse environmental change, whereas people with diversified livelihoods (e.g. education, power, adaptability and security) are more secure and most likely to cope (United Nations Environment Programme (UNEP), 2002). Poor households cannot relocate freely, they have limited power to affect change, either politically or via the legal system, and they have limited resources (Alford and Friedland, 1975). Their vulnerability is aggravated by poor health and low immune systems caused by untreated or increased exposure to disease, malnourishment and under-nourishment, which increases the likelihood of adverse consequences and inhibits their ability to recover from environmental stresses. Poor households are often located on the least desirable, cheapest land, which is often ecologically fragile and prone to environmental hazards. They typically have poor sanitation, limited or no access to clean water (Plate 9) or pay a large proportion of their income for these basic services. Their vulnerability is further exacerbated by weak public health institutions and difficulty of access (Woolard, 2002).

Plate 9 **Water being collected from a contaminated stream downstream of gold and uranium mine residue deposits and a dewatering gold mine**

From the above studies, the sources of harm from MRDs and the pathways for exposure are summarised in Figure 1. Taken together, these studies indicate the need for precautions and safety in land use planning in the vicinity of MRDs and MRD-polluted lands.

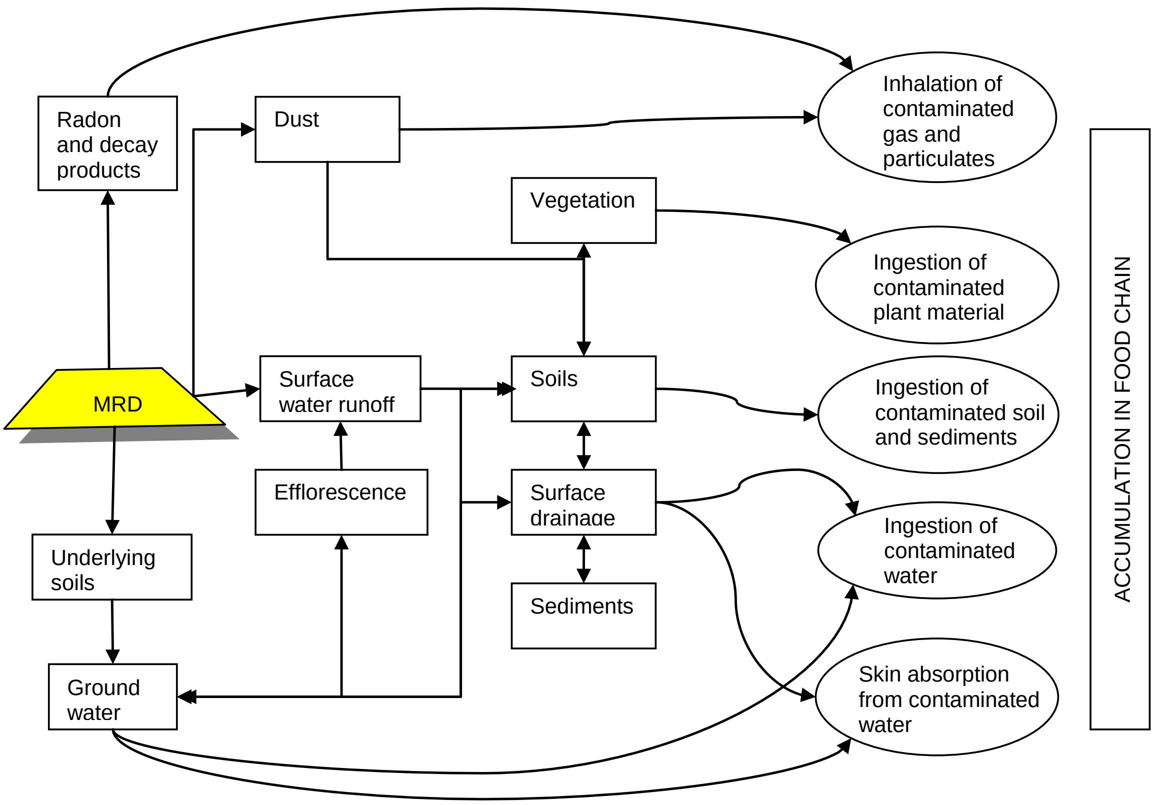

Figure 1 **Sources of harm from mine residue deposits and pathways for exposure (after Chevrel *et al.*, 2003)**

1.6 Use of Geographical Information Systems and Remote Sensing Data in Environmental Risk Assessment

1.6.1 Geographical information systems

(a) Introduction to geographical information systems

Geographical information systems (GIS) are computer-based resources (Bernhardsen, 1999) that enable several forms of data to be systematically analysed according to their shared location on the planet (McHarg, 1998). These 'geographic' data have a number of formats, including vector data models and raster models. Vector data models use points, lines and polygons to represent real-world features and are best used for discrete objects (Jha *et al.,* 2007). Raster models are useful for storing and analyzing data that is continuous over a wide area, such as remote sensing images (e.g. aerial photographs and satellite images) or scanned maps (Jha *et al.,* 2007).

Geographical information requires linking data on qualities and characteristics, otherwise known as attributes, to geographical locations (Bernhardsen, 1999). These attributes may be parameters such as type of feature (e.g. river, road, building or tree) or classifications such as soil type, lithology and land use. Tabular data (e.g. containing attributes linked to specific locations through geographic coordinates) can also be imported into a GIS.

(b) Uses for geographical information systems

A GIS is a tool for data inventory and query, spatial analysis and decision-making (Goodchild, 1998, Vairavamoorthy *et al*., 2006). It can process georeferenced data and be used: to record an inventory of the environment; to provide information on the particulars of a given location; to identify the relationships and systematic patterns of a region including the distribution of selected phenomena; to identify, record and assess changes since a previous analysis; to extrapolate data and make predictions based on current practices and management plans or to predict the impact of a specific event; and for processing data to be displayed in digital map layers (McHarg, 1998; Bernhardsen, 1999; Kurucu and Chiristina, 2007).

The ability of a GIS to integrate various forms of data and store relationships between features in addition to feature locations and attributes are important strengths (Bernhardsen, 1999). Combining these functions with modelling tools enables the conversion of large amounts of data into information and then into knowledge that is useful for risk assessment (Rejeski, 1993; Vairavamoorthy *et al.*, 2006).

1.6.2 Remote sensing

(a) Introduction to remote sensing

Remote sensing can be defined as, "the detection, identification, and analysis of objects or features through the use of imaging devices (sensors) located at positions remote from the subjects of investigation," (Avery, 1977, p. 1).

From modest beginnings in 1858, when photography from kites and balloons was first used to obtain pictures of the Earth, the more common forms of remote sensing have advanced through photographs in visible wavelengths from powered aircraft to using one or several of the visible, infrared, or microwave portions of the electro-magnetic (EM) spectrum from Earth orbiting satellites (Jha *et al*., 2007).

Remotely sensed data are digital in nature and can be efficiently interpreted and analyzed using various kinds of software packages (Jha *et al.,* 2007). The combination of GIS and remote sensing plays an important role in the linkage and analysis of data (Star *et al*., 1997; Kurucu and Chiristina, 2007). While remote sensing can provide extensive spatial coverage at regular intervals, which is essential for GIS to be effective, GIS data layers can contribute correlative data to improve the accuracy of the remote sensing data (Star *et al*., 1997). Through technological progress, remote sensing has changed from a relatively *qualitative art* relying on inference for information to a *quantitative science* capable of detailed measurements (Jha *et al*., 2007).

Remote sensing techniques can be divided into two main types - “passive” and “active” - depending upon the source of EM energy sensed (Lillesand and Kiefer, 2000). With the former, naturally reflected energy from the target is measured, while with the latter signals are artificially generated and the return signals are measured. Sensors that obtain pictures of visible (e.g. conventional aerial photography), near-infrared (NIR) and thermal infrared (TIR) energy are passive remote sensing techniques, while active remote sensing techniques include radar, laser and lidar (Jha *et al*., 2007). Sensors that detect emitted energy (e.g. gamma and thermal radiation) can be used during the day or night (Jha *et al*., 2007).

At the target, different light wavelengths are absorbed, reflected or transmitted. Reflectance is the relative amount of energy reflected from a surface, out of the total incident energy. The spectral reflectance and emittance characteristics of materials (i.e. vegetation, soils, rocks and water) in different wavelength regions are a consequence of the chemical composition and physical structure of these materials (Mouat *et al*., 1995); where a graph of reflectance vs. wavelength gives a spectral reflectance curve. Spectral libraries can contain thousands of such curves (Clark *et al.*, 2003). Identification of the material depends on the uniqueness of the spectral signature and our ability to distinguish it. Thus, by comparing the spectral features in each pixel of a remote sensing image with defined spectra, we can map the extent of identifiable materials (Mutanga, 2004).

(b) Pre-processing of remote sensing data

Remote sensing data requires pre-processing to remove atmospheric noise (Wilson *et al.*, 2004). Atmospheric corrections cater for aerosol scattering and haze in the atmosphere and absorption by trace gases, with the result in relative units of energy (i.e. reflectance).

A further requirement for integrated processing of remotely sensed and other GIS data is that they are rectified and spatially referenced (Ehlers, 1997). When an atmospheric correction model is applied to satellite images, the distance of the instrument from the surface can be considered to be constant throughout the entire image, since the field of view (FOV) of the satellite sensors is very small with respect to the satellite distance. On the contrary, when dealing with a sensor mounted on an aircraft, as is the case for aerial photographs, the optical path coming from the centre of the flight line is considerably different from that coming from its edges (Silvestre *et al.*, 2003).

An orthophotograph is a continuous-tone photo image depicting terrain features in their true plan positions; which requires that geometric distortions and relief displacements are removed (Avery, 1977). In order to rectify aerial photographs for comparison between ground and remote measurements they are geometrically corrected so that they appear as they would on a map, always looking straight down and not from off to a side. Further, digital elevation model (DEM) data are added to correct for varying heights within the image (Avery, 1977). The data is linked to locations on the Earth's surface through coordinate systems and ground control points (Bernhardsen, 1999). Once sufficient links have been established between features in the aerial photographs and ground control points (with known coordinates), a warping transformation is applied (rotation, scaling and translation) (Silvestre *et al.*, 2003). The process for defining how raster data is situated in map coordinates is known as georeferencing. The rectification of the perspective aerial photograph into an orthophotograph permits the "corrected" image to be used as a planimetric map (Avery, 1977).

(c) Uses for remote sensing data

The increasing availability of remotely sensed data at various spatial and spectral resolutions provides opportunities to monitor the biophysical characteristics of ecosystems at various landscape scales (Tieszen *et al*., 1997). They have become one of the main sources for providing information on land and water related subjects (Jha *et al.,* 2007). Remote sensing data save time and can be applied to a wide range of environmental problems, e.g. where data needs to be collected simultaneously over large areas; from inaccessible areas, highly protected areas and sites with potentially hazardous contamination; and, given the consistency and repeatability of data collection, from sites that need routine and frequent monitoring (Silvestre *et al.*, 2003; Wilson *et al.*, 2004; Wu *et al.*, 2005; Alexandridis *et al.*, 2007; Govender *et al.,* 2007).

Chevrel *et al.* (2003) conducted a study of active or abandoned mining environments over a portion of the East Rand to assess the potential of high spatial resolution spaceborne sensors (i.e. IKONOS) in a risk assessment and management perspective. They added imagery from two other spaceborne multi-spectral scanners (ASTER and Landsat TM), airborne radiometrics, a geological map, a geotechnical map, topographic maps (12 years apart), and some field sampling, all in a GIS environment. They concluded that the method was valuable for:

- Detailed identification and mapping of surface disturbances, such as: physical disturbances from exposed mine residue; major sources of erosion/sediment loadings; characterisation of the main erosion and deposition processes; and characterisation of the mine residue-laden surface water/drainage system;
- Detailed identification and mapping in a risk assessment perspective of pollution sources and pathways (for water), and the populations or ecosystems potentially at risk;
- Appraisal of the impacts of historical mining activities;

- Combined with appropriate environmental data it assists in identifying high risk areas for further detailed studies.

(d) Sources of remote sensing data

i Spaceborne Multi-Spectral Scanners

Unlike photographic interpretation, spectral analysis is based only on reflectance and emittance values (and derived indices). Such analysis may identify materials rather than functionality and field measurements are still required for validation, capture of local variants and mixtures of materials (Wende and Neuman, 2004). Multi-spectral scanners measure simultaneously the spectral response of the landscape in two or more narrow wavelength bands of the EM spectrum and record the information electronically (Jha *et al.,* 2007). Spaceborne examples include ASTER, briefly described below, as well as many others, which are beyond the scope of this study.

The Terra satellite was launched in December 1999, into a polar, Sun-synchronous, 705-kilometer orbit. The Terra satellite is one of a series of Earth Observing System (EOS) satellites designed to provide data as part of a mission-based NASA initiative called Earth Science Enterprise. Multiple sensors are flown aboard Terra, including the ASTER instrument. Using three separate high-spatial-resolution multi-spectral sensors covering 14 bands, ASTER obtains detailed maps of surface temperature, emissivity, reflectance and elevation (see Table 1).

Table 1 Terra ASTER instrument bands (Chevrel *et al.,* 2003)

Band	Wavelength Interval (μm)	Spectral Response	Resolution (m)
1	0.52 - 0.60	green	15
2	0.63 - 0.69	red	15
3	0.76 - 0.86	NIR	15
4	1.600 - 1.700	SWIR	30
5	2.145 - 2.185	Mid-IR	30
6	2.185 - 2.225	Mid-IR	30
7	2.235 - 2.285	Mid-IR	30
8	2.295 - 2.365	Mid-IR	30
9	2.360 - 2.430	Mid-IR	30
10	8.125 - 8.475	TIR	90
11	8.475 - 8.825	TIR	90
12	8.925 - 9.275	TIR	90
13	10.25 - 10.95	TIR	90
14	10.95 - 11.65	TIR	90

Through earlier studies, ASTER has been shown to be a useful source of information for: land use classification; the mapping of environmental parameters related to slope instability (e.g. major rock groups and geomorphological and structural features); and mapping of built-up areas, major road networks, cultivated slopes and vulnerable cultural features (Chevrel *et al.,* 2003; Liu *et al*. 2004; Fourniadis *et al.*, 2007). However, the spatial resolution of 15 m was found inadequate to delineate such features as minor roads (Fourniadis *et al.*, 2007).

ii Aerial photography

Aerial photography has very high spatial resolution (thus an even smaller pixel size), but limited spectral resolution (Mouat *et al*., 1995). Panchromatic film has a similar sensitivity range as visible light. Images are depicted in various shades of grey, with the tone matching the density of colour observed by the human eye (Avery, 1977). Photographic interpretation usually requires a considerable amount of subjective judgment, “To learn to identify objects on aerial imagery, one needs to study known features on many photographs so that the characteristic clues of shape, size, tone, pattern, shadow, and texture become automatically associated with particular subjects,” (Avery, 1977, p. 1).

According to Hansen *et al.* (2002) this lack of objectivity combined with extensive time requirements means that manual methods of photographic interpretation are limited in their application. However, the advantages of using aerial photography over satellite imagery include the very high spatial resolution (Schmidt, 2003) and the long duration of the available record (Fensham and Fairfax, 2002).

1.7 Review of Methodological Approaches Based on the Literature

1.7.1 Use of environmental risk assessment in this study

In my study, findings from the analyses and literature search will be used to assign relative ratings for incorporation into a simplistic semi-quantitative risk assessment similar to that of Al-Adamat *et al.* (2003). However, it is likely that there will be a shortage of empirical evidence and a number of assumptions may need to be made. It is also recognised that science provides probabilities, not certainties (Fairman *et al.*, 1998), and scientific conclusions may be altered as further or more reliable data becomes available. The method should, nevertheless, provide a “first-order” risk assessment, using publicly accessible data, in order to focus effort and limited available resources. Thereafter, through an iterative process, new information can be incorporated into the assessment, which will continually improve decision making (US EPA, 1998). The risk assessment in this study will involve the following three steps:

- MRD classification: Whereas Al-Adamat *et al.* (2003) considered risk factors associated with land use, in this study the risk factors will be those related to MRDs. This will require identification of the hazards associated with MRDs and scoring of the potential consequences for each MRD type, status, footprint sort and historical failure.

- Determination of vulnerability (or likelihood of occurrence): Rather than assessing groundwater vulnerability, in this study I will assess land use vulnerability by identifying exposure pathways, measuring proximity of MRDs to sensitive land uses, evaluating results and scoring.
- Risk evaluation: This is the product of MRD classification and vulnerability.

The tables and maps produced by this exercise will provide a general guide to land use vulnerability and risks posed by MRDs in EMM. This will be of use in prioritising MRDs for mitigation and to make meaningful recommendations for future land use; whereby mining companies and government will be better positioned to allocate scarce resources judiciously.

1.7.2 Use of remote sensing in this study

(a) Locating and classifying mine residue deposits

Despite the long amount of time that may be required for inspection, historical aerial photography will be used in my study for locating MRDs (including MRD sites that have subsequently been developed into other land uses since the earliest aerial photographic record available, which is 1938); classifying the MRDs in terms of type (waste rock dumps, sand dumps and slimes dams), status (active, dormant, reworking and footprint) and footprint sort (if applicable); identifying MRD side wall failures; and delineating mine residue spillage.

(b) Detecting mineral indicators of mine residue and associated contamination

For risk assessments, the detection of hazards by remote sensing is only possible if each hazard type exhibits distinct characteristics that can be distinguished by their spectral characteristics, tone, texture, pattern, shape, size or shadow (Werz and Hötzl, 2007). Remote sensing using spectral scanners has become popular for assessing and mapping the spatial variation of soil physical and biogeochemical properties. The process of pyrite oxidation at the surface of a MRD may produce acidic water that is progressively neutralized as it drains away from the MRD, depositing different Fe-bearing secondary minerals at various distances (Swayze *et al.*, 2000). The discrete Fe-bearing secondary minerals are indicators of the geochemical conditions under which they formed. A number of studies have shown that, under laboratory conditions, certain soil constituents such as Fe oxides, carbonates, organic matter and clays have unique and distinguishable spectral signatures (Kooistra *et al.*, 2003; Wu *et al.*, 2005). Remote sensing can thus be used to rapidly screen entire mining districts for potential sources of surface acid drainage and to detect acid producing minerals in mine waste or un-mined rock outcrops because each of these secondary minerals has a unique spectral signature (Swayze *et al.*, 2000).

Several other parameters that are important for determining vulnerability to the impacts of MRDs are based on information beneath the Earth’s surface that cannot be provided directly by remote sensing data due to the fact that passive sensors have no ground penetrating capabilities (Werz and Hötzl, 2007). However, through inference and correlation, remote sensing technology can also be used to identify certain subsurface phenomena (e.g. polluted groundwater), sometimes up to tens of metres deep, provided the phenomena have affected (e.g. through capillary action or plant uptake) the near surface environment (Mouat *et al*., 1995).

In the earlier study by Chevrel *et al.* (2003), IKONOS, ASTER and Landsat TM images were compared for use in risk assessment. They suggested that despite its lower spatial resolution than IKONOS, ASTER imagery better differentiated between mine residue and urbanised areas because of its better spectral resolution and range. In my study, ASTER imagery will be used to detect indicators of mine residue contamination; even though the low spatial resolution (pixel size of 30 m), means that many of the smaller contaminated sites will go undetected. The application of a minimum mapping unit, which is often used in land cover classifications, will not be applied because the pixel size already requires a relatively large area to contain a mineral signature for it to be detected. Although smaller sites may still pose a threat, it will suffice in this study to bring attention to the larger contaminated areas. Notwithstanding, ASTER is readily accessible and the spectral signatures are available for several minerals of interest (i.e. minerals associated with gold mine residue; Heller, 2006). Ideally, a number of other potential signature minerals (e.g. gypsum, goethite and melanterite) would be included but these cannot be distinguished because of the broad bandwidth of ASTER (Margalit, personal communication). Reference spectra for four of the selected minerals (pyrophyllite, chlorite, jarosite and copiapite) are available from the United States Geological Survey (USGS) Spectral Library (Clark *et al*., 2003). A fifth, as yet unidentified mineral, has a unique spectral signature that was acquired with a hand-held analytical spectral device (ASD) from gold and uranium mine waste pans in the Welkom region in August 2005 (the dry season) (Margalit, personal communication). The chemistry of these pans, in comparison to non-waste pans, has been characterised in detail (Cukrowska *et al.*, 2006), and they contain gold and uranium mine residue, as well as unusually high concentrations of chlorides, sulphates, some metals and metalloids, and uranium, due to their having being used as facilities for the evaporation of mine process water for over 60 years. At the time of spectral acquisition the surface of the pans was dry, exposing a mixture of residual tailings and sulphate- and chloride-rich crusts containing elevated concentrations of uranium. The spectral feature acquired is not in the USGS library, but from other studies (Margalit *et al.*, 2006; Weiersbye *et al.*, 2006a), was found to be associated without exception with all known gold and uranium mine tailings and waste sites in the Welkom, Klerksdorp and

Carletonville areas, and also with some adjacent highly polluted soils. For the purposes of my study the spectral feature is hereafter referred to as 'mincrust' and I tested whether it was associated with MRDs and various land uses. Mincrust was found to be associated in a dose-dependent fashion with milled uranium (uraninite) ores and with uraninite-bearing rock samples provided by AngloGold Ashanti Ltd, but not with gold-bearing conglomerates in the absence of uranium-bearing minerals (Margalit *et al*., 2009). All the samples measured contained either uranium ores or tailings, as well as their oxidative weathering products – in some cases as fairly extensive crusts enriched in uranium and sulphates, and the identification of the mineral is currently under investigation using mineralogical analytical microscopy and spectroscopy.

Pyrophyllite (aluminium silicate hydroxide) and chlorite (iron aluminium magnesium silicate hydroxide) are minerals (disilicates) of metamorphic rocks associated with gold-bearing reef (ore). They are stable under normal atmospheric conditions and I therefore considered them signatures of bulk tailings transport by wind, water or other mechanical means, including truck and haul.

The Fe(III) rich copiapite (hydrated iron magnesium sulphate hydroxide) is an efflorescent sulphate salt formed by evaporation of acid mine waters around waste rock dumps, slimes dams and river banks (Naicker *et al.,* 2003; Espana *et al*., 2005). Friedlander *et al.* (2007), found that the formation of copiapite required a solution pH of 0-1.5. A study by Swayze *et al.* (1996), showed that pyrite weathered first to copiapite, then to jarosite and eventually to goethite or hematite. Jarosite (potassium iron sulphate hydroxide), which was identified by Naicker *et al*. (2003) on and in the vicinity of MRDs on the Central Rand, is a ferric iron crust, which also requires formation from an acid-sulphate brine (Marion *et al*., 2008). It precipitates in the vicinity of ARD discharge points at a slightly higher pH than copiapite of approximately 2-4 (Espana *et al.,* 2005). It decomposes to produce ferric oxyhydroxides in humid climates but can persist in arid environments (Langmuir, 1997). I therefore considered jarosite and copiapite to be signatures of water-borne contamination and ARD. The accumulation of salts plays an important role in the transient storage of metals and acidity as they readily re-dissolve and enter the water systems during rainfall events (50-90% within a few hours of the first rainfall event after the dry season) causing a rapid decrease in pH and a high increase in dissolved solids (Espana *et al*., 2005).

It is also recognised that the minerals could be associated with reef outcrops and their natural weathering. In my study I will identify the extent of MRDs and mine residue spillage from aerial photographs and compare the results with the detection of the abovementioned minerals by ASTER. An assessment will also be made of differences in detection of minerals based on the MRD classification.

(c) Detection of vegetation cover

Vegetation could mask the detection of indicator minerals by ASTER therefore a means is required to determine presence or absence of vegetation. The Normalised Difference Vegetation Index (NDVI) uniquely characterizes the presence of photosynthetically active (or ‘green’) vegetation (Tucker, 1979).

NDVI has been used in previous studies to measure canopy cover, chlorophyll content (Schowengerdt, 1997) and plant stress, although it may not differentiate between plant stress induced by deficient or toxic concentrations of nutrients or essential minerals (Schuergera *et al*., 2003). Generally, as plant stress levels increase, chlorophyll levels tend to decrease and NDVI values become lower (Lichtenthaler, 1996). In my study NDVI will be used as an indictor of live vegetation cover. ASTER imagery will be interpreted for NDVI and its influence on the detection of the aforementioned minerals will be determined.

(d) Determining zones of influence around mine residue deposits

A number of subject experts and industry representatives were consulted by GDACE in determining buffer zones around hazardous sites, including waste rock dumps and slimes dams, based on broad information classes: environmental health requirements, desired environmental quality and a generalised understanding of activity impacts (GDACE, 2005). Consideration was given to landscape, topography, wind direction, potential for temperature inversions, hydrology, land use practices, settlement patterns, toxicity of pollutants, potential for explosions, nuisance factor and mobility of pathogens. They identified two standard buffer zones for each site category, which catered for a ‘best-case scenario’ (large buffer) and a ‘worst-case scenario’ (smaller buffer). The large buffer is GDACE’s preferred option and the smaller buffer is the absolute minimum based on information gathered and legal requirements.

Waste rock dumps were assigned a best-case buffer of 100 m and a worst-case buffer of 0 m. According to GDACE (2005), although the public should not be allowed access onto these dumps because of potentially unstable slopes, where sufficient access prevention is in place, no buffer is required. The best-case buffer of 100 m is for visual purposes because of the scale difference between rock dumps and residential areas. Their rationale was that these types of dumps do not pose major dust or other pollution threats and, in time, vegetation becomes well established. However, waste rock dumps may contain pyrite and other minerals (Hinde *et al.*, 1986; Handley, 2004), thus they are potential sources of ARD.

Slimes dams were assigned a best-case buffer of 1 000 m and a worst-case buffer of 500 m because it was recognised that they pose a major air pollution and health problem if not managed properly (GDACE, 2005). From the hazards of potential instability, dust and toxic seepage; wind load (i.e. dust) was used by GDACE as the principle factor in determining the buffer distance. Although wind-blown dust from MRDs can be of concern up till 3 km from the site boundary (DEAT, 2006), a best-case buffer of 1 000 m was specified because, according to GDACE (2005), beyond this distance dust levels can no longer be distinguished from ambient dust pollution. Furthermore, provided that adequate mitigation is applied the buffer can be reduced to a distance of 500 m (GDACE, 2005). These distances (500 and 1 000 m) will be used in my study to examine whether there is a significant difference in pollution indicators detected by ASTER within the different buffers.

(e) Spatio-temporal analyses of mine residue deposits and land use

Chevrel *et al*., (2003) recommend the use of time-series images to capture changes in land use post-mining and to take into consideration possible differences between wet and dry seasons, although they do not say what these may be.

Chevrel *et al.* (2003) distinguished changes in extent of tailings dams over time through the use of topographical maps compiled 12 years apart and the Landsat TM and ASTER images taken 9 years apart. However, maps are merely representations of a geographic area, which may emphasize some features at the cost of omitting others (Wende and Neuman, 2004). Topographical maps do not necessarily depict MRDs accurately and the Landsat TM and ASTER images are unlikely to be directly comparable because they use different sensors with a different number of bands, band widths and spatial resolutions. Furthermore, gold mining has been taking place on the East Rand for 120 years so the time periods of 9 and 12 years are inadequate. I have obtained historical aerial photographs covering a time period of 65 years (i.e. for 1938, 1964 and 2003), which will be examined for changes in the extent of MRDs during these periods.

Chevrel *et al.* (2003) also identified several U/Th anomalies (i.e. not in direct connection with known, identified or interpreted mining related features) and recommended that they were checked in the field. In my study, I will examine the historical aerial photographs for information on earlier land use and the presence of mining-related activities or facilities, thereby supplementing or, in some cases, providing an alternative to fieldwork.

1.7.3 Qualitative verses quantitative assessment of comparisons between remote sensing data

All comparisons (i.e. associations and correlations) made by Chevrel *et al.* (2003) appear to have been subjective, based on visual interpretation of GIS overlays (e.g. (a) between classifications from different remote sensing imagery; and (b) between a map of potentially contaminated areas (i.e. footprints based on differences in the extent of MRDs depicted on topographical maps for 1983 and 1995) and a soil contamination map based on U/Th ratios). In my study, associations, correlations and differences between remote sensing data will be examined using statistical tests.

1.7.4 Prioritising mine residue deposits for remedial and mitigation measures

At the time of embarking on this study, previous studies had focused on identifying vulnerable land uses near MRDs on the East Rand (Chevrel *et al.,* 2003) or establishing buffer zones around MRDs for land use planning and development approvals (GDACE, 2005). No evidence could be found of studies prioritising MRDs on the Witwatersrand basin for remedial and mitigation measures (i.e. source controls) based on different risk profiles, which is an objective of my study. However, at the same conference where I presented the results of my risk assessment (Sutton and Weiersbye, 2008), a similar study was presented by Chevrel *et al.,* (2008).

In their study, Chevrel et al. (2008) set their objectives as (a) historical monitoring of land use using Landsat TM and ASTER images, (b) Identifying pollution details and monitoring changes using ASTER images, and (c) Risk-based land management using remote sensing and other relevant data in a GIS combination. In addition to Landsat TM and ASTER imagery, topographic (raster), geological, soil and land use maps (vector), they had access to data sets from the Council for Geoscience, including very high-resolution airborne radiometric images, DEMs and vector files containing groundwater levels, sinkholes and boreholes.

They applied a simplified risk assessment approach based on scoring 17 parameters related to source, pathway and receptor. The scoring was from 0-3 and an uncertainty factor was included. The final scoring was divided into three classes: class 1, requiring further investigation and emergency response; class 2, requiring monitoring, and class 3, not requiring specific work except possible restrictions on urban development.

1.8 Key questions and associated tasks

To answer the key questions related to the aim and objectives I performed the following tasks

1.8.1 What are the environmental risks associated with gold and uranium MRDs?

(a) Reviewed the literature to assess the environmental hazards, exposure pathways and land use vulnerabilities associated with MRDs.

1.8.2 Does the environmental policy and legislative framework adequately address land-use vulnerabilities and the environmental risks posed by MRDs, what are the gaps and how can these be rectified?

(a) Critically reviewed the current policy and legislative framework related to mining based on the results of the risk assessment and land-use vulnerabilities, and made recommendations for improvement.

1.8.3 Do the identified environmental risks vary for different classes of MRDs?

(a) Identified and defined an appropriate study area based on the publicly-available information and databases;

(b) Constructed the database;

(c) Located MRDs, determined their extent, identified and quantified those that experienced side wall failures;

(d) Classified the MRDs in terms of type (waste rock dumps, sand dumps and slimes dams); status (active, dormant, reworking and footprint); and footprint sort (if applicable);

(e) Examined associations, correlations and differences between data sets using statistical tests;

(f) Made and recorded assumptions on environmental risks according to MRD classification based on the literature review where empirical data was lacking;

(g) Evaluated results and rated the potential consequences for each MRD classification.

1.8.4 What land uses are most and least vulnerable to risks from gold and uranium MRDs?

(a) Selected a suite of minerals (i.e. chlorite, copiapite, jarosite, pyrophyllite and mincrust) that could be detected by ASTER, and that were expected to be indicators of both MRDs, and MRD-derived contamination, through distribution in the landscape by physical means (tailings deposition, spillage, wind and water-borne erosion and haulage of tailings), and through aqueous transport of chemical weathering products (i.e. oxidation, leaching, and efflorescence);

(b) Acquired ASTER thematic images for these minerals on the study area at two different seasons (in order to also assess potential seasonal differences in detection – see below);

(c) Identified extent of indicators of mine residue contamination on different land uses;

(d) Examined associations, correlations and differences between identified mine residue contamination from remote sensing and land use using statistical tests;

(e) Made and recorded assumptions on land use vulnerability based on the literature review where empirical data was lacking;

(f) Measured proximity of MRDs to sensitive land uses;

(g) Evaluated results and assigned ratings.

1.8.5 Which MRDs are located in proximity (i.e. within the zone of influence) to sensitive or vulnerable land uses?

(a) Established whether there was a difference in the spatial extent of MRD-derived contamination (viz ASTER-detectable mineral indicators) between the different buffers in GDACE policy (1 000 m and 500 m) around MRDs.

1.8.6 Which MRDs are priorities for mitigation and/or remedial measures?

(a) Used findings from (1.8.2) to (1.8.4) above to assign relative ratings for MRD classes and land use vulnerabilities. Incorporated these ratings into a risk assessment:

1.8.7 Are historical aerial photographs useful for identifying, classifying, and quantifying the spatial extent of, MRD sites and mine residue spillage across different landscapes (despite possible subsequent changes in land use)?

(a) Assessed the use of historical aerial photography to locate MRDs, to determine their extent, and to identify and quantify MRDs that experienced side wall failures;

(b) Assessed the use of aerial photographs (i.e. through an examination of shape, location, texture and size) to classify the MRDs in terms of type (waste rock dumps, sand dumps and slimes dams); status (active, dormant, reworking and footprint); and footprint sort (if applicable);

(c) Assessed the use of historical aerial photographs for providing information on former mining-related activities or facilities (including MRD sites), where these may have subsequently been demolished or removed, when mineral anomalies were detected by ASTER;

1.8.8 Are thematic images for selected minerals derived from multi-spectral satellite-borne remote sensing (i.e. ASTER) useful for detecting indicators of mine residue and associated contamination?

(a) Assessed the use of ASTER thematic imagery for detecting selected minerals as indicators of contamination from gold and uranium MRDs, where there are multiple sources, pathways and receptors:

i Determined if ASTER thematic imagery for white micas (pyrophyllite and chlorite), and for a spectral signature derived from a chemically-defined gold and uranium mine waste pan (mincrust), could be used to detect mine residue;

ii Determined if ASTER thematic images for mincrust and for acidic water-borne products of sulphide mineral oxidation (jarosite and copiapite), could be used to detect both oxidized MRDs, and contamination of soils beyond MRDs;

iii Determined if there was a relationship between the spatial extent of minerals on the MRD detected by ASTER and the MRD classification in terms of mean particle size or texture. Mine tailings dumps differ in texture, and texture influences the rates of water and oxygen infiltration, drainage and thereby chemical speciation and chemical leaching, with higher rates of drainage from more porous structures. However, the area of particles exposed to weathering will also govern the availability of elements for leaching;

iv Determined the effect of season (wet and dry) and live vegetation cover (as indicated by NDVI), on the detection of minerals by ASTER:

CHAPTER 2

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2 Legal Review

Abstract

Mining is an important contributor to the South African economy but has the potential for significant negative impacts on the environment. Under section 24 of the Constitution of South Africa Act 108 of 1996 (the Constitution), the right to environmental health has been elevated to a basic human right, and since 1998 a series of Acts have been promulgated to prioritize environmental protection. In addition, the Mineral and Petroleum Resources Development Act 28 of 2002 (the MPRDA) and its Regulations (GN R527 in Government Gazette 26275 of 23 April 2004) have been promulgated to regulate the minerals and petroleum industry in terms of constitutional requirements. The MPRDA attempts to ensure sustainable development of mineral resources, equitable access to the benefits, better environmental protection, and includes provisions for mine closure. We reviewed the legislation applicable to mine closure to assess whether it adequately addresses constitutional and environmental requirements, including known risks to gold mine closure. Although the MPRDA does aim to provide for the protection of the environment at mine closure, it currently contains some flaws and gaps which need to be addressed. Some of the gaps are however potentially addressed by the provisions of other legislation, such as the National Environmental Management Act 107 of 1998 (the NEMA) and the National Water Act 36 of 1998 (the NWA). A key requirement of the MPRDA is for mining companies to undertake the necessary studies to determine the quantum required for the rehabilitation or management of impacts, and to make sufficient financial provision for these. In this regard a guideline document has been published to assist the Department of Minerals and Energy (DME) when reviewing the quantum of provisioning. The MPRDA also attempts to establish an exit route whereby mining companies, which demonstrate an agreed degree of environmental compliance, can then transfer their remaining liabilities to the State or a third party together with sufficient funds to address them. However, if funds are insufficient, the mining company and the directors in their personal capacity remain liable. Thus it is vital that mining companies and directors keep abreast of international trends in order to pro-actively minimize their exposure. Un-answered questions relate largely to end land-uses and restrictions thereon. Based on current information, we consider residential townships, edible crop production and livestock grazing to be high risk land-uses for tailings storage facilities (TSFs), TSF footprints and areas within the aqueous or aerial zone of influence of TSFs and metallurgical plants in South Africa. Failure by the regulators and industry to agree on suitable `soft’ end land-uses and buffer zones could exacerbate liabilities for closing mines by resulting in subsequent land-uses that are sub-economic or risky.

2.1 Introduction

In contrast to earlier views that environmental legislation impacts negatively on company financial performance (Leonard, 1988), international experience is beginning to demonstrate that there is little evidence for negative effects, and in some cases regulation has actually encouraged improved financial performance (Porter and van der Linde, 1995). Mining has the potential for significant negative environmental impacts, and the role of emerging legislation in guiding the performance of mining companies in South Africa is of the utmost importance. Although mining contributed 8.1% to the GDP in 2002, is a major foreign exchange earner and a significant employer (CoM, 2003); abandoned and derelict mines could cost the state SAR100 billion to rehabilitate (Mail and Guardian, 2007).

Minerals and environmental legislation prior to the Constitution failed to prevent significant environmental damage through mining, and created legacies for citizens to bear and the State to address. The recent MPRDA and its regulations promulgated by the DME therefore focus on sustainable development and end-land use post mining, together with internalisation of social and environmental costs. Further, in terms of section 43(1), the holder of a mining right or similar remains responsible for any environmental liability, pollution or ecological degradation, and management thereof, until the Minister has issued a closure certificate to the holder concerned.

We selected gold mining to assess whether the new minerals legislation meets constitutional requirements and is aligned with sound environmental principles. We also identified areas in the minerals legislation that need clarification or further development. In South Africa the risks and impacts of gold mining on the Witwatersrand Basin may include, *inter alia,* contamination and alteration of surface watercourses through tailings spillages, surface instability through seismicity and sinkholes, TSF failure, contaminated decant from underground workings, and dust, as well as noise, vibration, radioactivity from naturally occurring radioactive materials (NORMs), soil and ground water contamination, air pollution, land degradation and loss of productivity, bioaccumulation of metals and NORMs, loss of biodiversity, impairment of ecosystem services, contributions to ozone depletion, contributions to global warming, and human health impacts (Rudd, 1973; Funke, 1990; Pulles, 1992; Cogho *et al*., 1992; Coetzee, 1995b; Weiersbye *et al*., 1999; 2006b; Rösner and Van Schalkwyk, 2000; Hodgson *et al*., 2001; Rösner *et al*., 2001; Winde, 2001; Naiker *et al*., 2003; Tutu *et al*., 2003; 2004; 2005; Weiersbye and Witkowski, 2003; 2007; Coetzee *et al*., 2004; Cukrowska and Tutu, 2004; Harington *et al*., 2004; Mphephu *et al*., 2004; Winde *et al*., 2004a;b;c; Steenkamp *et al*., 2002; 2005; Sutton *et al*., 2006; O’Connor and Kuyler, 2006).

2.2 Review

2.2.1 Protection of communities and the State from having to bear costs of impacts

Section 24 of the Constitution affords all South Africans the right to an environment that is not harmful to their health or well-being; and to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development. To give effect to this right, the NEMA was promulgated by the Department of Environmental Affairs and Tourism (DEAT). NEMA contains a set of 18 environmental principles that must guide administrative and court decisions in the field of environmental management. These principles are themselves guided by the ideal of sustainable development, as defined by the Brundtland Commission (WCED, 1987). Section 2(4)(a) of NEMA requires that sustainable development considers all relevant factors related to the disturbance of ecosystems, the loss of biological diversity, pollution and degradation of the environment, the disturbance of landscapes and sites that constitute the nation's cultural heritage, the generation of waste, and the use and exploitation of non-renewable natural resources. Overall, section 2(4)(a) recognises that, for development to occur, there will possibly be some negative impacts, however, it calls for a risk-averse approach and for any of these impacts to be anticipated, prevented whenever possible, or otherwise minimised and remedied. Another of the principles in NEMA (section 2(4)(p)), commonly known as the 'polluter pays' principle, refers specifically to who must bear these costs;

"The costs of remedying pollution, environmental degradation and consequent health effects and of preventing, controlling or minimising further pollution, environmental damage or adverse health effects must be paid for by those responsible for harming the environment."

The DME has also used the term sustainable with an object of the MPRDA, given under section 2(h), being to give effect to section 24 of the Constitution by ensuring that the nation's mineral and petroleum resources are developed in an orderly and ecologically sustainable manner while promoting justifiable social and economic development. Nonetheless, despite the good intentions of the MPRDA to give effect to constitutional and national environmental policy and principles with regard to mining, it is a complete rewrite of minerals legislation. Consequently there are some errors and gaps, which could be taken advantage of by mining operators or expose mining companies to risk. At the time of coming into effect the MPRDA required existing mining and prospecting rights (`old order rights') to be converted to `new order rights' under specified conditions otherwise the rights were lost. However, not only did the holder of unused old order mining rights lose rights after a period of one year under Section 8 of Schedule II but obligations were also incidentally lost, which could be interpreted as any obligations for rehabilitation and mine closure. It is possible that this type of gap could also exist when the continuation period of 5 years for used `old order rights', which are not converted, expires.

Another area that requires clarification relates to the definition and scope of mining. According to Scholes in Tyrer (2005), there is an anomalous position in the MPRDA whereby this Act does not apply to gold slimes dams produced under title granted through legislation prior to the MPRDA (known as `old order mine dumps') simply because the MPRDA refers to mine residue stockpiles and deposits, and defines these as resulting from the depositional activities of the holder of a "new order" mining right. Furthermore, the transitional arrangements do not specifically mention ownership of residual minerals in tailings deposits as qualifying for an "old order" mining right; so, strictly speaking, there is no transitional process to convert from an "old order" mining right to a new one. Consequently, Scholes is of the opinion that once the "old order" right lapses the owner can continue processing residual minerals in tailings deposits without needing to approach the DME and without a mining authorisation.

Lastly, in accordance with MPRDA Regulations, a guideline on financial provisioning for mine closure has been produced for use by the DME when reviewing the quantum determined by mining companies. Within this guideline gold and uranium processing waste has erroneously been defined as basic, salt producing (DME, 2005), which could result in financial provisioning requirements for gold mine residue deposits being significantly underestimated. Since the requirement is for the mining company to carry out the necessary studies to determine the quantum the DME accepts no liability for any shortfall and in such an event the mining company and its directors, in their personal capacity, remain liable. Gold is largely mined from sulphidic ores in South Africa, and there are approximately 6 billion tonnes of gold mine tailings in unlined facilities on the Witwatersrand Basin of South Africa (Chevrel *et al*., 2003), containing an estimated 30 million tonnes of sulphur (Witkowski and Weiersbye, 1998a) and 430 000 tonnes of low grade uranium (Wilson and Anhaeusser, 1998). The generation of acid mine drainage and contaminated seepage by these tailings is well established (Rösner *et al*, 2001; Naiker *et al*., 2003; Tutu *et al*., 2003; Winde *et al*., 2004a; b; c), as are the substantial environmental and financial liabilities incurred worldwide through pollution of water and soil resources (Sasowsky *et al*., 2000; Jarvis and Younger 2000). Although the Constitution prescribes an environment not harmful to human health, practical means of limiting human exposure to harm are not adequately dealt with in current legislation. For example, buffer zones to human settlement, cropping and grazing need to be defined and legally enforced around TSFs and residual contamination, and limits need to be set upon the uses of contaminated water (discharge, polluted streams and groundwater) for crop irrigation.

2.2.2 Identification and management of all actual and potential environmental impacts

Although seeking to reduce the exposure of mines to environmental liabilities, the Environmental Impact Assessment (EIA) guidelines of the MPRDA could have the opposite effect. The Constitution and the NEMA clearly established the DEAT as lead agent for environmental protection and the EIA process in South Africa. Division of the responsibility for environmental protection between departments on a favoured industry basis will result in a lowering of standards as the MPRDA in section 39(1) advocates `accelerated' EIAs for the mining industry by requiring an EIA, as well as environmental management programme (EMP), to be submitted within 180 days. This EIA process is not based on scientifically sound principles, and mines therefore face the risk of having operations endorsed under the provisions of the MPRDA, only to find later that they have incurred liabilities which could easily have been avoided by adhering to sound EIA practices.

Just as all areas are not equal in terms of mineral resources; neither are all areas equal in terms of natural capital and biodiversity. The majority of gold and coal mines in South Africa occur in a region known as the Grassland Biome. The South African Grassland Biome is classified by le Roux (2002) as highly diverse in flora and fauna, with high levels of endemism, but critically endangered due to habitat loss, fragmentation and development threats, principally due to deep-level gold mining, surface coal mining, and cropping. The impact of deep level gold mining on carbon storage and water quality is considered the highest of all land-uses in the Grassland Biome, with soil erosion one of the highest (O'Connor and Kuyler, 2006).

Unfortunately, the MPRDA EIAs can be conducted at any time of year, although the influence of seasonality on detection of flora and fauna, and evaluation of biodiversity, is well recognized worldwide. For example, within the Grassland Biome, most plant species (83% of which are actually non-grasses, Reyers and Tosh, 2003), and smaller fauna experience seasonal dormancy, whereas some avian species are migratory. At worst, if not conducted in appropriate seasons and for biologically relevant time periods, the EIA could under-represent biodiversity by almost 95%. Assessment of hydrology requires a full hydrological cycle to encompassed, and assessment of ecosystem goods and services could be similarly compromised by an `accelerated' EIA. A preliminary, conservative estimate of the value of ecosystem services in South African grasslands is SAR9.7 billion per annum, or SAR29 000/km^2 of grassland per annum (De Witt and Blignaut, 2006). With respect to social aspects, rural and urban livelihoods of the poor in South Africa are highly dependent on ecosystem goods, and potential impacts on community resource bases can rarely be assessed within such short time periods (Dovie *et al*., 2005; Shackleton *et al*., 2007).

Planning mining operations for closure, and thus avoiding high risks and minimizing impacts, is globally considered the most cost-effective approach in any setting. The EIA is the foundation of this approach, and should be undertaken in accordance with ecologically-sound principles.

2.2.3 Maintenance of mine amelioration or mitigation measures after mine closure

Regulations 56, 60 and 62 of the MPRDA Regulations require that residual and possible latent impacts are identified and quantified, but do not provide any practical manner for dealing with them, which renders financial estimation difficult. Although the Minister of the DME may, under Section 41(5) of the MPRDA, retain such portion of the financial provision as may be required to rehabilitate the closed mining or prospecting operation in respect of latent or residual environmental impacts, latent impacts by their definition are unknown or at best merely suspected, and therefore provision is seldom made for them. For example, gold deposits on the Witwatersrand Basin naturally co-occur with uranium, other NORMs and metals such as Mg, Cu, Zn, Mn, As, Ni, Cr, Co and Pb. In addition, long-lived cyanide-metal complexes persist in TSFs, and Hg is still used for gold amalgamation by artisanal miners.

The latent impacts on biota, including humans, of bioaccumulation and exposure to elevated levels of metals and NORMs are established in the international scientific literature. Furthermore, the mining industry should have gained enough experience from the asbestosis and silicosis catastrophes in South Africa to justify application of precautionary principles in respect of other suspected latent impacts. Where feasible, a mining company should take steps to minimize future exposure before a closure certificate is granted by the DME. Alternatively, risk insurance products could be used to cover future exposure and currently unsuspected latent impacts.

In order to address residual and latent liabilities, we recommend that gold-mining operations in South Africa adopt the precautionary approach, and consider the following risks when determining financial provision:

- The near certainty of contaminated water, which will require some form of decontamination treatment, decanting from closed underground mines, or from lower-lying interconnected neighbouring mines (Pilson *et al*., 2000; Hodgson *et al*., 2001);

- The near certainty of sulphate, chloride, metal and NORM contamination of soils and sediments by seepage from unlined tailings storage facilities (TSFs), tailings spillages and plant discharges, and the potential for contamination of downstream / downwind soils and sediments (Witkowski and Weiersbye, 1998a; Rösner and Van Schalkwyk, 2000; Rösner *et al*., 2001; Mphephu *et al*., 2004; Tutu *et al*., 2003; 2004; 2005);

- The near certainty of sulphate, chloride, metal and NORM contamination of surface water bodies and their sediments, and ground water, by seepage from unlined tailings storage facilities (TSFs), tailings spillages, plant discharges and underground workings (Cogho *et al*., 1992; Coetzee, 1995b; Pulles *et al*., 1996; Hodgson *et al*., 2001; Winde, 2001; Coetzee *et al*., 2004; Winde *et al*., 2004a; b; c). In addition, the potential contamination of surface soils overlying shallow polluted groundwater via evaporative pathways during dry seasons (Naiker *et al*., 2003; Tutu *et al*., 2004);

- The potential for `salt', sulphate, chloride, metal and NORM contamination of crop soils irrigated with contaminated surface water or contaminated groundwater (Sutton *et al*., 2006; Philips, 2007).

- The near certainty of selection for an acid mine drainage and salt-tolerant flora on polluted soils and water, use of which would be expected to reduce TSF and soil rehabilitation costs (Angus, 2005; Weiersbye and Witkowski, 2003; 2007; Weiersbye *et al*., 2006b; Straker *et al*., 2007);

- The concomitant loss of genetic / biodiversity, and potentially ecosystem goods and services on disturbed, fragmented or polluted properties (Angus, 2005; O'Connor and Kuyler, 2006; Weiersbye and Witkowski, 2007);

- The potential for bioaccumulation of some metals and NORMs by flora and fauna (Weiersbye *et al*., 1999; Weiersbye and Witkowski, 2003; Cukrowska and Tutu, 2004; Steenkamp *et al*., 2005; McIntyre *et al*., 2008);

- The potential for exposure of fauna and humans to bioaccumulated pollutants (Steenkamp *et al*., 2005; Cukrowska and Weiersbye, 2010);

- The potential for acute and latent toxicity impacts of bioaccumulated pollutants on humans (Steenkamp *et al*., 2002); and the potential for radioactivity impacts from NORMs on humans (Philips, 2007);

- The potential for human disease as a result of exposure to wind-blown dust from TSFs (CoM, 2001);

- The potential for structural damage to buildings and other structures, and human injury, by mining-exacerbated seismicity (Le Roux, 2005);

- In dolomitic regions, the potential for structural damage to buildings and other structures, and human injury, by mining-exacerbated sink-hole formation (Funke, 1990; Buttrick *et al*., 2001);

- The potential for uncontrolled future land-uses on, or within the zone of influence of TSFs, footprints and mineral processing facilities, such as human settlement and recreation, food crops and home vegetable gardens, livestock grazing, and informal re-mining or scavenging, all of which are incompatible with safety and the fragile status of lands under rehabilitation, and could exacerbate liabilities for mining and the State post-closure (Sutton and Weiersbye, 2008; Reichardt and Reichardt, 2007).

2.2.4 Establishment and achievement of closure objectives

Regulation 61 of the MPRD Regulations requires closure objectives to be established at the outset of the project in order to guide project design, development and management of environmental impacts, to provide broad future land use objectives and to enable closure costs to be estimated. At a later stage, when preparing the detailed closure plan for a mine, regulation 62 of the MPRD Regulations requires a description of the closure objectives and how these relate to the mine’s environmental and social setting. To achieve this in practice requires consultation with local planning authorities and consideration of the integrated development plan. Some level of public participation is also required. Clear, specific and measurable targets then need to be set in accordance with these objectives so that future performance can be assessed and the State can determine the acceptability of risk and liability prior to issuing a closure certificate (DWAF, 2004). The DME and the MPRDA recognizes the requirement for regional mine closure plans, and for the probability of residual and latent impacts by mining operations, together with the need to make financial provision. However, the Act does not adequately address the possibility that some damage may be irreversible, and hence require long-term site containment and financial provision, and/or compensation, and/or the replacement of land to affected parties.

2.2.5 Alternatives to mine closure

(a) Polluting mineral residues

Secondary pathway exposure to metals and NORMs are recognized as potential hazards to humans worldwide. This risk has been inadequately addressed in South African legislation due to the lack of locally-orientated scientific knowledge prior to the 1990’s, thus exposing the local gold and uranium mining industry. The NEMA, the NWA, the Environment Conservation Act and the MPRDA do not adequately address bioaccumulation and exposure through secondary pathways as a consequence of inadequate mine waste disposal. All the legislation and guidelines have an end-of-pipeline approach that focuses on the control of the primary emission pathways (i.e. dissemination of pollutant loads above a specified standard to air and water) and do not take adequate cognisance of the affinity of different classes of pollutants for specific media and biota. International experience has established that, (a) sediments are significant and reversible sinks for metals and NORMs, (b) aquatic and terrestrial bioaccumulation and secondary pathway exposure are significant risks, and (c) that these risks cannot be established from simple determination of pollutant levels in the primary emissions to air and water.

Precautions related to the safe handling, transport and containment of long-lived NORMs are addressed by the Nuclear Energy Act 46 of 1999 (the NEA) and the National Nuclear Regulator Act 47 of 1999 (the NNRA). TSFs and other gold and uranium processing facilities in South Africa have to be registered with the National Nuclear Regulator (NNR) if the radioactivity exceeds 0.5 Bq/g. However, as the NNR is solely mandated to ensure protection from radioactivity, the risk of toxicity from NORMs is not addressed in their regulations or guidelines. There are internationally-accepted models for secondary pathway exposure to radioactivity via what are considered common routes, but these do not always have direct relevance to the South African social and environmental setting. Models of secondary exposure to radioactivity also lack relevance to the potential toxicity of bioaccumulated uranium and other NORMs – even where radioactivity from NORMs is well within NNR requirements, NORMs may still be highly bioavailable and present a toxicity risk through bioaccumulation pathways (Tutu *et al*., 2003; 2004; 2005; Winde *et al*., 2004a; b; c; Cukrowska and Weiersbye, 2010). Similarly, despite the widespread co-occurrence of low-grade uranium with gold in South Africa, the DWAF, DEAT and National Department of Agriculture (NDA) have not produced guidelines for monitoring of NORMs in water, soils or foodstuffs. Some gold mining companies therefore lack awareness of the risks posed by bioaccumulation, and how to minimize these through emissions control, safer rehabilitation measures, and `soft' or restricted land-uses.

(b) Alternatives to restoring land to unrestricted end land-uses

Contaminated land policy world-wide is shifting towards restricted `soft' end land-uses, instead of the multifunctional approach - which by insisting that clean-up to allow for all land-use eventualities effectively denies practical implementation of any. The same approach should govern outcomes for closure. Remediation of some sites to multifunctional end land-uses is not always feasible, meaning that unrealistic goals are pursued for closure. Restoration and rehabilitation are dynamic processes that span long periods of time. The MPRDA provisions for land rehabilitation and/or restoration assume that all damage can be rehabilitated. However, some degradation associated with mining is irreversible from an ecological perspective, at least within the span of a few to many generations.

The omission of alternative solutions will render it difficult for responsible holders of mining rights to effect legitimate closure. For example, the end land-uses stipulated for TSF footprints and other contaminated sites in many South African mine EMPs is `agriculture' or `grazing', which may imply edible crop production, or pasture and rangelands populated by livestock. Apart from the high risk to mining companies of enabling edible crops and grazing systems on contaminated or degraded (fragile) sites, grazing as an end land-use is considered sub-economic on rehabilitated mine pastures in South Africa (O'Connor and Kuyler, 2006). Furthermore, an estimated 80% of gold mine properties on the Witwatersrand Basin are considered to be irreversibly transformed, meaning that restoration is not technically-achievable; although in some cases ecosystem services comparative to the original services could be achieved. Rehabilitation of mine sites must be undertaken, but on contaminated sites and degraded sites, safer and `soft' alternative land-uses need to be implemented. Description of the range of soft land-uses suitable for interim and end-land uses should be included in regulatory guidelines in order to support mining companies in their decisions and financial provisioning. Provision should also be made for environmental compensations for irreparable damage and/or irreversible loss of ecosystem services to be paid to affected parties (i.e. downstream users) and for trade-offs of devastated land for land in better condition. These actions should complement, and not replace, technically-achievable methods of land and water rehabilitation.

(c) Restricted and `soft' end land-uses

Not all risks can be addressed by the gold mining industry. Future land-uses must be addressed by the regulator to ensure that current rehabilitation practices are not short-sighted or incompatible with end land-uses, and that municipal development plans are risk-averse. Simple examples of the former are the grassing of TSF footprints in the Johannesburg region, at great cost to the industry, only to have the land converted shortly thereafter to industrial sites or landfills. Examples of the latter include residential and agricultural developments well within the zone of influence of TSFs, and the use of contaminated water for crop irrigation (Sutton *et al*., 2006). The presence of contaminated mine water and soils in South Africa has long been recognized (Rudd, 1973; Funke, 1990; Pulles, 1992), and the World Health Organization has identified hand-to-mouth activity in young children worldwide as a significant risk factor in the consumption of contaminated soil. The proximity of poorer and high density residential areas, together with household food gardens, to TSFs and acid mine drainage in South Africa could expose to risk the sector of the population that is least equipped to deal with it (Sutton and Weiersbye, 2008).

There is also a lack of regulatory guidance regarding what land-uses TSFs and footprints can potentially be converted to during and post-closure, and this has resulted in gold mining companies allocating resources to short-term measures for dust control and aesthetics. Guidelines for sustainable closure options which minimize future risks to the industry and the State should encompass the conversion of gold mine tailings and mine water to resources, and mainstream the objectives of the Kyoto Protocol, to which South Africa is a signatory, and the Marrakesh Accord of 2001 which supports the use of new land forms as carbon sinks. Examples include the treatment of mine water to standards suitable for industrial purposes, with concomitant recovery of useful chemical compounds (W. Pulles and J. Maree, personal communication), and the conversion of TSFs and footprints to restricted `soft' land-uses that combine rehabilitation with economic returns – at least on a break-even basis (Ilgner, 2006; Limpitlaw, 2006). Restricted end land-uses that are potentially suitable for mine closure outcomes in the semi-arid South African climate include industrial sites, lined landfills, graveyards, sewage sludge disposal and land-farming, and carbon sinks facilitated by the growth of low-water demand and high root-biomass crops, such as certain fibre, pharmaceutical and biofuel species.

2.2.6 Modifications in design and operating practice towards achieving closure objectives

The current legislation and guidelines in South Africa all support an end-of-pipeline approach to pollution control. Many of the pollution control and monitoring measures appear to have been designed with the more commonly-known inorganic pollutants, such as sulphates and chlorides or `salts' in mind. Although the impacts of acidity and salinity on ecosystems are indeed severe, these pollutants do not bioaccumulate, and the latter require stringent measures to be in place for emissions reduction. Legislation and guidelines to assist the mining industry in reducing risk and achieving closure objectives should adopt a strict Cleaner Production (CP) approach for the extractive and waste disposal phases of new mining operations and incorporate the precautionary principle for medium-term to older operations. New mining operations requiring a CP approach also include the reclamation of older sand and slimes dams for residual gold, as there is evidence for remobilization of contaminants (such as uranium and cyanides) during disturbance of old tailings deposits (Mphephu, 2004; Tutu *et al*., 2004).

2.2.7 Provision of sufficient finance for mine closure, including unexpected occurrences

In terms of section 41(1) of the MPRDA, an applicant for a prospecting right, mining right or mining permit must, before the Minister approves the EMP in terms of section 39(4), make the prescribed financial provision for the rehabilitation or management of negative environmental impacts. The quantum of financial provision must cover planned closure, premature closure and post-closure monitoring and maintenance. Furthermore; the requirement to maintain and retain the financial provision remains in force until the Minister issues a certificate in terms of section 43 to such holder, but according to section 41(5) the Minister may retain such portion of the financial provision as may be required to rehabilitate the closed mining or prospecting operation in respect of latent or residual environmental impacts.

Thus it appears that legislation requires sufficient funds to be provided to achieve closure and to provide for any latent impacts. The main challenges are therefore to determine the extent of liability, predict the latent impacts and calculate the amount required, and also for the mining company to reach agreement on these issues with numerous different Government departments via the DME as lead agent for mine closure (i.e. the DWAF and its' regional authorities, the DEAT and its' regional authorities, the NDA, the Department of Health and the Department of Labour). This task "will challenge researchers in both non-market valuation and natural resources accounting" (Poulin and Jaques, 2004).

(a) Unexpected occurrence of disease and adverse health impacts

There are numerous examples of the difficulty herein, one of which relates to the unforeseen occurrence of occupational disease due to asbestos exposure. Asbestos is a fibrous mineral. When mining was taking place, only the long fibres had any commercial value so short fibres were discarded onto dumps. For many years these dumps were not recognised as being of any particular concern; they simply caused the occasional dust nuisance (Fuggle and Rabie, 1996). Although the carcinogenic nature of the fibres had long been suggested by international studies, acceptance in South Africa came too late for thousands of workers and residents in asbestos mining areas who developed lung diseases such as mesothelioma and asbestosis. The consequent legal determination of liabilities delayed Gencor from unbundling its SAR18 billion stake in Impala Platinum until sufficient provision had been made for asbestos-related diseases injury claims (IOL, 2003). The DME in South Africa has had to undertake the responsibility of covering abandoned asbestos mine tailings, at significant cost to the State (Mail and Guardian, 2007) and ultimately the taxpayer.

Silicosis is another incurable and ultimately fatal respiratory disease, associated with exposure to alpha quartz particles from the quarrying or blasting of silicaceous rock. Exposure to alpha quartz is recognized as a major risk by the South African gold mining industry, which implements various measures to reduce the probability of worker exposure. The industry routinely screens workers for symptoms of silicosis, but considers the occupational risk to be largely associated with underground worker exposure to particles from the blasting of rock, and to be negligible from public or worker exposure to TSF dust. However, alpha particle concentrations in gold mine tailings dust can potentially also exceed regulatory limits, and this is of concern due to the large volumes of dust generated over long time periods by unprotected tailings (total erosive losses can reach 500 tonnes / ha / annum, of which a significant portion may be airborne, Blight, 1991; Annegarn, personal communication). Financial provisioning for protection of tailings during operations, in addition to final rehabilitation, is expected to mitigate the requirements for latent impact provisioning.

(b) Accurate assessment of financial provision

In terms of section 41(3) of the MPRDA, the holder of a prospecting right, mining right or mining permit must annually re-assess their environmental liability, and increase their financial provision to the satisfaction of the DME, thereby providing for new developments and discoveries to be included. Subsection (4) provides for the possibility that the Minister is not satisfied with the assessment and financial provision contemplated. In this event, the Minister is empowered under section 41(4) to appoint an independent assessor to conduct the assessment and determine the financial provision. In order to recognize the adequacy of provision, it is therefore essential for the State to stay abreast of scientific developments, to provide adequate standards and guidelines, and to implement them in a timely manner.

In similar manner to provisions in the NEMA and the NWA, in the event of ecological degradation, pollution or environmental damage, section 45(1) provides for the Minister of DME to direct the holder of the relevant right to undertake various measures. If, however, the Minister establishes that the holder, or the successor in title, is deceased or cannot be traced or (in the case of a juristic person), has ceased to exist, been liquidated or cannot be traced, the Minister may, in terms of section 46(1) instruct the Regional Manager concerned to take the necessary measures. According to section 46(2) the measures taken must be funded from the financial provision made by the holder, or if there is no such provision or if it is inadequate, from money appropriated by Parliament for that purpose.

In other words, in the event of the aforementioned, and the Minister failing to adequately assess the amount of financial provision necessary, the State may be required to meet the costs of rectifying environmental impacts. It also appears that it is the intention of the legislation that the State will take responsibility for rectifying environmental impacts once a closure certificate has been issued because section 43(1) provides that the holder of the right or permit remains responsible … until the Minister has issued a closure certificate, implying that once the closure certificate has been issued this is no longer the case. It seems that the intention is for the Minister to retain sufficient funds from the financial provision to cover any latent or residual impacts, this being provided for in section 41(5).

But what happens if the amount was underestimated? It does not appear to be the intention of the DME to then turn to the previous holder of the right or permit, otherwise why issue a closure certificate? However, for the state to then take responsibility is contrary to the ‘polluter pays’ principle in South Africa’s over-riding environmental legislation, i.e. the NEMA.

2.2.8 Transfer of environmental liabilities when mining operations are sold

According to section 43(1) of the MPRDA, the holder of a right remains responsible for any environmental liability, pollution or ecological degradation, and the management thereof, until the Minister has issued a closure certificate to the holder concerned. From this it seems as though, in terms of the MPRDA, the environmental management and liability for environmental pollution or ecological degradation can be transferred when the right is ceded or transferred because only the holder of the right is responsible for any environmental liability relating to the relevant operation. An exception to this rule is to be found in 43(2) of the MPRDA, which provides that when applying for a closure certificate, the holder of a right may apply to the Minister for permission to transfer the environmental liabilities and responsibilities that are identified in the EMP and any closure plan to a person with prescribed qualifications.

Thus section 43(2), at first glance, appears to make it possible for a mining company to 'walk away' from its environmental liability before the closure certificate is issued, by transferring the environmental liabilities to the suitably qualified person. However, this does not mean that the mining company has no further responsibility; the provisions of the NEMA and the NWA will still apply. In terms of section 28(1) of NEMA, every person "*who causes, has caused or may cause significant pollution or degradation of the environment must take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring, or, in so far as such harm to the environment is authorized by law or cannot be avoided or stopped, to minimize and rectify such pollution or degradation of the environment*."

The words 'has caused' here indicate that the duty of care is retrospective, and that the previous owner of a prospecting or mining operation remains liable for pollution or degradation caused by the operation whilst they were still the owner or in control. This responsibility for damage caused remains even though they are no longer the owner of the operation, and regardless of whether they have been granted a closure certificate. In addition, the person to whom the operation was transferred must also take reasonable measures to prevent, minimize or rectify the pollution or degradation, regardless of when the pollution or degradation occurred.

Similarly section 19(1) of the NWA provides that – *"An owner of land, a person in control of land or a person who occupies or uses the land on which any activity or process is or was performed or undertaken; or any other situation exists, which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring."*

The words "*was performed or undertaken*" and "*has caused*" clearly indicate that the previous prospecting or mining operation owner would have been responsible to fulfil the requirements of section 19(1) when they were in control of the prospecting or mining operation and will remain liable for any pollution or degradation caused whilst they were still in control. The NWA therefore also requires that the person to whom the operation was transferred would also be responsible for taking reasonable measures to prevent any pollution from occurring, continuing or recurring regardless of when the cause of the pollution or degradation arose.

2.2.9 Enforcement of environmental law

Compliance by the prospecting or mining rights holder with the environmental management requirements of the MPRDA is achieved via the EMP, which is approved in terms of section 39 of the MPRDA. A person who prepares an EMP must, in terms of section 39(3)(d), describe the manner in which they intend to (a) modify, remedy, control or stop any action, activity or process which causes pollution or environmental degradation; (b) contain or remedy the cause of pollution or degradation and migration of pollutants; and (c) comply with any prescribed waste standard or management standard practices.

The EMP-approach attempts to move away from the traditional directive-based regulations towards a co-regulatory instrument. The mining company sets itself environmental objectives in consultation with government departments and other stakeholders and then describes methods of achieving these objectives in the EMP, which must then be approved by the government departments. Nevertheless, the MPRDA reverts back to command and control regulation when the holder does not comply with its requirements. For example, according to Section 47(1)(c), the Minister may cancel or suspend any right if the holder is contravening the approved EMP. In terms of Section 98(a)(iii) it is an offence to fail to comply with the requirements of an approved EMP. In terms of Section 99(1)(c) a person convicted of this offence is liable to a fine not exceeding SAR500,000.00 or to imprisonment for a period not exceeding 10 years or to both such fine and imprisonment.

Once a closure certificate is issued in terms of section 43(1) the holder of a right is no longer liable for environmental damage in terms of the MPRDA. However, as discussed previously, the holder still remains liable in terms of the NEMA and the NWA. According to section 28(4) of the NEMA, the DEAT may direct any person who fails to take the measures required in terms of section 28(1) to (a) investigate, evaluate and assess the impact of the specific activities and report thereon; (b) commence taking specific reasonable measures before a given date; (c) diligently continue with those measures; and (d) complete them before a specified reasonable date. Similar provisions are contained within the NWA.

Should a person fail to comply, or inadequately comply, with such a directive given by the DEAT, the DEAT may, in terms of section 28(8), themselves undertake the reasonable measures to remedy the situation and recover the costs from any or all of the following persons:

- Any person who is or was responsible for, or who directly or indirectly contributed to, the pollution or degradation or the potential pollution or degradation (this would include the previous owner of a prospecting or mining operation or the owner of a 'closed' mining operation);
- The owner of the land at the time when the pollution or degradation or the potential for the pollution or degradation occurred, or that owner's successor-in-title (this will include the current and previous owner of the prospecting or mining operation, if the land is owned by the operation);
- The person in control of the land or any person who has or had a right to use the land at the time when the activity or the process is or was performed or undertaken or the situation came about (this would include the holder of the mining or prospecting right because this is a right to use the land); or
- Any person who negligently failed to prevent the activity or the process being performed or undertaken or the situation from coming about.

The NEMA also empowers private individuals and communities affected by mining. According to Section 32(1) any person or group of persons may seek appropriate relief in respect of any breach or threatened breach of any provision of NEMA, or any other statutory provision concerned with the protection of the environment or the use of natural resources either in that person's or group of person's own interest; in the interest of, or on behalf of, a person who is, for practical reasons, unable to institute such proceedings; in the interest of or on behalf of a group or class of persons whose interests are affected; in the public interest; or in the interest of protecting the environment.

There have been a number of recent examples of residents and communities in South Africa approaching the court, and recently the court found in favour of residents in Kagiso and Davidsonville near Johannesburg. In the first case the court gave the National and Gauteng DME two weeks to implement measures to control dust on an old TSF and to rehabilitate the mine within 2 years. In the second case the judge declared that the pollution and environmental damage caused by an unused TSF required urgent remedial measures. In the latter case the application was against a mining company and its board of directors, the DME and DEAT and other provincial authorities (Citizen, 2006).

The NEMA also provides for private prosecutions and criminal proceedings in sections 33 and 34 respectively and sections 34 (5) to (9) of the NEMA make provision for personal liability on the part of directors, managers, agents and employees should they be found guilty of an offence in terms of the Act. The common law remedies of interdict, delict and nuisance are also available as civil remedies to prevent or obtain recourse for environmental harm even after the mine has been granted closure.

2.2.10 Competency of persons involved in environmental management

Within the MPRDA and its regulations there are limited references to competency regarding environmental management. Regulation 54(2) requires that the quantum of financial provision is annually reviewed and updated in consultation with a competent person; regulation 73 requires that mine residue stockpiles and deposits are classified and designed by a competent person; regulation 58 allows environmental liabilities and responsibilities to be transferred to a competent person; and regulation 55(4) permits, but does not require, an independent competent person to be appointed by the holder of a mining right to conduct the performance assessment report of the EMP. A competent person is defined as meaning a person who is qualified by virtue of knowledge, expertise, qualifications, skills and experience; is familiar with the provisions of the MPRDA and other related legislation; and has been trained to recognise any potential or actual problem in the performance of the work.

The lack of a strict requirement in conducting the MPRDA EIA or performance assessment report is problematic. The NEMA makes provision for personal liability on the part of directors, managers, agents and employees should they be found guilty of offence. Such offences include inaccurate reporting of liabilities, irrespective of whether this is due to ignorance, uncertainty or concealment. This personal liability renders an absolute requirement for competency essential in the MPRDA. Requirements for environmental management implementation in the mining industry should include minimum educational standards, certificates of competency and legal appointments.

Other disciplines that have important reporting requirements and/or responsibilities have either recognised professional registration, government certificates of competency, or are appointed in terms of legislation. In addition to ensuring a minimum level of knowledge and competency, professional registration or legal appointments can bring about accountability. An annual financial statement would not be accepted without it being signed off by a chartered accountant; the safety of a dam must, in terms of section 117(a) of the NWA, be signed off by an “approved professional person” registered in terms of the Engineering Profession of South Africa Act No. 114 of 1990. However the MPRDA EIA, the quantum of financial provision and the environmental risk report, can all currently be signed off by anybody. This is a significant risk for the mining industry, and steps must be taken to require some form of professional registration and proof of competency.

2.3 Conclusion

We found that minerals legislation in South Africa sets out to provide for the protection of the environment at mine closure but contains some flaws and gaps. While some gaps may enable mines to externalise impacts and costs, others could result in increased long-term liabilities and costs because appropriate measures were not taken. The DME is the lead agent for granting mine closure but can only grant such after approval by the DWAF. Since the DEAT and its provincial authorities are the constitutionally-appointed custodians of the environment, their approvals should also be incorporated. Most importantly, even after a closure certificate is granted by the DME, the provisions of other legislation, such as the NEMA and the NWA, could still prevail in the event of undisclosed or future environmental damage. Un-answered questions largely relate to closure mechanisms and guidelines, and especially to the need for regulation of future (i.e. post-closure) land-uses in order to minimize potential liabilities. When assessing economic and environmental viability of future land-uses in mining regions, the regulators, planners and developers must consider the potential for latent impacts such as impaired ecosystem functioning and bioaccumulation of contaminants, long after mine closure. As a result, we do not consider residential townships, edible crop production or livestock grazing to be safe end land-uses for TSF footprints or areas within the aqueous or aerial zone of influence of TSFs and metallurgical plants. Failure by the regulator and industry to agree on suitable land-uses and buffer zones could exacerbate liabilities by leading to subsequent land-uses that are sub-economic or risky.

CHAPTER 3

3 MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location

The gold fields within part of the Eastern region of the Witwatersrand basin, *viz* the Ekurhuleni Metropolitan Municipality (EMM) of Gauteng Province, were selected for this study. Parts of two major goldfields fall within the EMM; these are the Central Rand and East Rand gold fields. The latter used to be the most productive of the Witwatersrand gold fields and although annual production is now relatively minor, with only 20 t recovered in 1994, by 1992 it had yielded over 9 500 t of gold (Robb and Robb, 1998). The Central Rand gold field comprises the area 24 km west of Johannesburg to 24 km east of the City. The East Rand gold field lies to the east of the town of Boksburg, and, as the name suggests, extends as far as Heidelberg (Whiteside *et al*., 1976), with Nigel being the southernmost town within EMM (Figure 2).

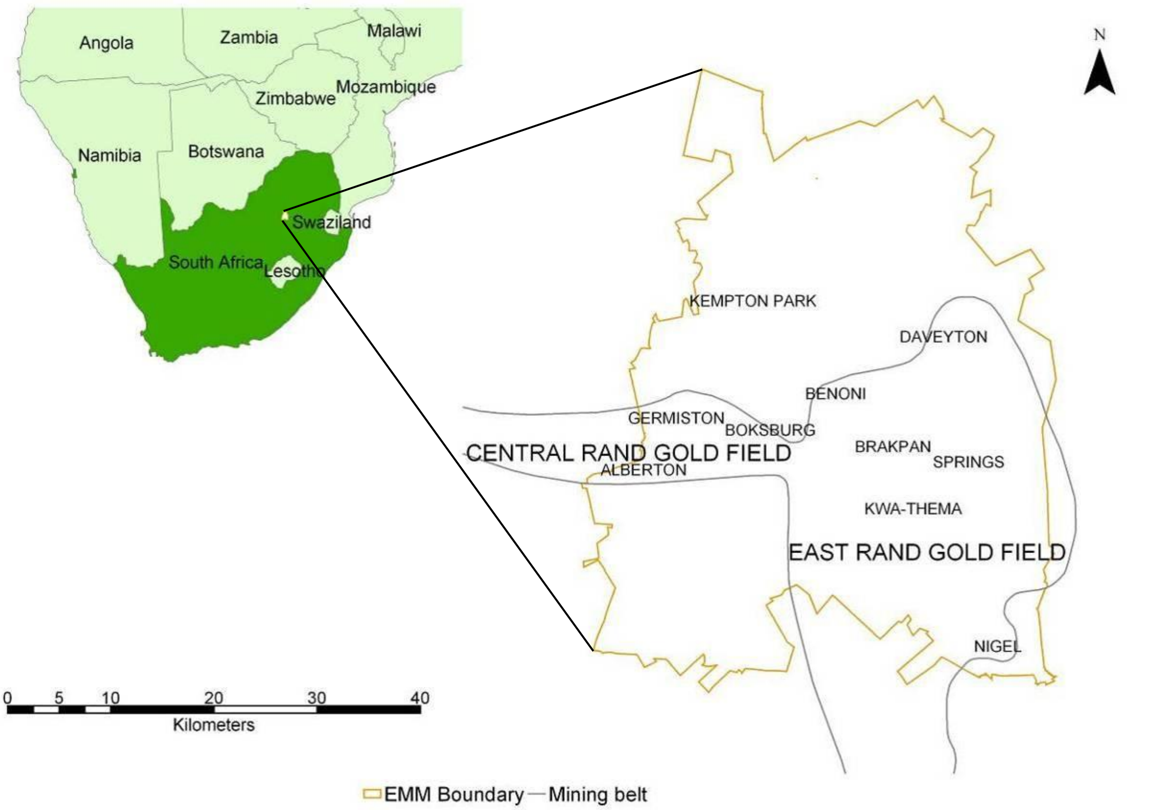

Figure 2 Study area of Ekurhuleni Metropolitan Municipality containing parts of the Central and East Rand gold fields

3.1.2 Climate

EMM is situated on the Highveld of South Africa with a highly seasonal climate, which falls within the early-summer (peaking December or earlier) rainfall belt (Schulze, 1997) with pronounced winter drought. Long-term mean annual precipitation is 500-750 mm with high inter-annual variability (25-30%). A-pan equivalent evaporation (the reference potential evaporation for southern Africa) is 2 000 – 2 250 mm (i.e. 2.7 – 4.5 times higher than rainfall), resulting in annual water deficits and a semi-arid climate (Schulze, 1997). The region experiences seasonal extremes of temperature. Mean daily maximum ambient air temperature peaks in January at 25 to 27.5^{o}C, with a mean daily minimum in July of <0^{o}C.

3.1.3 Geology

The Witwatersrand sedimentary basin was laid down about 2 970 million years ago on a granite-greenstone basement known as the Kaapvaal Craton (McCarthy and Rubidge, 2005). The accumulated sediments within the basin are collectively known as the Witwatersrand Supergroup and are made up of the West Rand Group and the Central Rand Group. The lowermost sedimentary strata of the West Rand Group, which attains a maximum thickness of 5 000 m, were deposited largely in a shallow sea and are comprised of shales and quartzites. The Witwatersrand ridge, which extends from Randfontein to Germiston, is an outcrop of the West Rand Group (McCarthy and Rubidge, 2005).

The West Rand Group is overlain by quartzites and conglomerates of the Central Rand Group. These sediments are an accumulation of river deposits and certain of the conglomerate layers contain high concentrations of gold and uranium (McCarthy and Rubidge, 2005). The Witwatersrand basin now forms an approximately oblong shape some 350 km x 160 km, underlying southern Gauteng, North West and northern Free State provinces; with the principle axis running south-west to north-east.

About 2 714 million years ago two micro-continents, the Zimbabwe and Kaapvaal Cratons, collided, rupturing the crust and causing vast amounts of lava to erupt. This was followed by a period of mountain building, stabilisation and erosion. These volcanic and sedimentary rocks form the Ventersdorp Supergroup (McCarthy and Rubidge, 2005). Rifting of the Kaapvaal Craton occurred about 2 650 million years ago followed by erosion and then subsidence of the continent below sea level. This caused river systems to be drowned and buried by beach and shallow-water marine deposits, thereby forming the conglomerate, sandstone and mudstone deposits of the Black Reef Formation. Within this shallow sea bacteria thrived and their growth resulted in the accumulation of more than 1 000 m of dolomite and large amounts of iron and manganese, which were precipitated by oxygen released by cyano-bacteria (McCarthy and Rubidge, 2005).

The most important gold bearing conglomerate layers in the Central Rand gold field are the Main Reef, Main Reef Leader and South Reef (Whiteside, 1964). Uraninite has never been sufficiently concentrated in the Central Rand to make it economically feasible to extract (Robb and Robb, 1998). The Nigel Reef, which is now known to be an extension of the South Reef (de Jager, 1986), is the most important gold bearing reef in the East Rand (Robb and Robb, 1998). Conglomerates and pyritic quartzites close above and below these reefs and known as the Upper Leaders and Footwall Reefs as well as the Kimberley Reefs and Black Reef have also been mined but to a lesser extent (Whiteside, 1964). The Kimberley Reef zone has also been important for uranium (Robb and Robb, 1998). The conglomerate band at the base of the Black Reef Formation is typically narrow with small pebbles and abundant pyrite but occasionally occurs in well-defined channels and gullies (Robb and Robb, 1998).

3.1.4 Drainage systems

The low hills and ridges of the Witwatersrand form a major watershed that divides the Vaal River basin to the south from the Limpopo River basin to the north (McCarthy and Venter, 2006). The EMM area straddles this watershed with the mining belt located in the Vaal River basin. The Klip River and Blesbokspruit catchments lie within the Vaal Barrage catchment with the Klip River draining the southern slopes of the Witwatersrand ridge between Roodepoort and Germiston while the Blesbokspruit drains the southern slopes of the ridge between Benoni and Daveyton. Both catchments discharge into the Vaal Barrage.

Within EMM there are two underground water basins (Central and Eastern), separated by a block of un-mined ground. These two basins are dewatered to allow mining. Surface and underground water are interconnected through surface water ingress and underground water pumping.

(a) Klip River catchment

Of the three sub-catchments making up the Klip River catchment, only the Rietspruit falls within the EMM. This sub-catchment is characterised by a gently undulating topography with MRDs covering the landscape, particularly in the region of the headwaters. Prior to the discovery of gold the Klip was probably a perennial river with a low flow, sustained during the dry winter months from groundwater recharge, which has probably been significantly altered; originally by mining and subsequently by urban development (McCarthy and Venter, 2006).

The upper reaches of the Rietspruit and its tributaries, the Withokspruit, Natalspruit and Elsburgspruit exhibit a strong impact from mining pollution (de Fontaine, 2004). The Natalspruit, whose main headwaters arise within the mining belt, contributes most of the base flow, predominantly from rainwater runoff from urban areas, discharges from sewage works and pumping from an underground mine; all of which provide for year-round discharge. Agricultural use (mainly crop irrigation and livestock watering) is now the predominant water use, whereas historically it was industrial (de Fontaine, 2004). Domestic use of river water is largely confined to the washing of clothes and related uses, predominately in the vicinity of informal settlements in the catchment (de Fontaine, 2004).

The Klip River is the largest contributor to salinity in the lower Vaal Barrage, mainly as sulphates, while other pollutants include manganese - the main inorganic pollution sources include water pumped from underground to allow mining, and diffuse runoff from mining areas and industrial sites (de Fontaine, 2004).

(b) Blesbokspruit catchment

The main tributary of the Blesbokspruit flows from west to east, via a series of man-made lakes and dams with canalised diversions around MRDs. The canal then flows eastward through highly urbanized areas before flowing through an intensively mined area where there are a number of open pit mines along the river bank. In this area a number of MRDs have been reclaimed, some of which were adjacent to or in the watercourse itself. The canal then joins the Blesbokspruit, which arises within agricultural holdings further to the north, and shortly thereafter it receives an average of 75 Ml/day partially treated underground water (van der Merwe and Lea, 2003) before flowing almost due south for about 30 km. Within this stretch a large wetland dominated by reed beds and open shallow water extends for more than 20 km. A number of closed and operating gold mines and MRDs are situated adjacent to the wetland and riparian irrigation occurs along the Blesbokspruit (DWAF, 1999a).

3.1.5 Soils and Vegetation

The EMM encompasses parts of the *Themeda triandra-Eragrotis curvela* grassland, the *Rhus leptodictya-Acacia caffra* Mountain Bushveld and the *Loudetia simplex-Trachypogon spictus* grassland subdivisions of the grassland biome of southern Africa (O'Connor and Bredenkamp, 1997). The *Themeda triandra-Eragrotis curvela* grassland is the most characteristic and prevalent grassland on the central high plateau. However, large areas have been ploughed because the deep, red and yellow eutrophic soils are well-suited for agriculture. Where relict patches of grassland exist they are often degraded from intensive grazing by cattle and sheep (Table 2).

Table 2 Grassland condition and area covered within Ekurhuleni Metropolitan Municipality (Institute for Soil, Climate and Water (ISCW), 2001)

Condition	% Cover	% of EMM	Ha
Good	>60	31.0	59 816
Intermediate	40-60	9.2	17 641
Bad	20-40	3.1	5 696
Very low	<20	2.9	5 488
Bare soil		0.7	1 358

The rocky ridges of the Witwatersrand and Suikerbosrand are the habitat of *Rhus leptodictya-Acacia caffra* Mountain Bushveld and *Loudetia simplex-Trachypogon spictus* grassland. The former occurs on sheltered sites as islands of temperate mountain bushveld and consists of many woody species. The latter is confined to exposed sites, on rocky soils, particularly on the crests of quartzite hills. Overall, the vegetation is characterised by high species diversity as the rocky surroundings create a variety of micro-habitats, with shallow and deep soils within short distances, thereby preventing dominance by any single species (O'Connor and Bredenkamp, 1997).

3.1.6 Land use

Some 35% of the EMM consists of urban/built-up areas, with a further 26.5% of the EMM having been transformed to anthropogenic, non-urban land uses; thus, only 38.5% of the EMM remains 'natural' features (SRK, 2004). For this study I selected a number of transformed land use categories for assessment (Table 3).

Table 3 Land use categories (after Ekurhuleni Metropolitan Municipality, 2005)

Land use Category	Description
Business/Commercial	Offices, retail, general business, recreation, entertainment, light service industries.
Industrial	Light and heavy industries, service industries, warehouses and commercial uses. Noxious industries as per local town planning scheme.
Irrigated agriculture	Rural residential uses and agricultural uses. Supportive uses such as community facilities, local business and farm stalls.
Rain-fed agriculture	Rural residential uses and agricultural uses. Supportive uses such as community facilities, local business and farm stalls.
Formal residential	Existing and future urban residential areas. Access to treated water and connected to sewerage systems. Includes supportive uses such as community facilities, local business, parks and open space, recreation and entertainment.
Informal residential	Large proportion of poor people, limited or no access to clean water and poor sanitation. Limited to no services.

3.1.7 Socio-economic framework

(a) Background

The statistics within section 1.7 were sourced from 2001 census data (Statistics South Africa (SSA), 2001) unless otherwise stated. Ekurhuleni is one of six metropolitan municipalities within South Africa. The population of EMM was estimated at 2.48 million, which was 28% of the total population of the Gauteng Province. Population densities were generally high with an average of approximately 1 300 people/km^2. The most densely populated settlements were typically situated on the outskirts of the urban areas and accommodated approximately 65% of the total population. A century ago the EMM was the world's largest producer of gold but mining now contributes only about 2% to the economy and in terms of employment opportunities, manufacturing and mining are the largest and smallest contributors respectively (SRK, 2004).

(b) Housing and settlement

Approximately 29% of the households in the EMM were classified as living in informal dwellings. Many of these informal dwellings were constructed from unsafe materials and are situated in inappropriate locations, e.g. over the Sasol oil / gas pipeline, on dolomites, on undermined land, on contaminated mining land, close to landfill sites and in flood areas (SRK, 2004). Land for about 37 000 erven needs to be identified to accommodate this housing backlog, which is complicated by the aforementioned factors. The EMM want to see land within the mining belt being rehabilitated and made available for housing but it was reported that even after rehabilitation has been undertaken it could take up to 10 years before certain of these areas can be safely developed for human habitation (SRK, 2004).

(c) Potable water and sanitation

A large portion of the local population has water services below the Reconstruction and Development Programme (RDP) standards, while about 1% is still dependent on natural water sources such as springs and rivers (SRK, 2004). However, although the same information source has ostensibly been used, according to the SSA 2001 census viewed on the SSA website on 7 September 2007, all categories are substantially higher (by a factor of 10) although the total percentage is only double at 2% (SSA, 2001) (Table 4).

Table 4 Number of households in Ekurhuleni Metropolitan Municipality reliant on sources of water vulnerable to contamination

Water Source	Total	Total	Percent
Reference	(SRK, 2004)	(2001 Census - SSA, 2001)	
Borehole	890	9796	1.3
Spring	46	571	0.1
Dam/pool/stagnant water	503	2901	0.4
River/stream	126	750	0.1
Total	1565	14018	1.8

3.2 Data Acquisition

I acquired spatial data from various publicly accessible sources to identify the extent and category of MRDs (the source of the hazard), the extent of mine residue spillage (indicating some pathways and constituting a secondary source), other potential pathways and the proximity to various categories of land use and sensitive locations (the receptors).

3.2.1 Historical aerial photographs

I obtained aerial survey photographs (orthorectified and geo-referenced) taken in February 2003 from the Development Planning Department Corporate Office of EMM. These were the most recent "ready to use" photographs accessible from the public domain and were used for identifying mine residue, georeferencing and fitting other spatial data when required. Historical aerial photographs for 1938 and 1964 were obtained from the Chief Directorate: Surveys and Mapping archive imagery and from the Chamber of Mines (CoM) archive material, at EMPR Services, Johannesburg respectively (Table 5). The 1938 hard copy photographs had been scanned at 450 dots per inch (dpi) producing an equivalent ground sampling distance of 1 m, and were georeferenced and orthorectified by the Centre for Geographical Analysis, Stellenbosch University with a 10 m DEM generated from 5 m contours with TOPOGRID in ARC/INFO and mosaicked using hot-spot removal and colour-balancing between overlaps. The 1964 photographs were only available in hard copy. I scanned these at 800 dpi, and then geo-referenced them using ESRI® ArcGIS™ 8.3. These latter photographs were not orthorectified or mosaicked, therefore they did not have the same positional accuracy as the 1938 and 2003 photographs. Nevertheless, for the purposes of this study they provided useful information on the presence, extent, type and status of MRDs in 1964 provided reference was continuously made to the other photographs.

Table 5 Historical aerial photography used in the geographic information system

Area	Company	Date	Scale	Access
West and East Rand	South African Defence Force imagery; Chief Directorate: Surveys and Mapping archive imagery; Orthorectification by the Centre for Geographical Analysis, Stellenbosch University	May to Sept. 1938	1/18 000	Council for Geoscience, Pretoria, South Africa
Witwatersrand Mine Dump Survey	Aircraft Operating Co. (Aerial Surveys) Ltd. EMPR Services, Johannesburg archive imagery;	Oct. to Nov. 1964	1/9 000	CoM, Johannesburg, South Africa
East Rand	Unrecorded	Feb. 2003	-	EMM

3.2.2 Geographical data

GIS vector files of geology, land use, soils, streams, dams and wetlands were obtained from the EMM and the GDACE (Table 6). I used these to derive further data on MRD proximity to pathways and different land uses.

Table 6 List of GIS data files obtained from the Development Planning Department Corporate Office of Ekurhuleni Metropolitan Municipality and the Gauteng Department of Agriculture, Conservation and Environment

File Name	Shape	Field	Source
Landuse_North	polygon	LU_CAT	EMM
		LU_DESCR	EMM
Landuse_South	polygon	CATEGORY	EMM
		CLASSDESCR	EMM
Geology	polygon	LITH1	EMM
Informal_Settlements	polygon	TYPE	EMM
Dams	polygon	FEATURE	EMM
rivers	polyline	ANNOTAT	GDACE
wetl_sens_data	polygon	TYPE	GDACE
au, ag, u-outline	polyline	FID_	GDACE

3.2.3 Location of known gold and uranium mine residue deposits

The CoM Dump Indexes of 1966 and the early 1990s were obtained from EMPR Services (CoM, 1966; undated). I used these, together with the historical aerial photographs, to create a new GIS vector file showing the location and classification of MRDs.

3.2.4 Satellite imagery

Four ASTER images taken within a 24 month period, but covering wet and dry seasons (Table 7), were obtained from NASA archive imagery. The supplied images had undergone radiometric correction, rectification and georeferencing. I provided the service provider (Bar-Kal Systems Engineering Ltd, Israel) with a polygon (goldres.shp) encompassing the mining belt and requested thematic images in the form of GIS vector files (Table 8) for the signatures of five minerals, which I had selected as likely indicators of gold and uranium MRDs and MRD-derived contamination, and for which the spectral features could be derived from ASTER (namely: pyrophyllite, chlorite, jarosite, copiapite and mincrust – Chapter 1). I further requested thematic images for NDVI.

Table 7 ASTER images obtained from NASA

Reference Number	Date of Image	Season	Rainfall
AST_L1B.003:2019016590	07 Jan 2002	Summer	Wet
AST_L1B.003:2008705798	06 Oct 2002	Early Spring	Dry
AST_L1B.003:2012471587	31 Mar 2003	Late Summer	Wet → Dry
AST_L1B.003:2018226064	25 Oct 2003	Spring	Dry → Wet

Atmospheric corrections of imagery were performed using the ATCOR 2.3 model (DLR-German Aerospace Centre), which accounts for approximately 80% of typical atmospheric data obtained by satellite imagery (Richter, 2003). Field and laboratory-based ground-truthing measurements were used to improve the accuracy of the reflectance data. Due to the use of historical ASTER images the ground-truthing was retrospective (i.e. it was not carried out at the time of the spaceborne measurements). Ground spectra were acquired by Bar-Kal Systems Engineering during August 2005 (winter) using a hand-held field ASD from targets encompassing light to dark materials, including some (e.g. tarmac and paving stones) that show no seasonal changes - tarmac, paving stones, playing field, ploughed field, open bare soil, representative wet and dry mine residue (slimes, sand and rock), mineral efflorescence crusts on tailings dams, mine waste evaporation pans and areas with acid mine seepage into soils, damp sediments and vegetation (Plate 10).

Table 8 List of GIS data files from NASA provided as thematic images by Bar-Kal Systems Engineering Ltd (Bar-Kal)

ASTER	File Name	Shape	Field	Source
AST_L1B.003:2018226064, 25 Oct 2003	Mincrust_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	Mincrust_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	Mincrust_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	Mincrust_01072002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2018226064, 25 Oct 2003	Jarosite_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	Jarosite_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	Jarosite_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	Jarosite_01072002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2018226064, 25 Oct 2003	Pyrophyllite_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	Pyrophyllite_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	Pyrophyllite_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	Pyrophyllite_01072002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2018226064, 25 Oct 2003	Copiapite_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	Copiapite_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	Copiapite_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	Copiapite_01072002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2018226064, 25 Oct 2003	Chlorite_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	Chlorite_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	Chlorite_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	Chlorite_01072002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2018226064, 25 Oct 2003	NDVI_10252003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2012471587, 31 Mar 2003	NDVI_03312003	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2008705798, 06 Oct 2002	NDVI_10062002	polygon	GRIDCODE	Bar-Kal
AST_L1B.003:2019016590, 07 Jan 2002	NDVI_01072002	polygon	GRIDCODE	Bar-Kal

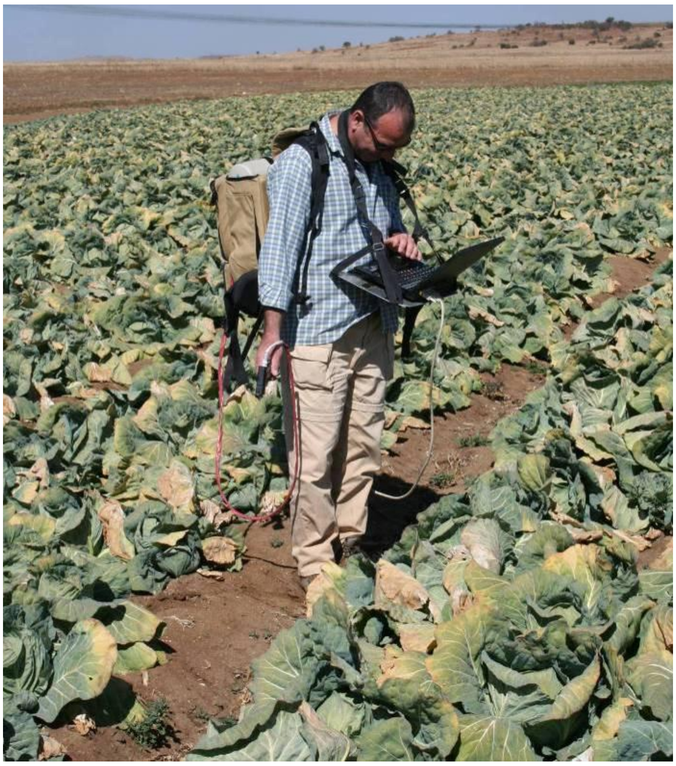

Plate 10 **Example of the acquisition of ground spectra using a hand-held field ASD from targets encompassing light to dark materials**

The ground spectra were resampled to ASTER spectral resolution using ENVI 4.2 software (Figure 3).

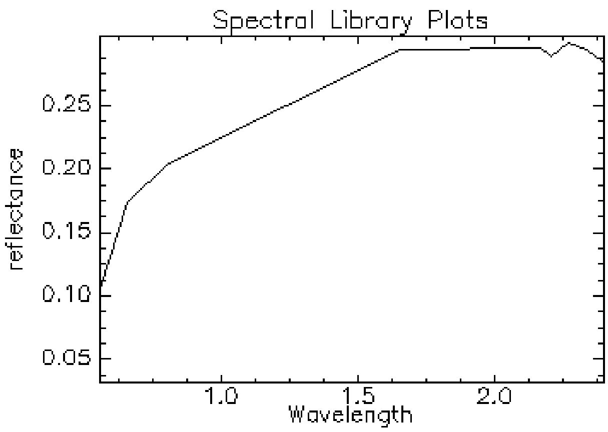

Figure 3 **The ground spectrum adjusted to ASTER spectral resolution**

Distinguishing the minerals was carried out using the VNIR –SWIR region of the sensor (bands 1-9, 0.55-2.39 µm). Matched filtering (ENVI, 2005), which is a partial un-mixing method was used to identify them. The minerals spectra were then resampled to ASTER spectral resolution (Figure 4).

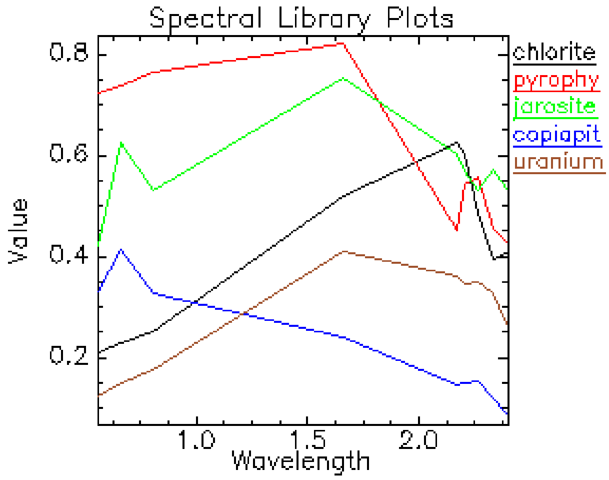

Figure 4 **Minerals reference spectra used to produce thematic images for this study (after Clark *et al*., 2003; Margalit *et al*., 2006)**

NDVI captures the marked contrast between chlorophyll's strong absorptance in the visible wavelengths and strong reflectance in the near-infrared wavelengths (Tucker, 1979; Myneni *et al*., 1995) (Figure 5). It will be used in this study to determine the effect of masking of minerals by live vegetation cover.

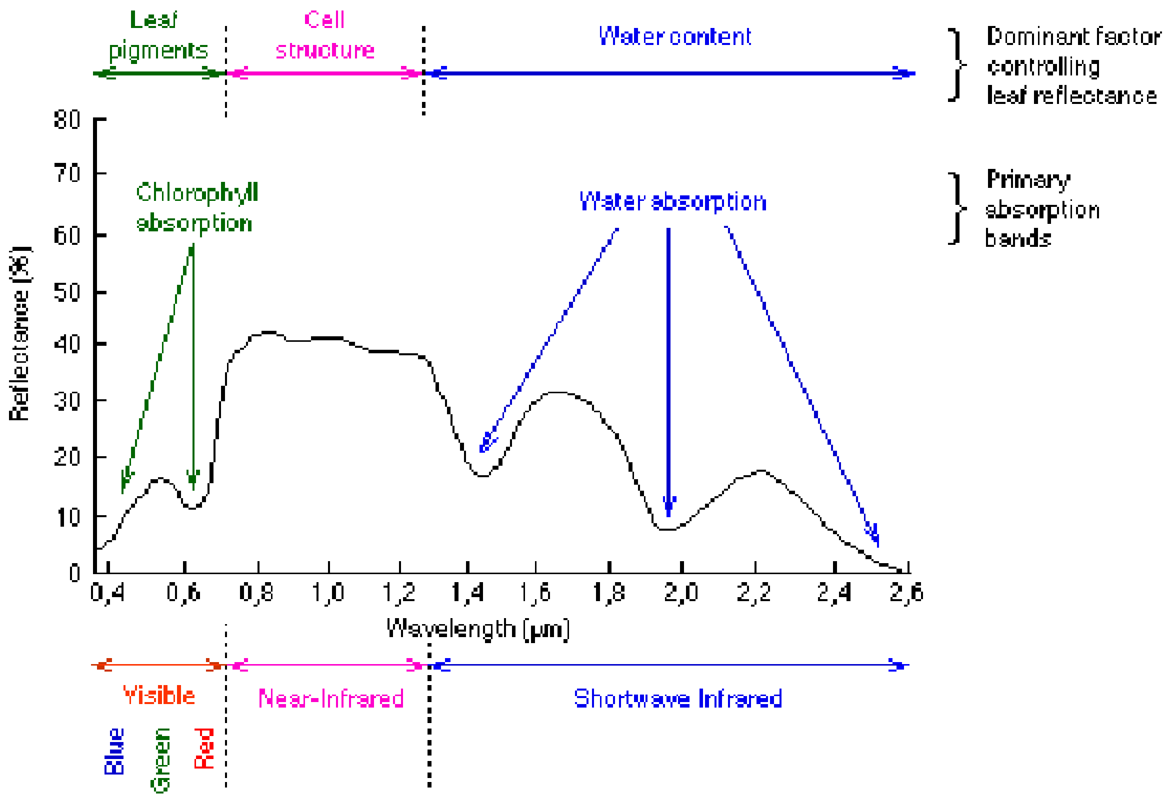

Figure 5 **Vegetation reflectance (%) (after Myneni *et al*., 1995).**

NDVI = (NIR - Red) / (NIR + Red) (1)

The process from acquiring remote sensing data to input to GIS is shown in Figure 6.

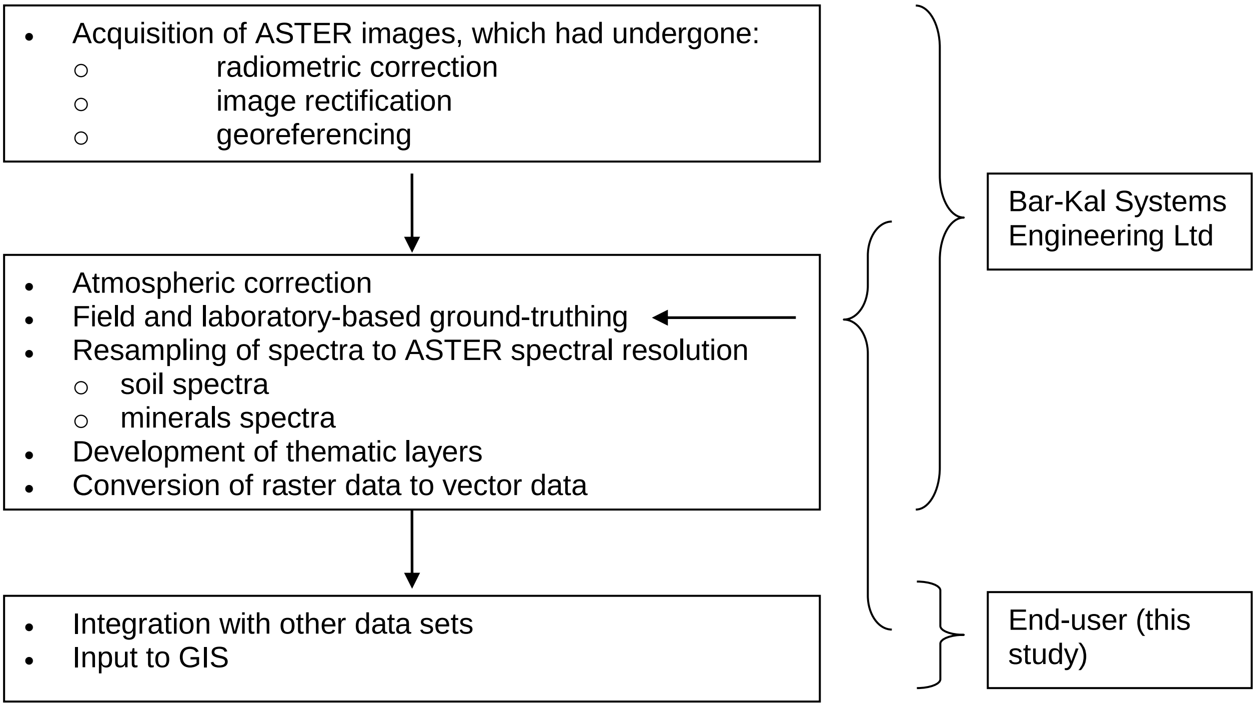

Figure 6 Process for extracting data from digital satellite imagery for use in a geographic information system (modified after Jha *et al.,* 2007)

3.2.5 Rainfall data

Since moisture is known to mask reflectance from the soil surface by decreasing spectral contrast (Wu *et al.*, 2005) as well as change mineral chemistry (Naicker *et al.*, 2003), I acquired rainfall data from the South African Weather Service to test whether cumulative rainfall prior to the acquisition of an ASTER image was associated with a change (increase or decrease) in the detectable spatial extent of each mineral. I obtained rainfall data for 3 stations (Appendix IV) close to the mining belt in EMM. The data were manipulated to provide cumulative rainfall for various durations prior to the dates the ASTERS were taken (Table 9).

Table 9 Average cumulative rainfall prior to the taking of ASTER images taken from 3 stations (Appendix IV) close to the mining belt in Ekurhuleni Metropolitan Municipality

Date of Aster	Season	Average Cumulative Rainfall (mm)						
		On day	-5d	-10d	-20d	-30d	-60d	-90d
07 Jan 2002	Summer	0.0	16.4	17.4	61.0	90.3	157.7	304.1
06 Oct 2002	Spring	6.2	6.2	6.2	6.2	9.2	38.0	39.8
31 Mar 2003	Summer	0.0	0.0	20.1	68.6	73.4	170.3	248.9
25 Oct 2003	Spring	0.0	11.8	41.0	43.6	43.6	47.4	54.6

3.3 Use of a Geographical Information System and Statistical Analysis Software

I carried out an environmental classification of MRDs from remote sensing and geographical data using Environmental Systems Research Institute (ESRI®) ArcGIS™ version 8.3 software, which includes ArcMap™, ArcCatalog™ and ArcToolbox™ with Spatial Analyst™. I predominantly used the PC-based Statistical Analysis System (SAS® Enterprise Guide® version 3.0.0., SAS Institute, Cary, NC, USA) to examine associations, correlations and differences between mine residues identified by the different remote sensing techniques and between different dates. In addition I used STATISTICA statistical analysis software to perform the Friedman ANOVA and Wilcoxon matched pairs tests, as these tests are not available in SAS® Enterprise Guide®. The aforementioned results were combined with data derived from the literature review and compiled into tables, which were used in a risk assessment. The results of the risk assessment were subsequently fed into the GIS to produce MRD risk maps and reports. The process is shown in Figure 7.

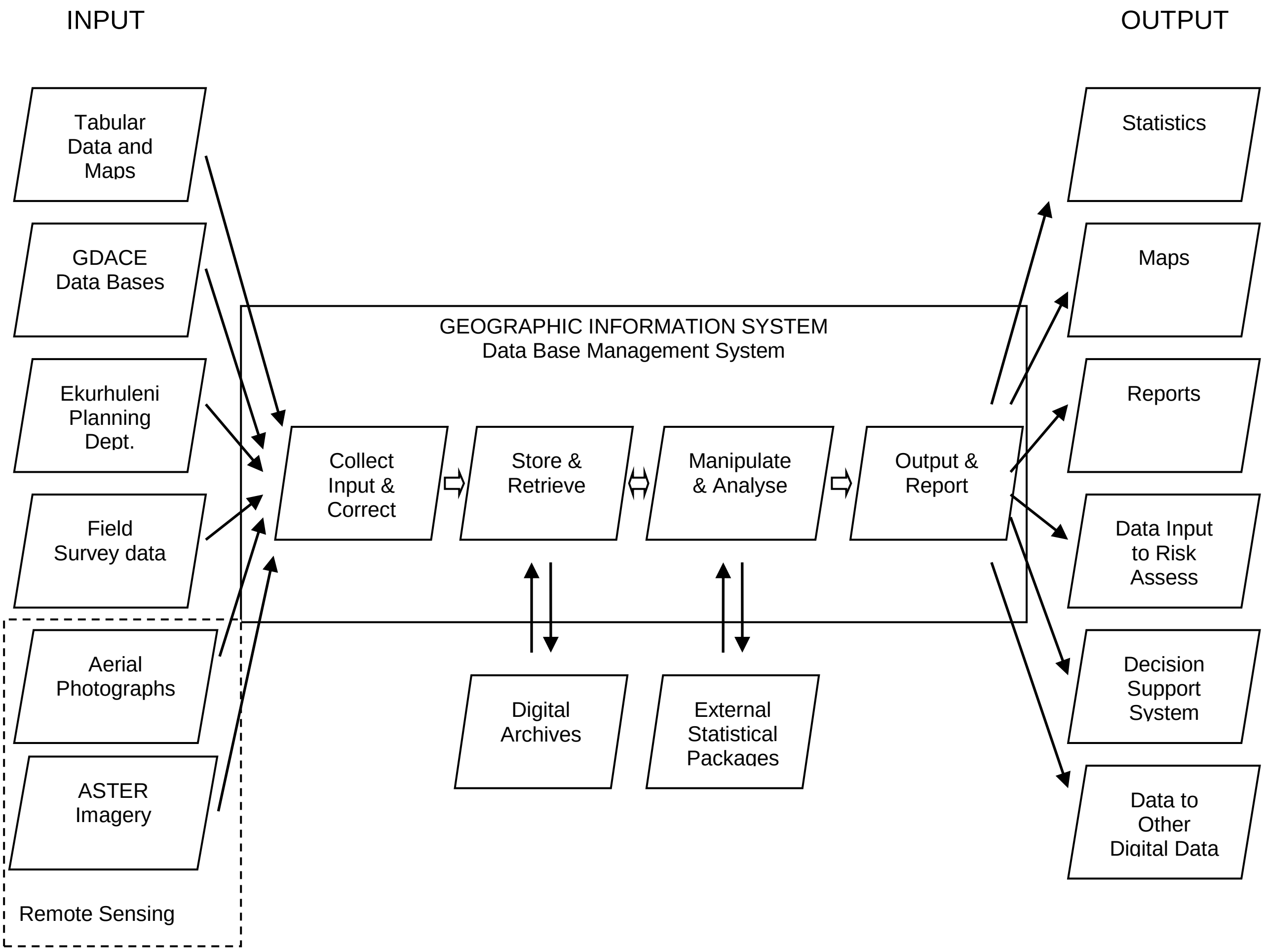

Figure 7 Risk assessment process using geographic information systems and remote sensing technology (modified after Foresman and Millette, 1997)

3.4 Statistics

For all statistical tests significance was taken at the 5% level. For multiple comparison tests it is necessary to use an adjusted *p* value; therefore, I used the Bonferoni adjustment, which uses the level at which I am testing (i.e. 5%) divided by the number of tests (e.g. for 6 tests, only *p* values $< 0.05/6 = 0.0083$ are significant). For the presentation of results, *p* values that are significant are indicated in bold.

I used non-parametric tests (Friedman ANOVA and Wilcoxon matched pairs tests) to examine seasonal and inter-seasonal differences in the presence and spatial extent of minerals detectable by ASTER. The Friedman ANOVA can be used for skew data and can handle two factors simultaneously (i.e. 4 seasonal measurements on 36 plots). I used the McNemar test to examine seasonal and inter-seasonal differences in the probability of detecting minerals. The McNemar test uses 2×2 tables but whereas the chi-square (X^2) test of contingency tables looks at agreement, McNemar looks at disagreement (the off-diagonal elements). The null hypothesis is one of no difference.

Contingency tables were used to test associations between presence and absence of detected minerals and different features (i.e. vegetation cover, types of MRDs, buffer zones and land uses). Contingency tables treat all variables equally so that neither variable is considered as a predictor or a response variable (Quinn and Keough, 2002). The null hypothesis is one of independence, often expressed as no association or interaction between the two variables. The null hypothesis is tested using a X^2 test.

A further way of interpreting lack of independence in contingency tables is to examine the residuals, being the difference between the observed and expected values. Standardised residuals (being the residual divided by the square root of the expected value), also called Pearson residuals (Agresti, 1996), were calculated because these are directly comparable, whereas absolute residuals are difficult to compare when the frequencies vary (Quinn and Keough, 2002).

Odds ratios are also important summary measures of lack of independence or association in contingency tables. The odds ratio is the ratio of the odds of one outcome to the odds of another outcome. Odd ratios were selected rather than relative risk because of the underlying assumption that the probability of ASTER detecting the presence of minerals is low, as discussed in section 3.6. Where there was no area of mineral detected (i.e. the mineral could be there but ASTER did not detect it) odds cannot be calculated; thus, when any of the observed counts in a contingency table equalled zero, a simple correction of adding 0.5 to each cell was made to prevent the odds ratio from equalling zero or infinity (Agresti, 1996).

3.5 Derived technical data (Table 10 – list, and Appendix V – DVD containing data files)

3.5.1 Categorisation and extent of mine residue deposits

The initial area selected for this research was the EMM containing parts of the East and Central Rand gold fields. Within this area all MRDs were identified using the CoM 1966 and early 1990s Mine Dump Indexes together with historical aerial photographs.

(a) Mine residue deposit location and extent

I used the land use spatial data from EMM to provide the foundation for identifying MRD sites and created a new GIS vector file of known MRDs within the study area (Ekur_MRDs). I overlaid this vector file on the 1938, 1964 and 2003 aerial photographs and modified the MRD outlines to match those observed in the photographs. I also identified further MRDs (mainly rock dumps) from the 1938 and 1964 photographs, which had subsequently been removed, fully or partially, or were masked by development such as roads and buildings. When I attempted to identify mine residue from the aerial photographs using grey scale intensity alone, I found that many areas that were not mine residue were the same scale of grey. The identification of mine residue deposits was therefore also based on shape, location, texture and size, which involved individual inspection of each photograph at a consistent magnification (1:4 000) rather than the use of algorithms (Plate 11). I selected this scale because it was the lowest magnification at which I could adequately distinguish outlines of MRDs and spillage.

i Shape of mine residue deposits

Slimes dams, sand dumps and rock dumps have fairly distinct differences in shape, based on the construction method, which in turn was based on the mean particle size and method of transport. Slimes dams have a constructed angular shape whereas both sand dumps and waste rock dumps occur as heaps.

ii Location of mine residue deposits

MRDs are generally located in proximity to the mining area, in this case the gold and uranium mining belt. When a feature resembling a MRD was observed but it was not included in the CoM Mine Dump indexes then the EMM land use vector file was referred to. In all cases this assisted in explaining the feature (e.g. hazardous waste disposal site). A distinction was made in the database between waste rock dumps and overburden, with the term overburden being applied where the heap was located close to an open pit mine because the material has a shallow origin and is probably oxidised.

Table 10 List of derived GIS data files

File Name	Shape	Field	Description
ASTER_01072002	polygon	Boundary	Extent of ASTER (AST_L1B.003:2019016590, 07 Jan 2002) interpreted for minerals and NDVI
ASTER_01072002_Addition	polygon	Boundary	Extent of ASTER (AST_L1B.003:2019016590, 07 Jan 2002) added to ASTER (AST_L1B.003:2018226064, 25 Oct 2003) in order to cover study area
ASTER_03312003	polygon	Boundary	Extent of ASTER (AST_L1B.003:2012471587, 31 Mar 2003) interpreted for minerals and NDVI
ASTER_10062002	polygon	Boundary	Extent of ASTER (AST_L1B.003:2008705798, 06 Oct 2002) interpreted for minerals and NDVI
ASTER_10252003	polygon	Boundary	Extent of ASTER (AST_L1B.003:2018226064, 25 Oct 2003) interpreted for minerals and NDVI
Ekur_MRDs	polygon	Goldfield	Name of gold field within Witwatersrand Basin
		COM_NUMBER	MRD number according to CoM' 1966 Dump Index
		COM_NO_NEW	MRD number according to CoM' 1990s Dump Index
		NAME	Common name given to the MRD
		TYPE	MRD type, i.e. whether a waste rock dump, sand dump, slimes dam, overburden from an open pit or residue used for construction or land infill
		STATUS	MRD status at time of photograph (Feb. 2003) in terms of active, dormant, reworking or footprint
		FOOT_TYPE	For MRD footprints this describes whether the footprint has been developed, paddocked or is free-draining
		WATER_DIST	Distance of MRD from a watercourse
		DOLOMITE	Whether the MRD is on or off dolomites
		WALL_FAIL	Whether side-wall failure of a slimes dam was identified from 1938, 1964 or 2003 photographs
		Agricultural	Distance of MRD from agricultural land
		FORM_RES	Distance of MRD from formal residential land
		INFORM_RES	Distance of MRD from informal settlement
		INDUSTRY	Distance of MRD from industrial land
		RISK_SCORE	The risk index is calculated by multiplying the outputs of the MRD hazard classification and land use vulnerability assessment
		RISK_LEVEL	The risk class in terms of lower, medium, higher or much higher
EMM_Boundary	polygon	BOUNDARY	Municipality boundary derived from geology vectorfile.

File Name	Shape	Field	Description
goldres	polygon	TYPE	Polygon supplied to Bar-Kal to define area for ASTER interpretation
Landuse_Minerals_Boundary	polygon	BOUNDARY	Area within the EMM covered by the thematic ASTER images based on the polygon (goldres.shp) supplied to Bar-Kal
Minerals_Boundary_Less_Remaining_MRDs	polygon	DESCR	Area covered by Landuse_Minerals_Boundary excluding the area covered by remaining MRDs (i.e. active, dormant and reworking) but including footprints
Rivers_1938	polyline	ANNOTAT	GDACE's rivers.shp file revised according to watercourses observed in 1938 aerial photographs
Ekur_Mine_Spillage_2003	polygon	SELECTION	Extent of mine residue spillage plotted from 2003 aerial photographs
Time_Grid_36	polygon	Id	Sampling area covered by all four ASTER images taken on different dates, containing 36 sampling plots (4 x 4 km quadrats)

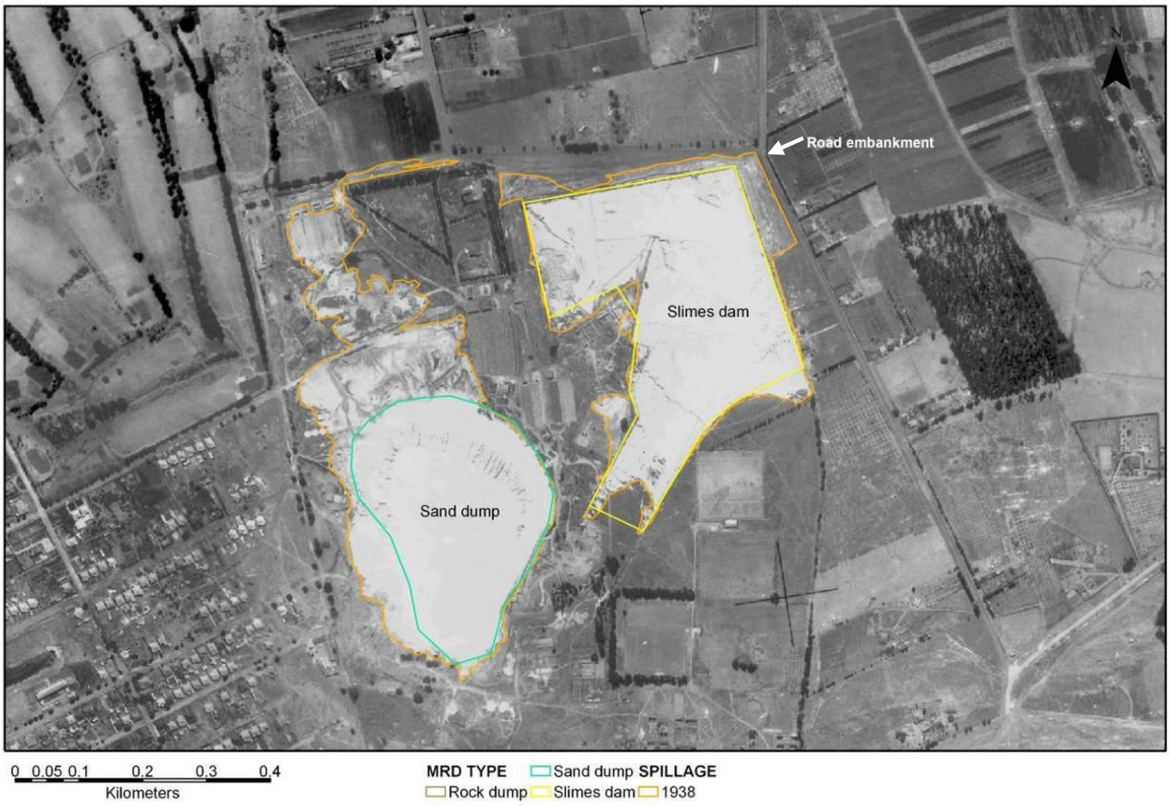

Plate 11 1938 aerial photograph of mine residue deposits and spillage showing the angular shape of slimes dams and spillage contained by a road embankment and the rounded shape of a sand dump

iii Texture of mine residue deposits

Sand and slimes are both fine textured and the colour appears fairly uniform although this can vary because of differences in moisture content across the deposit. Waste rock dumps are coarser; however, this can be difficult to distinguish because of the spatial resolution of the photographs.

iv Size of mine residue deposits

MRDs are relatively large features covering hundreds of square metres to several square kilometres.

(b) Mine residue deposit type and status

I used the CoM 1966 and early 1990s Mine Dump Index to categorise the MRDs in terms of type and footprint type and to locate any previously unidentified MRDs. From inspection I then recorded the status of the MRDs as of the date of the 2003 aerial photographs, in terms of active, dormant, reworking or footprint.

i Active

No sand dumps were considered active because the last sand was deposited in the 1960s (Funke, 1990). If the top of a slimes dam showed no traces of vegetation and there was still a pool of water then it was recorded as active based on the assumption that hydraulic deposition of slimes was still ongoing, or even if it had ceased this would have been recent and the penstock of the dam would still be under active management.

ii Dormant

If the MRD was not active and appeared undisturbed (i.e. no evidence of mine residue having been removed mechanically or by high pressure water monitoring), or supported vegetation on the top surface, it was recorded as dormant. This included MRDs that had lost mine residue through erosion.

iii Reworking

If there was evidence of mine residue having been removed but part of the MRD remained intact it was recorded as reworking.

iv Footprint

If the mine residue had largely been removed and the site vegetated, even if there was evidence of some scattered residue remaining, it was recorded as a footprint. Where development had taken place on the site it was always recorded as a footprint, even if relatively large amounts of mine residue were visible around the development.

3.5.2 Proximity of mine residue deposits to contaminant pathways and selected land uses

I used the 1938 aerial photographs to modify the 'rivers.shp' file provided by GDACE (2005) to conform to the position of drainage lines prior to mining in 1938 (Rivers_1938). Even though by 1938 the deposition of mine residue had caused changes in the position of streams and wetlands, the earlier drainage lines were more recognisable than from the 2003 aerial photographs.

Using the "select by location" function within ArcMap™ I classified the MRDs in terms of their distance from the following features or land uses:

- Watercourses (i.e. a river or spring; a natural channel in which water flows regularly or intermittently; a wetland, lake or dam into which, or from which, water flows) (which were corrected from 1938 aerial photographs);
- Dolomites;

- Residential areas (distinguishing between formal and informal);
- Industrial areas;
- Agricultural lands (distinguishing between irrigated and rain-fed).

In all cases I determined if the MRD was on or within the feature. I then determined if the MRD was within 100 m of watercourses because since 1978 it has been regulated by the DWAF that MRDs must not be located within this distance of a watercourse (Department of Water Affairs and Forestry, 1999b). For the distance from the boundary of MRDs to residential land use I selected distances of 500 and 1 000 m based on the GDACE policy for buffer zones (GDACE, 2005). Although this policy applies to residential land use the same distances were used for industrial and agricultural land uses in the absence of other guidance.

3.5.3 Extent of mine residue spillage

I used the 2003 aerial photographs to plot the extent of mine residue (sand or slimes) on the soil surface based on colour, shape and location (Ekur_Mine_Spillage_2003). When I attempted to identify mine residue from the aerial photographs using grey scale intensity alone, I found that many areas that were not mine residue were the same scale of grey. The identification of mine residue was therefore also based on shape, location and in some cases continuum with an existing MRD, which involved individual inspection of each photograph at a consistent magnification (1:4 000).

(a) Shape of mine residue spillage

Where there has been a slimes dam wall failure or seepage or other slimes spillage the shape is that of a flow. However, a spillage may also have an angular shape when contained by an embankment, such as that for a railway or major road, or a containment dam (see earlier Plate 11). Sand moves beyond the boundaries of the sand dump either mechanically (i.e. is loaded and dumped elsewhere) or is eroded down-slope or down-wind through the action of wind and rain. Waste rock is also moved mechanically and may occur as heaps. Fines washed from waste rock dumps have the shape of a flow, similar to slimes.

(b) Location of mine residue spillage

If the colour and shape resembled mine residue and it was contiguous to a MRD, or a pathway from an MRD could be distinguished (e.g. watercourse, trench or drainage line), then I judged it to be mine residue (Plate 12).

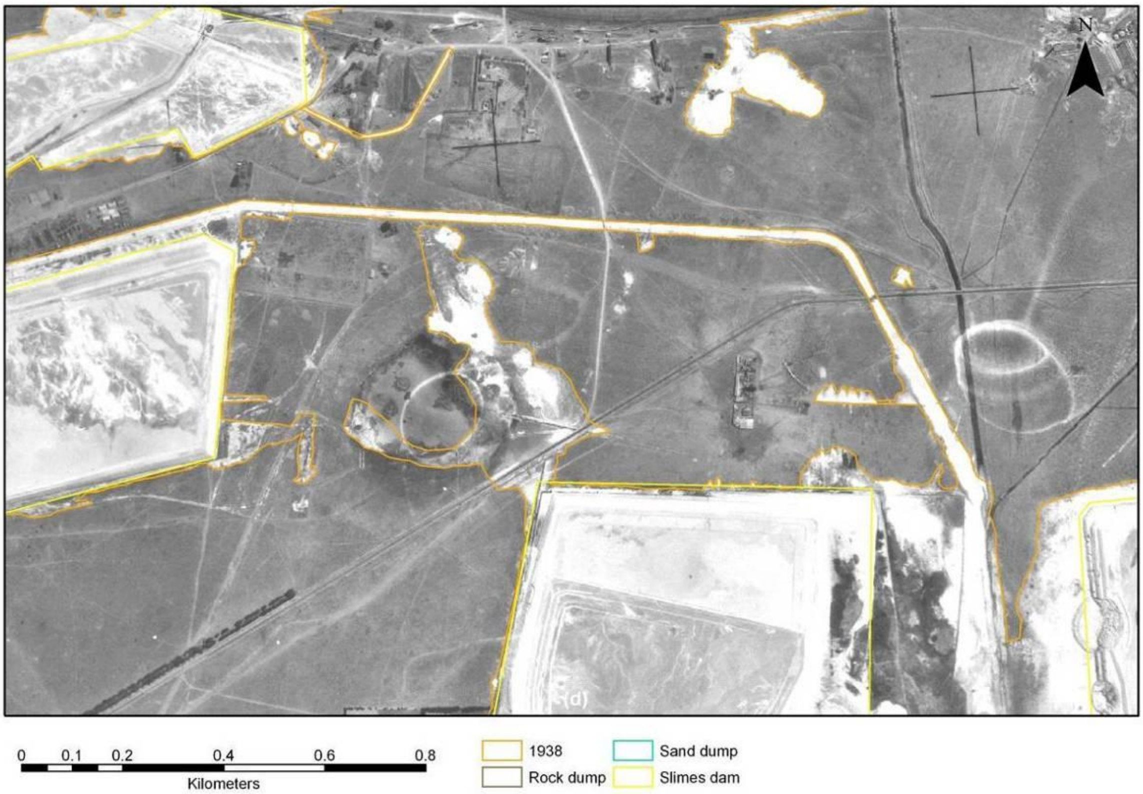

Plate 12 1938 aerial photograph showing pathways for water-borne transmission of mine residue along a watercourse, canal and trench

In the majority of cases it was not possible for me to assign spillage to one particular MRD as a point source because MRDs, and even different types of MRD, were often built directly adjacent to each another and sometimes even on top of one another (Plate 13). Therefore, I used the extent of mine residue spillage in 2003 simply as an indication of the magnitude of the secondary pollution source.

When comparing photographs from different dates I noted that side wall failures of slimes dams were often recognisable long after the spillages had been removed or masked (e.g. grown over or developed on) (Plate 14). It is reasonable to assume that these failures would have resulted in the release of slimes and process water; thus there is an increased likelihood of contamination of neighbouring land where such failures were observed compared to where no failures were observed. Therefore, I also recorded which slimes dams showed signs of having failed (i.e. top surface breach rather than just side-wall erosion) for all three dates.

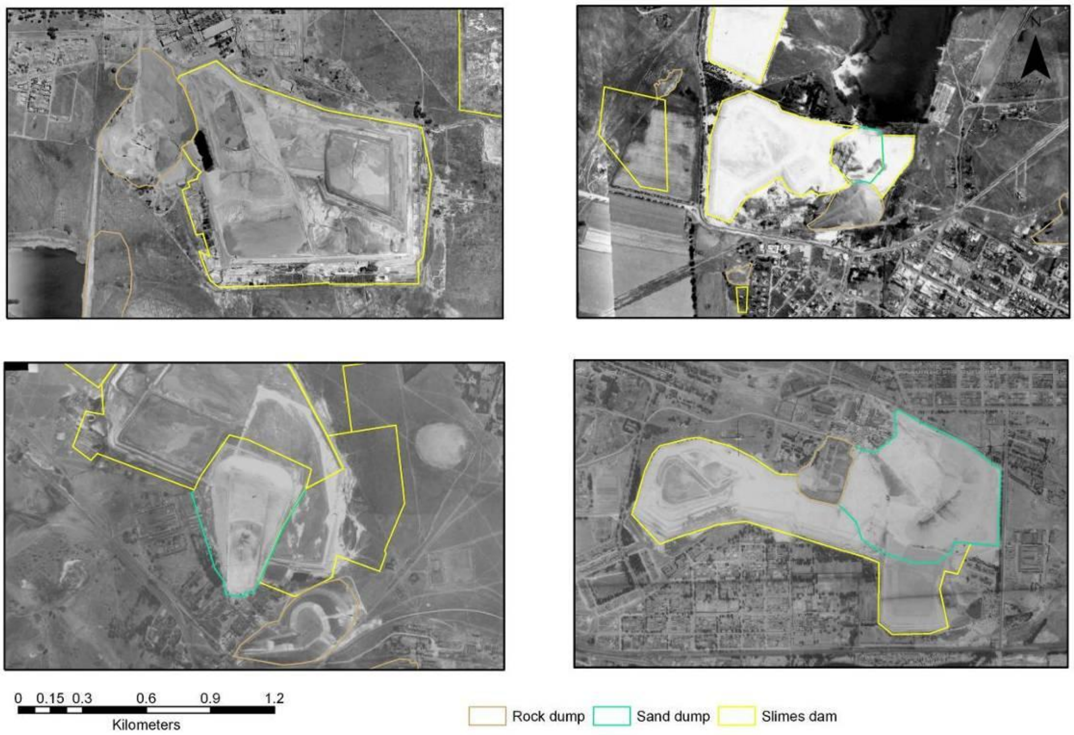

Plate 13 **Aerial photographs showing how different types of mine residue deposits could be combined**

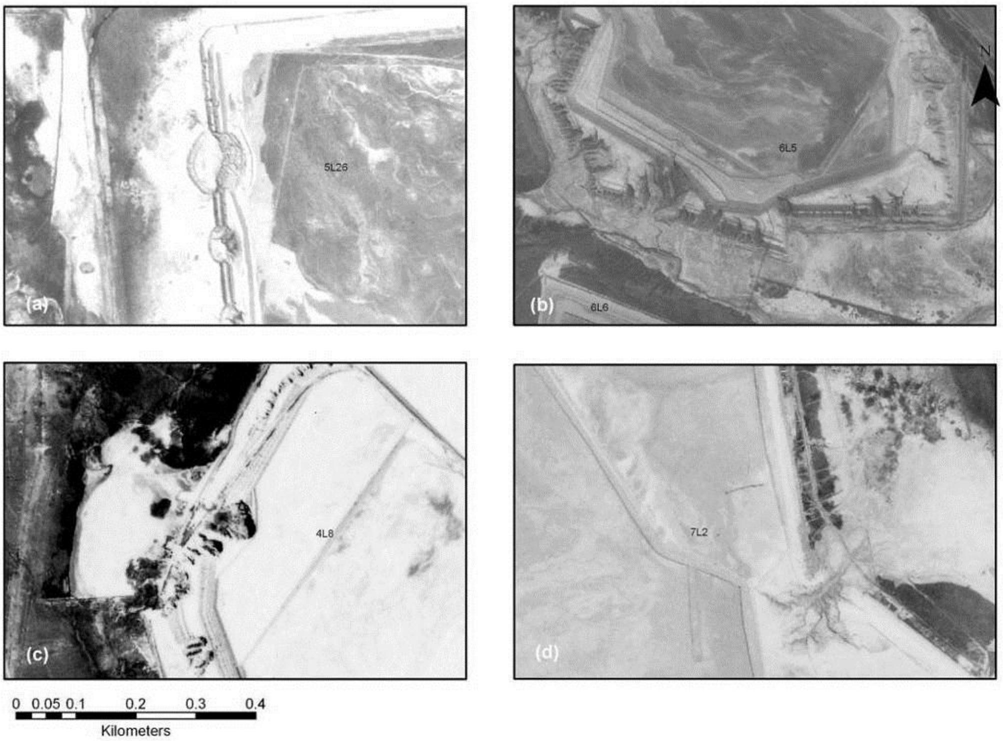

Plate 14 **Aerial photographs showing slimes dam wall failures (a) and (b) in 1938 and (c) and (d) in 1964**

3.6 Factors potentially affecting the detection of minerals by ASTER

Besides errors in interpretation and georeferencing, there are a number of other factors that can potentially affect the detection of minerals by ASTER. As detailed below, these include the spatial and spectral resolution of the sensor and seasonal influences on mineral formation, dispersion and masking (from detection). Errors with interpretation could lead to the thematic images indicating minerals that do not exist (and vice versa) and errors with georeferencing could show minerals in the wrong location. However ASTER images are georeferenced by the suppliers and the thematic images were ground-truthed for this study, which suggests that there are more likely to be occasions when ASTER does not detect minerals when they are present rather than the inverse.

3.6.1 Spatial and spectral resolution of the sensor

Although often referred to as having high spatial resolution (in comparison with other multi-spectral sensors), with only 30 m resolution in the SWIR the ASTER sensor is still not sensitive enough to detect small areas of minerals (Rockwell and Hofstra, 2008). Furthermore, it is unable to detect a number of minerals or low concentrations of specific minerals due to the wide band-width (Bedell, 2004). Although it was beyond the scope of my study, these factors can be examined by comparing the spatial extent of minerals detected by ASTER with airborne hyper spectral imagery.

3.6.2 Seasonal effect on the spatial extent of minerals and the probability of detecting them by ASTER

Various seasonal factors potentially influence the formation, dispersion and detection of minerals: soluble mineral formation depends on water and periods of drying (Naicker *et al*., 2003); rainfall and wind can disperse minerals (Naicker *et al*., 2003); vegetation growth increases chlorophyll and biomass, and fires remove biomass but deposit ash, all of which potentially mask the detection of minerals by ASTER. Therefore, to assess the effect of season on the use of multi-spectral remote sensing I used thematic imagery from the four ASTER images taken in two seasons (Austral spring – October, and Austral summer – January to March) within a 2-year period. Additional ASTER images were available but unsuitable due to the presence of cloud, which causes atmospheric noise and makes it difficult to distinguish between spectral signatures. Although the seasonal coverage might not have been optimal, which is an area for further study, the results should determine which of these two seasons is best for mineral formation and/or detection.

I assumed that only minor changes to the areas of minerals detected over the period assessed were as a result of removing from or adding to the sources of these minerals (i.e.

depositing on or removal of MRDs). This was a reasonable assumption because no new MRDs had been established in the study area since the earliest ASTER image (January 2002), with deposition being on top of existing facilities. Where MRDs were being reprocessed, removal to ground level could take five to ten years. For these tests I selected a sampling area covered by all four of the ASTER images taken on different dates (Time_Grid_36), containing 36 sampling plots (4×4 km quadrats) (Figure 8). For each mineral detected by ASTER I examined for any change in location or spatial extent between and within seasons. The overall null hypothesis was that mineral detection by ASTER was not influenced by season.

(a) Seasonal effect on mineral spatial extent

To determine if there was a seasonal effect on mineral extent, based on mineral formation, dispersion and/or masking, I calculated the area encompassed within each mineral theme (n=5) for all 36 plots on each ASTER image (n=4). The Friedman ANOVA was used to determine if there was a significant difference for the detection of each mineral between at least two occasions and the Wilcoxon matched pairs test was used to determine where any significant difference lay. The null hypothesis was that mineral extent was independent of seasonal influences.

(b) Seasonal effect on the probability of missing or detecting minerals using ASTER

I also determined if there was a seasonal influence on the probability of missing or detecting the minerals using ASTER. For these tests I measured (a) the area where each mineral was detected by any two ASTER images in the same location, (b) where it was detected at a particular location by one ASTER image but not the other (for the two ASTER images being compared), and (c) where it was not detected. The results were analysed using 2×2 tables to determine the McNemar statistic. The null hypothesis was that there was no seasonal difference in the probability of missing or detecting minerals using ASTER, based on mineral formation, dispersion and/or masking.

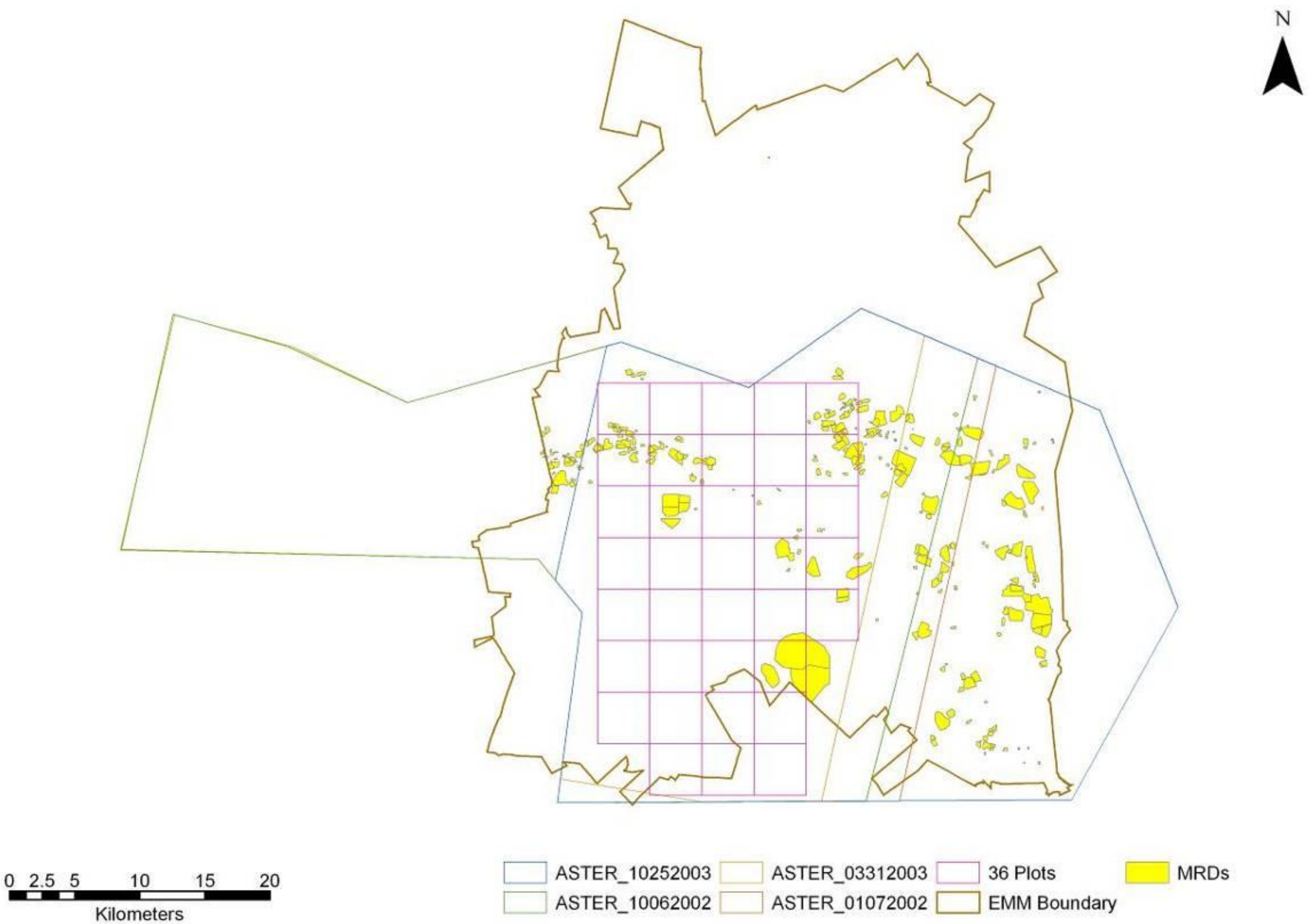

Figure 8 **Study area for ASTER seasonal changes - consisting of 36 plots covered by all four ASTER images**

(c) Seasonal effect on the probability of missing or detecting minerals beyond the mine residue deposit boundaries using ASTER

The assessment of signatures of mine residue contamination beyond the boundaries of the MRDs is a primary concern; however, in the previous analysis the large amounts of minerals on the MRDs can prevent other differences from being significant. Therefore, to determine if the probability of missing or detecting minerals using ASTER beyond the boundaries of the MRDs (i.e. mine residue spillage and associated contamination) is influenced by season, for each mineral I repeated the preceding exercise after excluding the area of, and minerals on, MRDs (including footprints). The null hypothesis was that there was no seasonal difference in the probability of missing or detecting minerals using ASTER. I once again used 2×2 tables to determine the McNemar statistic.

3.6.3 Masking of minerals by vegetation

NDVI was used to classify vegetation cover as either ‘actively growing vegetation’ or ‘no or dormant vegetation’ in order to determine whether mineral signatures are screened by actively growing vegetation. NDVI ranges between -1 and +1; however, the observed range is usually smaller: non-vegetated materials generally have a much lower NDVI (around 0) than dense vegetation (>0.7), since their near infrared and visible reflectance are more nearly equal (Tucker *et al.*, 2005).

I examined the effect of NDVI on the detection by ASTER of the five minerals. The results were analysed using 2-way (2×2) contingency tables to determine the X^2 statistic. The null hypothesis was that the detection of each mineral was independent of the detection of vegetation cover. Odds ratios were also calculated to summarise the relative association or lack of independence.

3.7 Associations between Mineral Detection and Risk Sources, Pathways and Receptors

3.7.1 Associations between mineral detection and risk sources

I added a portion of the ASTER dated 7 January 2002 (ASTER_01072002_Addition) to the one dated 25 October 2003 to obtain the maximum area within the EMM covered by the thematic ASTER images (Landuse_Minerals_Boundary) (Figure 9). The latter ASTER was selected because it provided the best coverage of the study area and the highest overall detection of minerals (most copiapite and jarosite; second most pyrophyllite and mincrust; although second least chlorite). Combining it with the ASTER dated 7 January 2002 was not ideal because although there was no significant difference between the aerial extents of minerals detected (except pyrophyllite) I did find a difference in the probability of detecting minerals (except jarosite) between these two dates (see Results, section 4.3). However, as it was a relatively small area I considered combining it to provide some coverage better than excluding it and having no coverage (Plate 15).

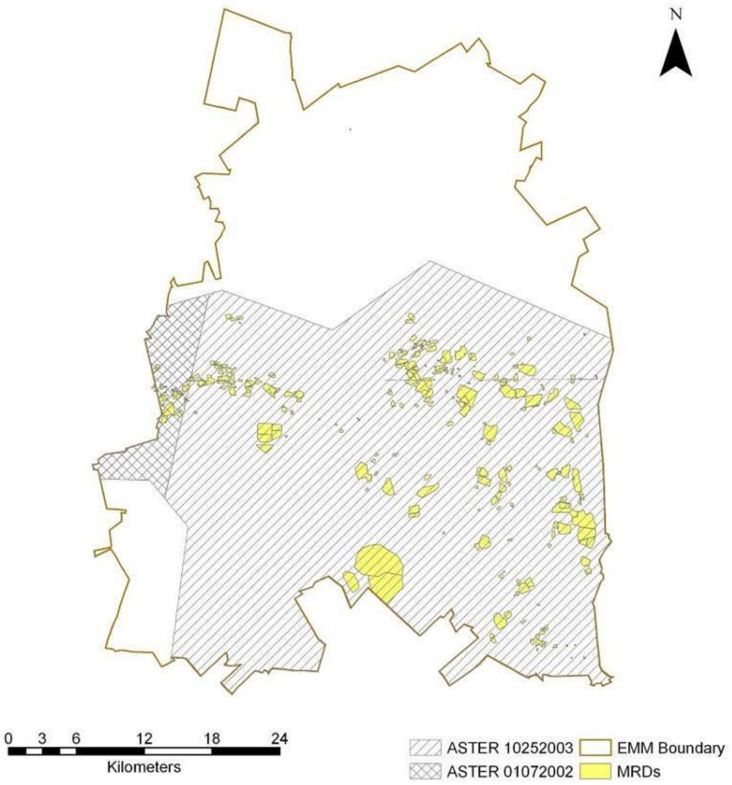

Figure 9 Study area for comparing mineral detection and risk components

(a) Association between mineral detection and type of mine residue deposit

I measured the areas where minerals were present (n=5) and where they were not for different types of MRD (n=3) (Plate 16). The results were analysed using 2-way (2×3) contingency tables to determine the X^2 statistic. The null hypothesis was that mineral detection was independent of MRD type. Odds ratios were also calculated to summarise the relative association or lack of independence

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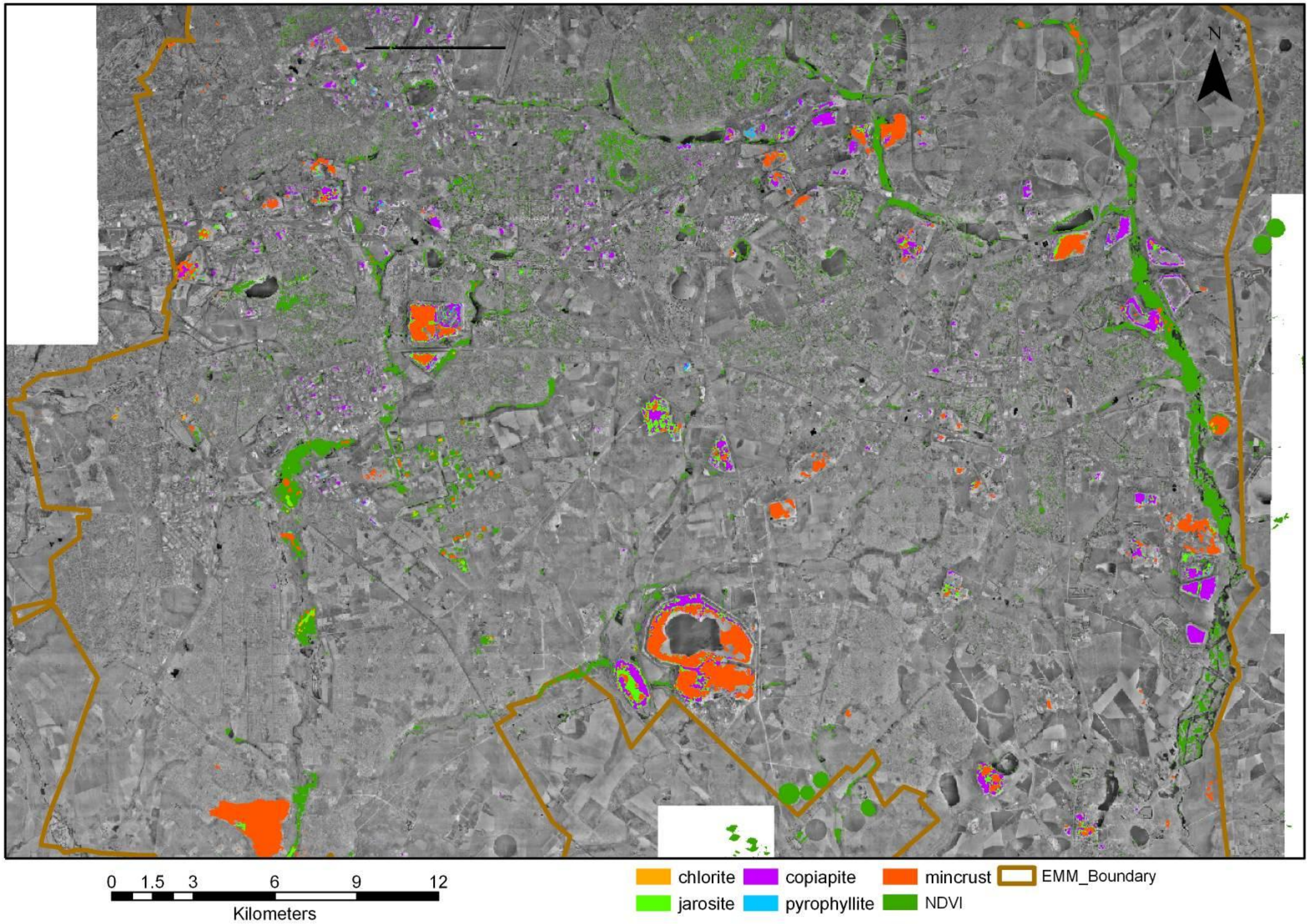

Plate 15 **ASTER for 25 October 2003 combined with portion from 7 January 2002 showing detectable minerals and NDVI in study area**

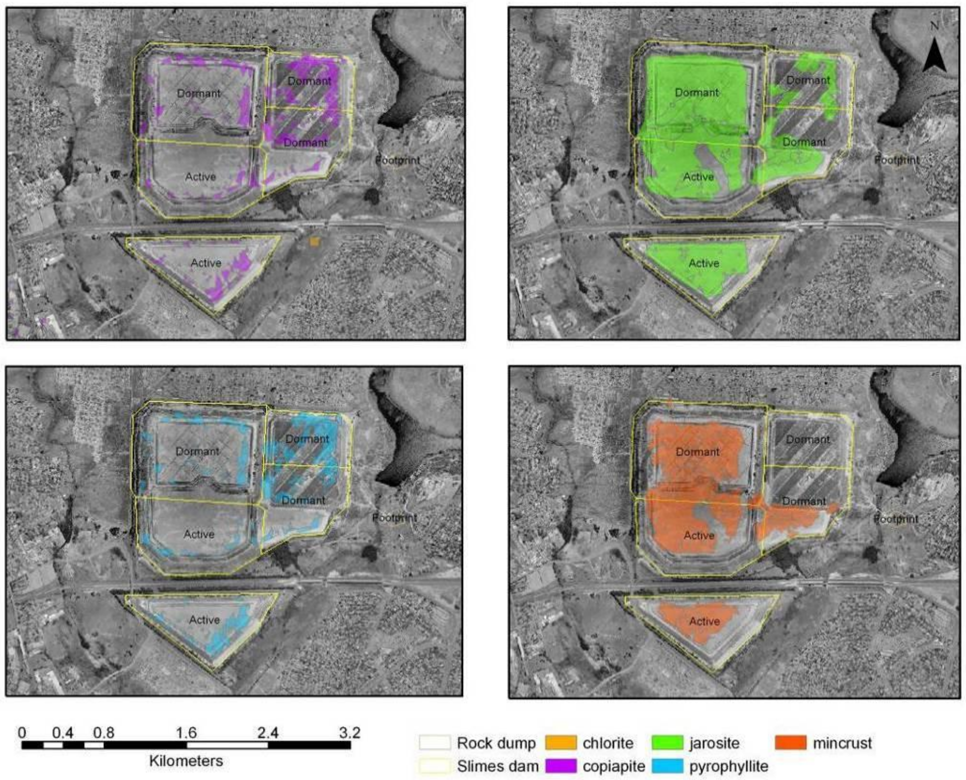

Plate 16 **Detail of ASTER showing example of detectable minerals on mine residue deposits**

(b) Association between mineral detection and different features of mine residue

To establish if there was a relationship between mineral detection (n=5) and various features of mine residue (n=3), I calculated (a) the area where each mineral occurred (i.e. overlaid) on the feature, (b) where each mineral occurred during one time but not the other (for both times), and (c) where each mineral was absent during both times. The features selected for assessment were: (i) remaining MRDs (i.e. those that were identified from 2003 aerial photographs as being active, dormant or reworking), (ii) slimes dam footprints, and (iii) spillage (Plate 17). The results were analysed using 2×2 contingency tables to determine the X^2 statistic. The null hypothesis is that mineral detection is independent of the mine residue feature.

(c) Associations between mineral detection and slimes dam footprints and spillage after excluding the influence of remaining mine residue deposits

When considering features other than MRDs the latter contribute to raising the amount of minerals beyond the feature so that often no significant association is found or the association is negative. However, the amount of mineral detected on the feature could still be significantly higher than “background”. Unfortunately it is now impossible to establish a pre-mining baseline of the extent of the selected minerals in the general landscape (which could have come from *inter alia* erosion of the reef outcrops); however, to remove the influence of the minerals that are associated with MRDs (i.e. those minerals that were detected within the MRD boundaries) I excluded the minerals within, and the area of, the MRDs (but including footprints) (Minerals_Boundary_Less_Remaining_MRDs) when examining slimes dam footprints and spillage. The results were analysed using 2×2 contingency tables to determine the X^2 statistic. The null hypothesis is that mineral detection is independent of the mine residue feature.

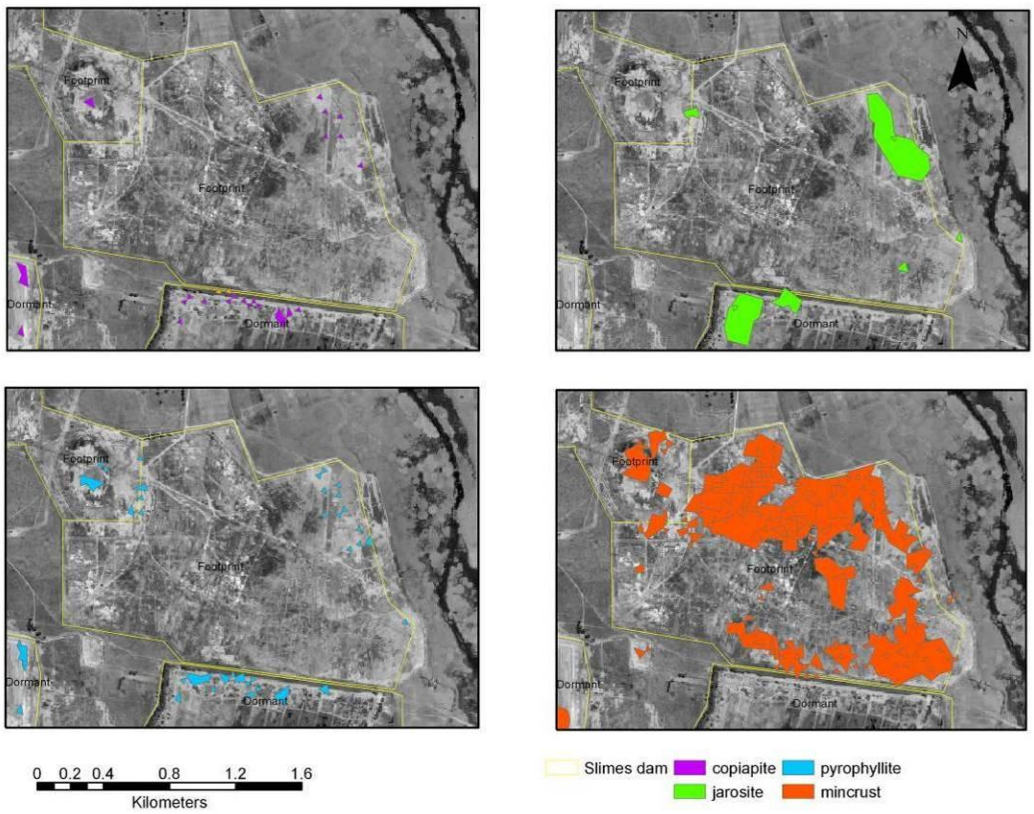

Plate 17 Example of detectable minerals on mine residue deposit footprints

3.7.2 Associations between mineral detection and risk pathways

The previous tests under subsection 7.1 (see Results, section 4.4) established that chlorite does not provide an indication of mine residue and mine residue contamination; therefore, for subsequent tests this mineral was excluded.

(a) Association between mineral detection and wetlands

Wetlands were examined for the detection of the selected signature minerals. For each mineral I measured the spatial extent (m^2) where the mineral occurred and did not occur within wetlands. Once again I excluded the minerals within, and the area of, the MRDs (but including footprints). The results were analysed using 2-way (2×2) contingency tables to determine the X^2 statistic. The null hypothesis is that mineral detection is independent of the feature (i.e. wetlands).

(b) Mine residue deposit sidewall failures

While modifying MRD boundaries from the 1938 and 1964 aerial photographs I identified the number of slimes dams that showed signs of sidewall failure (see earlier Plate 16). In many instances signs of spillage were visible; however, there were occasions when this was not the case in later photographs, which could be because the residue was removed or masked. In either event, water containing dissolved metals and NORMs would probably have been released (Coetzee *et al.*, 2006).

3.7.3 Associations between mineral detection and risk receptors

(a) Associations between mineral detection and selected land use categories

To establish if there is an association between mineral detection and selected categories of land use (i.e. business, industrial, informal settlement, formal residential, irrigated agricultural and rain-fed agricultural) identified from geographical data provided by EMM, for each mineral I measured the spatial area (m^2) within each land use where the mineral occurred and did not occur. The areas of all MRDs, including footprints, were excluded from these tests because minerals on these sites would bias the 'background' extent (as discussed in 3.7.1(c)). The results were analysed using 2×2 contingency tables to determine the X^2 statistic. The null hypothesis is that mineral detection is independent of the land use.

(b) Comparison between mineral detection on irrigated and rain-fed agricultural land

I used the area measurements from the previous test for two types of agricultural land (irrigated and rain-fed) to compare the detection of mincrust. The results were analysed using 2-way (2×2) contingency tables to determine the X^2 statistic. The null hypothesis is that the detection of mincrust is independent of the type of agricultural land. The odds ratio was also calculated to summarise the relative association or lack of independence.

3.8 Associations between Mineral Detection and Distance from Mine Residue Deposits

I measured the spatial area (m^2) for each mineral (n=5) within three distance categories (0 to 500 m, 500 to 1,000 m and >1,000 m) from MRDs. I also measured the extent where the mineral did not occur. The areas of all MRDs, including footprints, were excluded from these tests. The results were analysed using 2-way (2×3) contingency tables to determine the X^2 statistic. The null hypothesis is that mineral detection is independent of the distance from a

MRD. Odds ratios were also calculated to summarise the relative association or lack of independence.

3.9 Risk Assessment

3.9.1 Assignment of ratings

I used findings from the statistical analyses and literature search to assign relative ratings for incorporation into a simplistic semi-quantitative risk assessment model similar to that of Al-Adamat *et al.* (2003). I assigned relative ratings for hazard severity and receptor vulnerability ranging from 0 to 3; where 3 is high, 2 is medium, 1 is low and 0 is when there is no known hazard or vulnerability described. Although there is substantial literature on ARD from MRDs on the Witwatersrand, there is little distinction made between different classes of MRD.

I assumed that all MRDs are susceptible to wind erosion because physical covers have negligible presence in the study area and grass covers are short-lived on gold MRDs (Weiersbye *et al*., 2006b). Consequently, differential ratings for dust were only assigned between MRD classes and not between individual MRDs. A further assumption was that all gold and uranium mine residues in the EMM contain higher concentrations of pyrite, metals and NORMs than the surrounding lands, and no MRDs are lined. Thus, individual MRDs could be rated based on their proximity to aqueous pathways. The selected aqueous pathways were: (a) dolomitic substrata, which provide enhanced access for seepage to groundwater (Hodgson *et al.*, 2001); (b) perennial and seasonal watercourses — because of the potential for water and mass sediment-borne transfer of contaminants (Naicker *et al*., 2003; Tutu *et al.*, 2003; Winde, 2001); and (c) agriculture — although this land use is a receptor it can also constitute a secondary pathway for contaminants from water and soils into the diet of the general population (Jones *et al.*, 1990; Sutton *et al.*, 2006; Joubert, 2007). Other receptors selected were informal and formal settlements and industrial areas.

This study considered unmitigated risks posed by MRDs except where mitigation measures are considered the norm for a class of MRD, e.g. paddocks and trenches around active slimes dams reduce runoff when compared to a dormant dam; which, even if it had such measures, may not be maintained. A difficulty with rating pollution prevention measures for individual MRDs from aerial photography is determining their effectiveness. Paddocks and trenches are only effective if designed and operated to provide sufficient capacity (‘freeboard’) to prevent overflows. Furthermore, unless they are lined they can also lead to groundwater pollution via seepage. Therefore, I did not assess MRD specific pollution prevention measures. Where I believed slimes were used to construct a dam wall or infill part of the original watercourse between MRDs, based on observations from the historical aerial photographs, I gave them the same rating as slimes dams to be conservative.

3.9.2 MRD classification

The classification calculates the potential severity of the overall hazard posed by each MRD class by combining the relative ratings for each individual hazard (dust (d) and ARD (ard)) without weighting either one. I found dust and ARD signature minerals on many of the MRDs and on certain land uses in their vicinity, but could not assign the latter to specific sources. Thus the classification was also based on the literature, which I used to formulate assumptions (Table 11), which may be questioned and modified when updating this assessment.

Table 11 Assumptions for rating hazards associated with class of mine residue deposit based on references in the literature review

MRD	Class	Hazard	
		Dust (d)	**ARD (ard)**
Type	Rock	Process water used to allay dust at tipping point	Mainly un-mineralised ‘host’ rock
		Fine particles are washed into voids	Large inventories of fine particles and more permeable to oxygen than slimes dams
			Process water used to settle dump slopes
	Sand	No increase in ambient respirable dust but dust fallout is a nuisance	Oxidation of surface layer for sand dumps is deeper than for slimes dams
	Slimes	Easily eroded by wind	
Status	Active	Wet from deposition	Inadequate seepage control
	Reworking	Wet from hydraulic monitoring	Inadequate seepage control and disturbance increases pyrite oxidation
	Dormant	Dry surface between rainfall	Inadequate seepage control
Footprint type	Paddocks	No vegetation	Ponding creates hydraulic head
	Developed	Covered surface	Recharge from neighbouring areas
	Free-draining	Site grassed	Grassing increases infiltration

$$C = T + S + F + H \qquad (2)$$

Where:

C is the classification.

$T = (d_t + ard_t)/2$ where $_t$ denotes the rating assigned to the hazard for MRD type (Table 12).

$S = (d_s + ard_s)/2$ where $_s$ denotes the rating assigned to the hazard for MRD status (Table 12).

$F = (d_f + ard_f)/2$ where $_f$ denotes the rating assigned to the hazard for MRD footprint sort (Table 12).

Table 12 Ratings allocated to selected hazards associated with class of mine residue deposit

MRD	Class	Hazard		Mean
		Dust (d)	ARD (ard)	
Type (T)	Rock	1	2	1.5
	Sand	2	3	2.5
	Slimes	3	3	3
Status (S)	Active	2	3	2.5
	Reworking	2	3	2.5
	Dormant	3	3	3
Footprint type (F)	Paddocks	2	2	2
	Developed	0	1	0.5
	Free-draining	1	2	1.5

H is evidence of historical slimes dam failure. I allocated slimes dams that had failed a rating of H = 1 (rather than 3) because, although some of the spillage will remain in the sediments and/or soil for a long period of time (Mphephu, 2001), I assumed that it has less influence than MRD class. Where I did not observe any evidence of failure, H = 0.

3.9.3 Vulnerability assessment

I calculated the vulnerability index by combining the ratings for environmental pathways and receptors.

$$V = D + W + A + R \qquad (3)$$

Where:

V is the vulnerability index.

D is whether or not dolomite underlies part of the MRD (on dolomite = 3; off = 1).

W is related to proximity of the MRD to a watercourse (within = 3; <100 m = 2; >100 m = 1).

A is allocated according to distance of the MRD from agricultural land (within = 3; <500 m =2.25; >500 m but < 1,000 m = 1.5; >1,000 m = 0.75).

R is the combined rating for the receptor (i.e. land use). I examined informal settlements (IS), formal settlements (FS) and industrial areas (I) and derived ratings related to human exposure pathways for these land uses and distance from MRDs. For each land use I calculated the mean for human exposure pathways by rating each pathway between 0 and 3 (as described in 9.1 above) for the scenario that these land uses were taking place on the MRD or footprint, totalled and then divided by the number of potential pathways (i.e. 5) to provide a weighting ($_h$) between 0 and 3 (Table 13). I based the ratings on the assumption that small children may ingest contaminated soil when playing (EEA, 2002); children and the poor are most at risk and least able to cope (UNEP, 2002; EEA, 2002), with the latter having a low recovery ability; the 1–2% of the population in EMM that rely on springs and rivers for domestic water (SSA, 2001) stay in informal settlements; food plants are grown in home gardens of the poor and in nearby sediments; and there is uptake of contaminants by some vegetable species in these home gardens (Weiersbye and Cukrowska, 2008).

Table 13 Weightings allocated to land use based on human exposure pathways

Exposure Pathway	Informal Settlements (IS_h)	Formal Settlements (FS_h)	Industrial Areas (I_h)
Ingestion of water	3	1	0
Inhalation of particulates	3	3	2
Ingestion of plant material	3	3	0
Ingestion of soil or dust	3	3	1
Skin absorption	3	1	0
Total	15	11	3
Weighting (total/5)	3	2.2	0.6

From the above assessment I determined that industrial areas were lower vulnerability (i.e. <1) so I excluded them from the rating, thus:

$$R = (IS_h \times IS_d) + (FS_h \times FS_d) \qquad (4)$$

Where ($_d$) is the weighting allocated according to the distance of the land use to the MRD, such that land uses on the MRD or footprint were allocated the full rating, closer than 500 m were given 0.75, further than 500 m but closer than 1 000 m were given 0.5 and further than 1 000 m received 0.25 (Table 14). I selected these broad distance categories based on the findings of Witkowski and Weiersbye (1998a), for attenuation of soil pollution with distance around 56 slimes dam sites; anticipated metal solubility in Highveld soils and sediments (Naicker *et al*., 2003), and because beyond 1000 m, tailings dust levels can no longer be distinguished from ambient air quality (GDACE, 2005).

Table 14 Vulnerability ratings assigned according to mine residue deposits proximity to land use

Land Use	**Ratings at Different Distances from MRDs**			
	0 m	**< 500 m**	**< 1000 m**	**> 1000 m**
Informal settlement (IS_d)	3	2.25	1.5	0.75
Formal settlement (FS_d)	2.2	1.65	1.1	0.55

3.9.4 Risk evaluation

I calculated the risk index by multiplying the outputs of the MRD hazard classification and land use vulnerability assessment. For this study the minimum possible risk index (to the nearest whole number) is 8 and the maximum is 99. I divided this range into four equal classes: 8–30 (lower risk); 31–53 (medium risk); 54–76 (higher risk); and 77–99 (much higher risk).

CHAPTER 4

4 RESULTS

The results of this study have been published as follows:

Sutton, M.W., Weiersbye, I.M., Galpin, J.S and Heller, D., 2006. A GIS-based history of gold mine residue deposits and risk assessment of post-mining land uses on the Witwatersrand Basin, South Africa. In: A. B. Fourie and M. Tibbett (eds.), Mine Closure 2006: *Proceedings of the 1st International Seminar on Mine Closure*, Perth, ISBN: 0-9756756-6-4, pp. 667–678.

Sutton, M.W. and Weiersbye, I.M., 2007. South African legislation pertinent to gold mine closure and residual risk. In: A.B. Fourie, M. Tibbett and J. Wiertz (eds.), Mine Closure 2007: *Proceedings of the 2nd International Seminar on Mine Closure*, Santiago, ISBN: 978-0-9804185-0-7, pp. 89–102.

Sutton, M.W. and Weiersbye, I.M., 2008. Land use after mine closure – Risk assessment of gold and uranium mine residue deposits on the eastern Witwatersrand, South Africa. In: A.B. Fourie, M. Tibbett, I.M. Weiersbye and P.J. Dye (eds.), Mine Closure 2008: *Proceedings of the 3rd International Seminar on Mine Closure*, Johannesburg, ISBN: 978-0-9804185-6-9, pp. 363–374.

4.1 Categorisation and Extent of Mine Residue Deposits and Spillage

The EMM covers an area of some 192 339 ha of which 16 917 ha or 8.8% is zoned as mining. MRDs, past and present, are generally located within or in proximity of the mining belt (Figure 10).

I determined that MRDs have covered/cover an area of 7 956.5 ha (4.1%), with slimes dams (including slimes dam footprints) totalling 6 742.4 ha (3.5%) occupying the majority of this area (Table 15, Figure 11). I plotted a further 1 175.0 ha of mine residue spillage from the 2003 photographs.

Table 15 Mine residue deposit type, status and extent in Ekurhuleni Metropolitan Municipality

MRD : Area (Hectares)						
Type	**Status**	**Number of (N)**	**Median**	**Minimum**	**Maximum**	**Total**
All MRDs	**Total**	**287**	**9.7**	**0.4**	**893.1**	**7956.5**
Calcine dam	**Sub total**	**1**	**28.7**	**28.7**	**28.7**	**28.7**
	Dormant	**1**	**28.7**	**28.7**	**28.7**	**28.7**
Slimes constructed feature	**Sub total**	**4**	**6.2**	**5.7**	**56.9**	**74.9**
	Dam wall	**1**	**5.7**	**5.7**	**5.7**	**5.7**
	Land infill	**3**	**6.3**	**6.1**	**56.9**	**69.3**
Overburden	**Sub total**	**7**	**3.4**	**1.4**	**4.2**	**20.5**
	Active	**7**	**3.4**	**1.4**	**4.2**	**20.5**
Sand dump	**Sub total**	**42**	**10.9**	**0.5**	**36.8**	**525.1**
	Dormant	**7**	**15.3**	**3.8**	**18.4**	**89.7**
	Reworking	**14**	**22.2**	**5.0**	**36.8**	**295.8**
	Footprints	**21**	**5.2**	**0.5**	**16.5**	**139.6**
Rock dump	**Sub total**	**101**	**4.1**	**0.4**	**19.6**	**564.9**
	Dormant	**4**	**4.8**	**1.2**	**5.2**	**16.1**
	Dam wall	**1**	**11.5**	**11.5**	**11.5**	**11.5**
	Reworking	**16**	**8.2**	**2.8**	**19.6**	**147.6**
	Footprints	**80**	**2.5**	**0.4**	**18.5**	**389.7**
Slimes dam	**Sub total**	**132**	**20.9**	**0.4**	**893.1**	**6742.4**
	Active	**9**	**82.7**	**19.3**	**893.1**	**1476.7**
	Dormant	**31**	**31.4**	**1.9**	**145.1**	**1488.3**
	Reworking	**39**	**24.9**	**0.5**	**577.0**	**2073.3**
	Footprints	**53**	**14.5**	**0.4**	**226.2**	**1704.0**

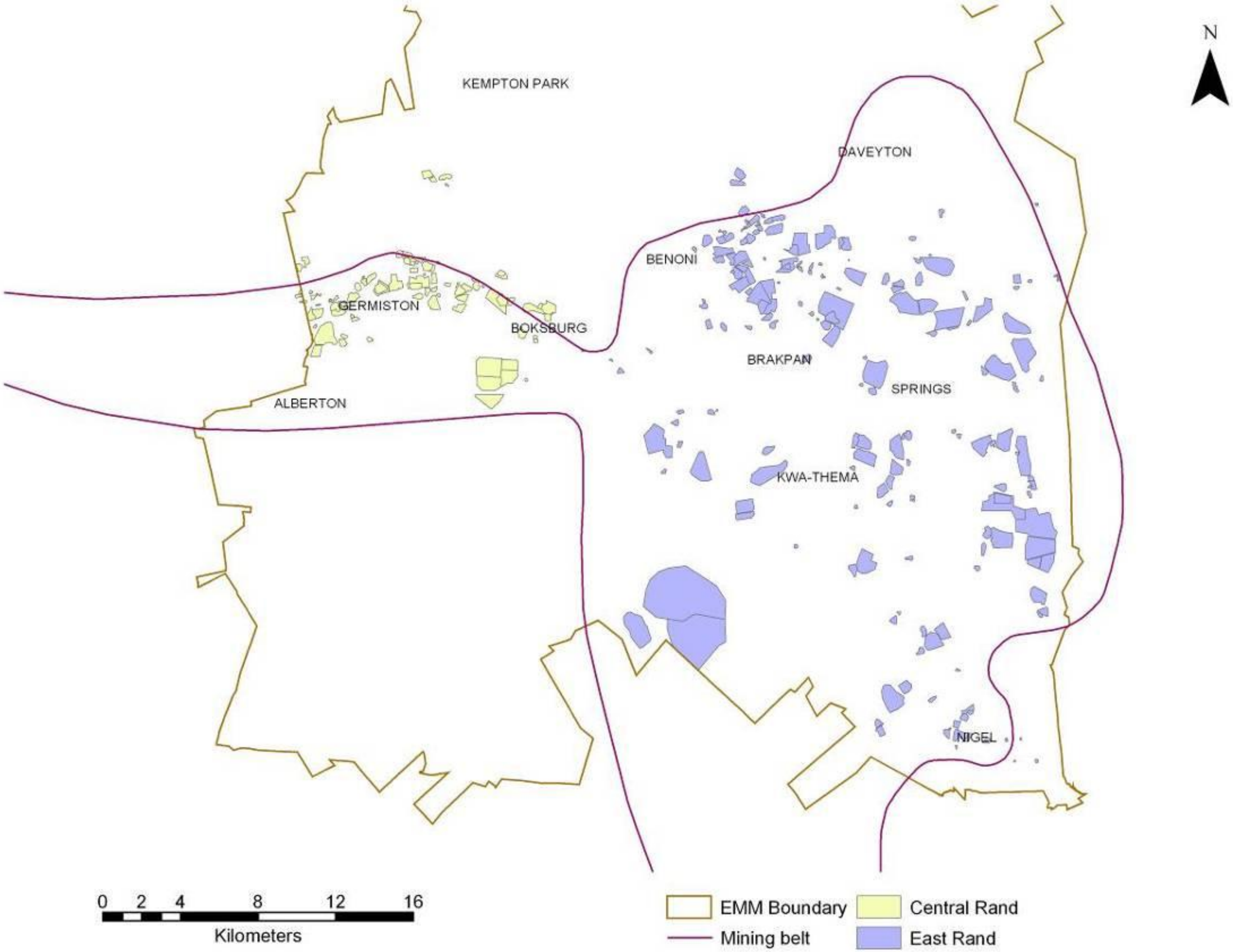

Figure 10 Mine residue deposits within the mining belt of Ekurhuleni Metropolitan Municipality

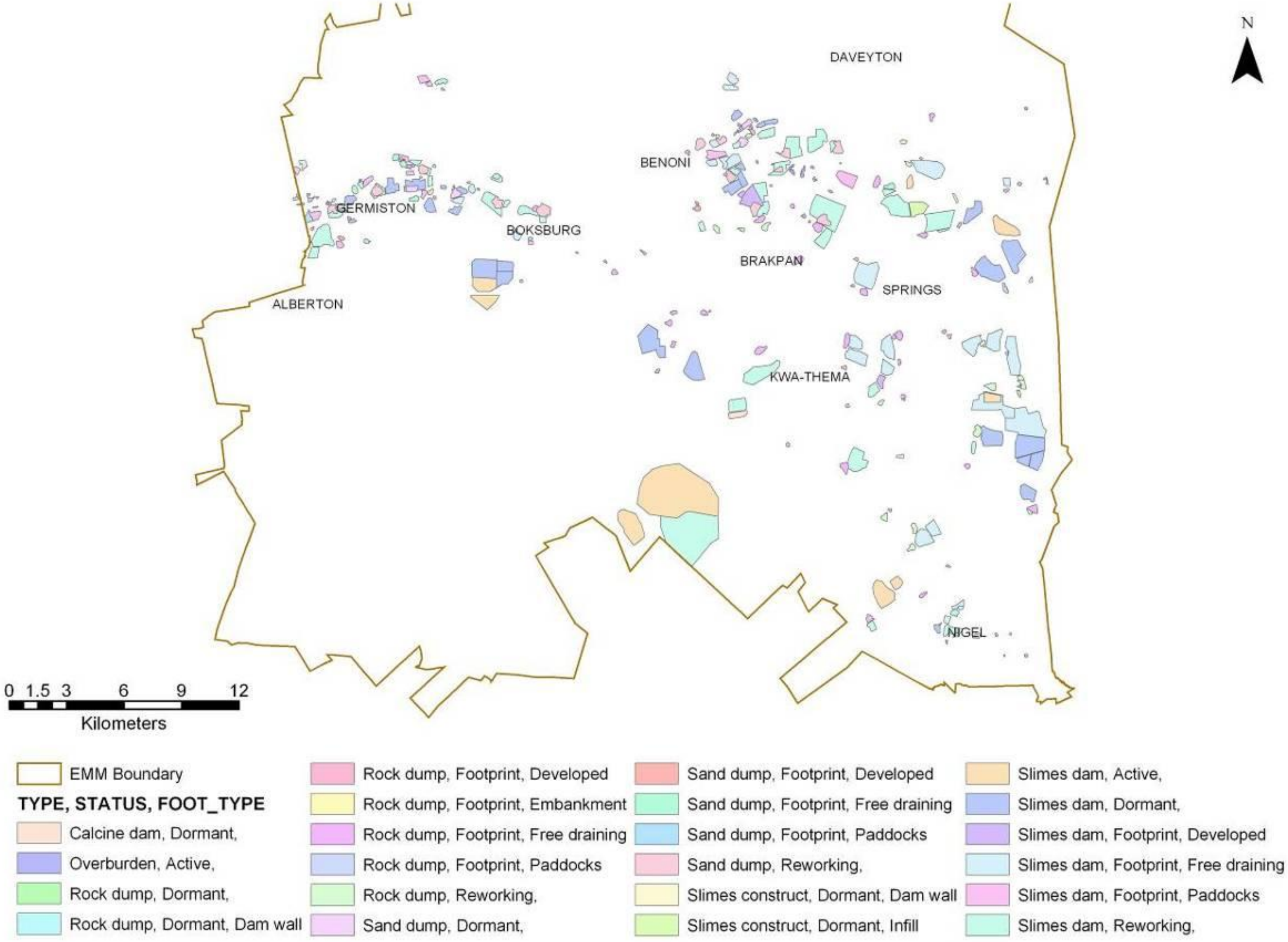

Figure 11 **Mine residue deposits categorised according to type and status in 2003**

4.2 Proximity of Mine Residue Deposits to Selected Exposure Pathways and Land Uses

I found that 53% of gold MRDs were situated within 100 m of a watercourse with 52% of these (i.e. 27% of the total) originally built within the watercourse (Plate 18). I also found that 15% of MRDs were constructed on dolomites (Table 16).

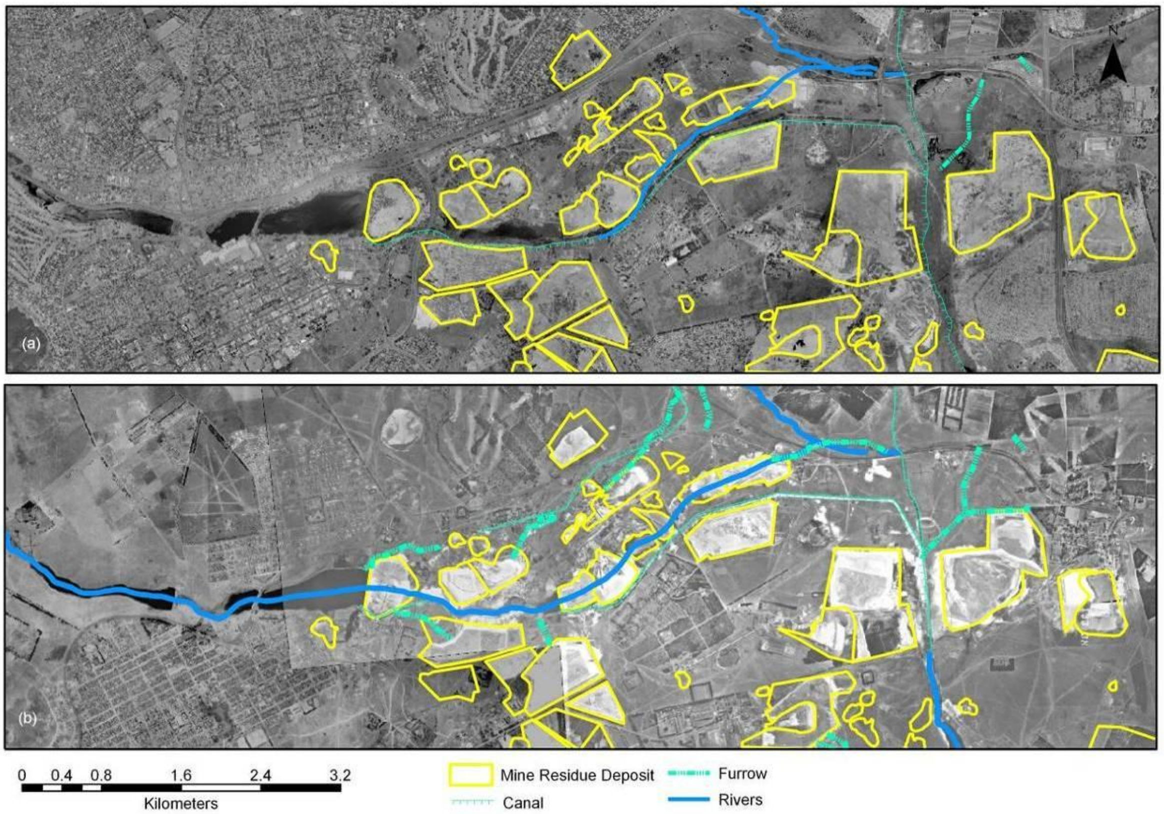

Plate 18 **(a) Watercourses according to drainage in 2003 aerial photograph, (b) 1938 aerial photographs enable pre-mining channels to be identified**

Table 16 **Proximity of mine residue deposits to selected exposure pathways**

Situation (N=287)	In or On		Within 100m	
	Number	%	Number	%
Watercourse	78	27	151	53
Dolomites	42	15		

Informal settlements were located on or directly bordering 6% of MRDs, with 28% within 500m of MRDs and 41% within 1 000 m. A large percentage (88%) of MRDs were found within 1 000 m of formal residential areas, 71% within 500 m and formal settlements were located on or directly bordering 5% of MRDs. Just under a quarter (23%) of MRDs were located within 500 m of agricultural land and 35% within 1 000 m; and industrial land use was on 9% of MRDs, with 40% of MRDs being within 500 m of industrial areas and 61% within 1 000 m (Table 17).

Table 17 Proximity of mine residue deposits to selected land uses

Situation (N=287)	Located in		Within 500 m		Within 1 000 m	
	Number	%	Number	%	Number	%
Informal residential area	16	6	80	28	117	41
Formal residential area	13	5	204	71	252	88
Agricultural area	6	2	65	23	100	35
Industrial area	25	9	115	40	174	61

4.3 Factors Potentially Affecting the Detection of Minerals by ASTER

4.3.1 Seasonal effect on the spatial extent of minerals and the probability of detecting them by ASTER

(a) Seasonal effect on mineral spatial extent

From the measurements taken for the spatial extent of each mineral theme (n=5), for all 36 plots on each ASTER image (n=4), I determined the descriptive statistics (Table 18).

Table 18 Descriptive statistics for spatial extent (hectares) of minerals during different seasons

Mineral / Time	No. of plots with data	Spatial extent (hectares)			
		Sum	Median	Min	Max
Chlorite					
Time 1	24	108.2162	1.3656.1	0.0572	37.9407
Time 2	6	13.0180	0.7426.5	0.1215	8.6753
Time 3	7	77.0374	1.3116.8	0.1233	53.3358
Time 4	19	37.4523	0.4312.0	0.0127	11.8235
Copiapite					
Time 1	16	359.9628	8.7653.4	0.1215	147.6942
Time 2	17	329.5936	5.0247.7	0.2715	112.0723
Time 3	19	470.5942	8.1996.7	0.0616	189.6408
Time 4	23	524.6039	17.1331.4	0.0616	132.5212
Jarosite					
Time 1	24	943.3037	5.2782.5	0.2113	390.1542
Time 2	20	818.3296	11.5640.2	0.1804	360.0180
Time 3	16	685.3451	13.3220.2	0.7225	304.1097
Time 4	21	1013.3673	13.8969.0	0.5181	405.3073
Pyrophyllite					
Time 1	14	174.7233	4.7474.4	0.0616	93.0133
Time 2	18	520.5463	11.3324.4	0.4502	164.3827
Time 3	12	238.4751	6.2922.6	0.4914	97.3106
Time 4	22	480.5578	7.8199.9	0.0616	135.8837
Mincrust					
Time 1	31	951.9995	5.3467.9	0.0616	298.2538
Time 2	21	243.7162	1.5103.9	0.0256	134.0392
Time 3	21	192.0569	1.2288.6	0.0616	120.0929
Time 4	20	658.7725	16.5495.1	0.0044	225.8327

Where: Time 1: - 7 January 2002 (summer); Time 2: - 6 October 2002 (early spring); Time 3: - 31 March 2003 (late summer); and Time 4: - 25 October 2003 (spring).

From the box and whisker plots it was apparent that the data was skew (Figures 12a-12e).

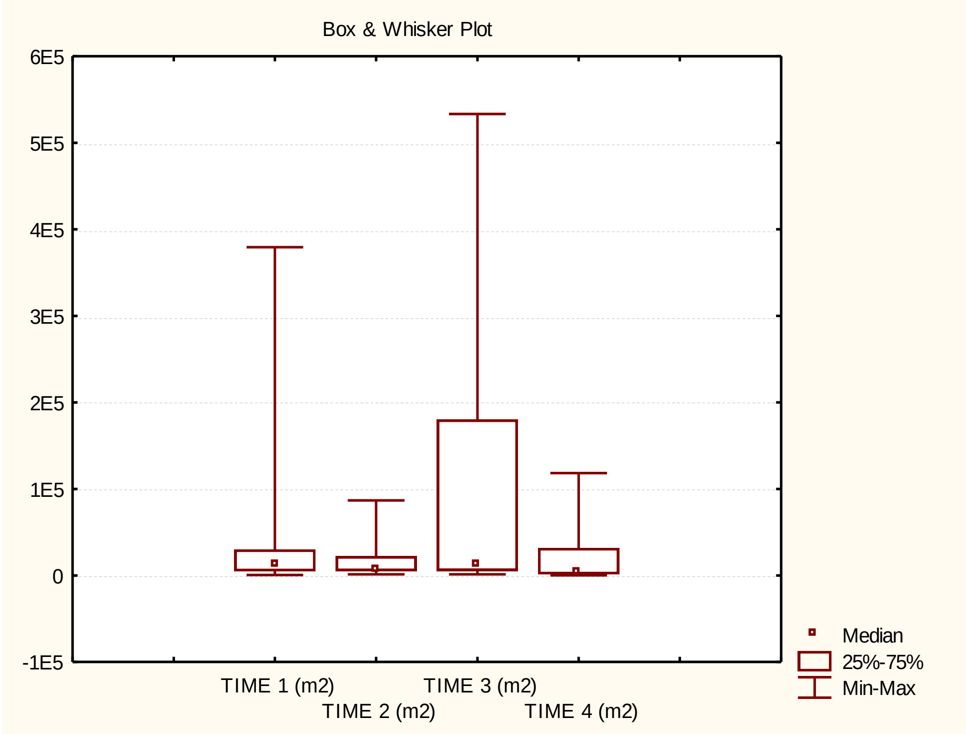

Figure 12a Box and whisker plots for spatial extent of chlorite detected by ASTER at different seasons

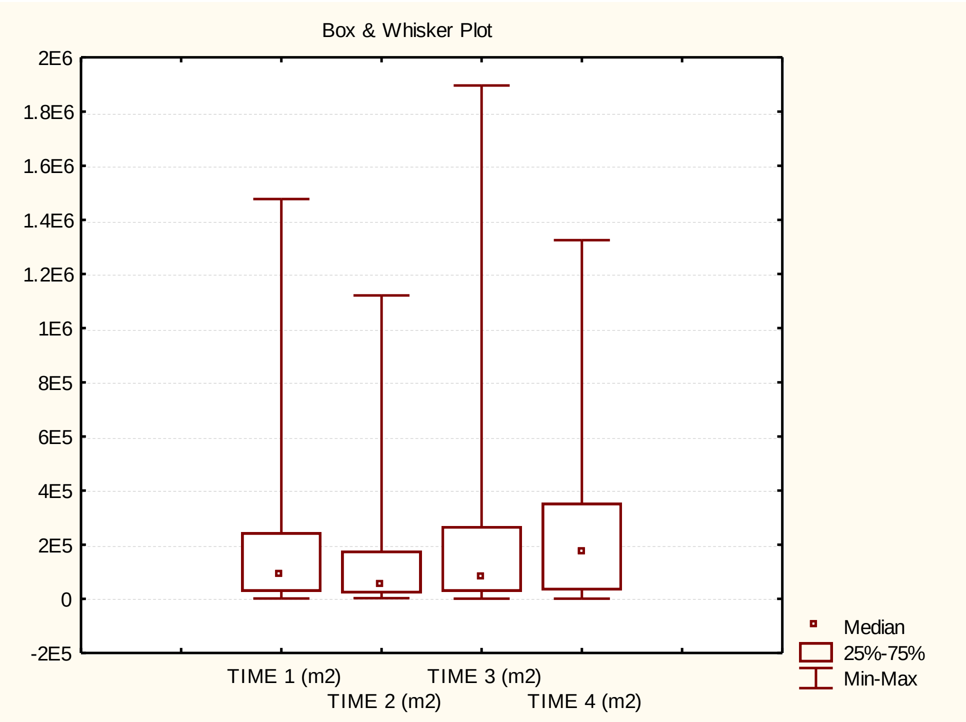

Figure 12b Box and whisker plots for spatial extent of copiapite detected by ASTER at different seasons

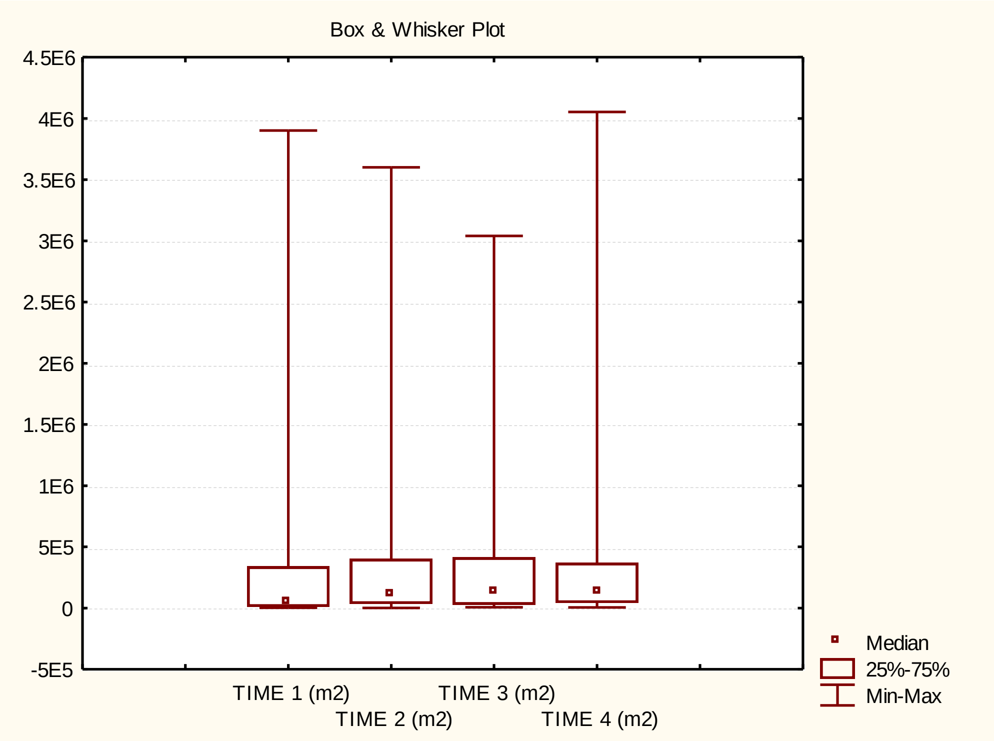

Figure 12c Box and whisker plots for spatial extent of jarosite detected by ASTER at different seasons

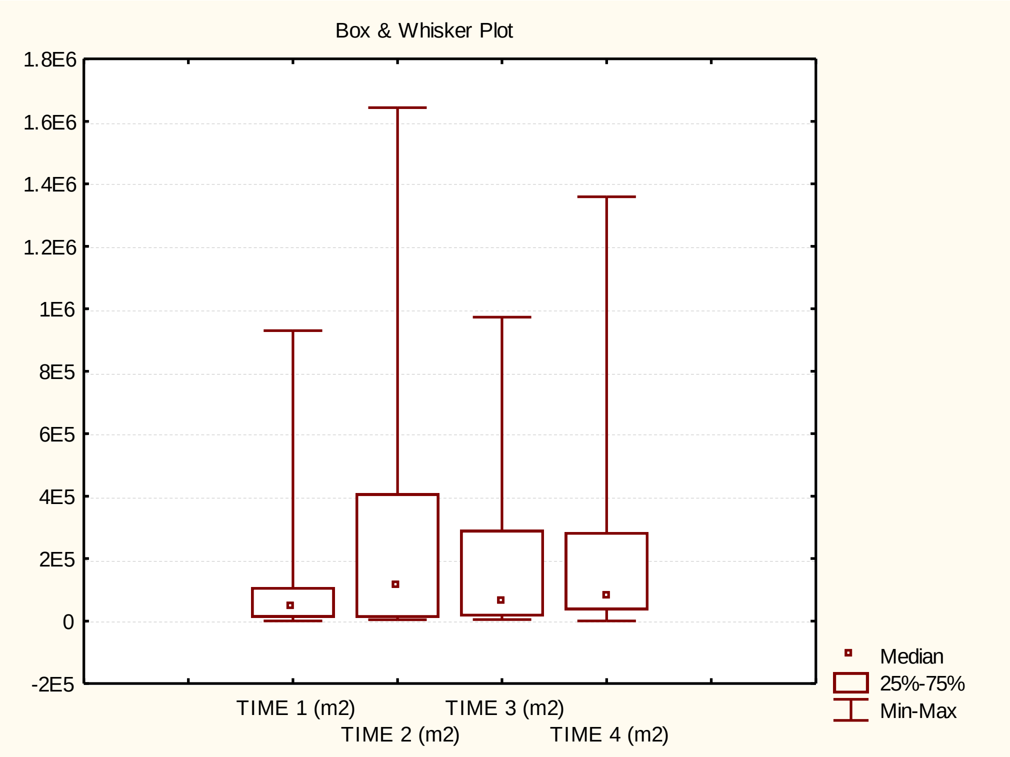

Figure 12d Box and whisker plots for spatial extent of pyrophyllite detected by ASTER at different seasons

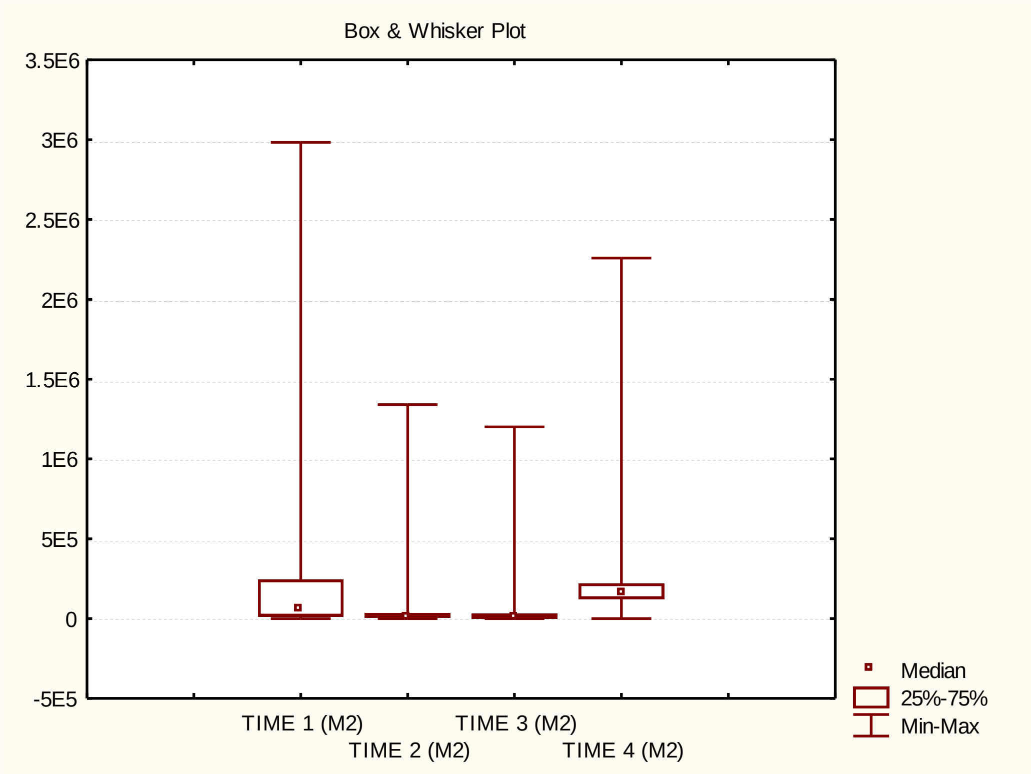

Figure 12e Box and whisker plots for spatial extent of mincrust detected by ASTER at different seasons

Using the Friedman ANOVA and Wilcoxon matched pairs tests, I determined the *p* values for the extent of mineral detected when comparing between seasons (Table 19, second row). The null hypothesis was that mineral extent was independent of seasonal influences, i.e. that there was no difference in the median amount of minerals detected on the four occasions. For chlorite there was no evidence to reject the null hypothesis of no difference in the spatial extent of mineral detected. However, for the other four minerals (copiapite, jarosite, pyrophyllite and mincrust) the null hypothesis of no difference was rejected; there was a significant difference in the spatial extent of mineral detected between at least two of the occasions for each of these four minerals. I therefore used the Wilcoxon matched pairs test to determine where the differences lay (Table 19, rows 3-8). For multiple comparison tests it was necessary to use an adjusted p value in testing, therefore I used the Bonferoni adjustment, which uses the level at which I was testing (i.e. 5%) divided by the number of tests (i.e. 6). Thus, only p values $< 0.05/6 = 0.0083$ were significant.

Table 19 Significance (*p* values) from the Friedman ANOVA and Wilcoxon matched pairs tests for the extent of mineral detected when comparing between seasons

Times	Chlorite	Copiapite	Jarosite	Pyrophyllite	Mincrust
1-2-3-4	0.0858	**0.0014**	**0.0003**	**<0.0001**	**<0.0001**
1-2		0.9176	0.7475	**0.0010**	**0.0019**
1-3		**0.0052**	**0.0045**	0.2132	**<0.0001**
1-4		0.0640	0.0429	**0.0010**	0.3317
2-3		0.0615	0.0557	**0.0022**	0.3305
2-4		**0.0015**	0.0929	0.9133	**0.0010**
3-4		0.0929	**0.0004**	**0.0029**	**0.0015**

Where: Time 1: - 7 January 2002 (summer); Time 2: - 6 October 2002 (early spring); Time 3: - 31 March 2003 (late summer); and Time 4: - 25 October 2003 (spring).

The large difference in the number of observations (i.e. plots available for analysis because minerals were detected within them on all four occasions) was probably why there was no significance for chlorite on the overall test (Table 20).

Table 20 Number of plots available for analysis (i.e. mineral detected by ASTER) by the Friedman ANOVA and Wilcoxon matched pairs tests for the extent of mineral detected when comparing between seasons

Times	Chlorite	Copiapite	Jarosite	Pyrophyllite	Mincrust
1-2-3-4	3	14	16	11	11
1-2		16	19	14	21
1-3		16	16	11	21
1-4		14	18	14	20
2-3		17	16	12	14
2-4		15	17	18	17
3-4		17	16	12	13

For 12 out of the 24 tests there was no reason to reject the null hypothesis of no difference in the spatial extent of mineral detected between seasons. For copiapite there was a significant difference in detection between Times 1 and 3 (summer and late summer) and between Times 2 and 4 (early spring and spring) with no difference between the other groupings. The lowest overall detection of copiapite was in early spring (Time 2) after the dry winter (however, 6 mm fell on the day of the ASTER) while the highest overall detection was just after the first good spring rains (Time 4 - 41 mm rainfall during the preceding 10 days but 4 dry days directly before the ASTER).

Conversely, for pyrophyllite there was no difference in detection between Times 1 and 3 (summer and late summer) or between Times 2 and 4 (early spring and spring) but there was a significant difference between the other groupings. The lowest overall detection of pyrophyllite was at the beginning of summer and the end of summer with no significant difference between the two. The highest detection of pyrophyllite was in early spring after a dry winter period and before the spring rains. The second highest detection of pyrophyllite was just after the first spring rains, with which there was also no significant difference.

For jarosite, there was a significant difference between Times 1 and 3 (summer and late summer) and 3 and 4 (late summer and spring). The lowest overall detection of jarosite was at the end of the summer with the second lowest overall detection at the beginning of the spring. As with copiapite, the highest overall detection of jarosite was just after the first good spring rains (Time 4), but this had no significant difference with either early spring or summer.

Then, for mincrust there was no difference in detection between Times 1 and 4 (spring and summer) or between Times 2 and 3 (early spring and late summer) but there was a significant difference between the other groupings. More mincrust was detected on the former occasions and less on the latter with maximum spatial extent in summer but this had no significant difference with spring.

(b) Seasonal effect on the probability of missing or detecting minerals using ASTER

The null hypothesis was no seasonal difference in the probability of missing or detecting the mineral, based on mineral formation, dispersion and/or masking. The results of the McNemar tests are summarised in Table 21; where: a = 1st time listed, b = 2nd time listed. Once again, for multiple comparison tests I used the Bonferoni adjustment, thus, only p values < 0.0083 were significant.

Table 21 Spatial extent (hectares) and significance (*p* values) from the McNemar test for comparing seasonal effect on the probability of missing or detecting minerals using ASTER

Mineral / Time a-b	Present both	Present a Absent b	Absent a Present b	Absent both	*p*
Chlorite					
1-2	1	107	12	57480	**<0.0001**
1-3	1	107	76	57416	0.0219
1-4	1	107	36	57456	**<0.0001**
2-3	2	11	75	57512	**<0.0001**
2-4	0	13	37	57550	**0.0007**
3-4	0	77	37	57486	**0.0002**
Copiapite					
1-2	185	175	145	57095	0.0935
1-3	214	146	257	56983	**<0.0001**
1-4	145	215	380	56860	**<0.0001**
2-3	193	137	278	56992	**<0.0001**

Mineral / Time a-b	Present both	Present a Absent b	Absent a Present b	Absent both	*p*
2-4	120	210	405	56865	**<0.0001**
3-4	198	273	327	56802	0.0275
Jarosite					
1-2	688	255	130	56527	**<0.0001**
1-3	571	372	114	56543	**<0.0001**
1-4	736	207	277	56380	**0.0015**
2-3	515	303	170	56612	**<0.0001**
2-4	662	156	351	56431	**<0.0001**
3-4	613	72	400	56515	**<0.0001**
Pyrophyllite					
1-2	110	65	411	57014	**<0.0001**
1-3	49	126	189	57236	**0.0004**
1-4	61	114	420	57005	**<0.0001**
2-3	127	394	111	56968	**<0.0001**
2-4	188	333	293	56786	0.1099
3-4	98	140	383	56979	**<0.0001**
Mincrust					
1-2	115	837	129	56519	**<0.0001**
1-3	91	861	101	56547	**<0.0001**
1-4	250	702	409	56239	**<0.0001**
2-3	64	180	128	57228	**0.0037**
2-4	119	125	540	56816	**<0.0001**
3-4	114	78	545	56863	**<0.0001**

For chlorite, Time 1-3 (summer and late summer), copiapite, Times 1-2 (summer and early spring) and 3-4 (late summer and spring) and pyrophyllite, Time 2-4 (early spring and spring) there was no evidence to reject the null hypothesis of no difference. However, for all other seasonal comparisons the null hypothesis of no difference was rejected; there was a seasonal difference in the probability of missing or detecting the mineral.

From these results I found that there was higher probability of detecting chlorite in summer and late summer; copiapite in spring and late summer; jarosite in spring; pyrophyllite in early spring and spring; and mincrust in summer, followed by spring.

(c) Seasonal effect on the probability of missing or detecting minerals beyond mine residue deposit boundaries using ASTER

The null hypothesis was that there was no seasonal difference in the probability of missing or detecting the mineral beyond mine residue deposit boundaries, based on mineral formation, dispersion and/or masking. The results of the McNemar test comparing the detection of minerals beyond the MRD boundaries (i.e. possibly related to spillage and contamination) in different seasons are summarised in Table 22, where: a = 1st time listed, b = 2nd time listed. Similarly to the previous tests, only p values < 0.0083 were significant.

Table 22 Spatial extent (hectares) and significance (*p* values) from the McNemar test for comparing seasonal effect on the probability of missing or detecting minerals beyond mine residue deposit boundaries using ASTER

Mineral / Time a-b	Present both	Present a Absent b	Absent a Present b	Absent both	*p*
Chlorite					
1-2	1	96	1	57502	**<0.0001**
1-3	0	97	0	57503	**<0.0001**
1-4	1	96	36	57467	**<0.0001**
2-3	0	2	0	57598	0.1573
2-4	0	2	37	57561	**<0.0001**
3-4	0	0	37	57563	**<0.0001**
Copiapite					
1-2	9	13	13	57565	1.0000
1-3	2	20	24	57554	0.5465
1-4	6	16	131	57447	**<0.0001**
2-3	2	20	24	57554	0.5465
2-4	6	16	131	57447	**<0.0001**
3-4	12	14	125	57449	**<0.0001**
Jarosite					
1-2	21	47	46	57486	0.9174
1-3	5	63	11	57521	**<0.0001**
1-4	10	58	56	57476	0.8514
2-3	6	61	10	57523	**<0.0001**
2-4	13	54	53	57480	0.9230
3-4	5	11	61	57523	**<0.0001**
Pyrophyllite					
1-2	5	5	34	57556	**<0.0001**
1-3	0	10	0	57590	**0.0016**
1-4	1	9	59	57531	**<0.0001**
2-3	0	39	0	57561	**<0.0001**
2-4	6	33	54	57507	0.0244
3-4	0	0	60	57540	**<0.0001**
Mincrust					
1-2	5	555	45	56995	**<0.0001**
1-3	2	558	6	57034	**<0.0001**
1-4	36	524	113	56927	**<0.0001**
2-3	0	50	8	57542	**<0.0001**
2-4	2	48	147	57403	**<0.0001**
3-4	1	7	148	57444	**<0.0001**

For chlorite between early spring and late summer, for copiapite between summer and early spring, summer and late summer, and early spring and late summer; for jarosite between summer and early spring, summer and spring, and early spring and spring; and pyrophyllite between early spring and spring, there was no evidence to reject the null hypothesis of no seasonal difference in the probability of detecting minerals. In all other cases there was evidence to reject the null hypothesis; there was a seasonal difference in the detection of minerals. From these results I found that there was higher probability of detecting chlorite in summer; copiapite in spring; jarosite in early spring, spring and summer; pyrophyllite in early spring and spring; and mincrust in summer, followed by spring.

Plate 19 shows the detection of pyrophyllite and copiapite on the roof of a large retail outlet. For reason of explanation the ASTERS are ordered from early spring to late summer according to day and month but ignoring the year. The first pair of plates (grouped vertically) shows a small accumulation of both pyrophyllite and copiapite on the roof in early October (early spring), at the time of the first rain following the dry season. The second pair of plates (late October - spring) shows a larger accumulation of both minerals. For pyrophyllite this was not significant over the entire study area, whereas for copiapite it was. In the third and fourth pairs of plates (January and March respectively; summer and late summer), no pyrophyllite was detected on the roof (and in late summer a negligible amount was detected across the entire study area beyond MRD boundaries) and only a small amount of copiapite.

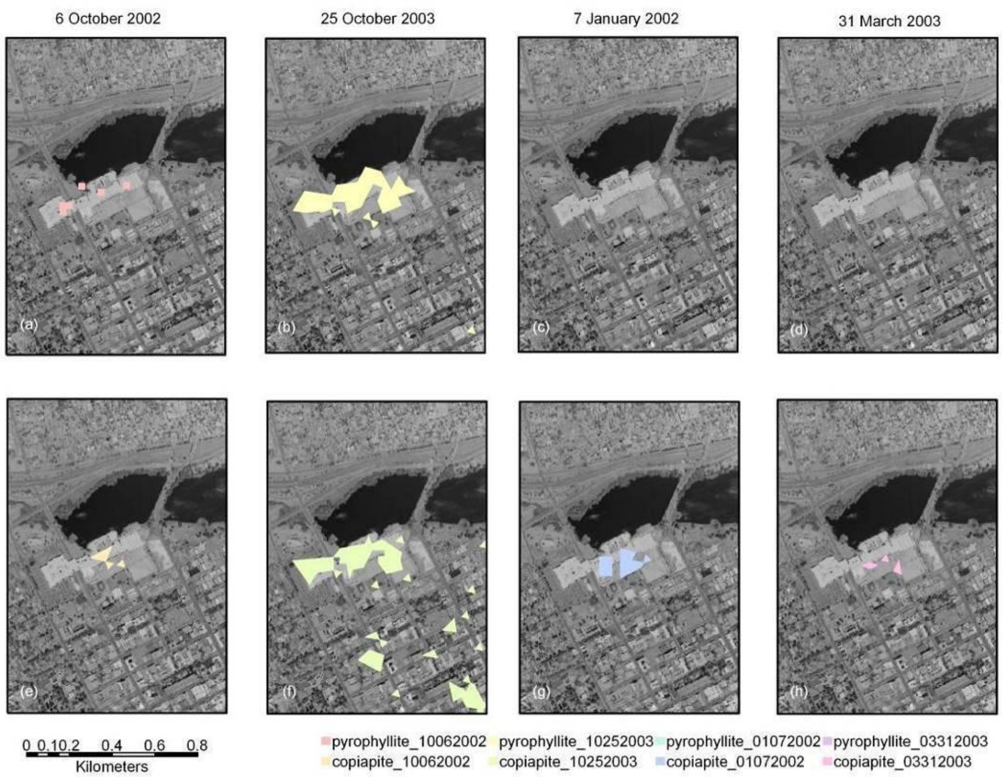

Plate 19 **Detection by ASTER of pyrophyllite and copiapite on the roof of a large retail outlet, (a) and (e) early spring at time of first rainfall (6mm) after the dry season; (b) and (f) spring with 55mm rain in the preceding 90 days; (c) and (g) summer with 304mm rain during the preceding 90 days; and (d) and (h) late summer with 249mm rain during the preceding 90 days**

4.3.2 Masking of minerals by vegetation

The null hypothesis was that the detection of each mineral was independent of the detection of vegetation cover. The number of observations and p values are summarised in Table 23.

Table 23 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing minerals and NDVI

Mineral Vegetation	Present Active	Absent Active	Present No	Absent No	p
Chlorite	42	3080	2	86476	**<0.0001**
Copiapite	0	3122	863	85615	**<0.0001**
Jarosite	17	3105	1711	84767	**<0.0001**
Pyrophyllite	1	3121	787	85691	**<0.0001**
Mincrust	117	3005	1137	85341	**<0.0001**

For all minerals the null hypothesis of independence was rejected. From the residuals (Table 24) it can be seen that there was:

- Less chlorite and mincrust detected on soils under no or dormant vegetation than expected but more detected on soils under actively growing vegetation than expected;
- Less copiapite, jarosite and pyrophyllite detected on soils under actively growing vegetation than expected but more detected on soils under no or dormant vegetation than expected.

Table 24 Standardised residuals and odds ratios for minerals and NDVI

Mineral Vegetation	Present Active	Absent Active	Present No	Absent No	Odds ratio	95% CL (odds ratio)
Chlorite	**32.68**	-0.73	**-6.21**	0.14	**589.61**	142.66 to 2436.78
Copiapite	**-5.48**	0.54	1.04	-0.10	**0.02**	0.00 to 0.25
Jarosite	**-5.57**	1.06	0.78	-0.15	**0.27**	0.17 to 0.44
Pyrophyllite	**-5.05**	0.48	0.96	-0.09	**0.03**	0.00 to 0.25
Mincrust	**11.09**	-1.32	**-2.11**	0.25	**2.92**	2.41 to 3.55

These results suggest that actively growing vegetation masks copiapite, jarosite and pyrophyllite but not chlorite and mincrust, and the latter two minerals were more likely to be found where there was actively growing vegetation (Plate 20).

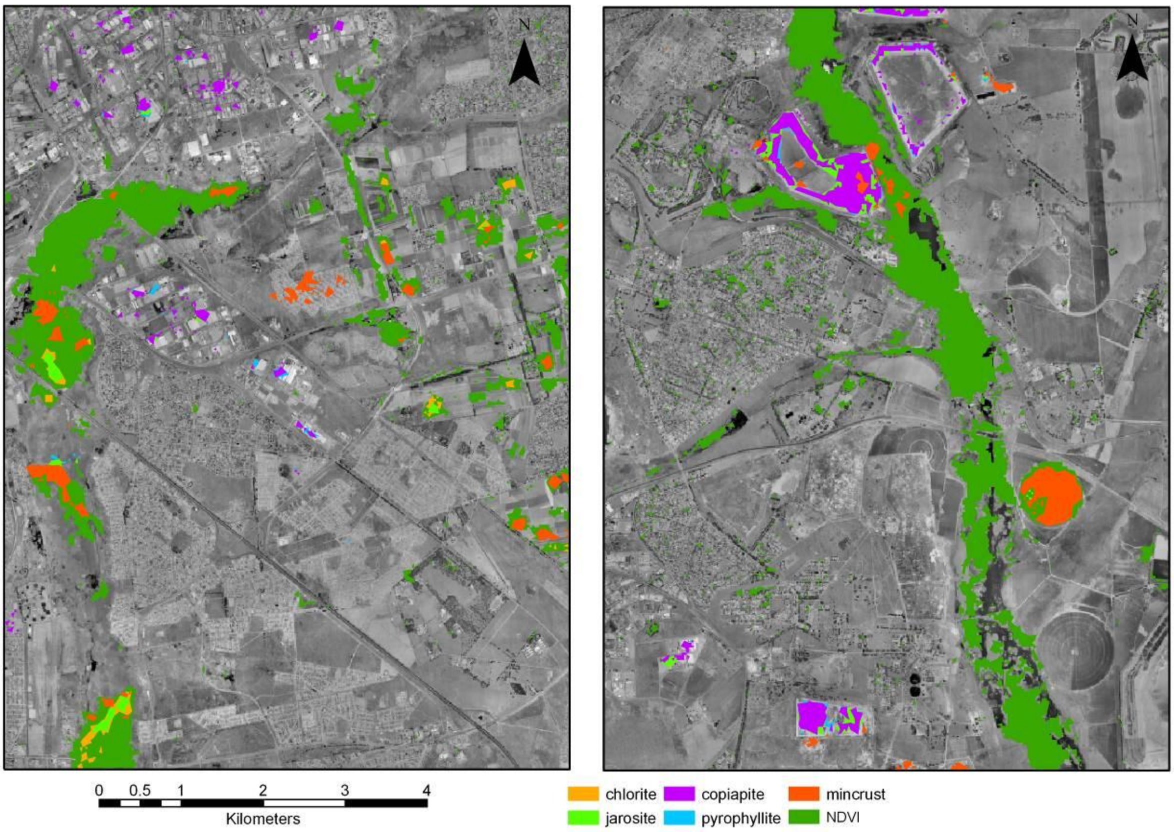

Plate 20 Examples of mineral detection and detection of actively growing vegetation

The odds ratio for detecting chlorite where there was actively growing vegetation verses no or dormant vegetation was 589.61, say 590 and for mincrust it was 2.92 (Table 24). In order to calculate the odds ratio for detecting copiapite I added 0.5 to all cells in the contingency table, as discussed earlier.

4.4 Associations between Mineral Detection and Risk Sources, Pathways and Receptors

4.4.1 Associations between mineral detection and risk sources

(a) Association between mineral detection and type of mine residue deposit

The null hypothesis was that mineral detection was independent of MRD type. The results of the 2×2 Contingency Tables are summarised in Table 25.

Table 25 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and type of mine residue deposit

Mineral MRD	Present Rock	Absent Rock	Present Sand	Absent Sand	Present Slime	Absent Slime	p
Chlorite	0	565	0	523	2	6735	0.8508
Copiapite	2	563	72	451	785	5952	**<0.0001**
Jarosite	2	563	86	437	1744	4993	**<0.0001**
Pyrophyllite	1	564	66	457	811	5926	**<0.0001**
Mincrust	1	564	36	487	1087	5650	**<0.0001**

For chlorite there was no evidence to reject the null hypothesis of independence; however, for copiapite, jarosite, pyrophyllite and mincrust the null hypothesis of independence was rejected. These four minerals have an association with gold mine residue, especially remaining slimes dams. From the residuals (Table 26) it can be seen that there was:

- Less copiapite and pyrophyllite detected on rock dumps than expected but more detected on sand dumps and slimes dams than expected (Plate 21(a) and (c));
- Less jarosite and mincrust detected on rock dumps and sand dumps than expected but more detected on slimes dams than expected (Plate 21(b) and (d)).

Table 26 Standardised residuals for mineral detection and type of mine residue deposit

Mineral MRD	Present Rock	Absent Rock	Present Sand	Absent Sand	Present Slime	Absent Slime
Chlorite	-0.380	0.006	-0.366	0.006	0.212	-0.004
Copiapite	**-7.622**	**2.676**	1.925	-0.676	1.671	-0.586
Jarosite	**-11.327**	**6.263**	**-3.294**	1.821	**4.197**	**-2.321**
Pyrophyllite	**-7.837**	**2.786**	0.955	-0.340	**2.003**	-0.712
Mincrust	**-8.898**	**3.644**	**-4.514**	1.848	**3.834**	-1.571

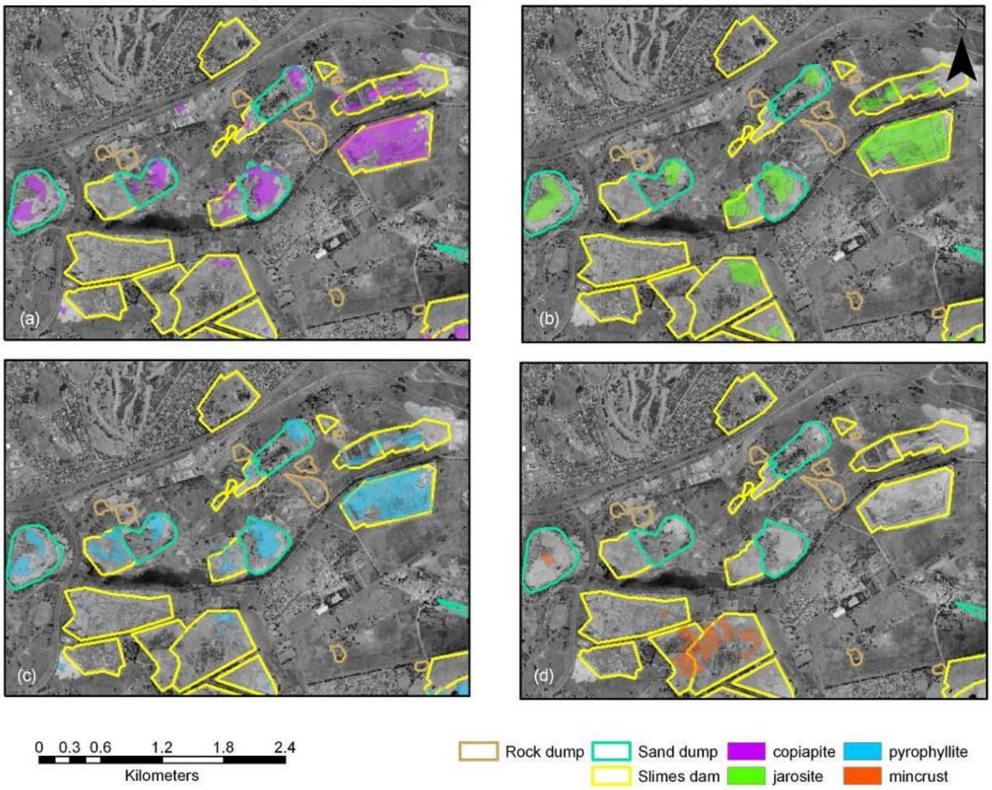

Plate 21 Mineral detection on different types of mine residue deposit

For both copiapite and pyrophyllite, the 95% CL for the odds ratios of having the mineral included one for the comparison of sand dumps versus slimes dams, which can be interpreted as meaning there was no real difference between the two (Table 27).

Table 27 Odds ratios for mineral detection and type of mine residue deposit

Mineral / **Type of MRD**	**Odds Ratio**	**95% CL (Odds Ratio)**
Copiapite		
Rock dumps versus sand dumps	**0.02**	0.01 to 0.09
Sand dumps versus slimes dams	1.21	0.93 to 1.57
Rock dumps versus slimes dams	**0.03**	0.01 to 0.11
Jarosite		
Rock dumps versus sand dumps	**0.02**	0.00 to 0.07
Sand dumps versus slimes dams	**0.56**	0.44 to 0.71
Rock dumps versus slimes dams	**0.01**	0.00 to 0.04
Pyrophyllite		
Rock dumps versus sand dumps	**0.01**	0.00 to 0.09
Sand dumps versus slimes dams	0.95	0.72 to 1.24
Rock dumps versus slimes dams	**0.01**	0.00 to 0.09
Mincrust		
Rock dumps versus sand dumps	**0.02**	0.00 to 0.18
Sand dumps versus slimes dams	**0.38**	0.27 to 0.54
Rock dumps versus slimes dams	**0.01**	0.00 to 0.07

(b) Association between mineral detection and mine residue feature

The null hypothesis was that mineral detection (by ASTER) was independent of the mine residue feature (identified from aerial photographs taken in February 2003). The results of the 2×2 Contingency Tables are summarised in Table 28.

Table 28 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and mine residue features

Mine residue feature **Mineral**	**Yes** **Present**	**Yes** **Absent**	**No** **Present**	**No** **Absent**	**p**
Remaining MRDs					
Chlorite	2	5721	65	115165	0.5006
Copiapite	848	4875	228	115002	**<0.0001**
Jarosite	1807	3916	270	114960	**<0.0001**
Pyrophyllite	860	4863	106	115124	**<0.0001**
Mincrust	988	4735	743	114487	**<0.0001**
Slimes dam footprints					
Chlorite	0	1699	67	119187	0.3284
Copiapite	8	1691	1068	118186	0.0641
Jarosite	20	1679	2057	117197	0.0844
Pyrophyllite	16	1683	950	118304	0.5046
Mincrust	134	1565	1597	117657	**<0.0001**
Mine residue spills					
Chlorite	0	1175	67	119711	0.4174
Copiapite	13	1162	1063	118715	0.4265
Jarosite	19	1156	2058	117720	0.7905
Pyrophyllite	12	1163	954	118824	0.3890
Mincrust	19	1156	1712	118066	0.5898

There was no evidence to reject the null hypothesis of independence for the detection of chlorite and any of the mine residue features. There was also no evidence to reject the null hypothesis of independence for the detection of the other minerals and 'Mine residue spills'. Further, there was no evidence to reject the null hypothesis of independence for the detection of three of the other four minerals (copiapite, jarosite and pyrophyllite) and 'Slimes dam footprints'. On the other hand, there was an association between detection of the other four minerals and 'Remaining MRDs'. There was also an association between the detection of mincrust and 'Slimes dam footprints'. From the residuals (Table 29) it can be seen that there was:

- More copiapite, jarosite, pyrophyllite and mincrust detected on remaining MRDs than expected;
- More mincrust detected on slimes dam footprints than expected.

Table 29 Standardised residuals for mineral detection and mine residue features

Mine residue feature **Mineral**	**Yes** **Present**	**Yes** **Absent**	**No** **Present**	**No** **Absent**
Remaining MRDs				
Chlorite	-0.66	0.02	0.15	0.00
Copiapite	**111.71**	**-10.58**	**-24.90**	**2.36**
Jarosite	**172.37**	**-22.78**	**-38.41**	**5.08**
Pyrophyllite	**120.44**	**-10.81**	**-26.84**	**2.41**
Mincrust	**100.12**	**-12.06**	**-22.31**	**2.69**
Slimes dam footprints				
Chlorite	-0.97	0.02	0.12	0.00
Copiapite	-1.83	0.17	0.22	-0.02
Jarosite	-1.70	0.22	0.20	-0.03
Pyrophyllite	0.66	-0.06	-0.08	0.01
Mincrust	**22.24**	**-2.68**	**-2.66**	0.32
Mine residue spills				
Chlorite	-0.81	0.02	0.08	0.00
Copiapite	0.79	-0.07	-0.08	0.01
Jarosite	-0.26	0.03	0.03	0.00
Pyrophyllite	0.85	-0.08	-0.08	0.01
Mincrust	0.53	-0.06	-0.05	0.01

(c) Associations between mineral detection and slimes dam footprints and mine residue spills, after excluding the area of remaining mine residue deposits

The null hypothesis was that mineral detection by ASTER was independent of the mine residue feature (identified from aerial photographs taken in February 2003) after excluding the area of remaining MRDs. The results of the 2×2 Contingency Tables are summarised in Table 30.

Table 30 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and mine residue features after excluding the area of remaining mine residue deposits

Mine residue feature Mineral	Yes Present	Yes Absent	No Present	No Absent	p
Slimes dam footprints					
Chlorite	0	1699	65	113466	0.3239
Copiapite	8	1691	219	113312	**0.0103**
Jarosite	20	1679	250	113281	**<0.0001**
Pyrophyllite	16	1683	90	113441	**<0.0001**
Mincrust	134	1565	609	112922	**<0.0001**
Mine residue spills					
Chlorite	0	1175	65	113990	0.4130
Copiapite	13	1162	214	113841	**<0.0001**
Jarosite	19	1156	251	113804	**<0.0001**
Pyrophyllite	12	1163	94	113961	**<0.0001**
Mincrust	19	1156	724	113331	**<0.0001**

After removing the influence of the minerals that are directly associated with (i.e. located on) remaining MRDs there was evidence to reject the null hypothesis of independence for the detection of all of the minerals except chlorite on both ‘Slimes dam footprints’ and ‘Remaining MRDs’. From the standardised residuals (Table 31) it can be seen that there was more copiapite, jarosite, pyrophyllite and mincrust present on both slimes dam footprints and mine residue spillage than expected.

Table 31 Standardised residuals for mineral detection and mine residue features after excluding the area of remaining mine residue deposits

Mine residue feature Mineral	Yes Present	Yes Absent	No Present	No Absent
Slimes dam footprints				
Chlorite	-0.98	0.02	0.12	0.00
Copiapite	**2.54**	-0.11	-0.31	0.01
Jarosite	**8.03**	-0.39	-0.98	0.05
Pyrophyllite	**11.55**	-0.35	-1.41	0.04
Mincrust	**37.18**	**-2.99**	**-4.55**	0.37
Mine residue spills				
Chlorite	-0.81	0.02	0.08	0.00
Copiapite	**7.02**	-0.31	-0.71	0.03
Jarosite	**9.79**	-0.47	-0.99	0.05
Pyrophyllite	**10.50**	-0.32	-1.07	0.03
Mincrust	**4.15**	-0.33	-0.42	0.03

From all of the tests under sub-section 4.4.1 it can be concluded that chlorite in this study did not provide a ‘signature’ of gold and uranium mine residue, whereas the other four minerals did. Therefore, for further tests I excluded chlorite.

4.4.2 Associations between mineral detection and risk pathways

(a) Association between mineral detection and wetlands

The null hypothesis was that mineral detection was independent of the feature (i.e. wetlands). The results of the 2×2 Contingency Tables are summarised in Table 32.

Table 32 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and wetlands

Mineral Wetlands	Present Yes	Absent Yes	Present No	Absent No	p
Copiapite	1	6497	226	108506	**0.0007**
Jarosite	18	6480	252	108480	0.4637
Pyrophyllite	2	6496	104	108628	0.0938
Mincrust	63	6435	680	108052	**0.0008**

For jarosite and pyrophyllite there was no evidence to reject the null hypothesis of independence. However, for copiapite and mincrust there was evidence to reject the null hypothesis; there was an association between these two minerals and wetlands. From the residuals (Table 33) it can be seen that there was more mincrust and less copiapite detected on wetlands than expected.

Table 33 Standardised residuals for mineral detection and wetlands

Mineral Wetlands	Present Yes	Absent Yes	Present No	Absent No
Copiapite	**-3.298**	0.147	0.806	-0.036
Mincrust	**3.260**	-0.263	-0.797	0.064

(b) Slimes dam wall failures

I found that 64% of slimes dams had failed prior to 2003 and there were instances of failures and the spatial extent of spillage in 1938 being virtually unchanged in 1964. The photographs depicted extensive sedimentation of watercourses due to residues from these failures.

4.4.3 Associations between mineral detection and risk receptors

(a) Associations between mineral detection and land use

The null hypothesis was that mineral detection was independent of the land use. The results of the 2×2 Contingency Tables are summarised in Table 34.

Table 34 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and land use

Land use Mineral	Yes Present	Yes Absent	No Present	No Absent	p
Business					
Copiapite	33	2174	194	112829	**<0.0001**
Jarosite	9	2198	261	112762	0.0888
Pyrophyllite	13	2194	93	112930	**<0.0001**
Mincrust	3	2204	740	112283	**0.0026**
Industrial					
Copiapite	129	5325	98	109678	**<0.0001**
Jarosite	13	5441	257	109519	0.9495
Pyrophyllite	40	5414	66	109710	**<0.0001**
Mincrust	3	5451	740	109036	**<0.0001**
Formal Residential					
Copiapite	11	26803	216	88200	**<0.0001**
Jarosite	129	26685	141	88275	**<0.0001**
Pyrophyllite	4	26810	102	88314	**<0.0001**
Mincrust	281	26533	462	87954	**<0.0001**
Informal Settlement					
Copiapite	1	1309	226	113694	0.3219
Jarosite	0	1310	270	113650	0.0777
Pyrophyllite	1	1309	105	113815	0.8509
Mincrust	56	1254	687	113233	**<0.0001**
Irrigated Agriculture					
Copiapite	0	2421	227	112582	**0.0271**
Jarosite	4	2417	266	112543	0.4773
Pyrophyllite	0	2421	106	112703	0.1313
Mincrust	59	2362	684	112125	**<0.0001**
Rain-fed Agriculture					
Copiapite	0	10253	227	104750	**<0.0001**
Jarosite	1	10252	269	104708	**<0.0001**
Pyrophyllite	0	10253	106	104871	**0.0013**
Mincrust	13	10240	730	104247	**<0.0001**

i Business

For jarosite there was no evidence to reject the null hypothesis of independence. However, for the other three minerals (copiapite, pyrophyllite and mincrust) the null hypothesis of independence was rejected; there was an association between the land use and the minerals. The spatial extent of copiapite and pyrophyllite was greater than background (i.e. more than on surrounding land) and the extent of mincrust was less.

ii Industrial

For jarosite there was no evidence to reject the null hypothesis of independence. However, for the other three minerals (copiapite, and pyrophyllite and mincrust) the null hypothesis of independence was rejected; there was an association between the land use and the minerals. The spatial extent of copiapite and pyrophyllite was greater than background while the extent of mincrust was less.

iii Formal residential

For all four minerals the null hypothesis of independence was rejected; there was an association between the land use and the minerals. The spatial extent of jarosite and mincrust are greater than background while the extent of copiapite and pyrophyllite was less. However, I observed from the 2003 aerial photograph that the detection of jarosite and mincrust on formal residential land was mainly at one location (Plate 22).

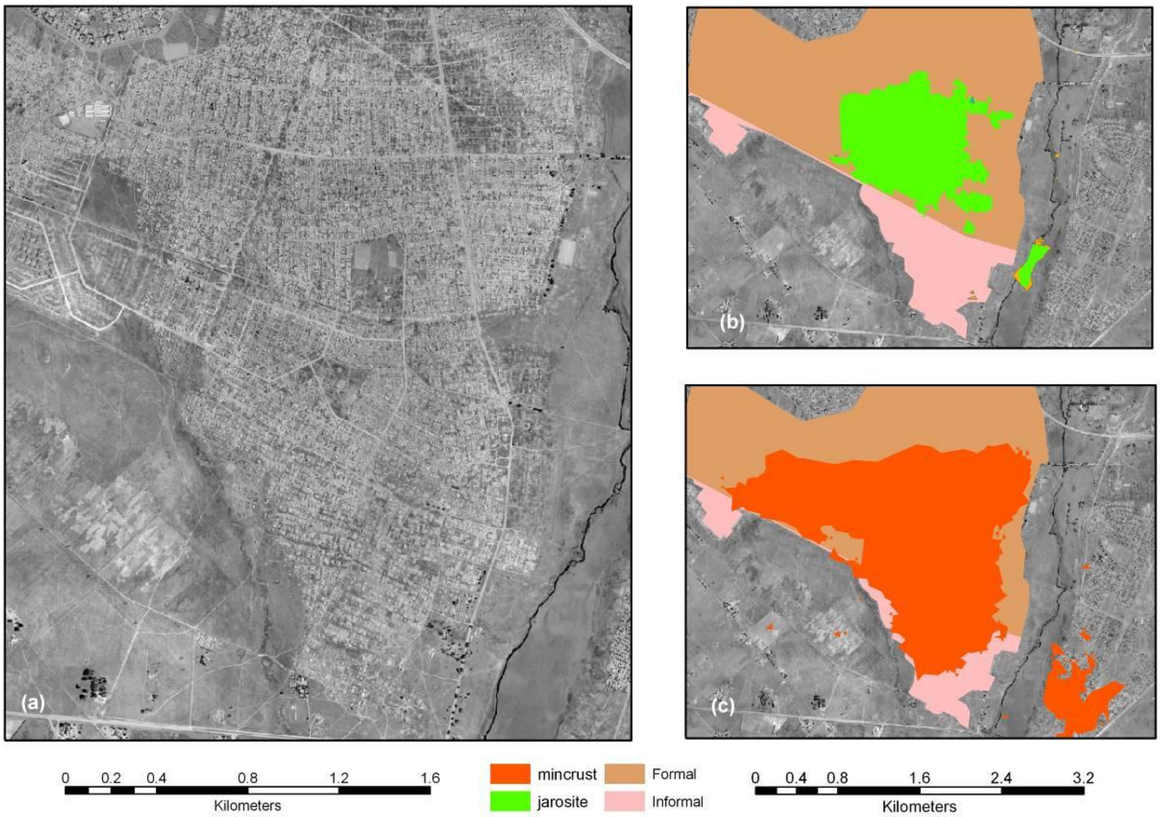

Plate 22 Jarosite and mincrust detected by ASTER on residential land: (a) 2003 aerial photograph showing residential area, (b) jarosite on formal residential land use, and (c) mincrust on formal and informal land use

iv Informal settlement

For copiapite, jarosite and pyrophyllite there was no evidence to reject the null hypothesis of independence. However, for mincrust the null hypothesis of independence was rejected; there was an association between informal land use and the mineral. The spatial extent of mincrust was greater than background. Similarly to formal residential land I observed that the detection of mincrust on informal land use was mainly at one location (Plate 22(c)).

v Irrigated agriculture

For jarosite and pyrophyllite there was no evidence to reject the null hypothesis of independence. However, for the other two minerals (copiapite and mincrust) the null hypothesis of independence was rejected; there was an association between the land use and the minerals. The spatial extent of mincrust was greater than background and the extent of copiapite was less.

vi Rain-fed agriculture

For all four minerals the null hypothesis of independence was rejected; there was an association between the land use and the minerals. The spatial extent of all four minerals was less than background.

(b) Comparison between detection of mincrust on irrigated and rain-fed agricultural land

The null hypothesis was that the detection of mincrust was independent of the type of agricultural land. The results of the 2×2 Contingency Tables are summarised in Table 35.

Table 35 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing the detection of mincrust on rain-fed and irrigated agricultural land

Mineral	**Present**	**Absent**	**Present**	**Absent**	**p**
Agricultural use	**Irrigated**	**Irrigated**	**Rain-fed**	**Rain-fed**	
Mincrust	59	2362	13	10240	**<0.0001**

For mincrust the null hypothesis of independence was rejected. From the residuals it can be seen that there was more mincrust detected on irrigated agricultural land than expected and less mincrust detected on rain-fed agricultural land than expected (Table 36). The odds ratio of mincrust being detected on irrigated land was between 10 to 36 times greater than for rain-fed (Table 36). Where mincrust was detected on irrigated agricultural land it typically extended over most of the site (Plate 23), although on two adjacent sites just outside the study area it only covered half of each site, giving the shape of butterfly wings (Plate 24). There was inadequate information to determine the source of irrigation (ground or surface water).

Table 36 Standardised residuals and odds ratios for detection of mincrust on rain-fed and irrigated agricultural land

Mineral	Present	Absent	Present	Absent	Odds ratio	95% CL (odds ratio)
Agriculture	**Irrigated**	**Irrigated**	**Rain-fed**	**Rain-fed**		
Mincrust	12.200	-0.921	-5.929	0.446	**19.69**	10.78 to 35.99

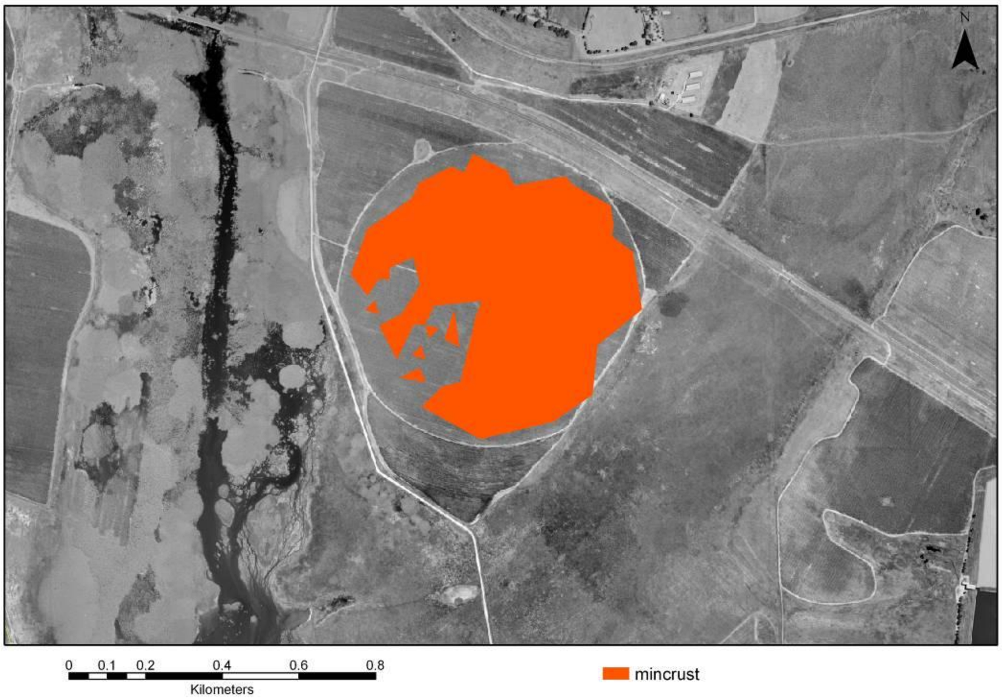

Plate 23 Mincrust detected by ASTER on irrigated agricultural land (a crop pivot) covers most of the site

4.5 Associations between Mineral Detection and Distance from Mine Residue Deposits

The null hypothesis was that mineral detection was independent of the distance from a MRD. The results of the 2×2 Contingency Tables are summarised in Table 37.

Table 37 Spatial extent (hectares) and significance (*p* values) from 2×2 Contingency Tables for comparing mineral detection and distance from mine residue deposits

Mineral	Present	Absent	Present	Absent	Present	Absent	p
Buffer zone	**<500**	**<500**	**500-1000**	**500-1000**	**>1000**	**>1000**	
Copiapite	50	21575	25	18758	141	72456	<0.0753
Jarosite	42	21583	8	18775	195	72402	**<0.0001**
Pyrophyllite	30	21595	12	18771	46	72551	**0.0017**
Mincrust	53	21572	9	18774	544	72053	**<0.0001**

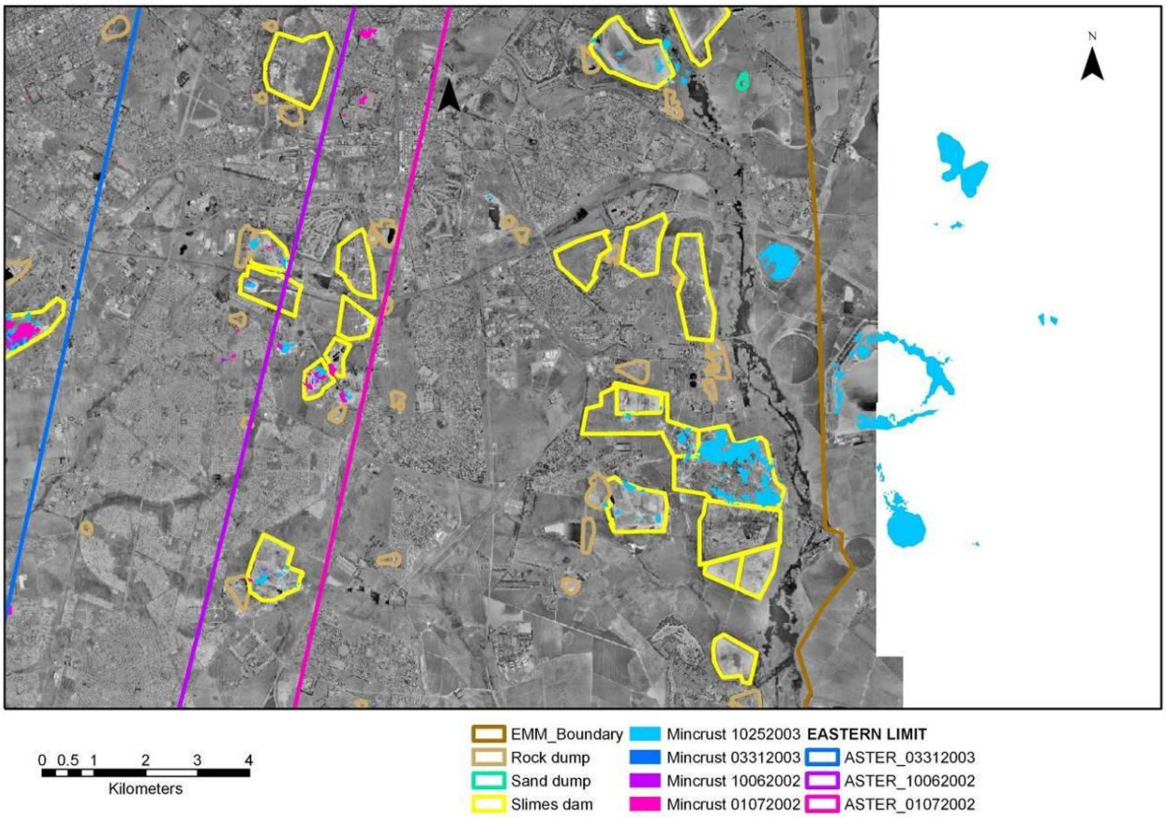

Plate 24 An example of the detection of mincrust beyond the eastern boundary of the study area. Only one image (10252003) covered this area

For copiapite there was no evidence to reject the null hypothesis of independence; however, for jarosite, pyrophyllite and mincrust the null hypothesis of independence was rejected, there was an association between mineral detection and distance from MRD. From the residuals (Table 38) it can be seen that there was:

- Less jarosite detected at 500 to 1000 m from MRDs than expected but more detected further away than 1 000 m from MRDs than expected;
- Less pyrophyllite detected further than 1000 m from MRDS than expected but more detected at 0 to 500 m from MRDs than expected;
- Less mincrust detected between 0 to 500 m and between 500 to 1000 m from MRDs than expected but more detected further than 1000 m from MRDs than expected.

Table 38 Standardised residuals for mineral detection and distance from mine residue deposits

Mineral	Present	Absent	Present	Absent	Present	Absent
Buffer zone	**<500**	**<500**	**500-1000**	**500-1000**	**>1000**	**>1000**
Copiapite	1.348	-0.061	-1.819	0.080	0.190	-0.007
Jarosite	-0.713	0.034	**-5.128**	0.241	**2.998**	-0.141
Pyrophyllite	**3.207**	-0.088	-0.687	0.022	-1.401	0.041
Mincrust	**-5.847**	0.430	**-9.140**	0.673	**7.840**	-0.577

The 95% confidence limits for the odds ratios of detecting jarosite included one for the comparison of detecting jarosite 0 to 500 m from MRDs versus > 1 000 m from MRDs and pyrophyllite 500 to 1 000 m from MRDs versus > 1 000 m from MRDs (Table 39). The strongest patterns were that the odds of:

- Jarosite and mincrust being detected was greater at further than 1 000 m from MRDs compared with 500 to 1 000 m from MRDs;
- Pyrophyllite being detected were greater at 0 to 500 m compared with 500 to 1 000 m from MRDs and further than 1 000 m from MRDs.

Table 39 Odds ratios for mineral detection at different distances from mine residue deposits

Mineral / Distance from MRD	Odds Ratio	95% CL (Odds Ratio)
Jarosite		
0 to 500 m versus 500 to 1 000 m	**4.57**	2.14 to 9.73
500 to 1 000 m versus > 1 000 m	**0.16**	0.08 to 0.32
0 to 500 m versus > 1 000 m	0.72	0.52 to 1.01
Pyrophyllite		
0 to 500 m versus 500 to 1 000 m	**2.17**	1.11 to 4.25
500 to 1 000 m versus > 1 000 m	1.008	0.53 to 1.90
0 to 500 m versus > 1 000 m	**2.19**	1.38 to 3.47
Mincrust		
0 to 500 m versus 500 to 1 000 m	**5.13**	2.53 to 10.40
500 to 1 000 m versus > 1 000 m	**0.06**	0.03 to 0.12
0 to 500 m versus > 1 000 m	**0.33**	0.25 to 0.43

4.6 Risk Assessment

In the previous sections I have shown (through data analyses but mainly through literature review) that all gold and uranium MRDs contain substances that are potentially harmful to communities and the environment but there are differences in the hazard level based on MRD classification. I also demonstrated that the aqueous pathway for the dissemination of pollutants is substantial and that certain land uses are more vulnerable to harm from MRDs than others. Results from the analyses of remote sensing data have been integrated with findings from similar or associated studies, as described in the literature review, to assign relative ratings to identified risk parameters.

After allocating ratings to the different parameters for each MRD the risk index and class were determined (Appendix VI). These data were entered as attributes in the vector file Eker_MRDs, from which a risk map was produced (Figure 13). The proximity of many MRDs to watercourses is apparent from the map, as is the extent of urbanisation. The main agricultural area is in the north east, which is predominantly upstream and upwind of MRDs and therefore less vulnerable to impacts from them (Figure 14). However, there are still a number of agricultural areas downstream and downwind (i.e. to the south) of MRDs (Figure 15). To the south and east the higher risk MRDs appear to be relatively large (Figures 16 and 17). Although size was not considered as a hazard in this study it makes sense that a larger MRD is more likely to be in proximity to a number of pathways and vulnerable land uses. Nevertheless, there are a number of smaller MRDs more towards the north west, in the Boksburg area, which are also higher risk (Figure 18). In these cases the MRDs are located on or adjacent to watercourses and in proximity to informal settlements.

Although a sensitivity analysis was not undertaken, it is expected that the resulting risk index would change substantially if:

- The relative ratings were different between classes of MRD (e.g. if rock dumps were given a higher hazard score than slimes dams or if developed footprints were given a higher hazard score than paddocked footprints);
- A specific MRD had effective pollution prevention measures in place (e.g. an effective vegetation cover to prevent dust; or effective seepage prevention measures); or
- A specific MRD had been rendered less harmful (e.g. pyrite and uranium had been recovered through the metallurgical process.

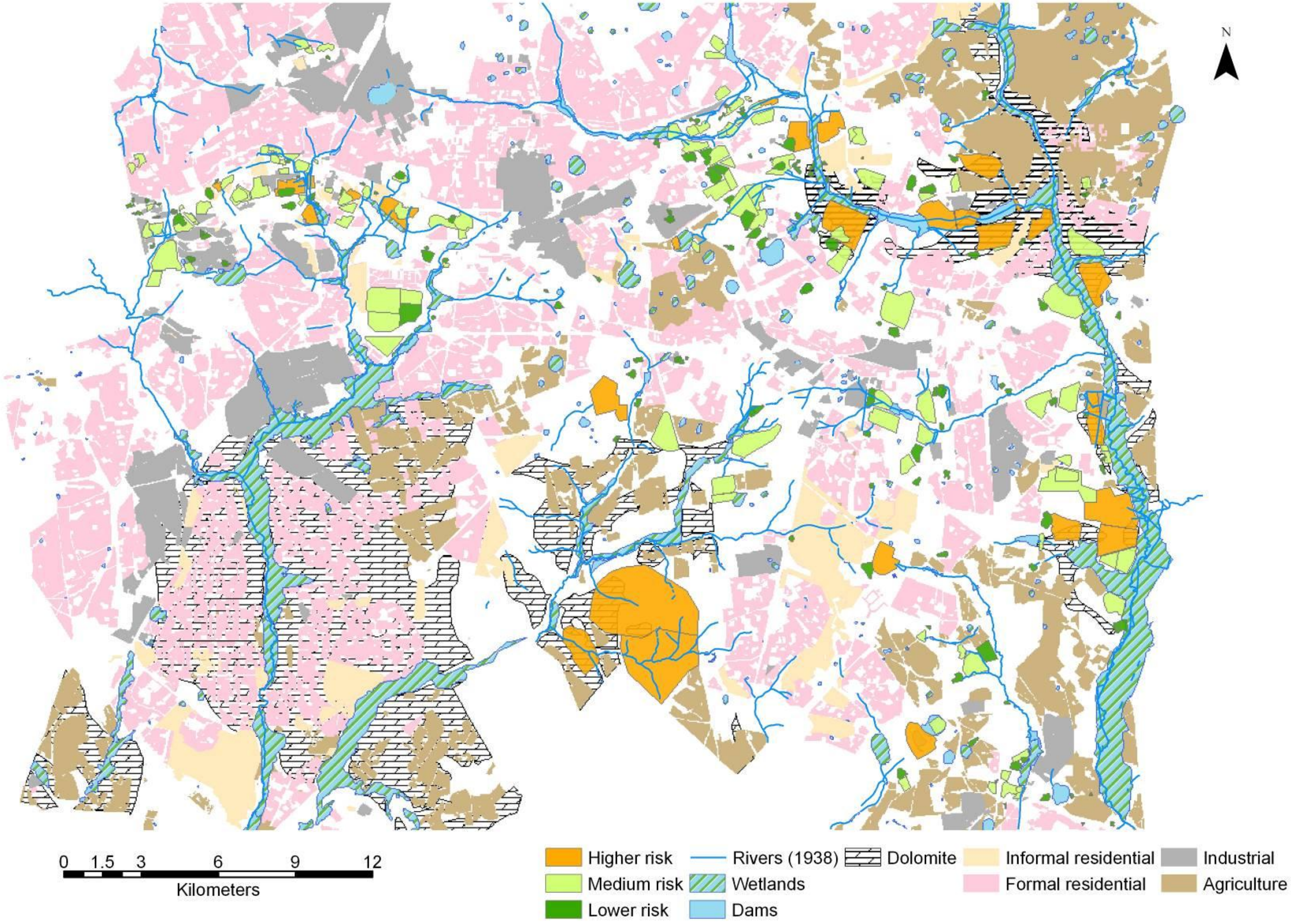

Figure 13 Results of the risk assessment of mine residue deposits in Ekurhuleni Metropolitan Municipality

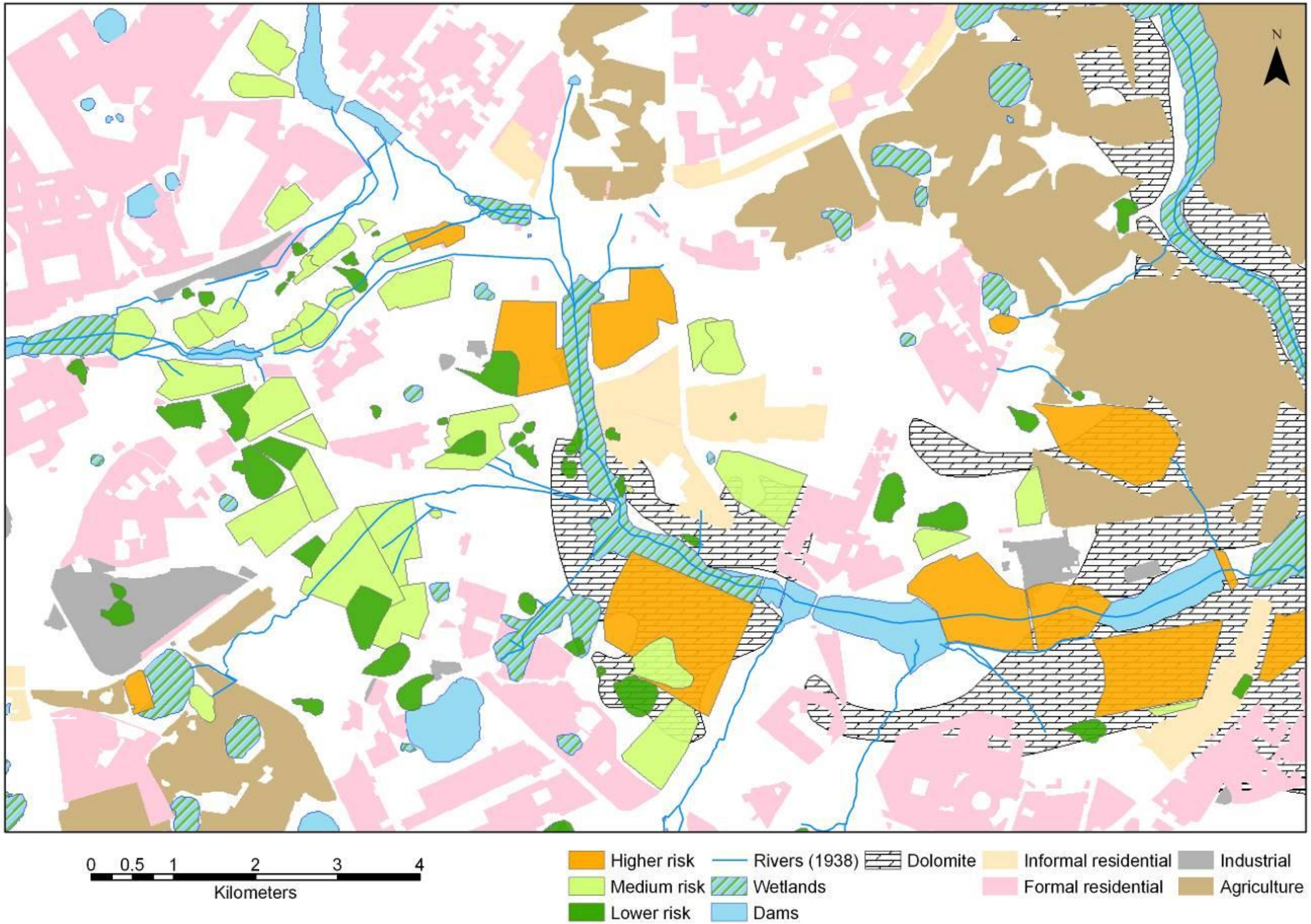

Figure 14 **Detail of the risk assessment of mine residue deposits in Benoni**

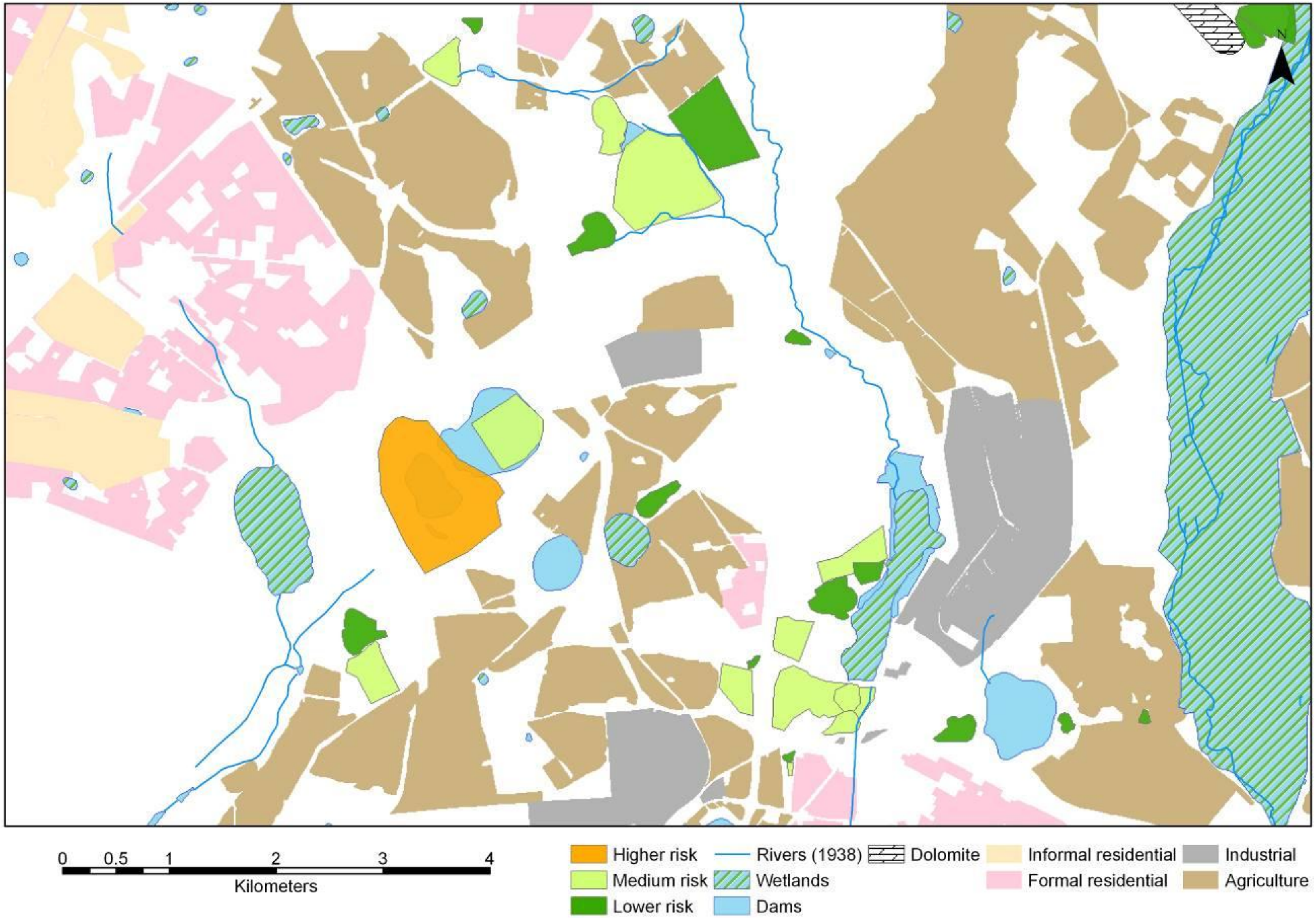

Figure 15 Detail of the risk assessment of mine residue deposits in Nigel

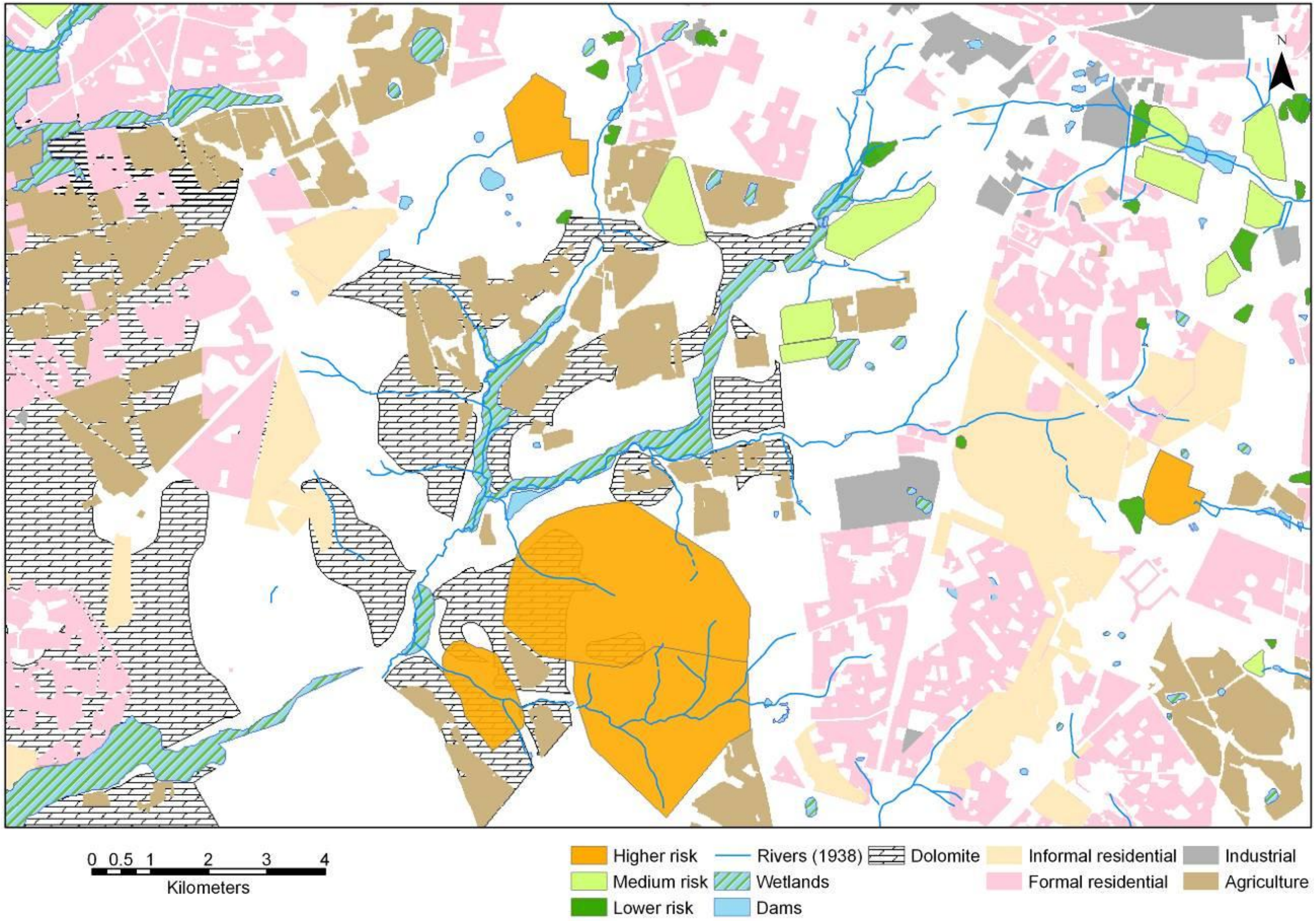

Figure 16 Detail of the risk assessment of mine residue deposits in Brakpan

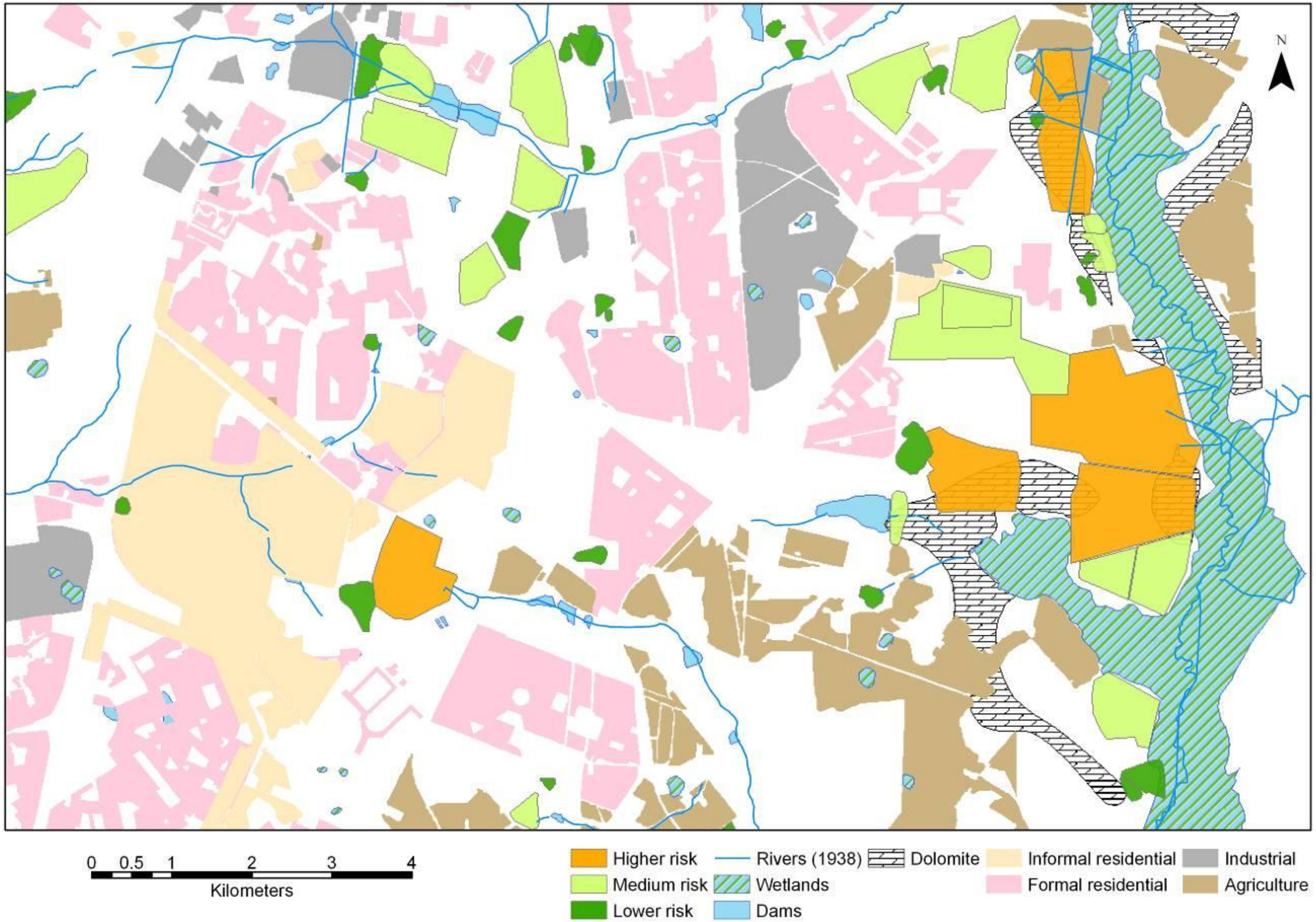

Figure 17 Detail of the risk assessment of mine residue deposits in Springs

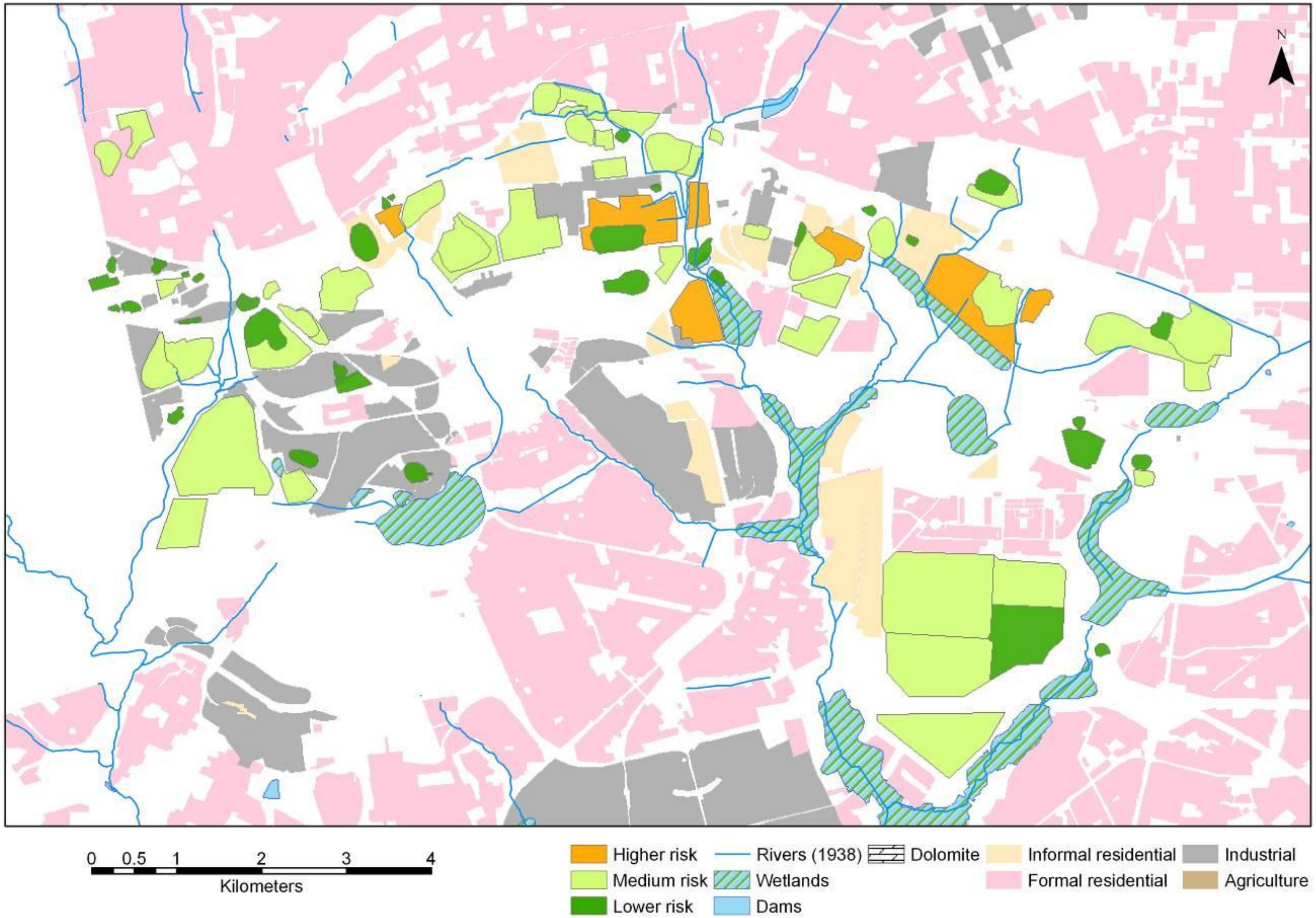

Figure 18 **Detail of the risk assessment of mine residue deposits in Germiston and Boksburg**

CHAPTER 5

5 DISCUSSION

5.1 Use of Aerial Photographs in Risk Assessment

5.1.1 Use of aerial photographs for identifying mine residue deposits

Areas of land disturbance are generally easily recognised using aerial photographs. However, when attempting to identify sand dumps and slimes dams from aerial photographs by colour alone I found that many areas that were not sand or slimes were the same scale of grey. Some roofs of buildings and other disturbed areas, e.g. quarries, cells for a solid waste disposal site, cleared land for construction and ploughed fields could all be mistaken for sand or slimes when based on colour alone. Waste rock was even more difficult to distinguish by colour alone, although “fines” washed from the toe of waste rock dumps were sometimes visible.

In places where MRDs had been vegetated they were still identifiable because of the patchiness of the vegetation. Where lower slopes on the perimeters were reasonably well vegetated in the 2003 photographs, the earlier aerial photographs showing unvegetated slopes, proved useful in determining the extent. The same applied to footprints, where they may have been covered with soil, organic matter and/or vegetation.

5.1.2 Use of aerial photographs for classifying mine residue deposits

Aerial photographs proved useful for identifying sand dumps and slimes dams based on a combination of colour, shape and size. Texture could not be used to differentiate between types of MRD because of the relatively small differences in grain size in comparison with the spatial resolution of the photographs at this scale. Size was also considered, as relatively large features were of interest rather than, say, a playground sand pit. Waste rock dumps were much more difficult to identify and relatively large heaps of soil, rubble, ash and other material could easily have been mistaken for waste rock dumps. One means of determining if it was likely to be waste rock was to look at neighbouring infrastructure to see if it resembled a mine shaft and associated buildings (e.g. winder house, timber yard, workshops, offices), however, a number of these old buildings have been demolished. Undeveloped footprints, especially of slimes dams, were sometimes able to be recognised in the 2003 aerial photographs because of boundary features and sometimes patches of mine residue were left on the site. However, earlier aerial photographs were required to confirm the presence of a MRD.

5.1.3 Use of historical aerial photographs for providing information on earlier land use

Chevrel *et al*. (2003) found a few sites with radioactive contamination that could not be readily explained (i.e. “not in direct connection with known, identified or interpreted mining-related features”). For example, one of the sites was between the suburbs of Rynsoord and New Modder, where it seemed to correspond to a dry pan. However, examination of the 1938 aerial photographs reveals that the so-called anomaly lies on the transport route, possibly an endless rope haulage or overhead ropeway, between the shaft (located North of the waste rock dump, now a footprint) and the metallurgical plant (Plate 25), suggesting that spillage from the wet ore (ore from underground is normally wet, Stanley, 1987a) is the source of the contamination. The 1964 aerial photograph shows fine material emanating from the direction of the shaft, approximately along the transport route and reaching the pan mentioned by Chevrel *et al.*; which supports this suggestion.

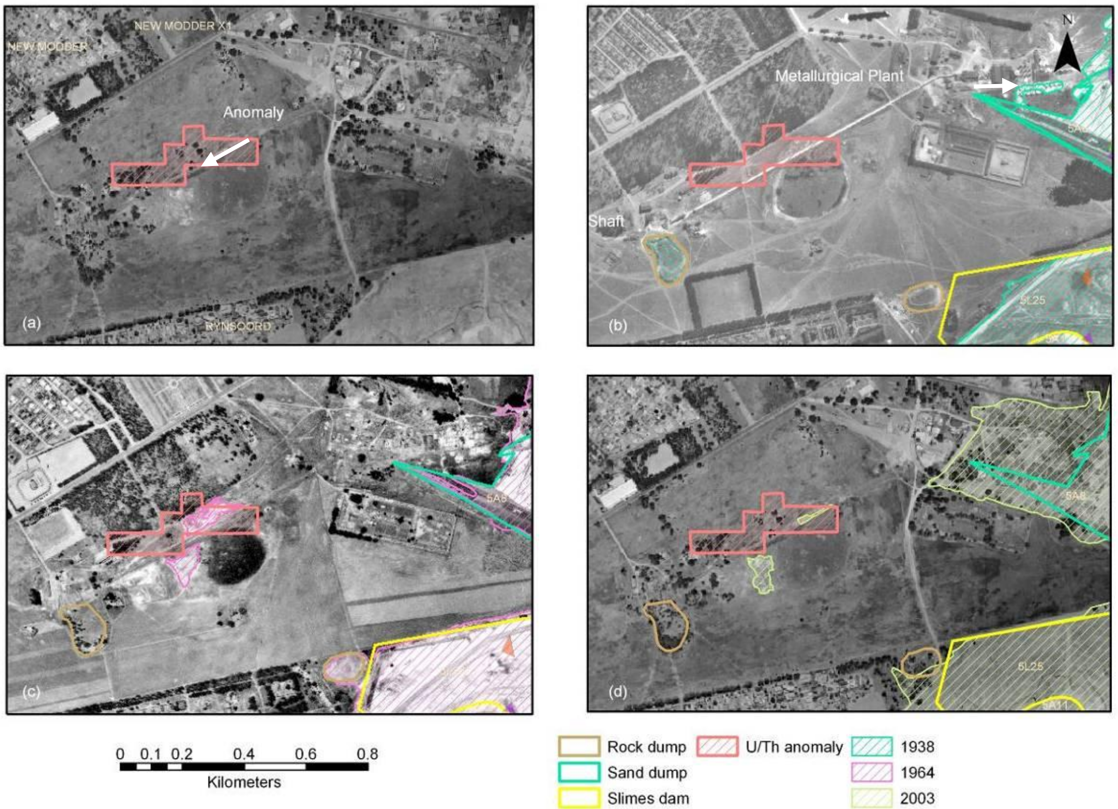

Plate 25 **Use of historical aerial photographs to explain uranium/thorium anomaly; (a) 2003 - anomaly as shown by Chevrel *et al*. 2003, (b) 1938 - showing mining operations in vicinity of suspected anomaly with ore transportation over anomaly, (c) 1964 - shows fine material in vicinity of anomaly, (d) mine residue as plotted for 2003**

The historical aerial photographs proved invaluable in identifying old MRDs, especially waste rock dumps, where the sites have now been developed. Current land uses for some old waste rock dump footprints include major road networks, railway lines and factories.

5.1.4 Use of historical aerial photographs for identifying slimes dam failure and mine residue spillage

Of a total of 132 slimes dams, 84 were identified as having had side-wall failure to some extent. The aerial photographs of 1938 and 1964 depict extensive sedimentation of streams and channels due to residues from slimes dam wall erosion and failures, which agrees with the statement by Thomas (1968) about numerous 'breakaways'. Although aerial photographs proved valuable for identifying MRDs and physical signs of spillage they were not able to identify chemical changes and pollution. Once the spilled mine residue is exposed to air and water, chemical leaching takes place and all that the aerial photographs can show is the physical material, which could be inert. The movement of the dissolved contaminants cannot be determined by this technique. Uranium in particular is relatively mobile in oxidizing conditions across the whole pH range when compared to other cations. Conversely, it is immobile under reducing conditions (Rose *et al*., 1979).

It is also evident from the 1938 and 1964 photographs, that spillage into watercourses was left unaddressed for decades. In some cases the earlier spills into watercourses are possibly masked by subsequent sedimentation from eroded soils and vegetation (Plate 26).

Plate 26 Mine residue spillage in a watercourse between two old mine residue deposits is hidden by wetland vegetation

Mphephu (2001) found that stream sediments downstream of MRDs often contain large amounts of tailings material and Ndasi (2004) mapped the sediments in a dam on the Central Rand where mine residue had accumulated for more than ninety years, allegedly due to erosion from old MRDs upstream of the dam. The sediments had formed banded layers, averaging 2 m in total thickness and up to 7 m in some areas, which had subsequently largely been removed and reprocessed, yielding an average of 2 g/t of gold, but with values of up to 30 g/t in some areas (suggesting that some of the material could have been spillage from a gold plant). From the incomplete reprocessing of the sediment in the dam, a section through the deposit was left exposed revealing a well-layered stratigraphy, which Ndasi (2004) was able to record. It consisted of layers of carbonaceous clay and fine silt partings covered by a reddish brown clay soil with grass roots and an average thickness of 90 mm. Thus the mine residue would be impossible to distinguish using aerial photography alone.

5.2 Use of ASTER

5.2.1 Factors potentially affecting the detection of minerals by ASTER

(a) Seasonal effect on mineral detection

I found a large number of seasonal differences in the detection of minerals. Although the only climatic data that I collected was rainfall, this is only one of the climatic factors that could affect detection; including the occurrence of the minerals (e.g. moisture is required for the formation of secondary minerals such as copiapite and jarosite but rainfall can also dissolve these secondary minerals or cause erosion and the spread of minerals) (Naicker *et al*., 2003). Another climatic factor is high evaporation leading to capillary rise of contaminated groundwater and the formation of efflorescence, possibly in the form of jarosite, on the soil surface (Naicker *et al*., 2003). Other climatic factors include wind speed and direction, which transport dust particles from the MRDs and deposit them on surrounding surfaces (Blight, 1989); nonetheless, it was beyond the scope of my study to examine their influence and the following discussion about seasonal differences in mineral detection is based on general climatic patterns.

Pyrophyllite, which was found to be associated with mine residue and large roofs in commercial and industrial areas, had the highest detection in early spring but no significant difference with spring. Similarly to pyrophyllite, copiapite was found to be associated with the roofs of large industrial and commercial buildings. In their study on the East Rand, Chevrel *et al*. (2003), found that there was an over-classification of mine residue using IKONOS, which is a space-borne multi-spectral scanner producing a high-resolution image, with roofs in industrial and residential areas frequently classified as tailings. In a further study, this time using ASTER, Chevrel *et al.* (2008) explain the confusion between tailings dams and industrial building roofs as either a thin layer of mine residue dust or paint pigments with a similar reflectance. This can be, and needs to be, confirmed through ground-truthing but in the absence of which my results could explain the dust option.

Copiapite forms as efflorescence on the surface of soils and mine residue, thus it is readily exposed to wind and rain erosion. It is a light mineral, with a specific gravity of approximately 2.1 (Pough, 1976), suggesting that it is prone to wind erosion. In addition, windborne dust from gold mine residue probably contains pyrite (Ojelede et al., 2008). Although wind data has not been obtained it is usual for the winds to get stronger prior to the wet season (mid-July though mid-October) and these winds acting on dry surfaces create the maximum amount of dust (DEAT, 2006). Referring to earlier Plate 19 and the vertically paired sequence of plates from left to right, mine residue dust composed of, inter alia, pyrophyllite, pyrite and copiapite, is eroded from MRDs and some settles on the roofs of industrial and business buildings, which are probably flat and large enough for the minerals to be detectable by ASTER. Copiapite is also readily dissolved (Pough, 1976), thus the small amount of rain that fell at the beginning of October was possibly sufficient to dissolve most of the copiapite but insufficient to wash the settled dust away. After the first rains but before the ASTER image taken in late October there were four dry days, where there could have been more dust and which could have provided sufficient evaporation to weather the (wet) pyrite and form efflorescence (i.e. copiapite). From November through March, frequent rain-falls limit dust generation by keeping the surfaces moist (DEAT, 2006). It can also be assumed that the rain dissolves the copiapite and most, if not all, mineral products are washed from the roof. During the drier autumn and winter months (April though mid-July), winds are calm and rarely generate dust (DEAT, 2006). In summary, there will be a fine balance between the minerals dissolving, precipitating or being dispersed based on wind and rainfall.

As with copiapite, the highest amount of jarosite was detected after the first good spring rains but this had no significant difference in detection with either early spring or summer. This can be explained by the first rains after the dry season causing a lowering of the pH through weathering of pyrite, thereby creating the acid-sulphate brine required for the formation of these minerals as precipitates; which one depending on pH, Eh and moisture (Swayze *et al*., 1996; Langmuir, 1997; Espana *et al.*, 2005; Marion *et al*., 2008). In a study by Bakatula *et al*. (2008) on a third generation MRD, they found a decreasing trend in pH from the tailings pond to the outer edge of the beach, which can be observed from the detection of jarosite closer to the pond and copiapite towards the outer beach (Plate 27). During the wet season, as weathering proceeds and pH increases (possibly through dilution by rain water), copiapite weathers to jarosite, which eventually becomes unstable and is replaced by other Fe-bearing phases (Swayze *et al*., 1996; Elwood Madden *et al*., 2004).

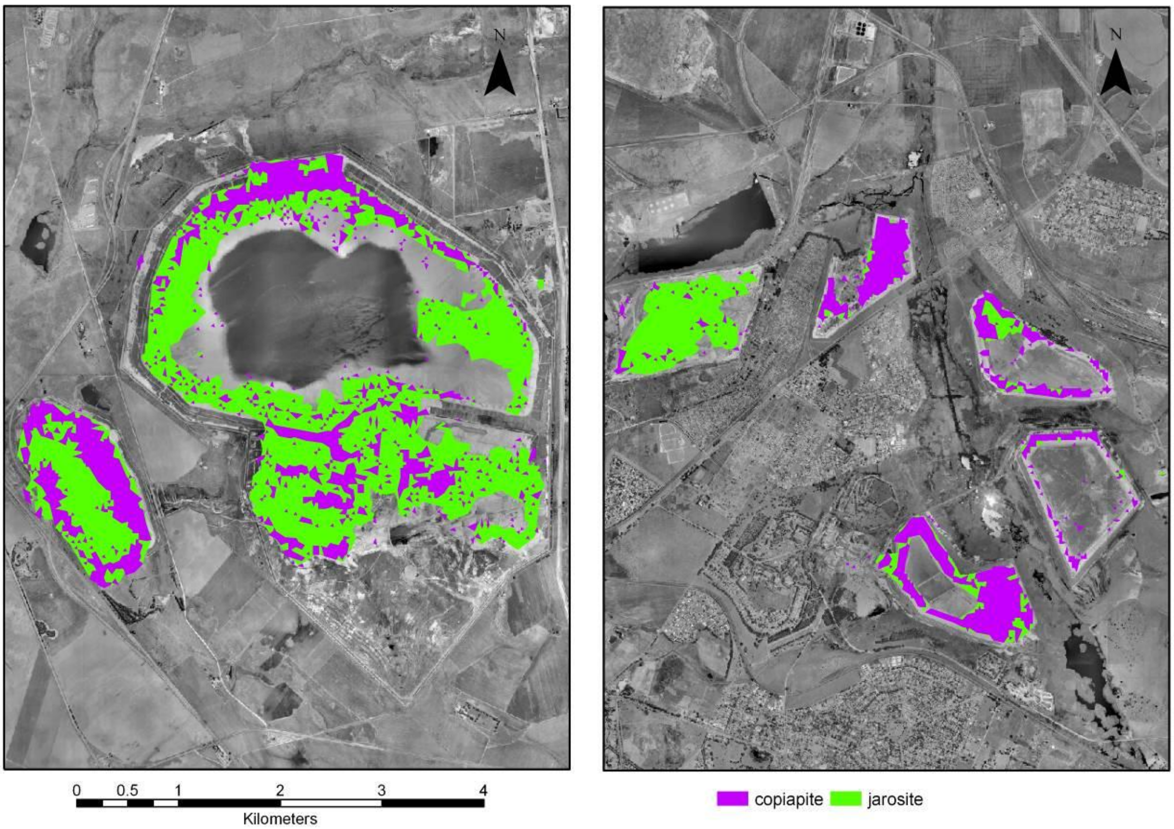

Plate 27 Precipitation chemistry for copiapite and jarosite depends on pH, Eh and moisture

The lowest overall detection of mincrust was from the end of summer to the beginning of spring with the highest amounts between the first good spring rains and the beginning of summer. A possible explanation for this is that the detection of mincrust is related to crop irrigation, which supplements rainfall.

The seasonal differences in the detection and/or presence of minerals appear to be related to changes in wetness, vegetation cover, mobilisation, and disturbance (including development). The findings of this study lead to the conclusion that, of the two seasons examined (spring and summer), the best time to take an ASTER image to detect mineral signatures of gold and uranium mine contamination is after a few dry days following the first spring rains; however, it is suggested that this is confirmed through a more extensive study including all four seasons and additional inter-season data.

(b) Masking of minerals from detection by ASTER

i Masking of minerals by vegetation

The examination of minerals association with level of vegetation, as distinguished by NDVI, indicates that spectra of chlorite and mincrust are not masked by vegetation, whereas the other mineral spectra may be. This result somewhat supports the argument for transportation of mincrust by water because actively growing vegetation will also be associated with water.

ii Masking of minerals by fire

Although not tested in this study, grassland fires (i.e. burnt `black' areas) are a significant feature of the Highveld environment. The black absorbs all the light so there's no reflectance and minerals cannot be detected by remote sensing – i.e. they're effectively masked through a change in spectral properties due to the ash. This could contribute to the low detection of minerals (except pyrophyllite) in early spring.

5.2.2 Use of ASTER for detecting contaminants of concern from gold and uranium mine residue deposits

(a) Associations between mineral detection and risk sources

i Use of ASTER to distinguish between different types of mine residue deposit

Minerals were not detected on rock dumps by ASTER. However, this does not mean that waste rock dumps do not contain them. Whereas much of a waste rock is barren of gold there may also be mineralised material but insufficient to be considered economical to process for gold recovery. However, in some instances the waste rock dump could include highly mineralised material because of a practice known as "cross-tramming", which is when ore gets tipped into the waste transport system (or vice versa but this causes dilution of the ore) (Handley, 2004). Hinde *et al.* (1986), refer to a study on a deep-level mine where the grade of development waste (i.e. off-reef development) close to its source averaged less than 0.3 g/t gold. However, on surface the waste had a grade of about 1.5 g/t before washing and 0.6 g/t after washing. Washing plants were constructed at some mines in order to separate the gold-bearing "fines" from the larger particle size waste rock, with the fines being sent to the metallurgical plant for processing.

In aerated environments, acid generation starts on the outer surface of a boulder, rock or grain (Hodgson *et al.*, 2001). Acidification of outer surfaces is therefore fairly rapid, while the inner portions remain unchanged. With rock dumps the rate of acidification is relatively slow because of the low surface to volume ratio associated with large particle sizes. However: the fine particles within the originally dumped rock (especially where there is no washing plant), together with the particles from weathering and acidification, are all washed into the inter-particle voids whenever it rains. This limits dust from rock dumps but the ARD percolates through the dump and infiltrates the underlying soils. Consequently, contrary to the DME guideline on financial provisioning for closure, which assumes that all waste rock dumps contain only barren rock (DME, 2005), waste rock dumps from gold mining may contain pyrites and other sulphates associated with the ore, which can serve as sources of ARD.

The greater extent of jarosite and mincrust on slimes dams compared with sand dumps is probably also related to particle size and age of the facilities. Many of the sand dumps were undisturbed for several decades, during which time they were exposed to oxygenated rainwater. This resulted in oxidation of the pyrite and other sulphides in the material, particularly an outer layer several metres thick. The sand dumps, being more permeable and older than slimes dams, were generally more seriously affected by this oxidation, and oxidation has typically reached a depth of about 5 m compared to about 2 m in the slimes dams (Kempe, 1983; Marsden, 1986).

The oxidation products are often transported downwards through the dumps by percolating rainwater, which then enter the underlying aquifers (Tutu *et al.*, 2003, Naicker *et al.*, 2003). Neutralising reactions, with mineral phases in sediment, often consume the acidity resulting in a groundwater plume at near-neutral pH but containing high concentrations of Fe and SO_4^{2-}. Upon discharge to nearby surface water bodies, ferrous iron undergoes oxidation and precipitates as ferric oxyhydroxide mineral phases. This reaction is also acid generating and the resulting low pH conditions can greatly increase the mobility and toxicity of dissolved heavy metals (Tutu *et al.*, 2003).

Plate 28 shows mincrust detected by ASTER on a sand dump where the surface has been disturbed by reworking; whereas, on the undisturbed surfaces, which are recognised by a sparse cover of vegetation, no mincrust is detected. This appears to confirm the transport of oxidation products away from the outer surfaces of the undisturbed dumps.

In comparing dormant with reworking MRDs for risk assessment, at issue could be the relative rates of pollutant release. From a perspective of urgency in dealing with it (or more correctly opportunity to address it), reworking of a MRD is a greater risk because large volumes of unoxidised residue are rapidly exposed to oxygen and water. Not only does this pose a pollution risk but if the intention is to recover pyrite and uranium then it can also lead to loss of product.

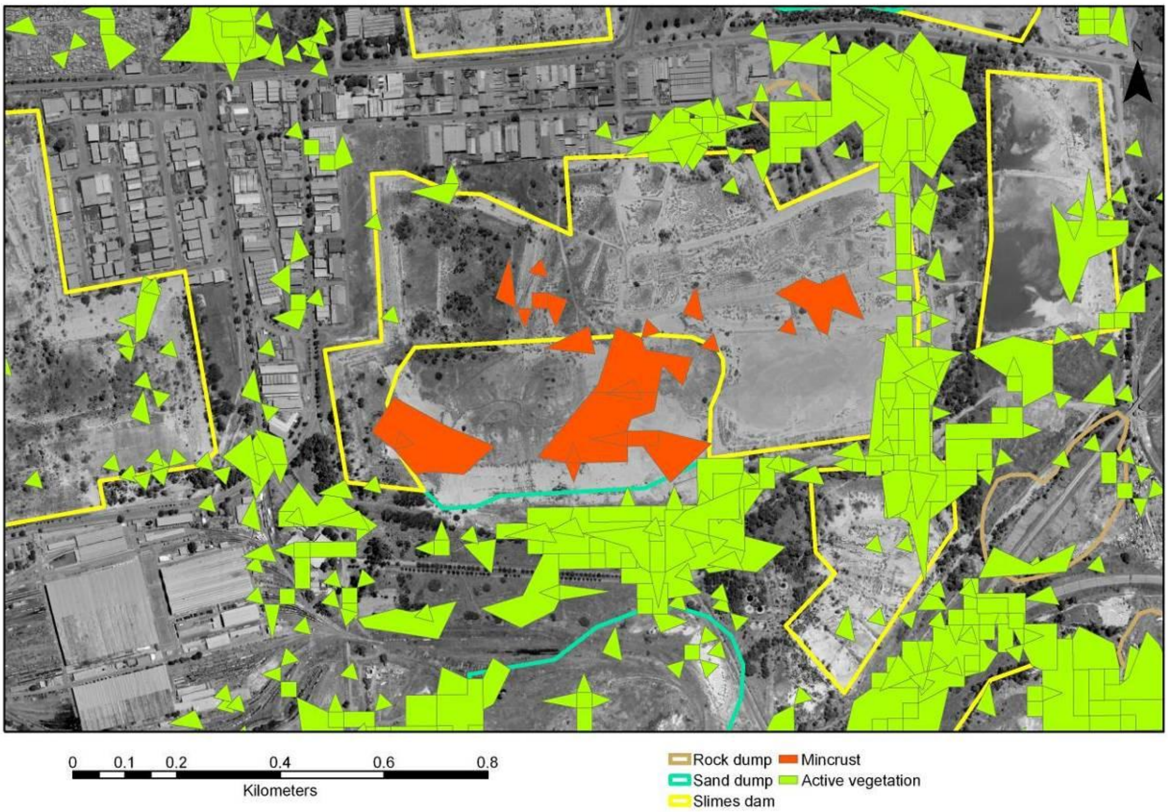

Plate 28 Aerial photograph showing mincrust detected by ASTER on more recently disturbed surfaces of a sand dump but not on relatively undisturbed surfaces, recognised by the presence of sparse vegetation cover. Vegetation cover can be seen on the aerial photograph but is not sufficiently active (or "green") to be detected by NDVI

ii Use of ASTER images to detect mine residue contamination on footprints

Whereas the reprocessing of hundreds of millions tons of gold mine residue has removed (to varying degrees) the direct cause of several significant impacts (e.g. dust, ARD) it is unrealistic to expect that there will be no residual impacts. Such impacts may arise from the earlier transport of contaminants, including uranium and its progeny, into the soil directly beneath and surrounding gold MRDs (Rösner and van Schalkwyk, 2000). There is also evidence that reprocessing exacerbates contamination though exposure of previously anaerobic tailings to air and water (Mphephu *et al.*, 2003; Tutu, 2005). The reprocessing of tailings dams requires that stabilised or vegetated surfaces be disturbed. Once a tailings dam has been disturbed, previously unexposed material starts to be oxidised, which can yield ARD. I found a positive association between the detection of mincrust by ASTER and slimes dam footprints.

Possible exposure pathways to humans include ingestion through eating crops and vegetables grown in the soil or animals, which have fed on contaminated foodstuffs. The roots and rhizosphere of plants create an oxidizing or “corrosive microenvironment” (Dunn, 1986), which results in increased solubility of micronutrients essential to plant growth, as well as increased bioavailability of potentially toxic metals and metalloids (Marschner, 1995) . A study of gardens contaminated by uranium processing waters found the highest concentrations of total uranium in root and stem vegetables, whilst fruit concentrations were generally the lowest (Tracy *et al.,* 1983). There is also evidence for the concentration of uranium by some plant species and soil micro organisms growing on slimes dams and over U-enriched ARD close to gold slimes dams on the Witwatersrand Basin (Weiersbye *et al*., 1999; Weiersbye and Witkowski, 2003; McIntyre *et al*., 2008). The accumulation of uranium in plant tissues implies that the soluble fraction is bio-available. Jones *et al*. (1990) found that plants growing on mineralised substrata could contain concentrations of uranium up to 100 times that of plants from other areas.

The grass *Cynodon dactylon* is used for grassing tailings dams and footprints in South Africa, and is a palatable grazing species. When grown on slimes dams or in slimes-polluted soils the roots of *C. dactylon* can accumulate uranium to levels greatly exceeding those in the soils. The spores of soil micro organisms (mycorrhizal fungi) associated with the rhizosphere of this grass contained up to 10 000 ug/g dry mass of uranium (Weiersbye *et al*., 1999). Certain tree species on ARD also accumulate U. Although these species are useful for cleaning contaminated soil, the litter can lead to the uranium enrichment of topsoil, and the high plant uranium levels increase the probability of exposure through secondary pathways (Weiersbye and Witkowski, 2003). By removing a MRD, there is an increased likelihood of the footprint being used for residential or agricultural purposes, and even left fallow the footprint may be accessed by cattle for grazing. Therefore, the overall `risk’ could be increased due to increased probability of `exposure’, despite the footprint being a lower pollution source and `safer’ than the original MRD.

iii Use of ASTER images to detect mine residue contamination

Having established that copiapite, jarosite, pyrophyllite and mincrust are associated with mine residue, examination for these minerals beyond the boundaries of the MRDs provides insight into their mobility and likely areas of contamination. Ideally, with no other interfering factors and in an infinitely transmissive landscape, there should be a perfect correlation between the volume or area or boundary (circumference) of a point source and its zone of influence. However, there are many factors that may influence the actual transmissivity (e.g. topography, biology, soil, geology, hydrology, development and land use practices).

(b) Associations between mineral detection and risk pathways

I found a positive association between mincrust and wetlands. McCarthy and Venter (2006) found increased abundance of Co, Ni, Zn, U, Pb, Cd and Hg in the uppermost metre of peat taken from a wetland on the Klip River; and Roychoudhury and Starke (2006) found significant enrichment of U, Hg, V, Cr, Co, Cu and Zn in the sediments of the Blesbokspruit. In the former study, McCarthy and Venter found the increases in the trace elements coincided with an increase in P and iron and they attribute this to the establishment of Johannesburg. Whereas they ascribe the elevated uranium only to mine tailings they suggest that the other trace elements could come from a combination of sources because of variability in metal enrichments. Through comparison of dust fallout measurements with the inorganic fraction of peat samples McCarthy and Venter (2006) concluded that water flow was the major pathway for the introduction of inorganic material.

The positive association between wetlands and mincrust is probably a result of fluctuations in the water level and sediments being exposed at low water levels. Wetlands are well known for sequestrating pollutants from water (McCarthy and Venter, 2006; Tutu *et al.,* 2003; Winde *et al*., 2004b). Neutralisation of acidic water flowing into and through wetlands, redox-initiated co-precipitation of uranium together with hydrous oxides of iron and manganese (Winde *et al*., 2004b), and the reduction of U(VI) to the U(IV) state (Tutu, 2005) in anaerobic “boggy” environments can result in the retention and accumulation of uranium in peat deposits.

(c) Associations between mineral detection and risk receptors

i Agricultural land

I observed that farmers sometimes plant different crops on the same pivot, which could be planted or harvested at different times. Thus, it is assumed that crop type, which can affect coverage (e.g. density of planting, or whether or not the plant is broad-leafed), and land status (e.g. fallow, recently ploughed, recently planted, recently harvested) play an important role in the detection of mincrust. This is of concern because although the overall percentage of irrigated agricultural land on which mincrust was detected was relatively low, at less than 3%, this is probably as a consequence of crop type or land status at the time of the ASTER image. It is likely that there are elevated concentrations of mincrust on other irrigated agricultural land, which appears to be substantiated by the different ASTER images detecting mincrust on different agricultural sites at different times (Plate 29). It is also recognised that the study area should have been enlarged to include land further away from the mining sources as mincrust was detected on a number of sites beyond the EMM borders.

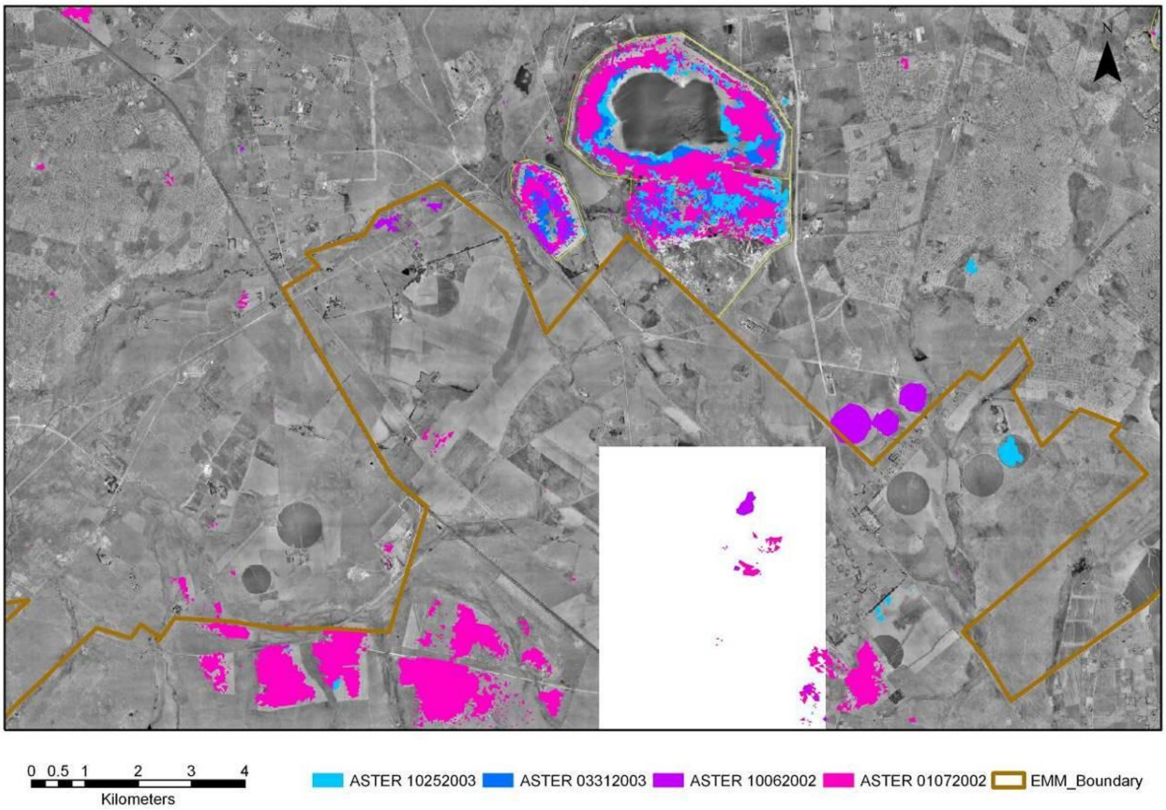

Plate 29 **An example of the presence of mincrust detected on different agricultural sites at different times. It should be noted that many of the sites (old agricultural lands) are beyond the southern boundary of the study area**

The accumulation of uranium on agricultural land is not new. Phosphate rocks can contain high concentrations of uranium (North African rock phosphate contains around 20-30 mg kg^{-1} U). In a long-term study of agricultural plots at Rothamsted, UK and in New Zealand, it was found that U, added as super-phosphate to the clay loam soil, was retained in the plough layer of arable soils or was adsorbed by the organic layers of soil under grassland (Rothbaum *et al*., 1979). However, if super-phosphate was the source for agricultural land in EMM, then I would not expect such a large difference between rain-fed and irrigated agricultural land because it is probably used on both. The mincrust that was detected on rain-fed agricultural land appears to come from spillage or runoff (visible as fine white material) from a neighbouring poorly constructed MRD, which is just beyond the EMM boundary (Plate 30). It is likely that the mine residue flowed towards the watercourse, seen in the North West corner of the aerial photograph, but has subsequently been ploughed into the soil.

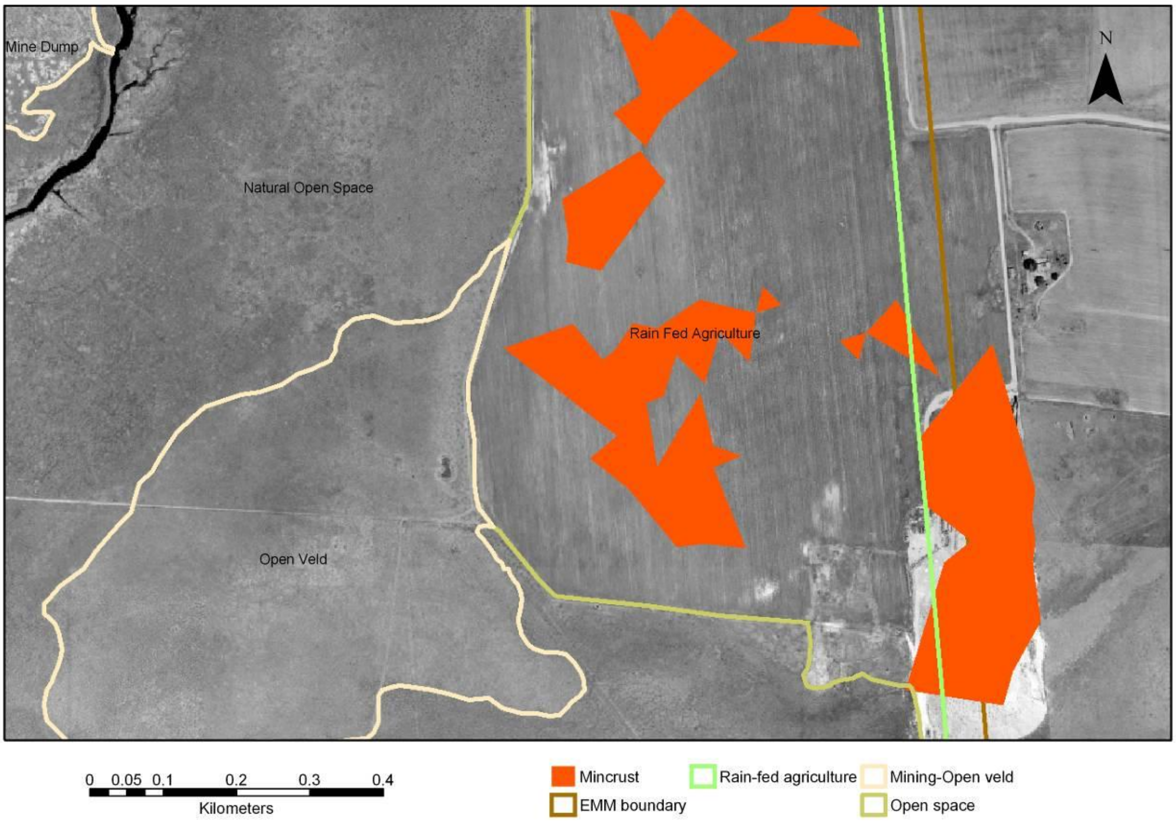

Plate 30 Aerial photograph showing mincrust on rain-fed agricultural land may be associated with mine residue spillage or run-off from an old mine residue deposit just outside the study area

Consequently, the most likely pathway for mincrust onto agricultural land is the aqueous. Irrigation water in the region comes from rivers and groundwater; both of which could be in receipt of natural uranium sources as well as mining sources. Although tests have been conducted on the use of gold and uranium mine water for crop irrigation there was no mention of uranium (it would seem that it was not analysed for) and concerns were only raised about the long-term accumulation of salts in the soils (Handley, 2004). This finding supports that of both Tutu *et al*. (2005) and Winde *et al*. (2001; 2004a; b; c), who found substantial evidence for the accumulation of uranium along rivers and streams across the Witwatersrand Basin. The implication of this regarding the risk assessment is that rain-fed agricultural land (indeed any land) in proximity to MRDs is vulnerable to runoff and spillage and irrigated agricultural land relatively remote from MRDs is vulnerable if irrigated with mining contaminated water.

ii Residential land

Whereas there is a positive association between mincrust and both informal settlements and formal residential land, there is only a positive association for jarosite with formal residential land. Further examination, this time of ordnance survey sheets, revealed that the formal and informal residential area is located on land that was recently agricultural holdings, in proximity to the Natalspruit, a known mining polluted watercourse from mine dewatering and MRDs (Naicker *et al.*, 2003; de Fontaine, 2004). Consequently, the minerals could have come from irrigation using river water. It was also found that the site is close to the "Black Reef" (Plate 31), so, this could mean that the site is affected by an accumulation of natural weathering products or by historical mining activity. Unfortunately I could not confirm the latter because my historical aerial photographs did not cover this area.

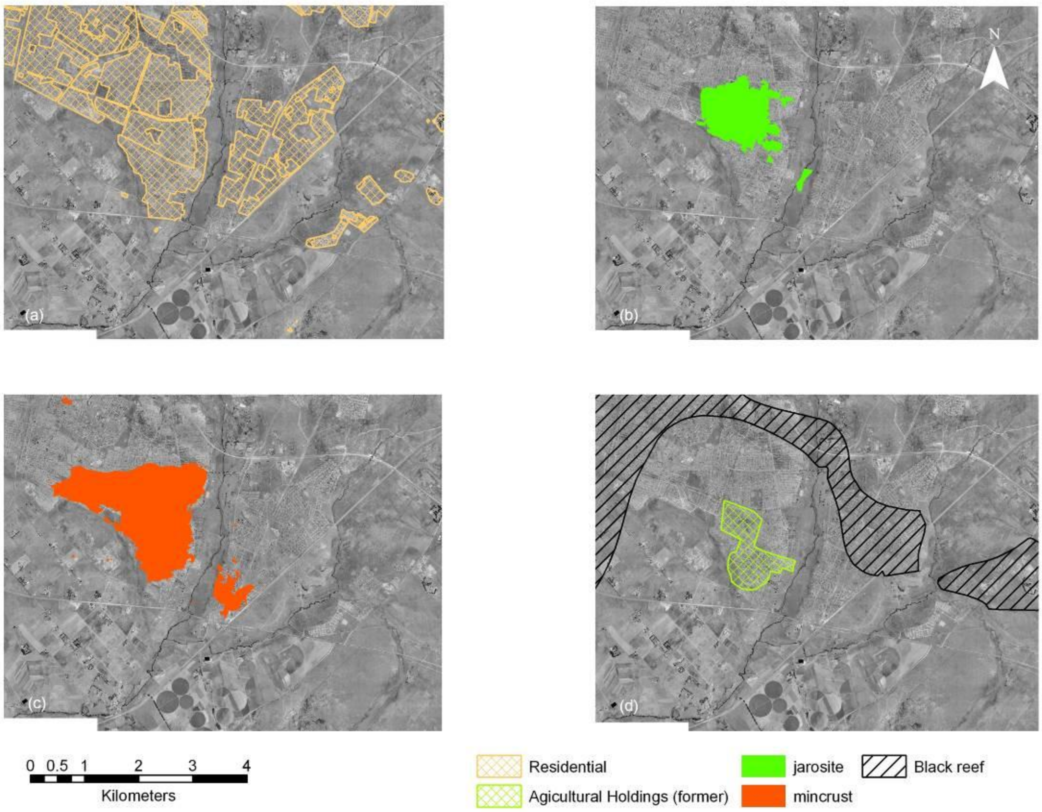

Plate 31 **(a) Residential land use where: (b) jarosite, and (c) mincrust, were detected by ASTER, and (d) shows the location of the Black Reef and former agricultural holdings**

iii Industrial and business land

The dry and windy period (typically from August to October) leads to the deposition of mine residue dust (containing pyrophyllite) on the surrounding landscape. The detection of pyrophyllite on industrial and business land use appears, from aerial photographs, to be associated with the roofs of buildings. This is possibly because the roofs of industrial and business premises are higher and larger than other features and they may act as traps for this dust. There is also a positive association between copiapite and industrial and business land use and between copiapite and pyrophyllite.

There was significantly less mincrust on industrial and business use land than ‘background’, possibly because the areas are built up and the surrounding surfaces covered with paving stones, tarmac and concrete. Unlike pyrophyllite and copiapite, which appear to be transported predominantly by wind (as dust), or in case of the latter, possibly results from the oxidation of pyrite minerals transported onto the roofs by wind, there is substantial evidence that mincrust is mainly transported by water.

5.2.3 Use of ASTER images to detect mine residue contamination at different distances from mine residue deposits

My findings that the odds ratio is higher for detecting pyrophyllite 0 to 500 m from MRDs compared with further away, and for detecting jarosite and mincrust greater than 1 000 m away compared with closer, fit my earlier assumptions that pyrophyllite is a signature of bulk residue transport (with most residues not moving very far from the source and windborne dust fallout being widely dispersed and often masked by vegetation) and jarosite and mincrust are predominantly signatures of water-borne contamination and ARD, which are transported over greater distances.

5.3 Risk and Land Use Vulnerability

5.3.1 Proximity of mine residue deposits to vulnerable land uses

An argument that has been put forward on the environmental merit of reprocessing old MRDs is that this provides opportunity to relocate mine residues to more appropriate and better contained sites (AngloGold Ashanti, 2005). However, in practice the problems have mainly been shifted and not solved, with new MRDs from the reprocessing of old mine residue being constructed on dolomites, across watercourses (Plate 32) or on existing (“leaky” and poorly sited) MRDs (Mphephu *et al.*, 2003). The processing of MRDs has also increased oxidation of mine residue through disturbance of the consolidated material, thereby enhancing ARD and uranium mobility (Tutu *et al*., 2003).

Requirements for selecting an ideal site for a MRD include remoteness from inhabited areas, main roads, power lines, rivers, and streams (Ruhmer, 1974). However, 88% of MRDs were found within 1 000 m of formal residential areas; with 71% within 500 m. Although some of these are mine villages, constructed many years earlier, new housing developments are still being constructed in proximity to MRDs despite the GDACE policy on buffer zones.

In South Africa, most MRDs are unfenced and can thus be used for recreation (e.g. quad-bikers, sand-boarding), and as informal playgrounds by young children. This informal use of MRDs presents a potential risk to both the users and owners. In addition to some of these activities increasing erosion and dust emissions, the increased hand-to-mouth activity (and ingestion of particles) exhibited by young children is known to place this population group at particularly high risk of metal toxicity (EEA, 2002).

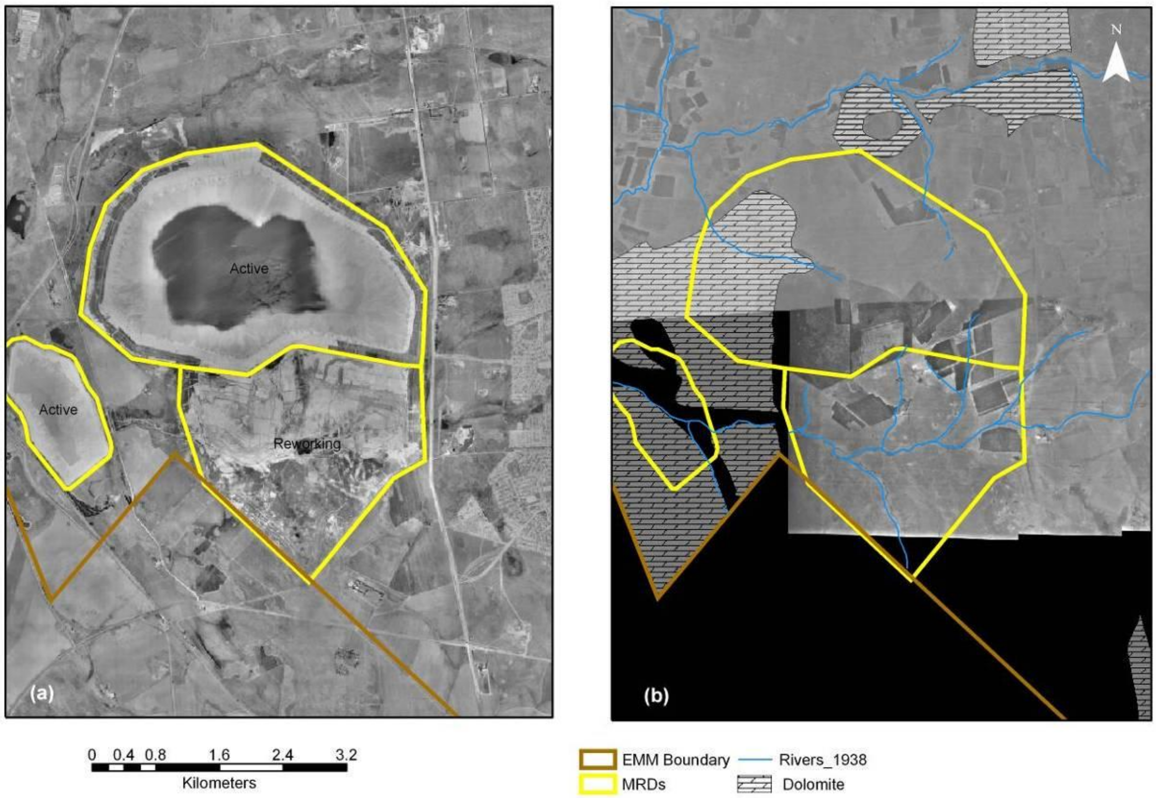

Plate 32 Aerial photographs showing mine residue deposits created from reprocessing old mine dumps are still situated on permeable sub-strata and drainage lines: (a) in 2003, the northern most MRD is active and the residue in the southern most MRD is being reprocessed (for the second time), (b) 1938 photograph shows that MRDs are located on dolomites and across watercourses

Approximately one-third (35%) of MRDs are located within 1 000 m of agricultural land; with just under a quarter (23%) within 500 m. Impacts of dust from MRDs include acidification and salinisation of soils and smothering, toxicity and reduced yield of crops (Weiersbye and Witkowski, 1998). It is well established that some plant species can accumulate metals to potentially toxic levels (Marschner, 1995) and that plants on tailings and ARD have elevated metal contents (Weiersbye *et al*., 1999; Weiersbye and Witkowski, 2003). More seriously, the recent death of a child in Johannesburg from multiple metal-poisoning is thought to be as a result of consuming an herbal remedy (Steenkamp *et al*., 2002). Although the source of the metals is uncertain, they were typical of gold MRDs, and found to be present in a range of herbal medicines (Steenkamp *et al*., 2005; Cukrowska and Weiersbye, 2010).

From a radiological perspective, three exposure pathways have been identified (on the Far West Rand) leading to potential doses to members of the public above the regulatory limit of 1 mSv per annum, based on water and sediment/soil sampling and a dose model (Joubert, 2007):

- Interception of NORMs by leaves due to irrigation of pasture and crop vegetation, in addition to the accumulation of NORMs in the soil through irrigation with mining contaminated water;
- Uptake of re-suspended sediments by cattle during watering at the banks of surface water bodies; and
- Agricultural use of land contaminated with slimes transported by storm water runoff from slimes dams.

Their study further established that the irrigation of agricultural land carried the highest radiological risk, thus it can be considered most vulnerable from a radiological perspective, whereas potable water consumption was safe from a radiological perspective. Consequently, the establishment of soft land uses, land use restrictions and the establishment of buffer zones around MRDs to mitigate vulnerable land uses should be a priority.

5.3.2 Water contamination by uranium from mine residue deposits

Although the concentrations of uranium in the reefs of the Witwatersrand Basin are two orders of magnitude lower than uranium deposits mined in Canada, the USA or Australia (Funke, 1990), uranium contamination in South Africa is possibly more severe than at many of the principal uranium mines in these countries (Winde *et al*., 2004a). Whereas it was estimated that there were about 160 million cubic metres of uranium mill tailings stored in temporary repositories in the USA with a cost for reclamation and remediation estimated to be billions of dollars (Zhu and Anderson, 2002) there are about six billion tons of gold and uranium tailings in South Africa (Winde *et al*., 2004a); much of which is deposited in poorly located, designed and managed facilities (Mphephu *et al.,* 2003). Moreover, for most of the 120 years that gold mining has taken place on the Witwatersrand all of the uranium was deposited onto MRDs without any recovery, meaning that concentrations of uranium in these MRDs is higher than in those of many of the principal uranium mines (Winde *et al*., 2004a).

Tutu (2005), found that the international specification of 20 μg l^{-1} U(VI) for natural waters was often exceeded (by up to 1 600 times) in surface and groundwater near MRDs. In addition to the mobilisation of uranium, the acid soil conditions in the vicinity of MRDs result in trace elements such as Cu, Co, Ni, and Zn becoming mobile, with the highest mobility taking place in stream sediments and topsoil (Mphephu *et al.,* 2003). The main reasons for the elevated uranium concentrations were seepage from the MRDs (Mphephu *et al.,* 2003; Tutu *et al.,* 2003; Winde *et al*., 2004a), runoff from the oxidising slopes of MRDs, and mine residue spillages (Mphephu *et al.,* 2003). According to Tutu (2005), uranium occurs predominantly as hydroxy-uranyl, uranyl-sulphate and uranyl-carbonate complexes, which are soluble forms. Carbonate complexes may either be neutral or negatively charged and as such are highly mobile in most soils and infiltrating ground water despite the presence of cation exchangers such as clays. Using gamma spectrometric analysis, Tutu *et al*. (2003) also found that significant leaching of uranium from MRDs had separated uranium from its decay series, thereby causing radioactive disequilibrium.

Whereas water quality has been shown to deteriorate in the proximity of MRDs and footprints it tends to improve further away (Mphephu *et al.,* 2003; Tutu, 2005; Tutu *et al*., 2008). The improvement in water quality towards the Vaal River is accredited to large bands of Malmani dolomite intercepting the watercourses and the presence of wetlands (Institute of Water Quality Studies (IWQS), 1995; Tutu *et al*., 2008). The dolomites, being alkaline in nature, lead to an increase of pH of water thereby enhancing the precipitation of iron and other elements. The wetlands trap metals in sediments and peat lands thereby serving as a sink for pollution (McCarthy and Venter, 2006).

Another study, this time by Lottermoser and Ashley (2005), found that seepage water from a rehabilitated uranium MRD in northwest Queensland, Australia, contained metals, metalloids and NORMs despite the repository being capped in 1985 and receiving an award for environmental excellence. Closure objectives were, “to leave the site in a safe and satisfactory condition consistent with future land use in the area (i.e. cattle grazing), and requiring no foreseeable on-going maintenance and a minimum of precautionary monitoring” (Lottermoser and Ashley, 2005, p. 122), which is similar to closure objectives for at least some of the gold and uranium MRDs in South Africa. The cover design consisted of a 0.5 m layer of rolled soil/loam/clay and a 1 m layer of unmineralised waste rock, which was vegetated. It is worth noting that this slightly exceeds the generally accepted cover design provided by the South African DME for acidic, metal-rich waste and far exceeds the requirements for basic, salt-producing waste, which is the category stipulated for gold and uranium waste (DME, 2005). Even though contaminant loads are relatively low (± 5kg of uranium per annum), some 20 years after rehabilitation was completed surface water downstream of the repository contains concentrations of TDS, U and SO_4 that exceed Australian national water quality guideline values for livestock watering.

5.3.3 Other sources of uranium contamination

My study has shown that mincrust is associated with mine residue, especially MRDs. It has also shown that mincrust is associated with wetlands (as a pathway) and irrigated agricultural land (as both a receptor and secondary pathway for contaminants into the diet of the general population). Although this study is focussed on an assessment of the environmental risks posed by MRDs, there are possibly other sources with the potential to produce the mincrust signature (or if not, to also pollute the environment); these being, natural weathering of reef outcrops, mine dewatering, spillage from metallurgical plants, spillage of mine residue and disposal of contaminated material into borrow pits. The frequency, timing and location of routine water quality monitoring are normally insufficient to identify the primary sources or measure the real impacts on water systems (McCarthy and Venter, 2006). Current monitoring is unlikely to capture the pulses of high metal and radionuclide concentrations during occasions such as: the first rains (Winde 2004a; Espana *et al*., 2005), disturbance of the sediments, or spills of mine residue or contaminated water. It is also worth noting that the DWAF did not require uranium to be measured by at least some of the gold mines as part of their water use licences or earlier (pre-1998) “discharge permits”.

(a) Natural weathering of reef outcrops

Natural sources for mincrust could include the weathering of reef outcrops or aquifers, which intersect uranium-bearing reefs. Plate 33 shows mincrust detected along a watercourse upstream of known gold and uranium mining activity. Although I initially ascribed this to natural weathering processes, careful examination of the 1938 aerial photographs revealed evidence of old diggings on the reef outcrop (typical linear trench-like feature) and even a small MRD (see Plate 34 (a)-(d)). Thus, mining activities could be the dominant source of mincrust. The occurrence of these old mine workings can easily be overlooked using recent aerial photographs, yet the excavations and pollution potential pose a risk to current land users (Plate 34 (e)-(h).

(b) Mine dewatering

Of the mines in EMM only one in the Central Basin and one in the Eastern Basin currently dewater underground workings by pumping; the former discharges into the Elsburgspruit a tributary of the Natalspruit and the latter into the Blesbokspruit.

Funke (1990) concluded that the effect of mine effluent, discharged from 13 West and Far West Rand mines was negligible, but that it could be assumed that radioactive contamination was present in the dolomitic mine service water and mine dewatering reaching the watercourse and in adjacent boreholes. Subsequent studies failed to demonstrate a radiological risk from uranium, however, they concluded that: a significant amount is discharged into the Wonderfonteinspruit from point and large-scale diffuse sources; the uranium is concentrated in the fluvial sediments and within groundwater; it could be remobilised; and it posed a hazard to water users because of its chemical toxicity (Wade *et al*., 2002; Coetzee *et al.*, 2006).

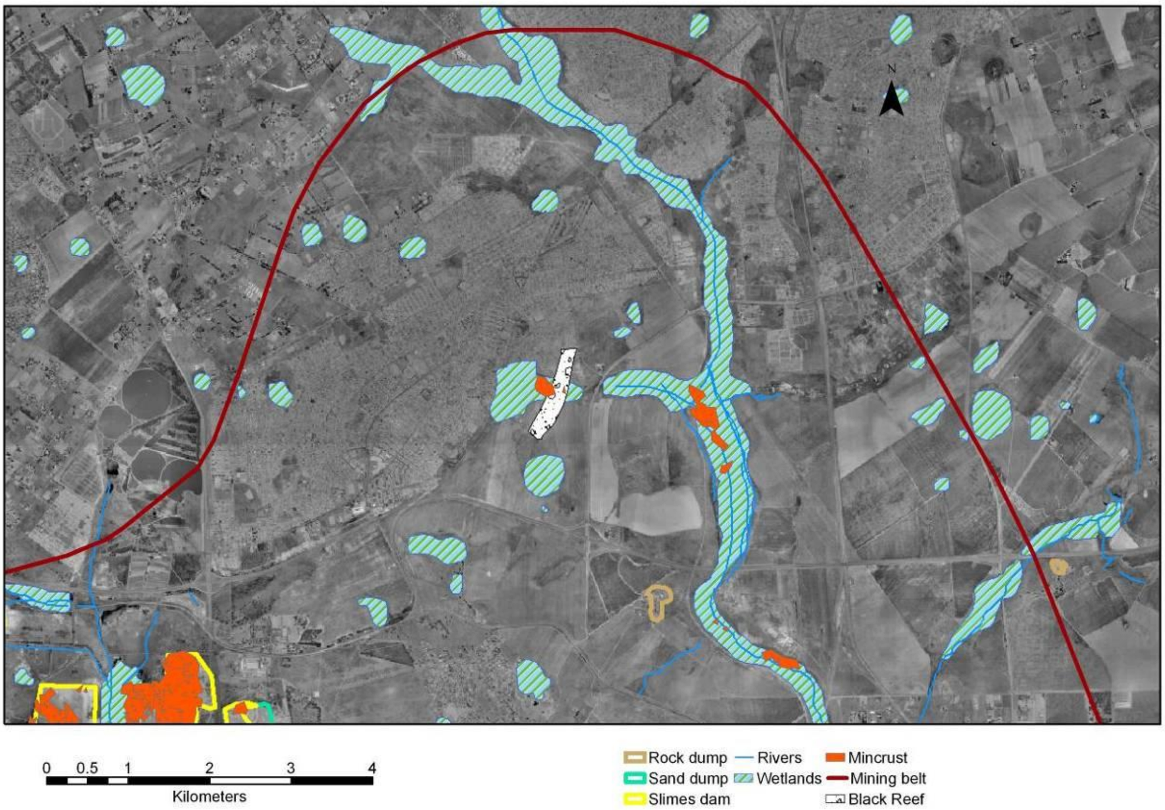

Plate 33 Mincrust detected by ASTER in a watercourse upstream of known gold and uranium mining activity, near Black Reef outcrop

(c) Spillage from metallurgical plants

The potential impacts of metallurgical plant spillage are not described in EMPRs (Pulles *et al*., 2005); however, it may be possible for the spillage of process material and residue to result in the mincrust signature. The large amounts of gold that accumulated in the soils beneath and around the metallurgical plants (Britten, 1954; Futcher and Morris, 1987) are an indication of large volumes of spillage over the years. Although continuous clean-ups are carried out, the final clean-up usually occurs during decommissioning, when excavations can range from a few centimetres to a few metres (IAEA, 2003). However, gold has restricted mobility (Jones *et al*., 1990) and other, more mobile contaminants, such as uranyl ions, will have gone even deeper into the soil and some may have entered groundwater and watercourses.

(d) Spillage of mine residue

Information on pipeline routes was not available for this study but no apparent linear features were detected by ASTER that could be attributed to pipeline failures. It is probable that ASTER is not sensitive enough to detect residual contamination from pipeline spills but airborne hyper-spectral remote sensing may well be. This is an area that requires research.

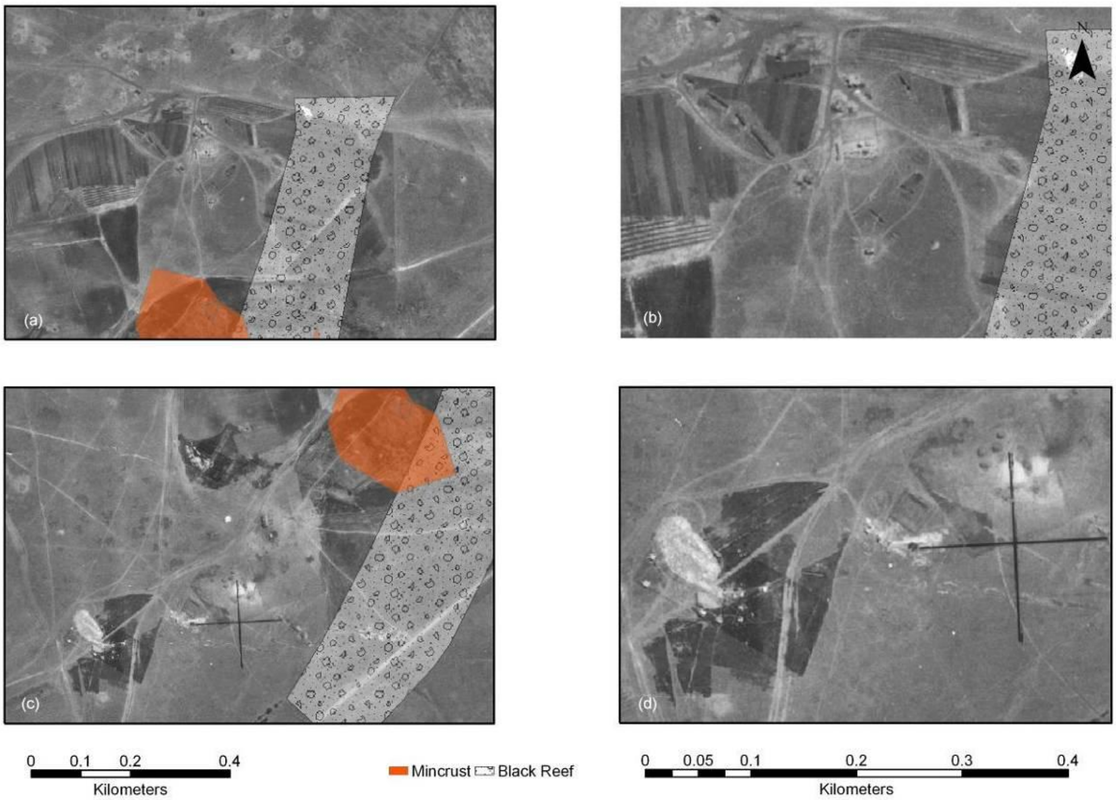

Plate 34 (a-d) Closer examination of mincrust in the watercourse and in the vicinity of the Black Reef shows historical mining activity. 1938 aerial photographs show: (a) and (c) old diggings to the north west and south west respectively. Further examination reveals linear diggings, to the north west and (d) a small mine residue deposit in the south west

A possible means of distinguishing between uranium from MRD seepage and residue spillage from MRD or pipeline failures is to also measure the presence of thorium. Very little thorium is found beyond MRDs or in wetland sediments except where surface erosion or spillage has occurred because, unlike uranium, it has low solubility and a high sorption tendency (Tutu *et al*., 2003).

(e) Disposal of contaminated material into borrow pits

Human (2008), reported on the historical disposal into borrow pits of contaminated material (ash, iron oxide, pyrite, slag, mine residue, waste rock, steel, rubber and scales from gold, uranium and acid plants), some of which was radioactive, by a gold and uranium mine. Although, in this reported case the site was "cleaned up", this referred only to radioactivity levels and no mention was made of other contaminants in the soil or groundwater. Furthermore, after treating half of the waste to recover gold and removing other recoverables (e.g. scrap steel) much of the waste was deposited on a MRD, which, as this study has shown, is a further source of potential harm.

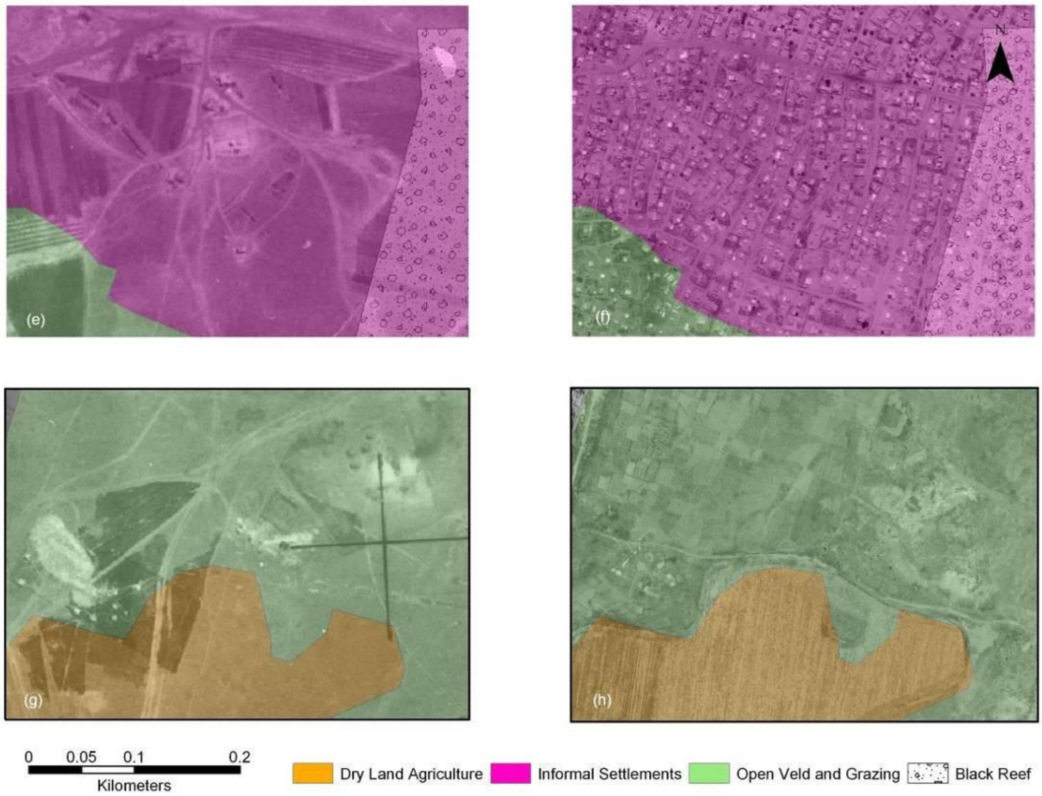

Plate 34(e-h) Comparison of historical mining activities of 1938 with current land use. (e) and (g) show mine workings in 1938 overlaid with current land use, (f) and (h) show 1938 aerial photographs replaced with those from 2003

5.3.4 Secondary pathway exposure of ecosystems to Naturally Occurring Radioactive Materials

The immobilisation of uranium occurs through various geochemical processes including: precipitation of uranium species with low water solubility; evaporative precipitation of salt crusts; co-precipitation with Fe and Mn oxyhydroxides as gels or coatings; co-precipitation with calcium carbonate; and pH-dependent adsorption onto humic acids and negatively charged surfaces (Szalay, 1964; Winde *et al*., 2004a). While the accumulation of uranium in the sediments of wetlands mitigates water-borne pollution it creates off-site secondary sources that may pose ongoing long-term risks (Coetzee *et al*., 2002; Winde *et al*., 2004c; Taylor and Hudson-Edwards, 2007).

Secondary pathway exposure to NORMs has been inadequately addressed on a world-wide scale, especially in South Africa (Sutton and Weiersbye, 2007). Immobilisation is in a hydrochemical rather than a mechanical sense since some of the solids, especially suspended solids and amorphous gels of oxyhydroxides, are easily moved downstream (Winde *et al*., 2004c). Uranium may be redistributed from soils and sediments into watercourses and surface water reservoirs as, or sorbed onto, particulate matter during storms and other modes of physical erosion (Tutu, 2005).

A number of organic acids may increase uranium solubility in soils (Szalay, 1957). Other natural processes for re-mobilising uranium from contaminated sediments include: desorption of uranium through replacement by other cations; oxidisation of reduced uranium species; reduction of iron and manganese hydroxides; and dissolution of uraniferous carbonates (Winde *et al*., 2004a). These changes in mobility make predictions of risk extremely difficult because the risk changes with even slight changes in environmental conditions. A further source of uncertainty is heterogeneity in heavy metal contamination of soil, which can significantly affect metal uptake (Millis *et al.*, 2004).

5.4 Use of remote sensing for identifying vulnerable land uses and prioritising MRDs for mitigation and/or remedial measures:

I found that aerial photography can be used to delineate physical disturbance in order to identify some sources of pollution and to obtain an indication of the environmental impact based on the extent of mine residue spillage, but not the full extent of the impact. Aerial photographs can also be used to identify the presence or absence of certain pollution prevention measures but not their effectiveness. Additionally, the use of historical aerial photographs can assist with dating the disturbance and identifying previous land uses or conditions that are now masked by development. However, there are significant limitations through only using aerial photography because contamination is often invisible to the human eye.

The use of ASTER multi-spectral images added more information about the environmental risks from pollution. The thematic ASTER images provided information on selected pollution signature minerals, which combined with field calibration, assisted with identifying the extent of pollution. In this study ASTER multi-spectral images proved valuable in identifying contamination of irrigated agricultural land relatively remote from mining activities. However, there are limitations to the use of ASTER, with the sensor not being spatially sensitive enough for relatively small quantities or low concentrations of minerals. For example, it is known that there have been numerous spillages from mine residue pipelines between old dumps and the metallurgical plants that were reprocessing the residue, yet no linear features were identified by ASTER. The ASTER sensor is also limited in the mineral signatures that it can differentiate between. Nevertheless, when combined with geographical data in the form of land use and watercourse overlays, and tabular data containing risk ratings, the technique proved useful for a screening level risk assessment. This study also proved valuable for identifying vulnerable land uses for rezoning or other protective measures.

The use of hyper-spectral remote sensing offers opportunities for overcoming some of the limitations imposed by ASTER. Ferrier *et al*. (2007) demonstrated the potential of airborne hyper-spectral remote sensing in identifying the distributions of mine waste and secondary iron minerals on a mine site and in adjacent rivers. Other research has shown that soil spectral reflectance can be used not only to assess soil contamination levels but by studying the correlation between spectrally featureless constituents and constituents with spectral features, even some of the former can be predicted (Wu *et al.*, 2005; Weiersbye *et al*., 2006a). For example, Kooistra *et al.* (2001) found that there was a positive correlation between Zn and Cd in floodplains along the river Rhine in the Netherlands and organic matter content; Wu *et al.* (2004) effectively used reflectance spectroscopy to predict Hg levels in agricultural soils; Wu *et al.* (2005) showed that laboratory reflectance spectra of soil samples taken from diffusely contaminated suburban agriculture fields can be used for predicting elevated metal and As contents, and Ferrier *et al*. (2007) identified the locations of hazardous material by integrating the results of the remote sensing study with laboratory-derived correlations of secondary iron species, cyanide and heavy metal concentrations.

Other opportunities lie with the incorporation of data held by various institutions such as the Council for Geoscience and mining companies. The study by Chevrel *et al.* (2008) makes use of additional data sets not publicly available and this data helps in refining the risk assessment. Incorporating airborne radiometric surveys in future will also enhance the risk assessment results, as this is a highly effective method of detecting and monitoring radioactive contamination of the environment and delineating pollution plumes (Coetzee, 2008). Other data made available to Chevrel *et al.* (2008) included: DTMs, which enabled them to include MRD quantities; and groundwater levels and boreholes, which allowed them to better quantify the threat to groundwater rather than simply use on/off dolomites, as I did in this study.

CHAPTER 6

6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

6.1 Conclusions

I found that four of the minerals detected by ASTER (copiapite, jarosite, pyrophyllite and mincrust) were detected on gold and uranium mine residue. The strongest detection was on MRDs and the weakest on spillage and footprints. They were also found to be detected on specific land uses and the pathways could be explained based on the history of land use and supporting literature on the chemistry. My findings suggest that jarosite and mincrust were predominantly associated with the aqueous pathway while pyrophyllite and copiapite were associated with wind blown erosion; although in the case of copiapite this was probably related to the oxidation of settled wind blown material or the wind blown erosion of copiapite crusts. The detection of chlorite by ASTER was found not to be associated with mine residue.

The evidence for pollution from gold mining on the Witwatersrand Basin has been identified in a number of previous studies with substantial evidence that ARD, seepage and decant from gold mines pose a risk to society and the environment, although natural systems are providing some attenuation (McCarthy and Venter, 2006). One of the more significant risks identified from the literature is the potential transport of metals and uranium into the food-chain, even though there remain some site-specific uncertainties regarding concentrations and speciation within the various exposure pathways. However, rather than demonstrating that the risks are acceptable, with or without mitigation, many are not even acknowledged in the EMPRs of mining companies (Pulles *et al*., 2005). My legal review showed that this is contrary to the risk-averse approach stipulated by the NEMA whereby impacts are to be anticipated, prevented whenever possible, or otherwise minimised and remedied. This study shows that minerals of gold and uranium mining origin are being transported onto agricultural land. The finding that there is far more likelihood of mincrust being on irrigated rather than rain-fed agricultural land, suggests that the dominant pathway is through the water systems.

“Where there are threats of serious and irreversible environmental damage, lack of scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation” (O’Riordan and Cameron, 1994). However, knee-jerk responses, such as closing mines, are unlikely to be appropriate. Although closing a mine is not a solution, preventing the reworking of an old MRD, unless this is in accordance with best practice, could be. In the case of the former there is unlikely to be sufficient funding to mitigate the risks highlighted and compromises need to be found. However, in the case of the latter, removal of the residue will increase pollution in the short-term and if the residue is not deposited on a properly contained site then it will continue to pollute for centuries. This means that the benefits of obtaining revenue from relocating the MRD will be lost. Consequently, strict requirements for understanding and addressing the mobility of metals, metalloids and NORMs need to be included, and enforced, in any mining authorisations. Other immediate measures could include:

- Independent monitoring of mine dewatering for uranium and other heavy metals and NORMs;
- Rezoning processes for land potentially impacted by mining for “risky” land use to require fully quantitative risk assessments;
- Renewed emphasis on State programmes for the provision of adequate clean water for domestic purposes (drinking, washing and bathing);
- Effective access controls around MRDs and process water systems, including the mandatory establishment of buffer zones;
- Public awareness campaigns on the hazards posed by MRDs;
- Improving natural attenuation processes by fostering vegetation types that act as pollution sinks (e.g. reed beds, wetlands, riparian woodlands, Weiersbye *et al*., 2006b; Dye *et al*., 2008);
- Incorporation of these findings into the integrated development plans and spatial development frameworks of the local authorities;

The enormity of the problem means that decision-making should be based on risk assessment at both the macro and local scale. At the macro scale, this study has shown that GIS-based historical aerial photography is valuable for characterising MRD sites, determining the extent of mine residue spillage, although not the extent of the impact, and detecting changes in land use of MRD sites. ASTER multi-spectral images were able to detect indicators of mine residue and proved valuable in identifying contamination of irrigated agricultural land relatively remote from mining activities. However, there are limitations to the use of ASTER, with the sensor not being spatially sensitive enough for relatively small quantities or low concentrations of minerals. The ASTER sensor is also limited in the mineral spectral signatures that it can differentiate between. Nevertheless, when combined with geographical data in the form of land use and watercourse overlays, and tabular data containing risk ratings, the technique proved useful for a screening level risk assessment. The study also proved valuable for identifying vulnerable land uses for rezoning or other protective measures.

Based on the findings of this literature study and research the following further requirements are indicated:

- Legislation that enables MRDs, footprints and other polluted areas to be classified as contaminated land with restrictions on future land uses;
- Prevention of informal settlements next to MRDs;
- Prohibition on using mine contaminated water, including impacted water bodies, for irrigation of food-crops;
- Fully quantitative risk assessments prior to using mine residue for construction purposes.

When assessing economic and environmental viability of future land uses in mining regions, my survey of the literature warns that the regulators, planners and developers must consider the potential for latent impacts such as impaired ecosystem functioning and bioaccumulation of contaminants, long after mine closure. As a result, residential townships, edible crop production and livestock grazing are considered vulnerable end land uses for MRD footprints or areas within the aqueous or aerial zone of influence of MRDs, mine dewatering and metallurgical plants. This does not mean that mine contaminated land is worthless or has to remain a liability. Restricted end land uses that are economically productive and potentially suitable for mine closure outcomes in the semi-arid South African climate include industrial sites, lined landfills, graveyards, sewage sludge disposal and land-farming, and carbon sinks facilitated by the growth of low-water demand and high root-biomass crops, such as certain fibre, pharmaceutical and biofuel species (Sutton and Weiersbye, 2007). Failure by the regulator and industry to agree on suitable land uses and buffer zones could exacerbate liabilities for all parties by leading to subsequent land uses that are sub-economic or risky.

6.2 Recommendations for further study

Despite attempts to objectively quantify risks, ERA remains a social choice, which reflects broader values and ethics towards such issues as poverty alleviation, human health, ecosystem functioning, biodiversity, climate change and consumerism (Cutter, 1993). However, perception of risk can change based on knowledge. For example, if it is found that pollutants are locked into the sediments (see the work by Winde *et al.*, 2004a;b;c) then the perception of risk will likely be lower than if it is found that under some circumstances sediments act as secondary sources, or that crops are being irrigated with polluted water. Thus, this risk assessment can be improved by a combination of: data held by various institutions and companies, further scientific study, and broad-based stakeholder education and involvement, to ensure low-risk land management choices are made.

The following studies will provide useful information for a more comprehensive risk assessment:

- Representative sampling of agricultural land (irrigated and rain-fed) to determine the concentration and speciation of heavy metals and NORMs, and to understand why mincrust was detected on some irrigated agricultural land close to sources of mine contaminated water and not detected on others. Reasons could be related to evapotranspiration, crop type, soil type, irrigation regime and status of the land (fallow, ploughed, planted or harvested).
- Representative sampling on industrial and commercial roofs to confirm the presence of pyrophyllite and copiapite during the Austral spring.
- Representative sampling of underground water at each treatment stage (liming, high-density sludge removal, desalinisation) to determine the concentration and speciation of heavy metals and NORMs in order to quantify the potential risks associated with each stage of dewatering. Depending on the quality of this water, the large quantities pumped from underground could make this the major source of offsite contamination

The use of airborne hyper-spectral remote sensing is also seen as a potential improvement worthy of further study due to its higher spectral and spatial resolution, which should provide better information regarding the extent and degree of contamination and could also show some of the pathways (e.g. pipeline spillages, changes in pH in watercourses, mineral traces along the banks of watercourses). Used as part of a monitoring programme it could also assist with determining the movement of contamination or the effectiveness of mitigation measures.

Finally, despite the opportunities for gathering further data and further refining the risk assessment I return to the statement by O’Riordan and Cameron (1994) “Where there are threats of serious and irreversible environmental damage, lack of scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation”. By all accounts: emissions, discharges and environmental conditions currently exceed national and/or international permissible standards and action is urgently required.

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APPENDIX I

APPENDIX II

APPENDIX III

APPENDIX IV

Rainfall data from the South African Weather Service for three stations close to the mining belt in Ekurhuleni Metropolitan Municipality gathered for 2001 to 2003

LEGEND

Daily rainfall (in mm) - only rainfall >= 0.1 mm is reflected on this report

---- indicates that data is not yet available

(blank) indicates that no rain fell on that day

*** indicates that data is missing or not yet available in the current month

= indicates that the total for the month is unreliable due to missing daily values

A or "B" indicates that no rainfall reading was taken on the day

but that any rainfall that did occur is included in the accumulation total at the end of the period

C next to a value indicates that the rainfall was accumulated over a number of days

Daily Rain (mm) Data for station [0476399 0] - JOHANNESBURG INT WO -26.1500 28.2300 1695 m
2001 08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	6.4	14.5		1.4	20.9							8
2					25.8							0.6
3		2.6		7.8	20.5							
4				0.3	0.4							1.6
5												1.2
6												3.8
7											23.2	0.2
8		17.6		1							7	
9			16.4	0.4			1.6				7.8	
10			8.6									1.5
11												
12	1.3								82.4		6	5
13	49	2.8							15.8			4
14	0.4	0.2										10.4
15									0.7	1	6	
16											8.3	2.2
17	5.1	6.6								0.4	1.1	1.6
18		3.4	1							10.1		5.6
19										0.2		10.8
20			1							15.9	3.6	
21			2						0.5	0.5		
22				9.8						0.1		
23		0.5	8.4							4		13.2
24		24.6	12							25.4	13.1	
25	2	14.4				0.2				50.2	0.3	6.7
26		0.2		2.6		4.4		5.2		5.3	23.8	
27	2.2	15.5		1.2				14.7		25.2	8.4	
28										1	0.4	
29	0.4	***				1					1.4	
30		***		6.6								0.2
31	6	***		***		***			***	38	***	
Tot	72.8	102.9	49.4	31.1	67.6	5.6	1.6	19.9	99.4	177.3	110.4	76.6

Daily Rain (mm) Data for station [0476399 0] - JOHANNESBURG INT WO -26.1500 28.2300 1695 m

2002 08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1		8.5										0.7
2	6.2				0.2							1.6
3			41.8									
4		0.2	2.2						3.6			
5					5							1.6
6			10.8		5					7.7		5.6
7		14	1		0.2					11.4		9.5
8				20.6						9.2		2.4
9									0.5			6.6
10											1.5	
11			2									
12	26.8		11.4	1.4								21.6
13	2.8	11	0.8			15.9						
14	27.3	20.5										
15	0.2	0.4		3								
16		2		0.2								1.2
17		9						0.6				17.8
18		22.8						0.8				
19	8.5											12
20											3.8	2.7
21										1.5		2.8
22					9.9					2.4	0.4	
23			13.4			2.4					0.6	11
24	14.5					0.4						
25		2.6										1.6
26								0.4		4.6		5.8
27								21		0.2		4.5
28	24	2								5		
29	1.2	***						1		11		32
30	8.2	***								3.8	16.3	
31	5.8	***		***	43.2	***			***	8.6	***	
Tot	125.5	93	83.4	25.2	63.5	18.7	0	23.8	4.1	65.4	22.6	141

Daily Rain (mm) Data for station [0476399 0] - JOHANNESBURG INT WO -26.1500 28.2300 1695 m

2003 08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1		0.5										
2											8.5	
3											0.2	
4	0.1											6.8
5			1.4			8						
6						12.2		8				8.5
7	0.1											
8	7.5	0.2										
9	3.6		4.1									
10		5.4		0.4						4.5	18.8	
11								0.1			1	1
12		0.1		0.1							1.6	
13		2.3							8.2	1.5		
14		0.1										
15											2.4	
16		14									0.1	
17		1										
18	0.5	3.6								7.2		
19		55.8	49.5							45.3		
20	18	22.6	0.3							25.5		
21										0.4		
22			5.1	2.8								16
23	34.5		30.1								5.2	
24	22.5		0.5								0.9	0.1
25	0.1											13.3
26											2.6	
27											1.8	
28	25.2											
29		***										
30	17.2	***										
31		***		***		***			***		***	
Tot	129.3	105.6	91	3.3	0	20.2	0	8.1	8.2	84.4	43.1	45.7

Daily Rain (mm) Data for station [0476762A3] - SPRINGS -26.2000 28.4330 1592 m 2001

08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2	29.4			15							1.8
2				0.8	14							1
3		1.6			0.4							
4					0.4							
5												0.4
6												***
7											3.2	1.0 E
8		13.4		0.2						1.8	0.2	***
9												
10		0.4					0.2					0.6
11												
12	0.2		0.4						4.8		0.6	
13	1.6	0.4							2.8			5.2
14		1.6								0.2	0.8	0.4
15									0.4		0.6	
16										0.6	1.8	
17	0.4										0.6	
18		5.2								3		0.4
19		2.6								0.8		1.4
20	2.4									2.4	0.4	
21			22.8						0.4	2	1.8	
22										0.2		
23		13.8	4.8							0.4		1.2
24	1.6	14.8	2.4							2	***	
25		10								4.2	***	2.4
26				1		3.8		1.6		1	2.4	
27		13		0.4				1.2		2	1.8	
28								0.2		1.8		
29	2	***		0.2		2.4					0.4	
30	0.6	***		10								0.8
31	1.6	***	***	***		***			***	5.2	***	
Tot	12.4	106.2	30.4=	12.6	29.8	6.2	0.2	3	8.4	27.6	14.6=	16.6=

Daily Rain (mm) Data for station [0476762A3] - SPRINGS -26.2000 28.4330 1592 m 2002

08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1		0.2										***
2	1			***		0.2						***
3			1.2	***					0.8			
4	***		0.8	***					1.8			
5	0.0 E				4.6				1			2.8
6	***		0.4						3	4		2.8
7		5	0.8							11.2		2.2
8	0.4	1.2		26.4						10.6		
9												7.8
10											0.8	
11	0.8		0.4								0.2	
12			0.4	6.2								7.4
13	0.2	3		0.6		8.2						
14	1.2	7.6				0.2						
15		0.2										
16		1.6		2								0.2
17								1				6.2
18		1.8						0.2			***	4
19	2										***	12.8
20											***	
21			22.8									
22					4					11.2		
23	1.2	***	4.8			1				1.6		3.4
24	4	***	2.4									
25		***										0.2
26		***		0.4				0.2		1.6		19.8
27	***	***						10.8		0.6		4
28	0.4	***								3.8		0.2
29	0.6	***								17.6	1.6	1
30	***	***								2.2	2.8	
31	0.6	***		***	29.8	***			***	3.2	***	
Tot			34		38.4	9.6	0	12.2	6.6	67.6	5.4=	
	12.4=	20.6=		35.6=								74.8=

Daily Rain (mm) Data for station [0476762A3] - SPRINGS -26.2000 28.4330 1592 m 2003

08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1										***		
2		2.4									6	
3											0.2	***
4						7						***
5						3.2						***
6						4		1.4				***
7	0.4											***
8	10.4	0.8	3							***		***
9	8		1									***
10				0.2						0.6	9.2	
11					0.4			0.4			2.2	
12											0.8	
13		15							3	1.2		
14		1.4									***	
15											1.6	
16		0.6									0.6	
17	0.2	0.8										0.4
18	2.4	2.6							0.2	4.8	5.8	19
19		40.6	19.6							***		
20	15.2	21.4								7	2.8	
21	1.6											
22	0.8		5.4	0.2							5.4	16.2
23	5.6		8.8								7.8	
24	13		0.6								6.4	
25												5.8
26											4.4	2.2
27											0.2	
28		9.4									3.4	
29		***										6.8
30		***										
31		***		***		***			***		***	2.8
Tot	57.6	95	38.4	0.4	0.4	14.2	0	1.8	3.2	13.6=	56.8=	53.2=

Daily Rain (mm) Data for station [0476835 0] - NIGEL - BRANDWEER -26.4170 28.4670

1573 m 2001   08:00   (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1					31.5						39	
2												
3												18
4												
5												
6												
7				1						44	4.5	
8												
9							5.5					25
10												
11												8
12			8.5						65.5			
13	4								17.5			15
14												
15										21	11	
16				9							5.5	
17	31	9								20.5		9
18												40
19										7.5	11.5	
20			7							2	0.7	
21			5									
22		4.5								3		9
23	1.5	15								19.5	14.5	4
24		39	9							50		36
25				2							13	
26						2.5		1.5		3.5		
27								11.5				
28												2
29	5.5	***									2	
30		***		20							8	
31	1	***		***		***			***	39	***	
Tot	43	67.5	29.5	32	31.5	2.5	5.5	13	83	210	109.7	166

Daily Rain (mm) Data for station [0476835 0] - NIGEL - BRANDWEER   -26.4170 28.4670

1573 m 2002 08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1			A									
2	28.5		14.0									
			C									
3	13.5		4								0.6	
4									5	A		
5		42			2.5				2	A		26
6		41								7.0 C		
7		8	9.5							7.5		
8				6.5					3.5	10		
9									2			
10											7	
11												
12		1	8.5	A								10.8
13		5	4.5	A		22						
14	5.5	16.5		2.0 C								
15		2.5										
16		0.2										
17		4						5				7.5
18		16.5						0.6			0.7	
19											2.5	35
20												
21			5									
22	1.5				10							
23						0.5				7.3		27
24		2.5										
25		19.5								A		
26										A		
27	3							23		17.0		
										C		
28	30.5									7		
29	1	***						7.5		24.5		
30	25.5	***			0.5					3.5		
31	11	***		***	34	***			***		***	
Tot	120	158.7		8.5=	47	22.5	0	36.1	12.5		10.8	106.3
			45.5=							83.8=		

Daily Rain (mm) Data for station [0476835 0] - NIGEL - BRANDWEER -26.4170 28.4670

1573 m 2003 08:00 (Extracted 2007/03/28 13:19)

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1												
2											15.5	
3						14		7.5				
4						7						
5						5						12
6												
7	0.5											13
8	18.5		5									
9	7.9										4	
10				2							3	
11					0.3			4			29	
12												
13		1.3										
14		26										
15											8.5	
16											3.5	1.5
17	A	0.7										4
18	A	0.2	23							27	4	
19	0.4 C	19	53							3.5		
20		24								0.7		
21											24	
22			8								11.5	22
23	13.3		1.8								2.5	
24	A									1.7		
25	A										4.5	10
26	12.0 C									26.5		
27												6.5
28	13.5	1.8										
29		***										
30		***										
31		***		***		***			***		***	
Tot	66.1=	73	90.8	2	0.3	26	0	11.5	0	59.4	110	69

APPENDIX VI

Risk index and class for all mine residue deposits within Ekurhuleni Metropolitan Municipality

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
1	2628AD/R/19	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	20	Low
2	2628AD/R/23	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	6.9	28	Low
3	2628AD/R/22	Rock	1.5	Dormant	3	N/A	0	N/A	0	4.5	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	39	Med
4	2628AD/L/28	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	0	3	500-1000	1.5	>1000	0.75	<500	1.65	7.9	43	Med
5	2628AD/A/2	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	6.9	35	Med
6	2628AD/L/28	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	43	Med
7	Post index	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	40	Med
8	2628AD/L/16	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	<500	2.25	>1000	0.75	>1000	0.55	5.55	36	Med
9	2628AD/L/27	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	38	Med
10	2628AD/R/9	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	>1000	0.55	5.55	17	Low
11	2628AD/A/1	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	6.9	28	Low
12	2628AD/L/26	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	<100	2	500-1000	1.5	>1000	0.75	500-1000	1.1	6.35	29	Low
13	2628AD/L/25	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	6.9	38	Med
14	2628AD/L/15	Slime	3	Active	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	56	High
15	2628AD/L/14	Slime	3	Active	2.5	N/A	0	No	0	5.5	Off	1	0	3	<500	2.25	>1000	0.75	>1000	0.55	7.55	42	Med
16	2628AD/R/20	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	<500	2.25	>1000	0.75	>1000	0.55	6.55	20	Low
17	2628AD/R/18	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	<100	2	<500	2.25	>1000	0.75	>1000	0.55	6.55	26	Low
18	2628AD/L/19	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	0	3	<500	2.25	>1000	0.75	500-1000	1.1	8.1	45	Med
19	2628AD/R/17	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	35	Med
20	2628AD/L/18	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	<100	2	<500	2.25	>1000	0.75	>1000	0.55	6.55	29	Low
21	2628AD/R/16	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	35	Med
22	2628AD/L/3	Slime	3	Rework	2.5	N/A	0	No	0	5.5	On	3	0	3	<500	2.25	500-1000	1.5	500-1000	1.1	10.85	60	High
23	2628BC/R/2	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	On	3	>100	1	500-1000	1.5	>1000	0.75	>1000	0.55	6.8	27	Low
24	2628AD/L/2	Slime	3	Active	2.5	N/A	0	Yes	1	6.5	On	3	0	3	<500	2.25	>1000	0.75	>1000	0.55	9.55	62	High
25	2628BC/R/1	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	500-1000	1.5	>1000	0.75	>1000	0.55	6.8	20	Low
26	2628BC/L/5	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	<500	2.25	>1000	0.75	>1000	0.55	7.55	53	Med
27		Slime	3	Active	2.5	N/A	0	No	0	5.5	On	3	0	3	<500	2.25	>1000	0.75	500-1000	1.1	10.1	56	High
28	2628AD/R/24	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	<500	2.25	>1000	0.75	>1000	0.55	7.55	23	Low

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
29	2628AD/R/8	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	20	Low
30	2628BC/L/3	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	<100	2	<500	2.25	>1000	0.75	>1000	0.55	6.55	39	Med
31	2628AD/R/15	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	27	Low
32	2628BC/L/4	Slime	3	Dormant	3	N/A	0	No	0	6	On	3	0	3	500-1000	1.5	>1000	0.75	>1000	0.55	8.8	53	Med
33	2628AD/L/13	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	<500	2.25	<500	2.25	<500	1.65	10.15	66	High
34	2628AD/R/5	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	22	Low
35	2628AD/R/26	Rock	1.5	Dormant	3	DW	0	N/A	0	4.5	On	3	0	3	0	3	>1000	0.75	<500	1.65	11.4	51	Med
36	2628BC/L/2	Slime	3	Dormant	3	N/A	0	No	0	6	On	3	0	3	<500	2.25	>1000	0.75	>1000	0.55	9.55	57	High
37	2628AD/L/24	Slime	3	Dormant	3	N/A	0	Yes	1	7	On	3	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	8.9	62	High
38	2628AD/R/25	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	24	Low
39	2628AD/L/6	Calcine	3	Dormant	3	N/A	0	N/A	0	6	Off	1	0	3	<500	2.25	>1000	0.75	>1000	0.55	7.55	45	Med
40	2628BC/L/1	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	On	3	0	3	<500	2.25	>1000	0.75	500-1000	1.1	10.1	56	High
41		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	<500	2.25	0	2.2	8.2	25	Low
42	2628AD/R/10	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	27	Low
43	2628AD/L/5	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	0	3	<500	2.25	>1000	0.75	>1000	0.55	7.55	42	Med
44	2628AD/R/14	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
45	2628AD/R/13	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
46	2628AD/L/23	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	>100	1	<500	2.25	0	3	<500	1.65	8.9	49	Med
47	2628AD/R/30	Rock	1.5	Dormant	3	N/A	0	N/A	0	4.5	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	30	Low
48	2628AD/R/32	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	<100	2	500-1000	1.5	<500	2.25	<500	1.65	8.4	34	Med
49	2628AD/L/12	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	32	Med
50	2628AD/R/31	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	On	3	0	3	500-1000	1.5	>1000	0.75	<500	1.65	9.9	40	Med
51	2628AD/R/29	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	On	3	0	3	500-1000	1.5	>1000	0.75	<500	1.65	9.9	40	Med
52	2628AD/L/11	Slime	3	Foot	0	Dev.	0.5	Yes	1	4.5	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	21	Low
53	2628AD/R/7	Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	0	3	500-1000	1.5	<500	2.25	<500	1.65	9.4	19	Low
54	2628AD/R/1	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	<500	2.25	>1000	0.75	>1000	0.55	7.55	23	Low
55	2628AD/L/4	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	500-1000	1.5	>1000	0.75	500-1000	1.1	7.35	48	Med
56	2628AD/R/12	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	18	Low
57	2628AD/L/10	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	500-1000	1.1	5.6	31	Med
58		Slime	3	Dormant	3	N/A	0	No	0	6	On	3	>100	1	<500	2.25	>1000	0.75	<500	1.65	8.65	52	Med

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
59	2628AD/L/8	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	39	Med
60	2628AD/R/28	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	0	3	<500	2.25	>1000	0.75	500-1000	1.1	10.1	30	Low
61	2628AD/R/4	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	>1000	0.75	500-1000	1.1	6.6	20	Low
62	2628AD/R/3	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	<500	2.25	>1000	0.75	<500	1.65	7.65	23	Low
63	2628AD/R/27	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	>100	1	500-1000	1.5	<500	2.25	<500	1.65	7.4	30	Low
64	2628AD/L/22	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	On	3	0	3	0	3	>1000	0.75	<500	1.65	11.4	63	High
65	2628AD/L/7	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	0	3	>1000	0.75	500-1000	1.5	<500	1.65	7.9	43	Med
66	2628AD/L/20	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	33	Med
67	2628AD/L/9	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
68	2628AD/R/6	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	500-1000	1.5	<500	1.65	7.9	24	Low
69	2628AD/R/11	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	21	Low
70	2628AD/R/21	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	21	Low
71	2628AD/L/21	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	<100	2	<500	2.25	<500	2.25	<500	1.65	9.15	41	Med
72	2628AD/L/1	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	61	High
73	2628AD/R/2	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
74	2628AC/L/1	Slime	3	Active	2.5	N/A	0	No	0	5.5	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	38	Med
75	2628AB/R/13	Rock	1.5	Foot	0	P	2	N/A	0	3.5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	25	Low
76	2628AA/L/85	Slime	3	Active	2.5	N/A	0	No	0	5.5	Off	1	>100	1	>1000	0.75	<500	2.25	500-1000	1.1	6.1	34	Med
77	2628AB/R/11	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
78	2628AB/L/31	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	<500	2.25	<500	1.65	7.65	42	Med
79	2628AA/L/88	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	41	Med
80	2628AA/L/84	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	47	Med
81	2628AB/L/37	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	50	Med
82	2628AA/L/52	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	>1000	0.75	500-1000	1.1	5.6	36	Med
83	2628AB/L/39	Slime	3	Dormant	3	N/A	0	No	0	6	On	3	0	3	<500	2.25	>1000	0.75	>1000	0.55	9.55	57	High
84	2628AA/L/92	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	37	Med
85	2628AA/A/44	Sand	2.5	Foot	0	P	2	N/A	0	4.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	28	Low
86	2628AA/L/58	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	0	3	>1000	0.75	>1000	0.75	500-1000	1.1	6.6	40	Med
87		Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	27	Low
88	2628AA/A/29	Sand	2.5	Foot	0	Dev.	0.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
89	2628AB/L/41	Slime	3	Foot	0	FD	1.5	No	0	4.5	On	3	>100	1	>1000	0.75	0	3	<500	1.65	9.4	42	Med
90	2628AB/L/28	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	On	3	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	7.9	51	Med
91		Rock	1.5	Dormant	3	N/A	0	N/A	0	4.5	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	30	Low
92	2628AA/L/53	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	500-1000	1.5	500-1000	1.1	6.35	41	Med
93		Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	29	Low
94	2628AB/L/1	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	56	High
95	2628AA/L/61	Slime	3	Foot	0	Dev.	0.5	No	0	3.5	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	23	Low
96	2628AB/L/38	Slime	3	Active	2.5	N/A	0	No	0	5.5	On	3	<100	2	500-1000	1.5	>1000	0.75	<500	1.65	8.9	49	Med
97	2628AB/A/10	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	On	3	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	6.6	33	Med
98	2628AA/A/24	Sand	2.5	Foot	0	P	2	N/A	0	4.5	Off	1	0	3	>1000	0.75	<500	2.25	500-1000	1.1	8.1	36	Med
99	2628AB/L/35	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	On	3	<100	2	>1000	0.75	<500	2.25	<500	1.65	9.65	63	High
100	2628AA/L/51	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	0	3	>1000	0.75	<500	2.25	500-1000	1.1	8.1	49	Med
101	2628AA/L/56	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	500-1000	1.1	5.35	35	Med
102	2628AA/L/80	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	<500	2.25	0	2.2	7.2	50	Med
103	2628AB/A/1	Sand	2.5	Foot	0	Dev.	0.5	N/A	0	3	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	18	Low
104	2628AA/L/91	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	40	Med
105	2628AA/A/45	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	31	Med
106		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	18	Low
107	2628AA/A/27	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	23	Low
108	2628AA/A/28	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	32	Med
109	2628AA/L/55	Slime	3	Foot	0	Dev.	0.5	Yes	1	4.5	Off	1	<100	2	>1000	0.75	>1000	0.75	500-1000	1.1	5.6	25	Low
110	2628AA/L/59	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	35	Med
111	2628AA/L/47	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	21	Low
112	2628AB/L/20	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	>1000	0.75	0	2.2	6.7	44	Med
113	2628AA/A/26	Sand	2.5	Foot	0	Dev.	0.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	500-1000	1.1	5.6	17	Low
114	2628AB/L/36	Slime	3	Dormant	3	N/A	0	No	0	6	On	3	0	3	500-1000	1.5	<500	2.25	<500	1.65	11.4	68	High
115	2628AA/A/23	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	18	Low
116	2628AA/A/36	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	<500	2.25	500-1000	1.1	6.1	24	Low

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
117	2628AB/A/7	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	30	Low
118	2628AA/L/90	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	56	High
119	2628AA/A/25	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	21	Low
120	2628AA/L/57	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	32	Med
121	2628AA/L/46	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	28	Low
122	2628AA/L/77	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	<100	2	>1000	0.75	<500	2.25	<500	1.65	7.65	54	High
123	2628AA/A/43	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	<100	2	>1000	0.75	<500	2.25	500-1000	1.1	7.1	36	Med
124	2628AA/L/50	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	36	Med
125	2628AB/L/27	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	On	3	0	3	>1000	0.75	500-1000	1.5	<500	1.65	9.9	64	High
126	2628AA/L/81	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	37	Med
127	2628AA/L/60	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	47	Med
128	2628AB/L/33	Slime	3	Rework	2.5	N/A	0	No	0	5.5	On	3	0	3	500-1000	1.5	>1000	0.75	<500	1.65	9.9	54	High
129	2628AA/L/54	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	28	Low
130	2628AA/A/22	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	21	Low
131	2628AA/L/86	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	0	3	500-1000	1.1	8.85	58	High
132	2628AA/L/72	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	<100	2	>1000	0.75	<500	2.25	500-1000	1.1	7.1	43	Med
133	2628AB/L/14	Slime	3	Foot	0	Dev.	0.5	No	0	3.5	Off	1	>100	1	<500	2.25	>1000	0.75	500-1000	1.1	6.1	21	Low
134	2628AB/L/32	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	32	Med
135	2628AA/A/40	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	41	Med
136	2628AA/A/32	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	33	Med
137	2628AA/L/83	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	48	Med
138	2628AA/A/35	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	>100	1	>1000	0.75	500-1000	1.5	>1000	0.55	4.8	26	Low
139	2628AA/L/82	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	<100	2	>1000	0.75	0	3	<500	1.65	8.4	59	High
140	2628AB/L/17	Slime	3	Foot	0	Dev.	0.5	Yes	1	4.5	Off	1	0	3	<500	2.25	>1000	0.75	<500	1.65	8.65	39	Med
141	2628AA/A/31	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	30	Low
142	2628AA/L/79	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	52	Med
143	2628AB/A/12	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	24	Low
144	2628AA/L/65	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	43	Med
145	2628AB/L/19	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	39	Med
146	2628AA/A/41	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	27	Low
147	2628AA/L/63	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	56	High

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
148	2628AB/L/7	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	<100	2	<500	2.25	>1000	0.75	<500	1.65	7.65	46	Med
149	2628AA/A/30	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	27	Low
150	2628AB/L/40	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	On	3	>100	1	<500	2.25	>1000	0.75	<500	1.65	8.65	48	Med
151	2628AA/L/62	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	30	Low
152	2628AA/L/66	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	47	Med
153		Slime	3	Active	2.5	N/A	0	No	0	5.5	On	3	>100	1	<500	2.25	>1000	0.75	<500	1.65	8.65	48	Med
154	2628AA/L/87	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	<500	2.25	<500	1.65	7.65	42	Med
155	2628AA/L/64	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	<100	2	>1000	0.75	0	3	<500	1.65	8.4	50	Med
156	2628AA/L/76	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	56	High
157	2628AA/A/42	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	27	Low
158	2628AB/A/4	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	26	Low
159	2628AB/L/30	Slime	3	Foot	0	P	2	No	0	5	On	3	<100	2	>1000	0.75	<500	2.25	<500	1.65	9.65	48	Med
160	2628AB/L/16	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	35	Med
161	2628AA/L/69	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	>100	1	>1000	0.75	<500	2.25	500-1000	1.1	6.1	37	Med
162	2628AB/L/13	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	28	Low
163	2628AB/A/8	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	26	Low
164	2628AA/A/37	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	35	Med
165	2628AA/L/75	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	500-1000	1.5	<500	1.65	7.9	51	Med
166	2628AA/L/78	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	45	Med
167	2628AA/L/68	Slime	3	Foot	0	Dev.	0.5	Yes	1	4.5	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	31	Med
168	2628AB/L/15	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	31	Med
169	2628AB/R/9	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	>100	1	<500	2.25	500-1000	1.5	<500	1.65	7.4	30	Low
170	2628AA/A/34	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	<100	2	>1000	0.75	<500	2.25	<500	1.65	7.65	31	Med
171	2628AA/L/71	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	0	3	>1000	0.75	500-1000	1.5	<500	1.65	7.9	43	Med
172	2628AB/L/34	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	On	3	0	3	<500	2.25	500-1000	1.5	500-1000	1.1	10.85	60	High
173	2628AB/L/24	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	45	Med
174	2628AB/L/2	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	23	Low
175	2628AB/L/5	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	23	Low
176	2628AB/L/8	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
177	2628AA/L/67	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	52	Med
178	2628AA/A/33	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	<100	2	>1000	0.75	<500	2.25	<500	1.65	7.65	31	Med

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
179	2628AB/L/3	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	43	Med
180	2628AB/A/9	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	>1000	0.75	500-1000	1.5	500-1000	1.1	5.35	27	Low
181	2628AB/L/29	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	>100	1	>1000	0.75	<500	2.25	>1000	0.55	5.55	36	Med
182	2628AB/L/10	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	46	Med
183	2628AB/L/4	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
184	2628AB/A/2	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	0	3	>1000	0.75	>1000	0.75	0	2.2	7.7	39	Med
185	2628AB/A/5	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	39	Med
186	2628AB/A/3	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	36	Med
187	2628AB/A/11	Sand	2.5	Rework	2.5	N/A	0	N/A	0	5	Off	1	>100	1	500-1000	1.5	<500	2.25	>1000	0.55	6.3	32	Med
188	2628AB/L/25	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	56	High
189	2628AB/L/11	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	28	Low
190	2628AB/L/26	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	0	3	500-1000	1.5	<500	2.25	<500	1.65	9.4	61	High
191	2628AB/L/12	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	43	Med
192	2628AB/L/23	Slime	3	Rework	2.5	N/A	0	Yes	1	6.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	40	Med
193	2628AB/L/21	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	50	Med
194	2628AB/A/6	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	39	Med
195	2628AB/L/22	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	>1000	0.75	500-1000	1.5	0	2.2	8.45	59	High
196	2628AB/L/18	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	36	Med
197	2628AB/L/9	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	>100	1	>1000	0.75	>1000	0.75	0	2.2	5.7	40	Med
198	2628AA/A/39	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	24	Low
199	2628AB/L/6	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
200	2628AA/L/74	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	40	Med
201	2628AA/A/38	Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	<100	2	>1000	0.75	500-1000	1.5	0	2.2	7.45	30	Low
202	2628AA/L/73	Slime	3	Foot	0	P	2	No	0	5	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	43	Med
203		Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
204	2628AB/R/12	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	0	3	>1000	0.75	<500	1.65	9.4	28	Low
205	2628AA/L/89	Slime	3	Dormant	3	N/A	0	No	0	6	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	28	Low
206	2628AA/A/21	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	0	2.2	5.7	31	Med
207	2628AA/L/49	Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	>100	1	>1000	0.75	>1000	0.75	0	2.2	5.7	31	Med
208		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	>1000	0.75	<500	2.25	<500	1.65	8.65	26	Low
209	2628AB/R/5	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	>1000	0.75	>1000	0.75	<500	1.65	7.15	21	Low
210	2628AB/R/2	Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	0	3	0	3	>1000	0.75	500-1000	1.1	8.85	35	Med

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
211	2628AB/R/1	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	0	2.2	6.7	20	Low
212	2628AB/R/8	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	18	Low
213	2628AB/R/10	Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	<500	2.25	>1000	0.75	>1000	0.55	7.55	23	Low
214	2628BA/A/1	Sand	2.5	Dormant	3	N/A	0	N/A	0	5.5	Off	1	>100	1	500-1000	1.5	>1000	0.75	>1000	0.55	4.8	26	Low
215	2628AB/L/11	Slime	3	Foot	0	FD	1.5	No	0	4.5	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	23	Low
216		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	Off	1	>100	1	>1000	0.75	500-1000	1.5	>1000	0.55	4.8	13	Low
217		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	On	3	0	3	>1000	0.75	<500	2.25	>1000	0.55	9.55	27	Low
218		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	Off	1	>100	1	>1000	0.75	500-1000	1.5	500-1000	1.1	5.35	15	Low
219		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	Off	1	>100	1	>1000	0.75	500-1000	1.5	>1000	0.55	4.8	13	Low
220		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	20	Low
221		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	>100	1	>1000	0.75	<500	2.25	<500	1.65	6.65	13	Low
222		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	18	Low
223	Post index	Slime	3	Rework	2.5	N/A	0	No	0	5.5	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	37	Med
224		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	18	Low
225	2628AA/L/70	Slime	3	Dormant	3	N/A	0	Yes	1	7	Off	1	0	3	>1000	0.75	<500	2.25	500-1000	1.1	8.1	57	High
226		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
227		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	21	Low
228		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	18	Low
229		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	500-1000	1.5	<500	1.65	5.9	18	Low
230		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	0	3	500-1000	1.1	6.85	21	Low
231		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	5.9	12	Low
232		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	21	Low
233		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	0	2.2	5.7	17	Low
234	2628AA/L/67 A	Slime	3	Foot	0	P	2	Yes	1	6	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	52	Med
235		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	<500	2.25	500-1000	1.1	7.6	23	Low
236		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	500-1000	1.5	500-1000	1.1	5.35	16	Low
237		Sand	2.5	Foot	0	Dev.	0.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
238		Sand	2.5	Foot	0	FD	1.5	N/A	0	4	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	21	Low
239		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
240		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
241		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	<100	2	>1000	0.75	>1000	0.75	0	2.2	6.7	13	Low
242		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	18	Low
243		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
244		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
245		Rock	1.5	Rework	2.5	N/A	0	N/A	0	4	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	25	Low
246		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	>1000	0.75	0	2.2	6.7	20	Low
247		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
248		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	0	3	>1000	0.55	6.3	19	Low
249		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	<100	2	>1000	0.75	<500	2.25	500-1000	1.1	9.1	27	Low
250		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	>1000	0.75	>1000	0.75	<500	1.65	7.15	21	Low
251		Slime	3	Dormant	3	DW	0	N/A	0	6	On	3	0	3	<500	2.25	<500	2.25	>1000	0.55	11.05	66	High
252		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	>100	1	>1000	0.75	0	3	<500	1.65	9.4	28	Low
253		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	21	Low
254		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	<500	2.25	>1000	0.75	500-1000	1.1	7.1	21	Low
255		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
256		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	10	Low
257		Rock	1.5	Dormant	3	N/A	0	N/A	0	4.5	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	30	Low
258		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	0	3	>1000	0.75	500-1000	1.1	6.85	21	Low
259		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	<100	2	<500	2.25	>1000	0.75	<500	1.65	7.65	15	Low
260		Slime	3	Dormant	3	I	0	N/A	0	6	On	3	0	3	500-1000	1.5	>1000	0.75	500-1000	1.1	9.35	56	High
261		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	<500	2.25	>1000	0.75	500-1000	1.1	7.1	21	Low
262		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	Off	1	<100	2	>1000	0.75	0	3	>1000	0.55	7.3	20	Low
263		Spoil	0.3	Active	2.5	N/A	0	N/A	0	2.8	On	3	<100	2	>1000	0.75	<500	2.25	>1000	0.55	8.55	24	Low
264		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	20	Low
265		Slime	3	Active	2.5	N/A	0	No	0	5.5	Off	1	>100	1	500-1000	1.5	<500	2.25	<500	1.65	7.4	41	Med
266		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	500-1000	1.1	4.6	14	Low
267		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
268		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	<500	2.25	<500	2.25	500-1000	1.1	8.6	26	Low
269		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	On	3	>100	1	500-1000	1.5	>1000	0.75	<500	1.65	7.9	16	Low
270		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	20	Low

ID	Chamber of Mines No.	Mine Residue Deposit								MRD Class	Proximity of MRD to (m)										Vuln	Risk	
		Type		Status		Foot		Fail			Dolomite		Water		Agricultural		Informal		Formal			Index	Class
271		Slime	3	Dormant	3	I	0	N/A	0	6	Off	1	<100	2	<500	2.25	<500	2.25	<500	1.65	9.15	55	High
272		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	20	Low
273		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	<500	1.65	6.65	20	Low
274		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	0	3	>1000	0.75	>1000	0.55	6.3	19	Low
275		Slime	3	Foot	0	FD	1.5	Yes	1	5.5	Off	1	<100	2	>1000	0.75	>1000	0.75	<500	1.65	6.15	34	Med
276		Slime	3	Dormant	3	I	0	N/A	0	6	Off	1	0	3	>1000	0.75	>1000	0.75	<500	1.65	7.15	43	Med
277		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	<500	2.25	>1000	0.75	>1000	0.55	5.55	17	Low
278		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	On	3	0	3	>1000	0.75	<500	2.25	>1000	0.55	9.55	29	Low
279		Slime	3	Foot	0	FD	1.5	No	0	4.5	On	3	<100	2	>1000	0.75	<500	2.25	>1000	0.55	8.55	38	Med
280		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	>100	1	>1000	0.75	>1000	0.75	<500	1.65	5.15	15	Low
281		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	<100	2	>1000	0.75	500-1000	1.5	<500	1.65	6.9	21	Low
282		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	<100	2	>1000	0.75	500-1000	1.5	500-1000	1.1	6.35	13	Low
283		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	>100	1	>1000	0.75	0	3	<500	1.65	7.4	15	Low
284		Rock	1.5	Foot	0	FD	1.5	N/A	0	3	Off	1	0	3	>1000	0.75	<500	2.25	<500	1.65	8.65	26	Low
285		Rock	1.5	Foot	0	E	0.75	N/A	0	2.25	Off	1	0	3	>1000	0.75	<500	2.25	500-1000	1.1	8.1	18	Low
286		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	<100	2	>1000	0.75	0	3	500-1000	1.1	7.85	16	Low
287		Rock	1.5	Foot	0	Dev.	0.5	N/A	0	2	Off	1	>100	1	>1000	0.75	<500	2.25	>1000	0.55	5.55	11	Low

D	Developed
DW	Dam wall
E	Embankment
FD	Free draining
I	Infill
N/A	Not applicable
P	Paddocks