A PRELIMINARY ASSESSMENT OF POLLUTION CONTAINED IN THE UNSATURATED AND SATURATED ZONE BENEATH RECLAIMED GOLD - MINE RESIDUE DEPOSITS

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Water Research Commission

A PRELIMINARY ASSESSMENT OF POLLUTION CONTAINED IN THE UNSATURATED AND SATURATED ZONE BENEATH RECLAIMED GOLD-MINE RESIDUE DEPOSITS

by

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ABBREVIATIONS AND ACRONYMS

ABV	Average background value
AEC	Anion Exchange Capacity
Alk	Alkalinity
AMD	Acid mine drainage
AVG	Average (mean value)
CEC	Cation exchange capacity
CL	Crisis limit
EC	Electrical conductivity
EMP	Environmental management plan
EMPR	Environmental management plan report
ICP-MS	Induced coupled plasma mass spectrometer
K	Hydraulic conductivity (m/s)
LOI	Loss on ignition
MAX	Maximum value
mg/l / mg/kg	1 mg/kg = 1/1000 g/kg (10^{-6} g/l)
MIN	Minimum value
MOB	Mobility in % (bio-availability)
n	Population of samples
n. a.	Information not available
n/d	Not detectable
NAPL	Non aqueous phase liquids
NGDB	National Groundwater Database, RSA
nm	Nano metre (10^{-9} m)
NTP	Normal temperature and pressure
P&T	Pump-and-treat approach
PI	Plasticity index
QA/QC	Quality control/quality assessment
RDP	Reconstruction and development program
RML	Recommended maximum limit
RSA	Republic of South Africa
SAR	Sodium adsorption ratio
STDEV	Standard deviation
TC	Threshold concentration
TCLP	Toxic characteristic leaching procedure
TDS	Total dissolved solids
TER	Threshold exceedance ration
µg/l	1 µg/l = 1/1000 mg/l (10^{-9} g/l)
XRD	X-ray diffraction analysis
XRF	X-ray fluorescence analyses

Government Departments, institutions and consulting firms

ASTM	American Society for Testing and Materials
DME	Department of Minerals and Energy, RSA
DWAF	Department of Water Affairs and Forestry, RSA
NRC	National Research Council, USA

PHD	Pulles Howard & De Lange (consulting firm), RSA
SABS	South African Bureau of Standards, RSA
SRK	Steffen Robertson & Kirsten (consulting firm), RSA
U.S.C.S.	United States Classification for Soils
U.S.-EPA	Environmental Protection Agency, USA
WHO	World Health Organisation, United Nations
WRC	Water Research Commission, RSA

EXECUTIVE SUMMARY

1. INTRODUCTION

Mining has a long history in South Africa, which has resulted in large quantities of mine waste. In 1996 a total of 377 million tons of mine waste was produced, accounting for 81 % of the total waste stream in South Africa. The presence of these mine dumps[1] resulted in large-scale pollution of the subsurface, affecting an area of approximately 180 km^2. This poses a potential threat to the scarce water resources (surface and groundwater) of South Africa and is cause for serious concern with respect to land development of sites, where tailings dams have been reclaimed. The majority of the tailings dams (> 200 deposits) were deposited 30-50 years ago and are situated within the Gauteng Province. Demographic figures for the Gauteng Province show that there is a growing population (8.5 million people in the year 2000), increasing industrial development and thus, an increased demand for clean water.

In view of the above, water pollution is an increasingly important socio-economic issue in South Africa. Experience overseas (Europe and North America) has shown that the costs involved in the remediation of large-scale polluted areas are far too high, owing to too large quantities of contaminated material being treated. The uncontrolled release of acid mine drainage (AMD) as a direct result of poor operational management is unequivocally the single most important impact of mining activities on the environment. AMD originates primarily from the oxidation of sulphide minerals, which occur in significant quantities (30-50 kg of sulphide minerals per ton) in the primary ore. This acid drainage emanating from the gold residue material in South Africa contains, as a rule, large quantities of salts (sulphate and chloride), significant concentrations of toxic heavy metals and trace elements such as Cu, As and CN, as well as radionuclides.

A number of tailings dams (approximately 70) in the Gauteng Province are being reclaimed and reprocessed in order to extract gold still present in economically viable concentrations in the tailings material. Once the tailings material has been removed, the land has a certain potential for land development. But it is important to take into account that the reclaimed tailings material leaves a contaminated footprint on the subsurface and the land situated in the prevailing wind direction has also been affected by the deposition of wind-blown tailings material.

2. OBJECTIVES OF THE STUDY

The project proposal defines the following four main objectives, which have to be met by the research program. The following research objectives were defined:

- To identify the nature and extent of contamination from unsaturated and saturated zones underneath reclaimed gold-mine dumps (in respect of tailings dams) in order to infer their potential to pollute the near surface environment, ground and surface water, and to define the need to develop appropriate rehabilitation measures for the reclaimed land.

- To evaluate and define the existing state of knowledge with regard to the long-term environmental effects of tailings dams.

- To assess the potential of residual contaminants in the soils underlying tailings dams to exhibit negative environmental effects.

- To define the type and scope of further studies in respect of prediction, impact assessment and rehabilitation measures for pollution originating from active and reclaimed tailings dams.

3. METHODOLOGY

In order to comply with the research objectives, a comprehensive literature survey has been conducted, a geographic information system (GIS) established and eleven case study sites selected. These sites are mainly situated in the Gauteng Province, South Africa and were selected to conduct further investigations in order to assess the *current and future status of*

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[1] The term *mine dump* has been replaced by the common term *mine residue deposit*. All investigated *mine residue deposits* are classified as *tailings dams* (equivalent to *slimes dams*).

contamination contained in the subsurface (unsaturated and saturated zone). Field and laboratory testing was conducted at seven sites only, where incomplete data sets were identified. In addition, a complete GIS-based mine residue deposit register for South Africa has been compiled, derived from various information sources as discussed in **Chapter 2**. During the course of the study, the pollution source (i.e. tailings dam), the barrier zone (unsaturated zone) and the receiving groundwater system were investigated in order to assess the migration pathways of different trace elements (e.g. heavy metals).

The trace element geochemistry of the soil samples retrieved from the investigated sites was compared with trace element concentrations from topsoil samples (particle size < 75 μm) of the Vryheid Formation and Malmani Subgroup, which are not affected by mining activities (background samples or baseline values).

The *current contamination impact* was assessed by comparing extractable element specific ratios to the total concentration contained in the solid phase (mobility, bio-availability). In addition, calculated threshold ratio exceedance indicates limited soil functioning.

The *future contamination impact* was assessed by implementing a geochemical load index, which classifies various pollution levels into six classes (I-VI). The application of this index is conservative, reflecting the maximum future pollution impact (worst-case scenario), assuming that the total concentration of contaminants contained in the solid phase of the unsaturated zone can be remobilised and therefore becomes bio-available.

The implementation of a groundwater risk assessment procedure such as the DRASTIC approach failed due to a lack of relevant data.

4. GOLD-MINE TAILINGS AS A POTENTIAL POLLUTION SOURCE FOR THE SUBSURFACE

4.1 IMPACT ON THE UNSATURATED ZONE

Gold-mine tailings contain significant concentrations of potentially hazardous trace elements such as As, Cr, Cu, Ni, Pb, U and Zn. Leaching tests conducted on such tailings samples revealed elevated extractable concentrations of elements such as Co, Cr, Cu, Ni, S, U and Zn. It is important to note that all samples were collected within the oxidised zone of the tailings dam and it is assumed that large quantities of contaminants have already migrated into deeper zones of the impoundment or left the impoundment via seepage or surface run-off, thereby contributing to the pollution.

As a result, the soil underneath reclaimed tailings dams has been contaminated with pollutants which typically originate from AMD seeping from tailings dams. An empirical positive correlation exists between soil pH and profile depth. Acidic conditions (pH 3-4) were encountered in samples collected in surface soil units, indicating leaching and remobilisation of trace elements bound to the easily soluble and exchangeable fractions. In contrast, slight acidic to fairly neutral pH conditions found at the bottom of the test pits (maximum depth 2.40 m) can be explained with the presence of buffer minerals such as carbonates and/or a fluctuating groundwater table causing dilution effects (mixing of acidic soil water with pH-neutral groundwater).

This investigation also showed that heavy metals such as Co, Ni and Zn are highly mobile, particularly in the surface soil units, and are therefore bio-available. High bio-availability may result in a limitation of soil functioning and could complicate rehabilitation efforts regarding recultivation. It is assumed that the highly mobile elements are present in easily soluble and exchangeable fractions. In contrast, the mobility of Cr, Cu, Fe, Pb and U is relatively low, indicating that the bulk of these trace elements are contained in the residual fraction. Significant trace element remobilisation takes place at pH values < 4.5, occurring mainly in the surface soil layers.

The implementation of the geochemical load index allows the characterisation of the investigated sites according to their *future contamination status* (worst-case scenario). The index was applied to the seven representative case study sites. One case study site was classified as excessively polluted (highest pollution class VI) with regard to U, whereas three case study sites are highly polluted (pollution class IV) with respect to heavy metals such as Co, Pb, U and V. The three remaining case study sites are moderately to highly polluted (pollution classes II-III) with respect to trace elements such as As, Co, Cr, Cu, Fe, Mn, Ni, Pb, Th, U and V.

In addition, geotechnical investigations revealed low to very low predicted permeabilities (values ranging from 10^{-7}- 10^{-10} m/s) for the soils in the investigation area. Significant concentrations of contaminants at greater depths (max 2.5 m) cannot be explained by percolation of seepage and/or rainfall through the porous media and would require alternative flow mechanisms that bypass the soil matrix (preferential flow). Soil conditions indicating preferential flow were observed in some test pits, but any attempt at identifying prevailing flow conditions would have been premature, owing to the lack of suitable in-situ infiltration test data.

4.2 IMPACT ON THE SATURATED ZONE

Limited groundwater data were available, but it is evident that groundwater in close proximity to tailings dams and other mine residues (sand and rock dumps) is affected by large salt loads. Unaffected groundwater in the study area is usually of the Ca-Mg-HCO_3 type as a result of dissolution reactions with the dolomitic rock of the aquifer. However, a predominant Ca-Mg-SO_4 signature indicates the impact of AMD from mining activities and facilities such as tailings dams. Groundwater quality in close proximity to the residue deposit occasionally shows elevated concentrations of trace elements (e.g. As, Cd, Co, Fe, Mn and Ni) and CN which exceed drinking water standards. Groundwater quality improves with increasing distance down-gradient from the pollution source, mainly as a result of dilution and solid speciation. These observations are based on water quality sampling of numerous monitoring boreholes.

The application of numerical groundwater models has shown that tailings dams continue to release seepage containing high salinity for an extended time period after termination of mining operations (predictions were given for about 50 years). Seepage and salt generation in tailings dams can only be mitigated by reducing the oxygen flux into the residue deposit (cover systems). These models have also confirmed that deterioration in groundwater quality occurs only in the immediate vicinity of the residue deposit. Predicted groundwater quality improves with increasing distance down-gradient of the residue deposit due to dilution and solid speciation effects. Seepage emanating from mine residue deposits (e.g. tailings dams) negatively affects water quality in nearby surface water systems and has an adverse impact on water users in the nearby area.

5. DISCUSSION AND CONCLUSIONS

Large volumes of mine waste such as tailings have been generated as a result of intensive gold-mining activities in South Africa. To date, more than 200 tailings dams have been constructed to store these fine-grained tailings material. Most of the tailings dams are situated south of Johannesburg within the highly populated Gauteng Province (approximately 8.5 million in the year 2000) and were deposited some 30 to 50 years ago. Up to 1998, 70 tailings dams were reclaimed throughout the East Rand area in order to extract the gold, still present in economically viable concentrations (currently approximately 0.4 g Au/ton). Once the tailings material has been completely reclaimed, the land has a certain potential for development. However, it is important to realise that the reclaimed tailings material leaves a contaminated subsurface (also known as a footprint).

It is known that gold-mine tailings are prone to the generation of acid mine drainage (AMD), which is recognised as a world wide problem. It is estimated that the remediation of environmental damages related to AMD will cost about US $ 500 million in Australia and US $ 35 billion in the United States and Canada. The cost figure for South Africa to rehabilitate existing tailings dams and to mitigate damages in the unsaturated and saturated zone is currently unknown. Clean-up costs for contaminated soil material (e.g. soil washing) range from US $ 100-200/ton. This study has shown that at least 5.5 million tons of material would have to be treated in South Africa, if only the polluted topsoil ($\leq$ 300 mm) underneath the reclaimed sites would have to be considered. Hence, only the topsoil clean-up would cost at least US $ 550 million, assuming the lower treatment cost scenario of US $ 100/ton. Additional rehabilitation measures such as cover systems for present mine-residue deposits, recultivation of reclaimed land or groundwater remediation were not taken into account for this cost scenario. It is obvious that these rehabilitation costs cannot be afforded either by the South African government or by the mining industry. It is also questionable if the predicted costs figures for Australia and North America will ever be spent, in order to rehabilitate such sites. Thus, rehabilitation (including treatment of soils and groundwater) of large-scale polluted sites is uneconomical and this should only be applied at highly contaminated sites or areas determined by a risk assessment as high risk areas (delineation of risk zones). It is important to realise that the understanding of the short- and long term behaviour of contaminants in the subsurface zone affected by such mining operations, forms an integral part of a risk assessment.

Eleven selected reclaimed tailings dam sites (gold-mining), situated in the Gauteng Province and North-West Province of South Africa, were investigated in this study. All reclaimed sites were analysed in terms of their current pollution status, and conservative predictions were also attempted to assess the future pollution impact. In addition, the pollution source (i.e. tailings dam) was geochemically and mineralogically characterised. Field and laboratory tests were conducted on samples taken within the unsaturated zone and from a shallow groundwater table. Further groundwater data of the investigated sites was obtained from mining companies, various government departments and associated institutions. Rating and index systems were applied to assess the level of contamination contained in the unsaturated zone underneath reclaimed gold-mine tailings dams.

In summary, this study has shown that pollution occurs in the subsurface underlying former gold-mine tailings. However, based on the findings of this study, it is premature to quantify this impact and to incorporate it into a risk assessment approach. This investigation therefore provides a first step towards a risk assessment and serves as a hazard assessment. It is important to understand that slight changes in the pH or Eh conditions of the soil (e.g. by land use, climate) can cause remobilisation of large amounts of contaminants, which are characterised by a geochemical behaviour that is time-delayed and non-linear. Additional field and laboratory testing would be obligatory for the in-depth understanding of the long-term dynamic aspects of these contaminant processes, which pose a serious threat to the vulnerable groundwater resources (i.e. dolomite aquifers) and land development. Salomons & Stigliani (1995) described these processes as "... *precisely the kind of response that catches policymakers, the public, and even scientists by surprise*".

The main findings of this investigation regarding reclaimed gold-mine residue deposits and existing deposits affecting the unsaturated and saturated zones (short- and long-term effects) are summarised below:

- Groundwater quality beneath and in close vicinity to the investigated tailings dams is dominated by the Ca-Mg-SO_4 type, indicating acidic seepage, although all sites with relevant groundwater data (sites H, I and K) are underlain by dolomitic rocks. In addition, high TDS (up to 8000 mg/l) values occur mainly as a result of high salt loads (SO_4^{2-} and Cl^-) in the groundwater system. In most of the samples, groundwater pH values are fairly neutral due to the acid neutralisation capacity of the dolomitic rock aquifer. There is a tendency for groundwater quality to improve further down-gradient of the tailings dams as a result of dilution effects and precipitation reactions caused by the high acid neutralisation capacity of the dolomitic aquifer. These observations have been confirmed with the application of numerical groundwater models. However, groundwater quality in close proximity to the sites is often characterised by elevated trace element (e.g. As, Cd, Co, Fe, Mn and Ni) and total CN concentrations, exceeding drinking water standards in some boreholes.

- Elevated trace element concentrations in the soils affected by AMD and the high mobility of phytotoxic elements such as Co and Ni complicate rehabilitation and recultivation attempts. The most commonly applied remediation method involves the addition of lime. However, where more than one trace element is involved in the rehabilitation (common situation), changing the soil pH may reduce the mobility of some elements whilst remobilising others such as Mo (under alkaline conditions).

- Preliminary tests indicate that the extractable trace element concentration of the selected reclaimed site shows greater exceedance ratios in the unsaturated zone and, furthermore, shows a variable spatial contaminant distribution. For example, Uranium exceeds the threshold value (0.04 mg/l) by three orders of magnitude. Cobalt, Ni and Zn exceed their threshold concentrations of 0.5, 1 and 10 mg/l, respectively. Chromium and Pb also exceed threshold values. Extractable As concentrations, and occasionally Pb and Cr, did not exceed the lower analytical detection limits.

- The mobility of trace elements is dependent on a number of parameters, including pH. All the trace elements examined are most mobile when the soil pH < 4.5, and least mobile when a soil pH > 6. Cobalt, Ni and Zn are the most mobile trace elements for the selected reclaimed site. Chromium, Cu, Fe, Pb and U are less mobile compared to the above elements, indicating that a significant portion of the latter trace elements is contained in the residual fraction of the solid phase.

- The potential hazard posed by the trace elements at the selected reclaimed site can be summarised as U>>Co=Ni=Zn>Cr=Pb>>As in the soil. This potential hazard series is a function of the degree and frequency with which a trace element exceeds the relevant threshold values.

- The application of the geochemical load index for the assessment of the future pollution potential (worst-case scenario) for seven sites classified three sites as moderately to highly polluted (pollution class III), three sites as highly polluted (pollution class IV) and one site as excessively polluted (pollution class VI). For comparison, pollution class VI reflects a 100-fold exceedance above the background value.

- Soil conditions indicating preferential flow (bypass of the soil matrix) were observed in some test pit profiles. However, the identification of dominant contaminant migration processes would be premature owing to the lack of in-situ infiltration tests.

- The extractable concentrations of Co, Cr, Cu, Ni and Zn found in gold-mine tailings samples exceed threshold concentrations. This confirms that gold-mine tailings are a source of trace element pollution. In addition, tailings dams continue to release significant salt loads contained in seepage for an extended time period after termination of mining operations. Seepage emanating from tailings dams also has a negative effect on water quality in nearby surface water systems, which impacts adversely on water users in those areas as a result. High sulphur concentrations are contained in the leachate. Consequently, incomplete reclamation of tailings would result in tailings material remaining on the surface. Such material provides an additional reservoir for acid generating processes and contaminant release.

- International guidelines such as the soil quality standards of the Netherlands (Holland List) are not directly applicable to South African conditions. The predominantly humid climate conditions in Europe do not correspond with South African conditions in the areas where the bulk of mining activities take place. Major difficulties which occur when different studies are compared could be avoided through the use of standardised approaches to analytical testing (e.g. extraction tests) and the establishment of background or baseline values.

6. RECOMMENDATIONS

The following recommendations for further studies emanated from this research project and are summarised in terms of the following categories:

Investigate gold-mine tailings dams:

- Field and laboratory testing: to sample at various depths of the deposit, mineralogical composition, acid base accounting, total and extractable or bio-available concentrations of toxic metals and selected radionuclides.

- Water balance modelling: to characterise the flow-conditions within a deposit and quantify seepage volumes of deposits under certain scenarios (deposition technologies, soil cover, vegetation, climate effects).

- Geochemical modelling: to predict seepage quality under different scenarios (no rehabilitation, cover systems, vegetation, climate effects).

Investigate the unsaturated zone underneath the gold-mine tailings deposit and in prevailing wind-direction:

- Field and laboratory testing: to sample at various depths, mineralogical composition, acid base accounting, total and extractable or bio-available concentrations of toxic metals and selected radionuclides including sequential extraction tests, in-situ infiltration tests, soil moisture and water retention tests.

- Unsaturated zone modelling: to predict seepage quantities and qualities entering the groundwater system under different rehabilitation scenarios (e.g. no rehabilitation, liming, addition of clay or fly ash to the contaminated soils, recultivation).

Investigate the saturated zone affected by seepage emanating from gold-mine tailings dams:

- Field and laboratory testing: to monitor groundwater quality (including toxic metals and selected radionuclides) up and down gradient of selected tailings dam sites, in-situ measurements by using a flow cell. Aquifer testing (if necessary).

- Flow and mass transport modelling: to predict velocity of contamination plume under various scenarios (e.g. no groundwater remediation option and hydraulic barriers).

General recommendation:

- Develop rehabilitation guidelines for land affected by seepage emanating from gold-mine tailings dams by using a risk assessment procedure (including radiological risks). This would enable to identify certain levels of land development, after tailings reclamation took place.

Please note that the majority of the above mentioned recommendations will be addressed in Phase II of this research project, which will commence in January 1999.

In addition, the following general recommendations are made:

- Develop soil quality standards and background values;

- Develop remote sensing technologies (e.g. satellite images) in connection with GIS applications to monitor the expansion of residential areas towards mine facilities and to assess environmental parameters such as dust erosion emanating from tailings dams;

- Develop guidelines for certain laboratory procedures for soils (such as the South African acid rain test or EPA leaching approaches such as the TCLP approach for waste dumps).

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

The uncontrolled release of acid mine drainage (AMD) as a direct result of poor operational management of tailings dams[1] (slimes dams), sand and waste rock dumps is the single most important impact mining has on the environment. In general, mine wastes consists of high volume, low toxicity wastes (U.S.-EPA, 1985).

Gold mining in the Witwatersrand Supergroup rocks in the Gauteng Province of South Africa has resulted in hundreds of tailings dams, which cover an estimated area of 180 km^2. Owing to urban expansion and/or agricultural land development, these tailings dams are often situated in close proximity to valuable residential, agricultural or industrial property. It is known that the ore of the Witwatersrand Supergroup contains significant modal proportions of sulphide minerals and the tailings dams are therefore prone to the formation of AMD. AMD is characterised by low pH values, high salt loads, as well as high concentrations of toxic trace elements and radionuclides.

Some of the tailings dams in the Gauteng Province are being reclaimed and reprocessed in order to extract remaining gold present in economically viable concentrations. Once the tailings material has been removed, the land has a certain potential for development, but below a footprint of the former tailings dam still remains, reflected by a polluted subsurface.

Land affected by reclaimed mine tailings is generally situated within highly developed urban areas. Initiatives such as the Reconstruction and Development Programme (African National Congress, 1994) of the South African government aim to improve the general conditions of previously disadvantaged communities. The availability of land is one of the central themes of the RDP and the use of reclaimed land for residential and industrial development could provide an alternative source of land closer to work centers.

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[1] *Tailings dams* (equivalent to *slimes dams*), *sand* and *waste rock dumps* are internationally termed *mine residue deposits*. The term *mine dump* has thus not been used in this report although it is contained in the original title of the project.

However, the potential adverse effects on human and animal health and agricultural productivity caused by the uptake of toxic trace elements and radionuclides released from such tailings and soils, would need to be assessed before land could be utilised.

The main objective of this project was to establish to what extent the unsaturated zone in areas where tailings dams have been removed, has been contaminated with heavy metals and uranium and thus, negatively impacts onto the groundwater system and potential land development.

This study is a continuation of the findings of a Water Research Commission (WRC) project completed in 1988 by SRK, entitled *Research on the Contribution of Mine Dumps to the Mineral Pollution Load in the Vaal Barrage*. The report came to a number of conclusions, of which the following are vital to the present study:

- Mine residue deposits (tailings dams and sand dumps) situated within the catchment area of the Vaal Barrage discharged approximately 50 000 tons of salts into the near surface environment in 1985 alone; the proportion of pollutants eventually transported by surface streams or ground water into the Vaal Barrage is unknown.

- Seepage from the mine residue deposits into the streams is the likely source of the high salt loads.

The extent and type of pollution contained in the unsaturated zone would define the type and extent of rehabilitation required for future land use and for the prevention of future groundwater contamination. The presence of tailings dams has resulted in large-scale pollution of the land, which poses a serious environmental threat to the scarce water resources (surface and groundwater) in highly populated areas in particular.

Population growth in the Gauteng Province will reach 8.5 million by the year 2000, which will constitute more than 40 % of the urban population of South Africa (Van Rooy, 1996). However, the Vaal River catchment produces only 8 % of the country's mean annual run-off (MAR). The combined annual run-off of South Africa's rivers, calculated on a per capita basis, amounts to only 19 % of the global average (Huntley et al., 1989).

Consequently, the protection of water resources and the mitigation of aquatic pollution are becoming an increasingly important issue in South Africa. Experience in North America and Europe has shown that large-scale polluted areas (e.g. land affected by mine tailings) are too large to be cleaned up with the technologies available and at a reasonable cost.

Finally, pollution extends not only to soils underneath and down-gradient of mine residue deposits, but also to sediments in waterways, as well as areas on which windblown tailings are deposited. Furthermore, new tailings dams are being generated with limited environmental protection. Since these areas are expected to remain contaminated for an extended period, it is important to understand the potential for contaminant mobilisation in the long-term under changing environmental conditions.

1.2 OBJECTIVES OF THE STUDY

The project proposal defines the following four main objectives which have been met by the research program. The following research objectives were defined:

- To identify the nature and extent of contamination from unsaturated and saturated zones underneath reclaimed mine dumps (in respect of tailings dams) in order to infer their potential to pollute the near surface environment, ground and surface water, and to define the need to develop appropriate rehabilitation measures for the reclaimed land.

- To evaluate and define the existing state of knowledge with regard to the long-term environmental effects of tailings dams.

- To assess the potential of residual contaminants in the soils underlying tailings dams to exhibit negative environmental effects.

- To define the type and scope of further studies in respect of prediction, impact assessment and rehabilitation measures for pollution originating from active and reclaimed tailings dams.

1.3 SCOPE OF INVESTIGATIONS

A literature study, which included a data request from various mining companies, was carried out in order to describe the pollution status and the various contaminant attenuation and migration mechanisms in various affected components (i.e. tailings dam, unsaturated and saturated zone). All relevant information was entered into a database linked to a GIS-based map which shows important features such as tailings dams, reclaimed sites, surface water systems, residential and industrial areas. The GIS map is based on information gathered from topographical and geological maps and technical drawings provided by mining companies and a satellite image of the Gauteng Province. Based on this information, selected case studies were carried out. A total of eleven sites (case studies) were identified as being suitable for the purposes of the study. Sampling was done at seven of the eleven sites in order to close gaps in the database. All the investigated sites were either partly or completely reclaimed for the recovery of gold, and are situated above Karoo or dolomite aquifer systems.

Furthermore, all sites are either located in close proximity to residential areas or areas of agricultural land use (distance < 1 km). Most of the mine residue deposits have been present in the area for decades. The case study sites are situated in the Gauteng Province and stretch from Brakpan in the north to Springs in the south, with the exception of one site, which is situated close to Potchefstroom in the North-West Province. The case studies comprised a visual site inspection of all sites with special reference to land use and development of residential areas. Samples were collected from the seven selected reclaimed sites and analysed with respect to geotechnical, mineralogical and geochemical parameters. The main objective of field and laboratory testing was to investigate the pathway of contaminant migration in association with acid mine drainage (AMD) from the pollution source (tailings dams) through the unsaturated zone into the receiving groundwater system. A geochemical load index was applied in order to indicate the worst-case scenario for these sites as regards the potential for future pollution and the resultant potential threat to water supply and land development.

1.4 PREVIOUS WORK AND RELATED STUDIES

Many authors and work groups have dealt with the water quality impact of mining activities in South Africa. A comprehensive summary of the previous work and related studies conducted in South Africa is presented below:

- Clausen (1969) predicted a salt load of 16800 t from mine deposits in the Klip River and Suikerbosrand catchments in 1970, decreasing to 6000 t in 1980 and 3000 t in 1990. The author ascribed the predicted reduction in the salt load from mine residues to the proposed construction of toe dams, the securing of slimes dams tops against surface run-off and the reduction with time of the residual oxidisable pyrite (much of which had already oxidised when the study was completed). It is important to note that this study did not consider the reclamation of mine residue deposits.

- Förstner & Wittmann (1976) analysed heavy metal concentrations in stream sediments and rivers affected by gold and platinum mines in the Witwatersrand and the Free State. AMD and the subsequent leaching of toxic metals such as Co, Cu, Fe, Mn, Ni and Zn resulted in an increase in metal concentrations to the order of three to four magnitudes, compared to unpolluted river systems in South Africa.

- Hahne et al. (1976) conducted a pilot study of the mineralogical, chemical and textural properties of minerals occurring in gold-mine dumps. Detailed information about the study were not available.

- Geotechnical investigations for the abatement of air and water pollution from abandoned gold-mine dumps in the Witwatersrand area were conducted in the early 1980s by Blight & Caldwell (1984). The main findings were that stabilisation and terracing of the tailings dam embankment may result in the minimisation of wind erosion of tailings material and hence, air pollution.

- Funke (1985) investigated the impact of mining wastes on the water quality of the Vaal catchment area and of the Vaal Barrage. The author found that the contribution of AMD from sand dumps and slimes dams towards a high salinity of the Vaal Barrage water is approximately 2 % compared to the pollution load originating from underground mine effluents which are pumped to the surface and discharged into the rivers.

- Marsden (1986) analysed borehole samples from different mine dumps at various depths with regard to the sulphur content as a function of depth. Rainwater run-off from these dumps can enter the Vaal Barrage system and contribute to the deterioration of water quality in the catchment of the Vaal Dam. Seepage leaving young mine dumps contains high levels of pollution. However, the author concluded that mine dumps more than 20 years old show no significant contribution to the current pollution load. These findings were derived from the amount of sulphur determined in mine tailings and thus reflect the generation of AMD.

- De Jesus et al. (1987) conducted an assessment of the ^{226}Ra concentration levels in tailings dams and environmental waters in the gold/uranium mining areas of the Witwatersrand. The authors concluded that ^{226}Ra concentrations are low in environmental waters released from mining areas (including tailings dams) as a result of a very low mobility of ^{226}Ra.

- SRK (1988) monitored selected mine dumps in the City Deep Area (central Johannesburg) which contribute to the pollution load (e.g. salt) of the Vaal Barrage Catchment. A summary of the findings are contained in **Chapter 1.1** above.

- The pollution potential of South African gold and uranium mines was investigated by Funke (1990). He found that the potential for the sulphur contained in mine dumps (which is still undergoing oxidation) to cause water pollution is low, particularly when compared with the pollution load deriving from mine pumpage and metallurgical plant operation.

- Evans (1990) conducted a study with regard to the geochemistry of a reed-bed adjacent to a gold slimes dam and related environmental aspects such as AMD generation and heavy metal pollution. The author found that the leached water can be derived from the oxidation of sulphide minerals (such as pyrite) within the slimes dam, resulting in sulphur-rich seepage and thus, deteriorating water quality downstream of the mine dump.

- Cogho et al. (1992) developed techniques for the evaluation and effective management of surface and groundwater contamination in the gold mining area of the Free State Province. The authors concluded that pollution at the mine disposal facilities (such as mine residue deposits) has reached a quasi steady-state situation from a distance of six kilometres downstream from the pollution source, owing to the fact that the mine residue deposits are situated mainly on Ecca sediments (low permeabilities). In contrast, disposal sites situated on Beaufort sediments (higher permeability than Ecca sediments) may show higher AMD and associated metal loads in surface and groundwater systems downstream from the pollution source. However, the authors also concluded that there is only limited environmental impact on the aquatic pathway, due to the young age of the disposal facilities and a large dilution factor.

- Walton et al. (1993) investigated the type and extent of groundwater pollution within Gauteng Province and identified pollution sources and their characteristics within the dolomitic aquifers. Two representative areas were selected for detailed field studies, the Elspark/Rondebult, and Rietspruit area south of Brakpan. The authors concluded that both study areas were subject to diffuse agricultural contamination, resulting in high nitrate concentrations in groundwater samples. Point source pollution was identified within the Rietspruit area in the vicinity of a tailings dam, reflected by elevated sulphate and metal (e.g. Ni, Cu, Fe) concentrations in both surface and groundwater systems.

- Radioactive and heavy metal pollution associated with a gold tailings dam on the East Rand was investigated by Znatowicz (1993) in the early 1990s. In this study, water quality sampling and an airborne radiometric method was used to identify anomalous amounts of heavy metals and radionuclides in the vicinity of a tailings dam. The author found that high concentrations of toxic metals (such as As, Cd, Ti and V) and radioactivity (U in one sample) in water samples downstream from the site exceeded permissible limits. High concentrations of toxic metals were also encountered in the stream sediments and soils. However, the bio-availability of these contaminants is uncertain, because no adequate tests (e.g. leaching tests) were conducted.

- An assessment of radioactivity and the leakage of radioactive waste associated with Witwatersrand gold and uranium mining was launched by Coetzee (1995), who also provided data from an airborne radiometric survey. The author concluded that very low concentrations of U were found in samples from pollution plumes of tailings dams, but that significant radiometric anomalies were detected. In his view, this indicates the migration of U into river systems other than those investigated and the deposition of ^{226}Ra in the environment.

- Pulles et al. (1995) conducted a preliminary situation analyis in order to characterise the impact of Witwatersrand gold-mines on catchment water quality. The authors concluded that mining activities contribute between 30 - 45 % of the total salt load (estimated 677 000 t/a in 1995) to the Vaal Barrage catchment, thus having a significant negative impact for agricultural and industrial users.

- Pulles et al. (1996) compiled in a manual for the environmental assessment and management of gold mining operations in South Africa on the water quality impact of three different mines in the Witwatersrand, the Carletonville and Klerksdorp area respectively. The authors concluded that seepage released from various waste deposits such as mine dumps has been identified as the most significant pollution source with regard to the deterioration of water quality. Although seepage only contributed approximately 11 % of the overall salt load, the contributions for heavy metals varied between 75-85 % in the Witwatersrand area.

- Rösner (1996) analysed more than thirty gold-mine tailings samples taken at various depths (< 1 m) from five different tailings dams in the East Rand area for their geochemical composition. The samples showed silicate oxide (SiO_2) concentrations of between 73-90 %, reflecting a high quartz content of tailings. Although all samples were taken within the oxidised zones of the tailings dam, significant metal concentrations of As, Cr, Ni, Pb and Zn were found. However, depth-related concentration trends could not be established.

- Lloyd (1997) and Blight & Du Preez (1997) published controversial findings in two different papers which discussed the escape of salt pollution from decommissioned gold residue deposits in the Witwatersrand area. Lloyd (1997) concluded that sand dumps may have contributed to the salt discharge from gold residue deposits in the past, but that their impact has progressively decreased due to rapid pyrite oxidation (which in his view is now complete). In contrast, Blight & Du Preez (1997) found that pollution arises from acid leachate formed by percolation through the more permeable sand dumps and, to some extent, from erosion gullies on tailings dams.

- Wates et al. (1997) investigated the environmental aspects related to the design and construction of tailings dams with regard to the recent environmental legislation in South Africa. The authors concluded that recent failures such as the Merriespruit disaster have led to intensified public awareness of the safety and environmental hazards associated with mine dumps. This will be reflected in the promulgation of existing legislation such as the new Water Act and the establishment of a new set of guidelines, The *Code of Practice for Mine Residue Deposits* was developed under the guidance of the South African Bureau of Standards (SABS, 1997).

1.5 REPORT STRUCTURE

Following the introductory **Chapter 1** in which the background, research objectives and previous work are presented, **Chapter 2** provides an overview of environmental issues related to gold-mine residue deposits in South Africa with regard to current legislation, technical information and reclamation approaches as well as land use after reclamation. It also comprises the evaluation of the mine residue deposit register (GIS-based) of current and reclaimed deposits. **Chapter 3** describes the flow mechanisms providing a transporting medium for contaminants within the unsaturated and saturated zones. **Chapter 4** provides information about the generation and fate of acid mine drainage (AMD). This chapter also describes the main hydrogeochemical processes which occur throughout the tailings dam, in the underlying unsaturated zone and within the groundwater system, with respect to the effects of seepage emanating from tailings impoundments. **Chapter 5** outlines the methodology applied during the course of this study with regard to data requirements, the compilation of a mine residue deposit register for South Africa, field survey, laboratory testing and data interpretation. **Chapter 6** contains the assessment of eleven selected case study sites in the Witwatersrand region with regard to their current pollution status and potential future pollution impact. **Chapter 7** summarises the findings from the case studies and discusses its results under regional environmental aspects. **Chapter 8** provides an overview of rehabilitation management options for reclaimed tailings dams and gives background information regarding experience from overseas. **Chapter 9** discusses the findings of the research project and presents the conclusions and derived recommendations regarding the rehabilitation of land affected by reclaimed gold-mine tailings in South Africa.

1.6 REPORT RESPONSIBILITIES

Chapter 1-2 and 4-10 were written by Thorsten Rösner (Pulles Howard & De Lange Inc.) including the compilation of the appendices. Chapter 3 was provided by Jan Vermaak (Yates Consulting) and modified by Reynie Reyneke (Geo-Hydro-Technologies (Pty) Ltd.). Paul Aucamp (Council for Geoscience) provided geotechnical, geochemical and mineralogical results of the samples which were collected at the seven selected reclaimed sites (case study sites A-G) in the study area.

1.7 CONFIDENTIALITY OF SITE DATA

It must be stressed that this research project would not have been possible without the co-operation of South African mining companies. As a result, permission for site access and additional site information has been given from mining companies on the base of a confidentiality agreement regarding the use of data for research purposes. Thus, all sites have been coded to ensure data confidentiality in the interest of the co-operating mining companies.

CHAPTER 2

GOLD-MINE RESIDUE DEPOSITS IN SOUTH AFRICA

2.1 INTRODUCTION

Historically, South Africa has been the largest producer of gold in the world (DME, 1996). Only in 1996 a total volume of 377 million tons of mine waste was produced, accounting for 81 % of the total waste stream in South Africa (Engineering News, 1997). These mine wastes contain large amounts of sulphide minerals (10-30 kg per ton), which give rise to the generation of AMD.

Precious metal, base metal, and coal reserves contain naturally occurring toxic substances. In addition, toxic substances which will eventually be contained in the mine tailings, are introduced during the various phases of the metallurgical extraction and treatment processes U.S.-EPA, 1985). Furthermore, it is known that the gold bearing reefs mined in the Witwatersrand area are associated with radioactive minerals such as Uraninite (UO_2). Until the 1990s, South Africa was one of the largest producers of U in the world. In 1989 alone, a total volume of approximately 42 million t of tailings was processed by nine mines for the recovery of U (Funke, 1990). Therefore, tailings dams resulting from such operations are internationally classified as low-level radioactive waste disposal sites with respect to the radioactivity emanating from such deposits.

The bulk of the gold-mine tailings material will always be disposed on the surface and results in a long-term threat to the surrounding environment. More than 270 gold-mine tailings dams have been identified in South Africa during the course of this study, most of which are situated in either highly urbanised areas or close to agricultural land. According to the international study "Tailings Dam Incidents: 1980-1996" (Mining Journal Research Services, 1996), it is assumed that there are a total of around 400 tailings dams in South Africa (from gold, coal and base metal mining). For comparison's sake, there are approximately 300 tailings dams in Canada, 400 in Australia and 500 in Zimbabwe.

The associated financial liability of mining operations has increased dramatically due to stricter environmental legislation as a result of improved public awareness. This resulted in increased pressure associated with the establishment of new mine waste disposal sites and in the rehabilitation of existing residue deposits which have been poorly designed and operated.

The high operating costs of underground gold-mines encouraged some companies to focus on the reclamation of existing tailings dams for the recovery of gold still present in economically viable quantities in the tailings. In addition, coarse waste material from such operations has been used for various purposes, e.g. waste rock dumps have been reclaimed for the recovery of construction materials.

2.2 LEGISLATION

Legislation in South Africa does not have a specific Act governing mine residue deposits. The provisions of a number of Acts such as the Minerals Act, Mine Health and Safety Act and Water Act apply, either directly or indirectly. Various government departments have an interest, under the various laws, in protecting the environment affected by mining operations. In an effort to simplify compliance with the legal provisions, these departments have adopted a holistic, coordinated approach in order to achieve a common goal.

Current legislation requires all mining companies to produce Environmental Management Programme Reports (EMPR's). A number of Acts, which may pertain directly or indirectly to mine residue disposal governs mine residue disposal in South Africa. The following Acts pertain directly to mine residue deposits:

- Minerals Act (1991);
- Mine Health and Safety Act (1996);
- Water Act (1956, 1998);
- Atmospheric Pollution Prevention Act (1956).

The following Acts have principles or requirements that may influence mine residue deposits:

- Constitution of South Africa (1996);
- Environmental Conservation Act (1989);
- Nuclear Energy Act (1993);
- Hazardous Substance Act (1973);

- Health Act (1977);
- Conservation of Agricultural Resources Act (1983);
- Physical Planning Act (1991).

As a result of the Merriespruit disaster, where a tailings dam collapsed, killing and injuring residents of the nearby suburb in Virginia, DME took an initiative to develop consistent guidelines for the construction, operation and rehabilitation and thus, appropriate environmental management of mine residue deposits.

Thus, the *Code of Practice for Mine Residue Deposits* has been developed in collaboration with the SABS (1997). The code is not restricted to the safety and stability of mine residue deposits and also includes the following environmental concerns:

- Water pollution;
- Dust pollution;
- Factors affecting soil requirements;
- Aspects of land use.

The code provides mining companies with a guideline to ensure good practice in the various stages of the life cycle of tailings dams.

Legal aspects dealing with tailings dams in South Africa are extensively discussed in literature such as Cogho et al. (1992), Fuggle & Rabie (1992), Richter (1993), DWAF (1995) and Wates et al. (1997).

2.3 CLASSIFICATION OF GOLD-MINE RESIDUE DEPOSITS

Various classification systems for mine residue deposits are available in South Africa (Funke, 1990 and Cogho et. al., 1992). A general classification system, based on the grain size of mine residues, results in the formulation of three categories:

1. *Waste rock dumps* consist of coarse-grained low-grade overburden material, the processing of which for the recovery of gold is not economically viable (Daniel, 1993).

In order to stabilise waste rock dumps for geotechnical purposes, unknown volumes of low-grade water are sprayed onto the waste rock dumps during the construction phase (Funke, 1990). Rock dump material is usable as construction material for infrastructure such as roads.

2. *Sand dumps* have been mechanically deposited in a moist state, reaching heights of up to 100 m above ground level. Because of the permeability of the loosely packed sand (fine to medium sand particle size), oxidation of sulphide minerals occurs up to depths of more than 10 m, resulting in the generation of AMD. The mechanical deposition of tailings material as sand dumps has been phased out, with the last sand dumps deposited probably in the early 1960s (Funke, 1990).

3. *Slimes dams*[1] (referred to as tailings dams) are characterised as hydraulically constructed ring dyke impoundments. The particle size of the slimes material is mainly (more than 75 % of the material) < 75 μm and thus, to be considered as fine-grained (SRK, 1988). Hence, the oxidation of sulphide minerals is confined up to a depth of a few metres below the surface of the impoundment. **Figure 2.1** shows a typical tailings dam in the East Rand area which has been partly reclaimed (reclamation status: approximately 50%). The solid to water ratio in the wet slime varies from 1:1 for gold tailings up to 1:4.5 in slimes dams generated from the combined recovery of gold, uranium and pyrite. Some of the operating tailings dams store large volumes of surplus water from the plant in pond systems for evaporation purposes on top of the dam. Tailings dams represent the most common deposition type in South Africa. Funke (1990) subdivides tailings dams into two subclasses: those that have been established only from the extraction of gold, and slimes dams from the combined extraction of gold, uranium and pyrite.

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[1] The word *dam* is used in the mining industry for hydraulically placed residue deposits.

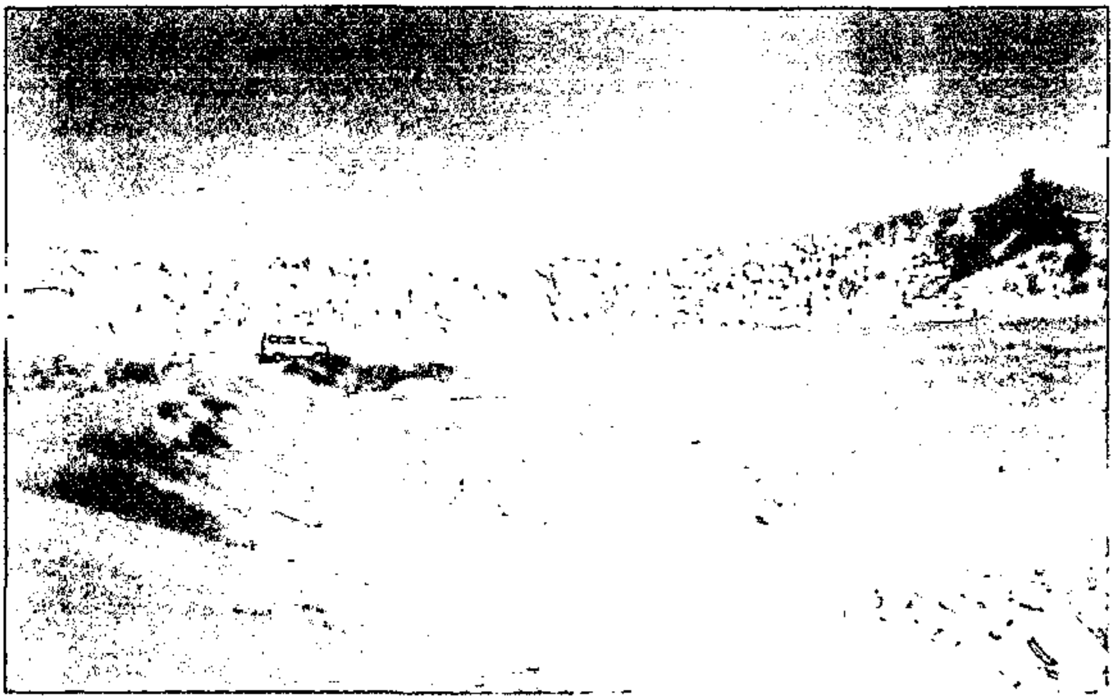


Figure 2. 1: Photograph of a partly reclaimed tailings dam in the East Rand area

2.4 DEPOSITION APPROACHES IN THE ESTABLISHMENT OF TAILINGS IMPOUNDMENTS

The South African gold mining industry introduced the sliming process for the recovery of gold in 1918, with the result that the construction of new sand dumps was finally phased out in the 1960s. Sand dumps have been deposited mechanically in a moist state (water/solid ratio <1). Since the 1960's, all mine residues from the gold, uranium and pyrite extraction process have been placed hydraulically (water/solid ration ≥1) by using ring dyke impoundment systems.

In these ring dyke impoundments (see **Figure 2.2**), the tailings slurry is pumped to the inner dam wall during the daytime (so-called day-paddocks), contained by a freeboard of about one metre. In the late afternoon, after settlement of the coarse material in the day-paddocks, the slurry decants via breeches into the large area of the night-paddocks, where sedimentation of the fine tailings material takes place.

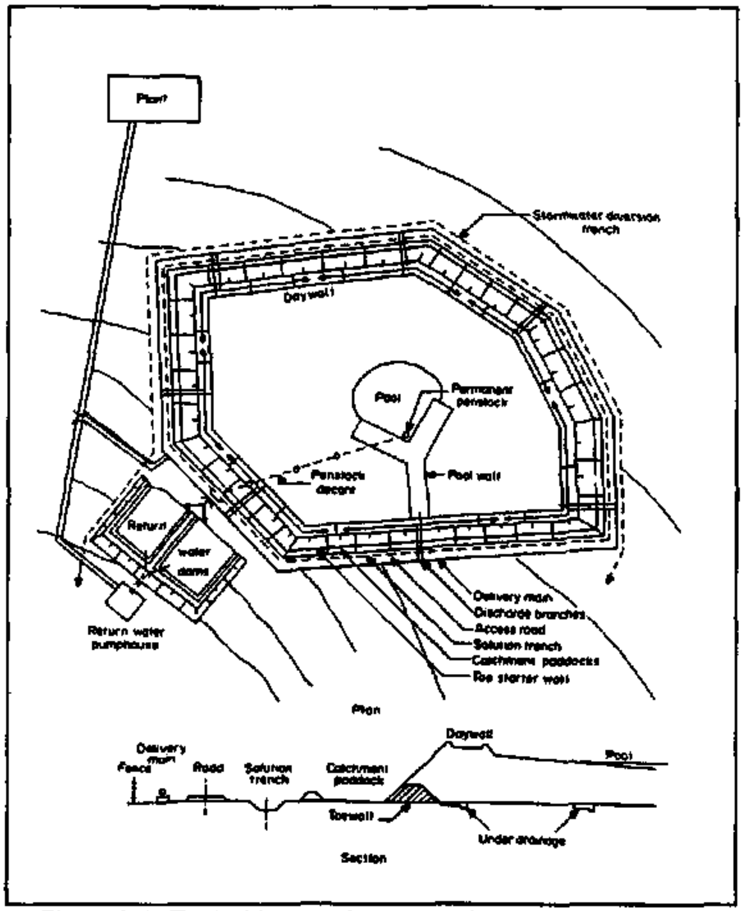


Figure 2. 2: Typical layout of a tailings dam (from: Funke, 1990)

Finally, the decanted water is collected in the lower-lying area around the penstock system, from where it is returned to the processing plant. The cycle time in the day-paddocks is determined by the rate of deposition required for the tailings to achieve desiccation, which is usually one to two weeks. The maximum rate of deposition in South Africa is 2.5 m/y which, according to Funke (1990), is a result of:

- Effective desiccation;
- Stable surface conditions;
- Access requirements;
- Experience with gold tailings with a relative density of 1.45 kg/m^3 and a cycle time in the dam's day-paddocks of approximately two weeks (allowing for the dessication, compaction and cracking of the slime to reduce the ratio between horizontal and vertical permeability).

2.5 GEOHYDROLOGICAL CONDITIONS OF TAILINGS DAMS

The tailings dam remains almost saturated during the operational phase, as well as for the period after decommissioning of the impoundment. This is mainly due to the particle size distribution (fine sand and coarse to medium silt particle sizes) of gold-mine tailings, which enables water retention by capillary forces. After a tailings dam has been decommissioned, the phreatic surface slowly subsides, at a rate which depends on the conditions of the under-drainage system and the size of the impoundment. Reported subsidance of the phreatic surface (line of zero pore water pressure) varies between 0.3 m/y and more (Blight & Du Preez, 1997).

Figure 2.3 shows the position of the phreatic surface in a tailings dam during operation and after decommission. It is important to note that the majority of tailings dams in South Africa were constructed without seepage collection systems.

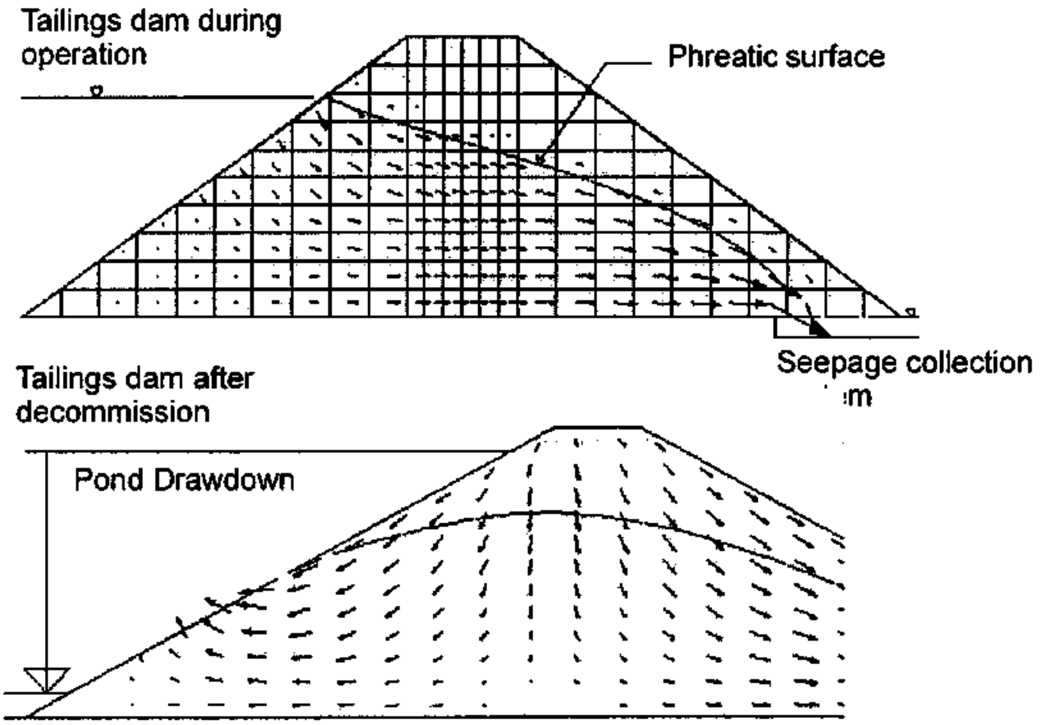


Figure 2.3: Position of the phreatic surface in a tailings dam during operation and after decommission.

In hydraulically constructed tailings dams, the *anisotropy coefficient*, which represents the ratio between horizontal and vertical permeability in porous media, is higher than in mechanically deposited and compacted dams. This is because the layered structure of hydraulically constructed tailings dams is strongly compacted because of the weight. The anisotropy coefficient is usually between 5 to 10, but can reach values of more than 200 in the case of poor construction (Williams & Abadjiev, 1997).

The high anisotropy found in most of the tailings dams inevitably results in a high phreatic surface, which frequently floods the horizontal drain systems and causes seepage at the slope surface. In turn, the seepage at the slope surface causes erosion and leads to a significant increase in the risk of dam failure and pollution by AMD and associated contaminants.

Most tailings dams contain built-in horizontal drainage systems which are ineffective because the elevated phreatic surface cannot be effectively lowered. Common practice when seepage on the dam slope occurs is to institute remedial measures such as elevated horizontal drains, buttresses, horizontally drilled boreholes from the slope toe, and cover and surcharge by cycloned tailings.

A new approach in South Africa could be the installation of vertical drains, which are simple to construct in a ring-dyke impoundment. A comprehensive description of the installation and function of vertical drains in controlling seepage flow (pollution control) is given in Williams & Abadjiev (1997).

2.5.1 Seepage losses from tailings dams

Van den Berg (1995) concluded that the seepage regime of tailings dams is controlled by the anisotropy factor, which results from a system of close layering and shrinkage cracks. Further factors include the tailings deposition cycle (**Chapter 2.4**) during the construction of the tailings dam. Authors such as Van den Berg, 1995, Rust et al., 1995 and Wagener et al., 1997 have described various approaches to the monitoring of the phreatic surface of tailings dams. Once the anisotropy coefficient is known, a flow net can be calculated by applying the relevant boundary conditions (Wagener et. al, 1997). The interpretation of such a flow net would provide useful information regarding the seepage regime in a tailings dam.

In general, seepage escapes from tailings impoundments through two typical pathways:

- Through the embankment structure;
- Through the foundation materials on the floor.

The quantity and rate of seepage is controlled by several factors, the most important ones being the following (Wagener et al., 1997):

- Geohydrological conditions of the impoundment foundation;
- Hydraulic conductivity of the tailings material;
- Hydraulic conductivity of the foundation;
- Geometry of the impoundment and embankment;
- The design, construction and operation of the impoundment.

Owing to the complexity of the impoundment and the number of variables involved, it is difficult to carry out a comprehensive analysis of seepage losses from an impoundment (Wagener et al., 1997). Mathematical models which apply the finite element method, such as SEEP/W and SAFE, are a useful tool for calculating the phreatic surface and the seepage regime.

The chemical composition of seepage from the tailings dam will not necessarily be the same as the slime composition at the time of tailings deposition. The quality of water leaking from the tailings dam through the unsaturated into the saturated zone or groundwater system is controlled by various hydrogeochemical and biochemical processes, which are described in more detail in **Chapter 4**. All the mechanisms that contribute to the attenuation of contaminants are important for the reduction of contaminant concentration levels in the tailings seepage.

2.5.2 Seepage control approaches

Typical pollution control measures at tailings dams are:

- Toe dams;
- Penstock systems;
- Drain systems.

Toe dams, as shown in **Figure 2.2**, considerably reduce the immediate pollution potential of a tailings dam or sand dump by collecting run-off and seepage water and retaining it for evaporation. The design and construction of the older mine residue deposits did not include toe dams. On modern tailings dams, excess water is controlled by penstock systems, where water is drawn off from the pond and returned to the plant for re-use. Trenches are also provided in order to drain seepage to the penstock pumps (SRK, 1988). Vertical and horizontal drain systems have been discussed in **Chapter 2.5**.

2.6 RECLAMATION OF MINE RESIDUE DEPOSITS

In the 1970s, various reclamation companies started to recover tailings from a large number of old mine residue deposits (mainly tailings dams) in the Gauteng Province. The recovered tailings material is reprocessed to extract gold in economically viable quantities (currently 0.4 g Au/ton according to Creamer, 1998).

In general, two different reclamation processes are applied: mechanical and hydraulical reclamation. Hydraulical reclamation (use of hydro-jets or water canons) is the most common method used in South Africa. Water is sprayed at high pressures onto the tailings material to produce a liquid sludge, which is then pumped to the processing plant.

Approximately 70 former tailings dams have been reclaimed in the Gauteng Province, resulting in nearly 13 km^2 of land becoming available for potential development. At the reclaimed sites investigated, it was found that tailings material was often not completely removed from reclaimed sites investigated, which means that this incomplete or partially reclaimed land is often devoid of any vegetation. Such areas for which there are no further legal requirements for additional reclamation have been referred to as *abandoned mined lands* (Sutton & Dick, 1984).

Owing to the inadequate vegetation cover on these abandoned mine lands, AMD and excessive erosion often occur, which is a major environmental concern. The Environmental Protection Agency of the United States (U.S.-EPA, 1976) reported approximately 100 times more erosion for abandoned mined lands compared to similarly located forest lands. The AMD process will be discussed in **Chapter 4**.

Furthermore, it is important to note that the reclamation of old mine residue deposits poses a potential pollution problem, as the reclaimed material allows further oxygen penetration, resulting in the continuous generation of AMD.

2.7 LAND USE AFTER RECLAMATION

The need for development of low-cost housing in highly urbanised areas such as the Gauteng Province is becoming increasingly important. Often the required land is situated close to operating mines or on sites of previous mining and mineral processing activities such as tailings dams. Hence, some degree of rehabilitation for contaminated land would be required after complete reclamation has taken place. Rehabilitation is primarily aimed at ensuring the protection of human health (risk reduction), conservation of the environment and land development.

Soils contaminated with toxic substances can have a direct influence on human health if houses are built and gardens are established on land affected by mine tailings. This not only applies to land where mine residue deposits have been reclaimed, but also to land which is affected by the deposition of wind-blown tailings material. Particles of soil or tailings handled or ingested by adults or children may carry irritant, poisonous and/or radioactive substances. The inhalation of such particles, or vapours from the pollutants, provides another adsorption route. Vegetable gardens or agricultural areas situated on polluted land may produce crops contaminated by the direct uptake of toxic substances or the deposition of contaminated particles on the growing plants (National Society for Clean Air and Environmental Protection, 1992).

2.8 REGISTER FOR GOLD-MINE RESIDUE DEPOSITS

2.8.1 The use of GIS as a supporting tool for the establishment of a register

Models and decision tool supporting systems are often used in order to identify polluted areas and to evaluate the impact of various pollution sources within catchment systems. Because of the large data requirements involved in the use of models such as ANSWER (Areal Nonpoint Source Watershed Environmental Response), the application of these models is limited.

Geographic Information Systems (GIS) can however be used to solve some of the problems related to data requirements because of its wide application in the environmental field. In this study, GIS technology (ArcView 3.0a) has been applied for the collection, management and evaluation of spatially varying data relating to the areas where mine residue deposits are situated.

Various map features have been digitised in order to evaluate tailings dams, surface water systems and mining activities in South Africa. The application of GIS enables the evaluation of the spatial distribution of mine deposits in the context of residential and industrial development. It also can be linked with borehole data registered in the National Groundwater Database (NGDB) of DWAF. An explanation for the application of the NGDB is given in Hodgson et al. (1993).

2.8.2 GIS-based register for gold-mine residue deposits

Most of the information used for the establishment of the register was gathered from topographical (1:50 000) and geological maps (1: 250 000) and from information provided by DME and DWAF. The following table, **Table 2.1**, shows the parameters of the GIS-linked database with regard to gold tailings impoundments and the sources for this information:

Table 2. 1: Parameters and source of information captured in the GIS-linked database

Parameter	Source of Information
General information	Mining companies
Name	DME
Index number	DME
Owner of the deposit	DME
Type of gold-mine residue deposit	DME
Size of gold-mine residue deposit (km^2)	GIS based calculation
Geological conditions underneath the Gold-mine residue deposit	Geological Maps (1:250 000, 1:10 000), Council for Geoscience
Surrounding land use (< 1 km)	
• Agricultural areas	Topographical Maps (1:50 000), Land Survey
• Residential areas	Topographical Maps (1:50 000), Land Survey
• Industrial areas (including mines)	Topographical Maps (1:50 000), Land Survey
• Recreational area	Topographical Maps (1:50 000), Land Survey
• Natural area (e.g. woodlands, rivers and wetlands)	Topographical Maps (1:50 000), Land Survey

The complete gold-mine residue deposit register is attached in **Appendix D.**

2.8.3 Statistical evaluation of the register

The statistical evaluation of the GIS-linked database revealed that there are currently 272 mine residue deposits (size > 0.01 km^2) in South Africa identified on topographical maps and covering a total area of about 181 km^2. However, Kempe (1983) reported an estimated area of 80 km^2 covered by mine residue deposits.

For comparison, estimates in 1986 in Canada have shown that at least 120 km^2 of land is covered by tailings dams, resulting in a total volume of 1.9 billion tons of tailings and 750 million tons of waste rock generated during a mining period of approximately 40 years (Feasby et al., 1997). **Table 2.2** shows the main statistical parameters of gold-mine residue deposits in South Africa:

Table 2. 2: Statistical parameters of gold-mine residue deposits and reclaimed sites in South Africa

Parameter	Area size covered by Gold-mine residue deposits [km^2]	Area size covered by reclaimed Gold-mine residue deposits [km^2]
MIN	0.01	0.01
MAX	14.51	1.07
AVG	0.67	0.19
TOTAL	181.03	12.8

All reclaimed gold-mine residue deposits are situated within the Gauteng Province, most of them close to the Johannesburg area. The total area being reclaimed is an estimated 12.8 km^2, which equals 7.1 % of the total area covered by gold-mine residue deposits in the country.

2.8.3.1 Classification of gold-mine residue deposits

Table 2.3 shows a classification of mine residue deposits in South Africa according to their size. Most of the impoundments (77.2 %) are < 1 km^2 in size. Only one impoundment is > 5 km^2.

Table 2. 3: Classification of gold-mine residue deposits with regard to the covered area size.

Class	Area size covered by gold-mine residue deposits	Area size [km^2]	Number of Cases	Frequency (in %)
A	Small	< 1	210	77.2
B	Medium	1-2.9	58	21.3
C	Large	3-4.9	3	1.1
D	Extremely large	> 5	1	0.4
TOTAL			272	100

Figure 2.4 shows the distribution of mine residue deposits with an area size of < 1 km^2. The figure indicates that most of the *Class A* tailings dams (n = 210 deposits) show an area size of less than 0.2 km^2.

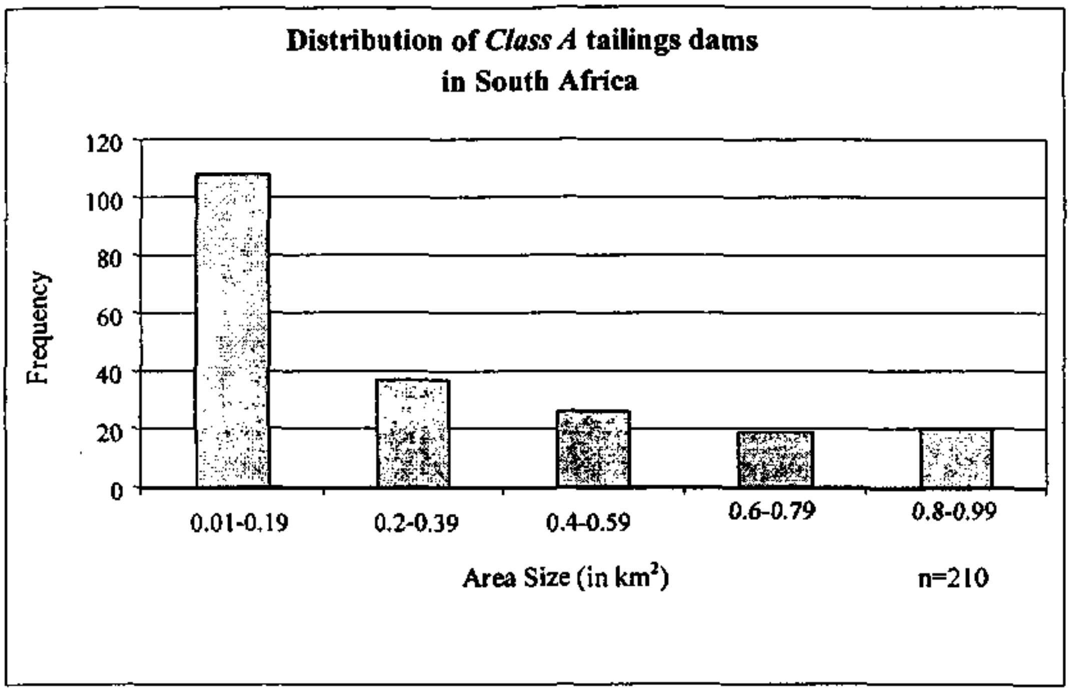


Figure 2. 4: Distribution of frequencies with regard to *Class A* gold-mine tailings dams (area size < 1 km^2, n = 210).

During the course of the study, it became apparent that not all gold-mine residue deposits could be traced with regard to their accurate size, deposit type and reclamation status. Sand and waste rock dumps are not indicated on topographical maps and thus have not been captured in the GIS-linked database. It is anticipated that most of the sand and waste rock dumps have long since been reclaimed and the land has already been re-utilised. Another common method was to deposit tailings dam material onto sand dumps. **Table 2.4** summarises the frequency of different deposit types such as tailings dams or reclaimed sites.

Table 2. 4: Summary of the frequency of gold-mine residue deposits (n = 272).

Type of gold-mine Residue deposit	Number of Cases	Frequency %
Tailings dams (not reclaimed)	196	72
Sand dump	-	0
Waste rock dump	-	0
Slimes dam/Sand dump	1	0.4
Partly or completely reclaimed	67	24.6
Unknown type	8	3
TOTAL	272	100

2.8.3.2 Spatial distribution of gold-mine residue deposits

Most of the deposits are located within the Witwatersrand area of the Gauteng province. **Figure 2.5** shows the distribution of gold-mine residue deposits related to the provinces and land covered by those deposits.

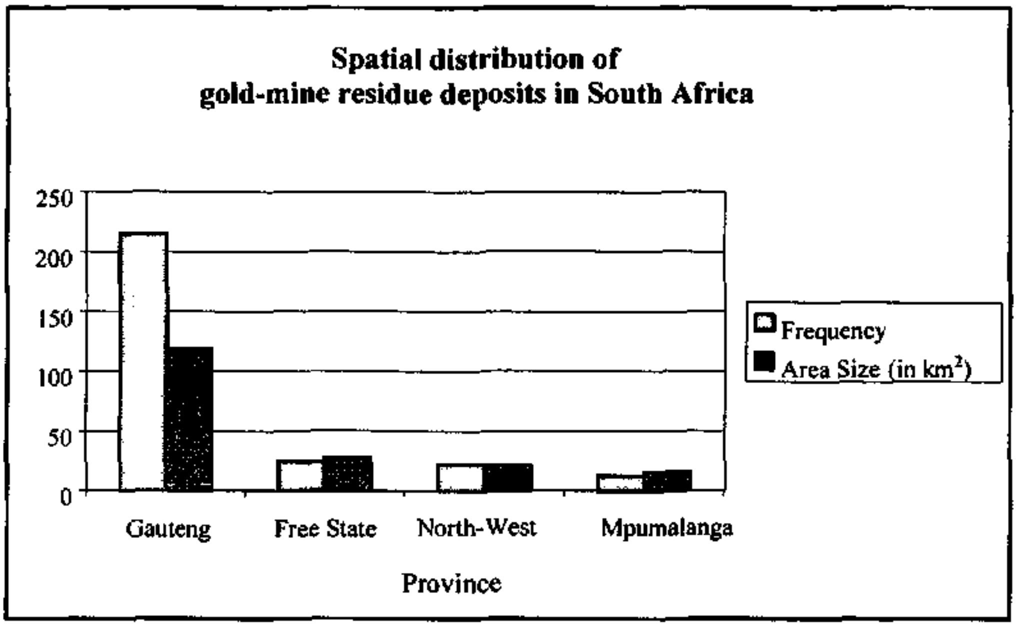


Figure 2. 5: Spatial distribution of gold-mine residue deposits related to provinces and covered land size (in km^2).

Only 21 % of the gold-mine residue deposits are situated in other provinces, i.e. the North-West, Free State and Mpumalanga Provinces, respectively that cover 45% of the total land area in South Africa. It is important to note that the highest density of gold-mine tailings dams and reclaimed dams was found close to the Johannesburg city area (topographical sheet 2628 AA Johannesburg).

2.8.3.3 Geological conditions underneath gold-mine residue deposits

Geological maps (1:250 000) have been used to determine the geology underneath current and former gold-mine residue deposits. **Table 2.5** lists the results with regard to cases and frequencies (expressed as percentages) in relation to different geological strata:

Table 2. 5: Geological conditions underneath gold-mine residue deposits (*no geological group available).

Geological Supergroup	**Number of Cases**	**Frequency (in %)**	**Rock type** (as described in the Geological Map 1:250 000)
Karoo	3	1.1	Diamictite, shale / quartzite
Karoo	*3*	*1.1*	*Diamictite, shale*
Karoo	1	0.4	Diamicitite, shale / shale
Karoo	37	13.6	Sandstone, shale, coal beds
Karoo	8	2.9	Sandstone, shale, coal beds / diamictite, shale
Transvaal	3	1.1	Quartzite, conglomerate, shale
Transvaal	1	0.4	Quartzite, conglomerate, shale / quartzite conglomerate
Transvaal	*1*	*0.4*	*Quartzite, conglomerate, shale / dolomite, chert*
Transvaal	1	0.4	Quartzite, conglomerate, shale / ferruginous shale, quartzite
Transvaal	1	0.4	Quartzite, conglomerate, shale
Transvaal	59	21.7	Dolomite, chert
Transvaal	1	0.4	Dolomite, chert / diamictite, shale
Transvaal	1	0.4	Dolomite, chert / dolerite
Transvaal	1	0.4	Dolomite, chert / quartzite, chert breccia, conglomerate
Transvaal	3	1.1	Ferruginous shale, quartzite
Witwatersrand	4	1.5	Lava, agglomerate, tuff
Witwatersrand	1	0.4	Shale
Witwatersrand	2	0.7	Shale / quartzite, conglomerate, sandy shale
Witwatersrand	3	1.1	Quartzite, greywacke, conglomerate, shale, tillite
Witwatersrand	7	2.6	Shale, quartzite, conglomerate
Witwatersrand	40	14.7	Quartzite, conglomerate
Witwatersrand	1	0.4	Quartzite, conglomerate / diamictite, shale
Witwatersrand	41	15.1	Quartzite, conglomerate, sandy shale
Witwatersrand	2	0.7	Quartzite, conglomerate, sandy shale / shale
Witwatersrand	1	0.4	Quartzite, conglomerate, shale / lava, agglomerate, tuff
Unknown	26	9.6	Geology unknown (no suitable map available)
Age*			
Jurassic	5	1.8	Dolerite
Jurassic	7	2.6	Dolerite / sandstone, shale, coal beds
Quaternary	3	1.1	Soil cover
Swazian	3	1.1	Gneiss, granodiorite, migmatite, ultramafic rocks
Swazian	2	0.7	Mafic to ultramafic rocks
TOTAL	**272**	**100**	

Table 2.5 indicates that more than 20 % of the deposits (62 sites) are situated on dolomitic rock and cover a land area of approximately 67.8 km^2, which represents 37.5 % of the total land covered by such deposits in the country. It must be stressed that the dolomitic formation of the Transvaal Supergroup is not only one of the most important groundwater sources in South Africa, but is also extremely vulnerable with regard to pollution (DWAF, 1995). **Figure 2.6** shows the distribution of tailings dams according to geological strata classification.

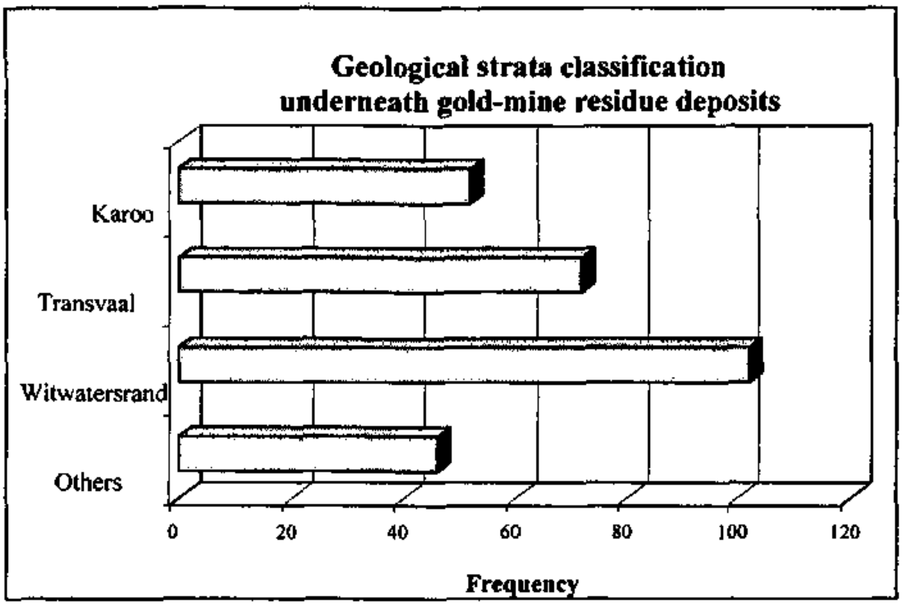


Figure 2. 6: Geological strata classification (Supergroup) underneath gold-mine residue deposits (n=272)

Most of the tailings dams are situated on rocks belonging to the Witwatersrand Supergroup (37.5 %), followed by the Transvaal Supergroup (26.5 %), Karoo Supergroup (19.1 %) and others (16.9 %).

2.8.3.4 Land use in close proximity to gold-mine residue deposits

Land use in close proximity (distance < 1 km) to gold tailings dams might be affected by pollution through various pathways (see **Figure 7.1**). Typical impacts are, for example, polluted borehole water, which is used for irrigation or domestic purposes downstream of the tailings dam, and the airborne transport of fine tailings material due to wind erosion, which could result in ingestion by humans and animals. Thus, any deterioration in groundwater quality should be evaluated in the context of potential beneficial use of the groundwater as determined by background quality and the available quantity of groundwater. **Figure 2.7** shows the distribution of various land use types in close proximity to gold-mine tailings dams.

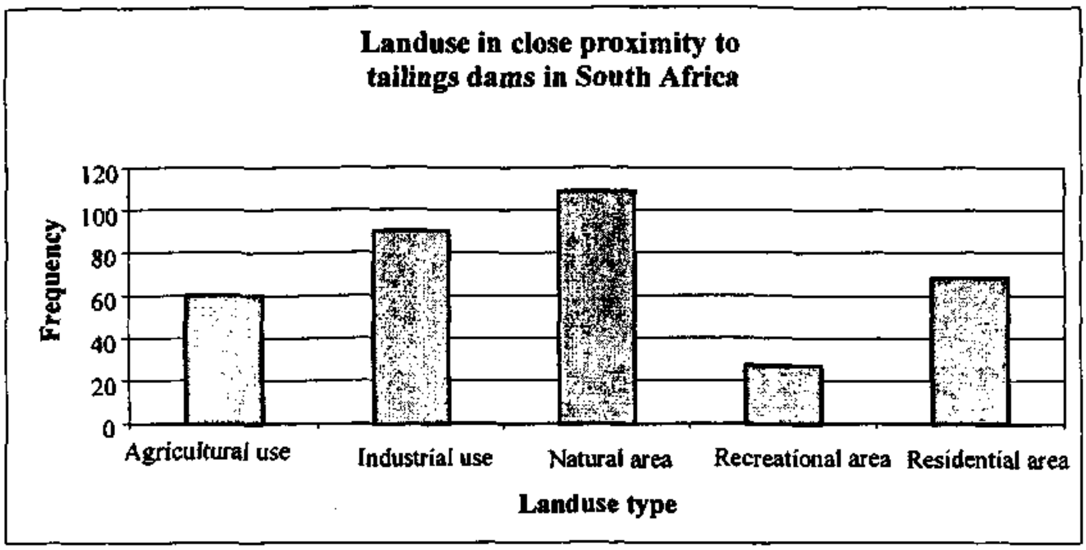


Figure 2. 7: Land use in close proximity to tailings dams.

Figure 2.7 shows that approximately 40% of the gold-mine residue deposits are situated close to sensitive natural areas such as rivers, dams, wetlands and woodlands. These areas could be affected by surface run-off of acid mine drainage, polluted groundwater discharging into the river or dust deposition of fine tailings which contain significant concentrations of heavy metals and other toxic substances (**Chapter 7.2**). It is important to note that all non-rehabilitated gold-mine residue deposits are subject to wind-erosion.

Industrial and agricultural use (including mines) in close proximity to gold tailings dams is common and may contribute to soil, surface and groundwater pollution. It is impossible to trace all potential pollution sources affecting aquatic systems, thus leading to an potential overestimation of the impact of such deposits. However, certain characteristic pollutants found in the seepage and the subsurface (such as As, Mn, CN, radionuclides and salts) can be used as tracers.

The GIS-based mine residue deposit survey revealed that 25 % of the deposits are located close to populated areas, which might be affected primarily by tailings dust and ingestion. It must be stressed that residential areas such as townships and squatter camps are fast developing communities, and it is very difficult to keep track of their dynamic development. In addition, it is of great concern that squatters are living illegally in the immediate vicinity of tailings dams areas and on reclaimed sites. Remote sensing techniques such as GIS-based satellite image evaluation techniques would provide a useful tool for the monitoring of these problematic areas on a continuous basis. **Figure 2.8** shows a satellite image of the Johannesburg and portions of the Witwatersrand area north of Johannesburg. Tailings dams are clearly visible as yellowish spots on the image.

Figure 2. 8: Satellite image of the Johannesburg area, showing the spatial distribution of tailings dams (yellowish), surface water systems (blue) and vegetation (reddish) indicating potential agricultural land use) (source: NASA, ST053-080-032/1,1994)

CHAPTER 3

GEOHYDROLOGY OF THE UNSATURATED AND SATURATED ZONES

3.1 INTRODUCTION

It was mentioned in **Chapter 2** that the need for more land in the highly urbanised areas for the development of low-cost housing is on the increase. Some of this land may be made available through the reclamation of old mine discard dumps. It is however important to investigate the suitability of these areas for urban development and one of the aspects that need to be investigated in this respect is the pollution-state of the reclaimed areas. This includes the levels of mine related contamination in the subsurface and its availability to human receptors, occupying land in and around these sites. The prevailing geological and geohydrological conditions at these sites can be regarded as the most important features, dictating the movement of pollution in the subsurface. This chapter focuses on the geohydrology of the subsurface and gives an overview on the main transport mechanisms, active in this zone.

The geological formations that contain water can be subdivided into two zones namely the unsaturated or vadose zone (characterized by a mixture of water and air) and the saturated zone (contains only water in the pore openings). Water, carrying solutes, must past through the unsaturated zone on its way to the saturated part of the geological formations when groundwater recharge occurs. The flow mechanism through these two zones differs and should therefore be discussed separately.

3.2 UNSATURATED ZONE

3.2.1 Basic concepts of the unsaturated zone

If one considers a homogeneous soil profile through the unsaturated zone, under static conditions, and omit the effect of evapotranspiration, it can be subdivided into three sub-zones namely the *capillary fringe*, *capillary zone* and *discontinuous zone* (Martin & Koerner, 1984a).

The *capillary fringe* is a zone that occurs directly above the groundwater surface. This zone is completely saturated and is under negative pressure. The thickness of the capillary fringe, h_c is analogous to the height of capillary rise in tubes. The specific diameter of the tubes is inversely proportional to the effective pore diameter of the soil (Martin & Koerner, 1984a). The effective pore diameter is dependent on the gradation (soil texture), porosity and other factors. The capillary fringe will be thick in fine-grained soils and thin in coarse-grained soils.

The *capillary zone* consists of soil in which the pores are filled with air and water. Matrix forces hold the water in the soil. Water fills the small pores while air fills the large pores in the soil. As the pore-water pressure decreases with distance above the groundwater surface, so does the radius of the curved water surface and the water consequently retreats into smaller pores. This leads to a decrease in water content. Fine-grained soils can retain high water contents for considerable distances above the groundwater surface (Martin & Koerner, 1984a).

In the *discontinuous zone*, water is only retained as adsorbed water since the pore-water pressure is too low to sustain capillary water. Water is strongly adsorbed on each soil particle. This water can be removed by evaporation.

3.2.2 Behaviour of a fluid in an unsaturated porous medium

Unsaturated conditions refer to a three-phase system comprising of solids, liquid and gas. It refers to a situation where the voids are filled with liquid and gas since most of the liquid would have been removed due to gravitational force. Forces that act against the force of gravitation to hold liquid in the porous medium are called *matrix forces*. These forces include *capillary* and *adsorption forces* and *electrical forces on a molecular level*.

In soil-plant environments, the matrix forces may include the effect of osmotic forces. Osmotic forces refer to the attraction of solute ions or molecules for water molecules. If pure water is separated from water containing solutes by a membrane that is not permeable for solutes, more water molecules will move towards the solute water mixture and will cause a higher pressure in the solute water side of the membrane. Since osmotic suction has little effect on movement of water through a porous medium, osmotic forces will be omitted for the purposes of this study.

At this point it will be useful to discuss some of the conventions employed in groundwater analysis. The pore water pressure, u_w, is one of the controlling variables in all hydraulic problems. Compressive water pressures are normally considered to be positive and the tensile stresses, that exist above the water table are therefore negative (Martin & Koerner, 1984a).

Water pressure is normally converted to a pressure head in groundwater studies and can be expressed as:

$$h_p = \frac{u_w}{\rho_w g} = \frac{u_w}{\gamma_w} \qquad [3.1]$$

Where the terms ρ_w and γ_w are the mass density and unit weight of water, respectively. The values of hp and u_w vary linearly with distance above the water table under static conditions.

3.2.2.1 Capillary forces

A wetting liquid, such as water, will rise in a capillary tube due to the pressure difference between the liquid and gas within the tube. The pressure difference occurs due to curvature on the liquid-gas interface, known as the meniscus in a capillary tube.

A porous medium, such as soil, can be compared to a bundle of capillary tubes, with varying and irregular radii, tied together. A concave meniscus extends from grain to grain across each pore channel. The radius of each curvature reflects the pressure difference between the liquid and gas (Freeze & Cherry, 1979). Forces that hold liquid in a porous medium due to capillary action are called capillary forces. Capillary forces are approximately inversely proportional to effective pore diameter, R_{eff} (Hillel, 1980). This can be expressed as follows:

$$R_{eff} = \frac{2\sigma\cos(\alpha_w)}{\rho g h} \qquad [3.2]$$

This value represents the radius of a hypothetical bundle of capillary tubes at macro-scale. On a micro-scale, however, great variations do occur due to variations in pore size.

In saturated flow the driving potential for groundwater flow is due to the pore water pressure and elevation above a reference datum. However, in unsaturated flow the pore water is under negative pressure caused by surface tension, called the capillary pressure and is a function of the volumetric water content of the soil. The Darcy velocity for unsaturated flow is less than that for saturated flow and steadily decrease as the moisture content of the porous medium decreases. Darcy's law for unsaturated flow can be described as:

$$q = -K(\psi)\nabla\phi \qquad [3.3]$$

where K is the hydraulic conductivity of the medium, Ψ the capillary pressure and ϕ the porosity of the medium.

3.2.2.2 Adsorption forces

In addition to capillary forces, adsorption of liquid molecules onto solid particles also takes place. Surface tension forces occur on the solid-liquid and solid-gas interfaces. The force that attracts a fluid to a solid surface is known as adhesion. Adsorbed liquids are held very tightly to the solid particles and cannot be removed, except by external forces such as evaporation (Hillel, 1980). Water that is adsorbed onto soil grains is called hygroscopic or adsorbed water.

The volume of water that is adsorbed onto soil grains is directly proportional to the specific surface of the soil which in turn is inversely proportional to the grain size of the soil. Clay minerals will have much higher specific surfaces than silt or sand grains due to their relative small size.

The adsorption area is greatly increased in certain clay minerals, especially smectites, due to the ability of clay minerals to incorporate water into their crystal lattices.

Since water is a bipolar molecule it is attracted to soil grains, especially clay minerals, due to net electrical charges that may exist on the surfaces of soil grains. Permanent negative charges occur on the surfaces of clay minerals due to isomorphous substitution. Net electrical charges also occur on the edges of clay minerals and on the surfaces of allophane and hydroxides of iron and aluminium due to their incomplete crystal lattices (White, 1989). This phenomenon is partly responsible for water being held in the soil matrix, particularly of clay soils. It is also partly responsible for the cohesion and plasticity characteristics of clay soils.

The charges on a mineral surface can be calculated by measuring the difference of moles of charge contributed, per unit mass, by cations and anions, adsorbed from an electrolyte solution at a known pH. The cations and anions adsorbed, are known as the Cation Exchange Capacity (CEC) and Anion Exchange Capacity (AEC), respectively, and are expressed as cmols charge per kilogram. Typical cation exchange capacities of common clay minerals are shown in **Table 3.1.**

Table 3. 1: Typical values of some properties of common clay minerals (White, 1989; Holtz and Kovacs, 1981)

Parameter	Kaolinite	Illite	Chlorite	Montmorillonite	Vermiculite
Thickness (nm)	50-2000	30	30	3	n.a.
Diameter (nm)	300-4000	1000	1000	100-1000	n.a.
Specific surface (km^2/kg)	0.015	0.08	0.08	0.8	n.a.
CEC $cmol_{(+)}/kg$	3-20	10-40	n.a.	80-120	100-150
Plasticity	Low	Medium	Medium	High	Medium
Swelling/ Shrinkage	Low	Medium	Low	High	n.a.

3.2.3 Specific retention and storage capacity

Specific retention, θ_r, can be defined as the volume of water that is retained by a unit volume of soil against the force of gravity during drainage. This minimum water content is known as specific retention, field capacity or the residual water content and can be determined from soil-water characteristic curves. The concept of specific retention is controversial since this point does not exists (Edworthy, 1989). Drainage never really ceases but drainage rates decrease progressively until the drainage rate is practically equal to nil. There is thus no definite point where water flow ceases. The extreme variability in unsaturated flow rates as well as the existence of preferential pathways complicates the determination of specific retention considerably.

Specific retention is reached in a static situation i.e. no external factors have been taken into account. However, in field situations evapotranspiration is responsible for a decrease in water content, lower than the specific retention value. This water deficiency zone can reach considerable depths in arid and semi-arid environments (Martin & Koerner, 1984a). When water does reach these zones, it will be retained in the soil due to the high sorption of the soil. The maximum volume of water that can be accommodated in the deficiency zone, V_{dz}, also known as the storage capacity of the vadose zone, can be approximated by using the following equation (Everett et al., 1984):

$$V_{dz} = (\theta_r - \theta_0) z_{dz} A \qquad [3.4]$$

The disposal of hazardous waste in water deficiency zones seems to be feasible since leachate would be retained in the soil matrix due to the high sorption of the soil (Martin & Koerner, 1984b and Levin, 1988). However, downward migration of leachate will continue albeit at a very slow rate. Calculations of storage capacity may be inaccurate due to complications in determining the specific retention value of the soil. The existence of preferential pathways may cause rapid movement of liquid waste along these pathways.

3.2.4 Preferential flow-paths in the unsaturated zone

The preceding discussion treated the unsaturated zone as a homogeneous, porous medium. The existence of macropores caused by plant roots, shrinkage cracks and animal burrows can form preferential pathways for the movement of water and solutes. These macropores can lead to *short-circuiting* of infiltrating water as it moves at a much greater rate than would be expected from the hydraulic conductivity of the soil matrix.

A second type of preferential flow is fingering, which occurs when a uniform infiltrating solute front is split into downward reaching "fingers" due to instability caused by pore scale permeability variations. These instabilities often occur where an advancing wetting front reaches a boundary where a finer sediment overlies a coarser sediment.

Funneling is another type of preferential flow that occurs in the unsaturated zone, beneath the root zone and is associated with stratified soil or sediment profiles. Funneling occurs when a sloping layer, with lower hydraulic conductivity, collects water and direct it down slope to the end of that specific layer. From here the water can percolate further downwards, but in a concentrated volume.

The occurrence of preferential flows as well as soil heterogeneity have disturbing implications for monitoring solute movement in the unsaturated zone.

3.2.5 Mass transport in the unsaturated zone

The steady state diffusion of a solute in soil moisture is given by:

$$J = -D_S^*(\theta)\frac{dC}{dz} \qquad [3.5]$$

where J is the mass of the solute per unit area per unit time, $D^*_s(\theta)$ the soil diffusion coefficient (function of the water content, the tortuosity of the soil and other factors relating to the electrostatic double layer) and DC/dz the concentration gradient in the soil moisture.

Soil moisture traveling through the unsaturated zone moves at different velocities in different pores due to the fact that the saturated pores through which the moisture moves have different-sized pore throats. As a result, soil water carrying a solute will mix with other soil moisture. This is analogous to the mechanical mixing of saturated flow and can be described by the following equation:

$$\text{Mechanical mixing} = \zeta|v| \qquad [3.6]$$

where ζ is the empirical soil moisture dispersivity and v the average linear soil moisture velocity.

The soil moisture dispersion coefficient, D_s, is the sum of the diffusion and mechanical mixing:

$$D_s = D_S^* + \zeta|\lambda| \qquad [3.7]$$

The total one dimensional solute flux in the vadose zone is the result of advection, diffusion and hydrodynamic dispersion. Diffusion and hydrodynamic dispersion combined results in the soil moisture dispersion coefficient and can be expressed as:

$$J = v\theta C - D_S\theta\frac{dC}{dz} \qquad [3.8]$$

where J is the total mass of solute across a unit cross-sectional area in a unit time, V the average soil-moisture velocity, C the solute concentration in the soil, θ the volumetric water content, dC/dz the solute gradient and D_s the soil moisture diffusion coefficient, which is a function of both θ & v.

3.3 SATURATED ZONE

3.3.1 Basic concepts of the saturated zone

The saturated zone can be described as that part of the subsurface, which is normally saturated with water. In South Africa most of the geological formations are hard rock or fractured formations and hence the term fractured aquifer.

In general, subsurface flows can be subdivided into three basic types of flow namely (1) channel flow, (2) fracture flow and (3) porous flow.

3.3.2 Hydraulic characterization of the saturated zone

Saturated flow will in the most cases be fractured flow and is dependent on the hydraulic conductivity, effective porosity, hydraulic gradient and fluid viscosity of the fluid as well as the properties of the aquifer and can be described by Darcy's law. Darcy's law states that the rate of flow through a porous medium is proportional to the loss of head and inversely proportional to the length of the flow path:

$$Q = K\frac{dh}{dl}A \qquad [3.9]$$

where Q is the volume rate of flow (length^3/time), A the cross-sectional area normal to the flow direction and K the constant of proportionality known as the hydraulic conductivity.

The hydraulic conductivity relates the volume of fluid passing through a given surface area at a specific difference of piezometric head. It may thus be considered as an indicator of how easy a fluid can flow through a porous medium and can be described by the equation:

$$K = \frac{k\rho g}{\mu} \qquad [3.10]$$

where k is the permeability of the porous medium, ρ the density of the fluid, μ = the dynamic viscosity of the fluid and g = the acceleration of gravity.

The average flow velocity in the saturated zone can be calculated using the following equation:

$$v = \frac{KI}{\phi} \qquad [3.11]$$

where v is the flow velocity, K the hydraulic conductivity, I the probable average hydraulic gradient and ϕ *the* probable average porosity.

3.3.3 Mass transport in the saturated zone

Mass transport in the saturated zone is the result of a combination of molecular diffusion, advection and dispersion. These processes will be discussed in the section below.

3.3.3.1 Diffusion

Solutes, dissolved in groundwater, will move from an area of greater concentration to an area with less concentration. This process is called molecular diffusion and it will occur as long as a concentration gradient exists. The mass of solute diffusing is proportional to the concentration gradient, which is expressed as Fick's first law (Fetter, 1992):

$$F = -D_d\left(\frac{dC}{dx}\right) \qquad [3.12]$$

where F is the mass flux of solute per unit area per unit time, D_d the diffusion coefficient (L^2/T), C the solute concentration (M/L^3) and $dC/dx$the concentration gradient ($M/L^3/L$).

The negative sign indicates that movement is from area with greater concentrations to areas with less concentration.

Diffusion occurs at a slower rate in porous media than in water because the ions must follow longer pathways around mineral grains. An effective diffusion coefficient, D^*, is therefore used:

$$D^* = \varpi D_d \qquad [3.13]$$

where ω is a coefficient that is related to tortuosity.

Tortuosity is a measure of the effect of the shape of the flowpath followed by water molecules in a porous media. Tortuosity in porous media is always greater than one as the path that molecules take must diverge around solid particles.

Diffusion will cause a solute to spread away from the place where it is introduced into a porous medium, even in the absence of groundwater flow.

3.3.3.2 Advection

Advection is the process through which dissolved solids are carried along with the groundwater. The amount of solute that is transported by advection is a function of its concentration in the groundwater as well as the quantity of groundwater flowing. For one-dimensional flow normal to a unit cross-sectional area of the porous media, the quantity of water flowing is equal to the average linear velocity times the effective porosity. Average linear velocity, v_x, is the rate at which the flux of water across the unit cross-sectional area of pore space occurs. It is not the average rate at which water molecules are moving along individual flow paths, which is greater that the average linear velocity due to tortuosity.

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \qquad [3.14]$$

where v_x is the average linear velocity (L/T), K the hydraulic conductivity (L/T), n_e the effective porosity and dh/dl the hydraulic gradient (L/L).

3.3.3.3 Dispersion

Two types of dispersion occur in groundwater systems. These are mechanical dispersion and hydrodynamic dispersion.

Mechanical dispersion is the result of mixing of groundwater along a flowpath, due to difference in the rate of groundwater movement. The result of mechanical dispersion is the dilution of the solute at the advancing edge of the flow. The mixing that occurs along the direction of the flowpath is called longitudinal dispersion. An advancing solute front will also tend to spread in directions normal to the direction of flow. This is called transverse dispersion.

Hydrodynamic dispersion is the combination of molecular diffusion and mechanical dispersion. The hydrodynamic dispersion coefficient, D, is represented by:

$$D_L = \alpha_L v_i + D^* \qquad [3.15]$$

$$D_T = \alpha_T v_i + D^* \qquad [3.16]$$

where D_L is the hydrodynamic dispersion coefficient parallel to the principal direction of flow (longitudinal), D_T the hydrodynamic dispersion coefficient perpendicular to the principal direction of flow (transverse), α_L the longitudinal dynamic dispersivity and α_T the transverse dynamic dispersivity.

The main emphasis of this chapter was to give the reader some background information on the hydraulics and therefore the transport mechanisms in the saturated and unsaturated zones. The reader should understand that although mechanical mixing, diffusion, dispersion and advection may change the concentrations of a specific constituent along the flow-path due to flow and equilibrium processes, chemical reactions such as dissolution and precipitation processes may also change the concentrations of various chemical constituents along the flow path. These processes will be discussed in the next chapter.

CHAPTER 4

ENVIRONMENTAL HYDROGEOCHEMISTRY

4.1 INTRODUCTION

Naturally occurring groundwater, which is part of the hydrological cycle, shows a chemical variability caused by natural processes and the interaction between the soil water and groundwater with the geological medium. This includes the percolation of rainfall water through the unsaturated zone into the aquifer, the flow of the groundwater, the geological formation through which flow takes place (vertical and lateral flow), chemical changes caused by seasonal flow fluctuations and mixing with other groundwater sources having a different water chemistry.

Water quality depends on various factors. The most important factors are listed below:

- Climate;
- Quantity of water;
- Characteristics of the unsaturated and saturated zone (subsurface);
- Contact time with solid phases.

The predominant hydrogeochemical reactions are summarised as follows:

- Dissolution and precipitation of minerals;
- Redox reactions;
- Ion exchange and sorption on clay minerals and organic matter.

These processes will be discussed in the following chapters, which rely heavily on Stumm & Morgan, 1970; Moore & Ramamoorthy, 1984; Lloyd & Heathcote, 1985; Appelo & Postma, 1994 and Langmuir, 1997)

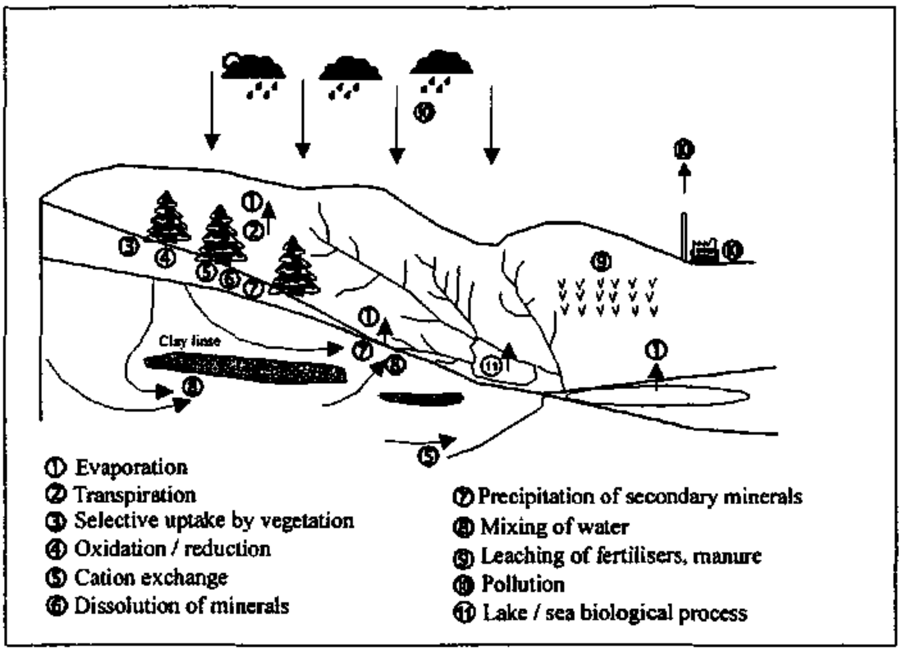


Figure 4. 1: A schematic overview of processes affecting water quality in the hydrological cycle (after Appelo & Postma, 1994)

Figure 4.1 gives a schematic overview of processes affecting water quality in the hydrological cycle. **Table 4.1** summarises the processes which are important as sources of different ions and the processes that may limit the concentration of ions in an aquatic system.

Table 4. 1: Important processes as sources of different ions and processes that may limit the concentration of ions in fresh water (after Appelo & Postma, 1994)

Element	**Process**	**Concentration control**
Na^+	Dissolution	Kinetics of silicate weathering
K^+	Dissolution, adsorption, decomposition	Solubility of clay minerals, vegetation uptake
Mg^{2+}	Dissolution	Solubility of clay minerals
Ca^{2+}	Dissolution	Solubility of calcite
Cl^-	Evapotranspiration	None
HCO_3^-	Soil CO_2 pressure, weathering	Organic matter decomposition
SO_4^{2-}	Dissolution, oxidation	Removal by reduction
NO_3^-	Oxidation	Uptake, removal by reduction
Si	Dissolution, adsorption	Chert, chalcedone solubility
Fe	Reduction	Redox-potential, Fe^{3+} solubility, siderite, sulphide
PO_4	Dissolution	Solubility of apatite, Fe, Al phosphates, biological uptake

4.2 BASIC HYDROGEOCHEMICAL PROCESSES WITHIN THE SUBSURFACE

In a closed system, the state of chemical equilibrium is reflected by the position of the highest thermodynamic stability. At equilibrium there is no chemical energy available to change the relative distribution of mass between the reactant and products in a chemical reaction. Away from equilibrium (disequilibrium), energy is available to move the chemical reaction towards a state of equilibrium.

Groundwater can be considered to be a partial equilibrium system. In a natural groundwater system, water quality is reflected by the concentrations of dissolved constituents, which are governed by the interaction of soil water and groundwater with the different solid phases (mineral and organic phase). The concentrations of constituents are controlled by two different chemical mechanisms, either by equilibrium or a kinetic approach in combination with flow velocities or contact time (Lloyd & Heathcote, 1985).

The main parameter for both concepts is the rate at which the chemical reaction proceeds. An equilibrium reaction is "fast" with regard to the mass transport process resulting in changes of concentration. In contrast, a kinetic reaction is "slow" in relation to the mass transport. Hence, the application of an equilibrium model for the description of a chemical reaction presumes that the mass is transferred instantaneously between reactants and products to attain the equilibrium state. However, if the systems transfer mass in a reaction at a rate slower than the physical or actual transport takes place, a kinetic approach should be adopted. The degree of competition between the reaction rates and the mass transport process might determine whether an equilibrium or kinetic based model is required (Domenico & Schwartz, 1990).

Theoretical approaches such as models provide a helpful tool to simulate the chemical composition of a solution. However, the methods provide no information about the time taken to attain the equilibrium state or reaction pathways involved (Domenico & Schwartz, 1990). In such a case only the use of a kinetic approach would provide such information. Sufficient information is available on reaction rates to support the decision whether to apply an equilibrium or a kinetic model. The following chapters describe the equilibrium and kinetic concept using simple examples. Equilibrium and kinetic concepts are an important tool in the understanding of the migration of AMD released from mine tailings into the subsurface.

4.2.1 The equilibrium concept and deviation from equilibrium

Different types of chemical reactions such as acid-base reactions, redox reactions and solid phase interactions are reversible and can be described in terms of the general chemical equilibrium reaction:

$$aA + bB \Leftrightarrow cC + dD \qquad [4.1]$$

where the substances A *and* B *react to produce the ions* C *and* D, *and* a, b, c *and* d *represent* the amount of moles of these constituents. In a dilute solution such as in a groundwater system, the principle of mass action describes the equilibrium distribution of a mass between reactants and products as:

$$K = \frac{[C]^c + [D]^d}{[A]^a + [B]^b} \qquad [4.2]$$

where K is the equilibrium constant and [C], [D], [A] and [B] are the molar concentrations of the reactants and products of the reaction. The reaction reaches an equilibrium position where A, B, C, and D are all present regardless from which side the reaction was started.

The equilibrium constants are usually derived from laboratory experiments, thermodynamic calculations and can be obtained from geochemical tables in textbooks (e.g. Stumm & Morgan, 1970; Rösler & Lange, 1972 and Morel, 1993).

Various equilibrium constants expressed as a function of temperature are also implemented into the databases of computer codes such as SOLMINEQ (Kharaka et al., 1988), EQ3/6 (Wolery, 1992), and PHREEQE (Parkhurst et al., 1990).

The equilibrium concept is illustrated below, using a typical example. Rainwater and soil water contain carbon dioxide gas from the atmosphere which dissolves in water and produces carbonic acid:

$$CO_2\,(g) + H_2O\,(l) \Leftrightarrow H_2CO_3 + \text{heat} \qquad [4.3]$$

If the concentration of carbon dioxide is increased by raising the CO_2 partial pressure, the reaction proceeds to the right to establish a new equilibrium by consuming carbon dioxide. If the temperature of the solution is increased, the equilibrium moves to the left, thus absorbing heat, because the production of carbonic acid releases heat (exo-thermodynamically). When the partial pressure of CO_2 (g) is known, the activity of carbonic acid (which appears in solubility products and reflects the chance that two ions may interact to produce a precipitate) can be calculated. Once the activity of carbonic acid is known, the activity of other species can be calculated (Lloyd & Heathcote, 1985).

Deviations from equilibrium are common, presuming that groundwater as a partial equilibrium system implies that some reactions may not be in equilibrium. A typical example is the dissolution and precipitation of minerals. The distance from equilibrium is reflected by the ion activity product (IAP), which is determined by substituting the activity values of a sample in the mass law equation for the relevant reactions.

For example, for a given groundwater quality with known activities of [A], [B], [C] and [D], the resulting IAP for the **Formula 4.4** is as follows:

$$IAP = \frac{[C]^c + [D]^d}{[A]^a + [B]^b} \qquad [4.4]$$

If the IAP > K, the reaction proceeds from the right to the left, decreasing [C] and [D] by increasing [A] and [B]. If the IAP < K, the reaction moves from the left to the right. If IAP = K, the IAP is equal to the equilibrium constant. This method allows the saturation state of groundwater to be determined according to one or more mineral phases.

IAP/K > 1	The groundwater is supersaturated with the mineral
IAP/K = 1	The groundwater is in equilibrium with the mineral
IAP/K < 1	The groundwater is undersaturated with the mineral

Supersaturation results in precipitation, undersaturation in dissolution of the relevant mineral phase. An alternative approach to the calculation of the saturation state is the use of the saturation index (SI), defined as the log (IAP/K). Examples are given by Domenico & Schwartz, 1990 and Appelo & Postma, 1994.

Ideal equilibrium conditions are rarely attained in a natural groundwater system, but the equilibrium concept provides a satisfactory explanation in most of the cases of observed groundwater quality, as shown above. However, a number of processes in aquifers are insufficiently explained by the equilibrium concept and a kinetic approach should be applied.

Geochemical models are useful tools for the calculation of equilibrium conditions in a batch of water containing reactants. They also allow researchers to calculate how a given water composition changes in response to a reaction such as the dissolution of minerals and gases or in response to a change in temperature. Various authors (e.g. Appelo & Postma 1994) have described commonly used geochemical models such as WATEQP and PHREEQE. The application of the model GEOCHEM is demonstrated in Sposito (1983).

4.2.2 Kinetic approach

Kinetic reactions provide a useful tool for the understanding of chemical reactions in relation to time and pathways. A kinetic description is applicable to any reaction, but is specifically required for irreversible or reversible reactions, where the reaction rate is slow in relation to the physical mass transport.

As an example, **Figure 4.2** shows the dissolution of the salt mineral halite (NaCl) in water. The concentrations are shown as a function of time.

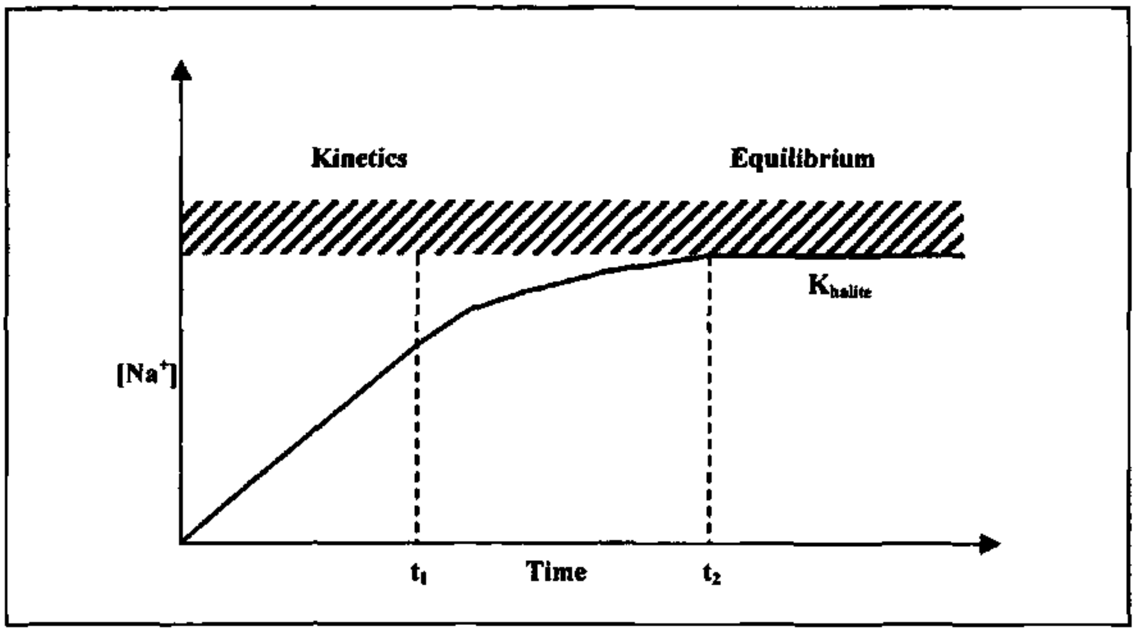


Figure 4. 2: The concept of equilibrium and kinetics, illustrated in a hypothetical dissolution experiment with halite (NaCl) (after Appelo & Postma, 1994).

In this type of dissolution experiment, the concentration of $[Na^+]$ increases with the time until equilibrium between the solution and the mineral phase is attained at time t_2. From t_2 onwards, $[Na^+]$ becomes independent of time and is determined by an equilibrium constant:

$$K_{NaCl} = [Na^+]\,[Cl^-] \qquad [4.5]$$

K_{NaCl} can be measured either in the laboratory or calculated from thermodynamic tables. In the example of NaCl dissolution (**Figure 4.2**), the first part of the reaction before equilibrium is attained should be considered under kinetic aspects. Qualitatively, it is expected that the rate of dissolution of NaCl depends on factors such as grain size, the amount of stirring, temperature and the distance from equilibrium. Consequently, equilibrium chemistry determines in which direction the reaction will occur. At time t_1, equilibrium chemistry predicts that dissolution, rather than precipitation, will take place, but not whether it will take 10 seconds or 10 million years before an equilibrium is attained.

In most of the cases, the equilibrium concept provides a satisfactory explanation of the measured groundwater quality. However, a number of processes in aquifers are insufficiently explained by the equilibrium concept.

There are two fundamental causes for lack of equilibrium at the surface of the earth.

1. Tectonic processes transport minerals from the environment where they were formed and stable, often from deep down in the earth at high pressures and temperatures, to environments at the earth 's surface, where they are unstable.

2. Photosynthesis, which converts solar energy into thermodynamically unstable organic matter. The subsequent decomposition affects the equilibria of redox sensitive compounds such as Fe. Furthermore, biological matter also disturbs carbonate equilibria due to production or consumption of CO_2 and bio-mineralisation (Appelo & Postma, 1994).

The understanding of reaction kinetics is still in a premature stage, in contrast to equilibrium chemistry, although rapid progress has been made in recent years (e.g. Sparks, 1989; Hochella & White, 1990). A general approach to a kinetic problem is usually divided into two steps (Appelo & Postma, 1994):

1. To describe quantitatively the rate data measured in the laboratory or in the field
2. To interpret the quantitative description of the rate in terms of mechanisms.

Hence, kinetic reactions provide a useful framework for studying reactions in relation to time and pathways.

4.2.3 Precipitation and dissolution reactions

The hydrological cycle interacts with the various geological rocks. Minerals dissolve or react with the soil water percolating through subsurface material and accumulate in the sediments of river and lakes. Consequently, precipitation and dissolution reactions are important processes in controlling the chemistry of groundwater (Stumm & Morgan, 1970).

Usually the chemical composition of natural waters is reflected by such interactions. However, slight changes in the physico-chemical conditions can result in the exceedance of solubility limits for constituents such as sulphates of Ca and Sr and carbonates of Ca, Sr and Co (Levin, 1988) and thus result in supersaturation of a solution.

Another example is given by the supersaturation of quartz (SiO_2) in most natural waters, which occurs because the rate of attainment of equilibrium between silic acid and quartz is extremely low. Generally, supersaturation occurs in a solution when the products of a dissolution reaction are present at a higher concentration than when they are in equilibrium with the undissolved counter parts.

Parameters such as temperature and high pressure control solubilities. The reaction of salts with water to undergo acid-base reactions is also very common. Another phenomenon is the complex formation of a salt cation and anion with each other and with one of the constituents of the solution. A typical example is the solubility of FeS(s) in a sulphide-containing aqueous solution, which is described in more detail in **Chapter 4.4.2**.

The extent of dissolution or precipitation reactions under equilibrium conditions can be estimated by considering the equilibrium constants, which have been described in **Chapter 4.2.1**. Examples are given by Stumm & Morgan (1970) and various other authors.

The solubility products of some minerals are shown in **Table 4.2**. The order of decreasing solubility is $CaSO_4$, $SrSO_4$ and $CaCO_3$.

Table 4. 2: Solubility products of common minerals in the aqueous phase by 25°C (after Fetter, 1992)

Compound	**Solubility Product (K)**	**Mineral name**
$CaSO_4$	$10^{-4.5}$	Anhydrite
$CaSO_4 \times 2\ H_2O$	$10^{-4.6}$	Gypsum
$PbSO_4$	$10^{-7.8}$	Anglesite
$SrSO_4$	$10^{-6.5}$	Celestite
$CaCO_3$	$10^{-8.35}$	Calcite
$CaCO_3$	$10^{-8.22}$	Aragonite
$FeCO_3$	$10^{-10.7}$	Siderite
$MgCO_3$	$10^{-7.5}$	Magnesite

4.2.4 Ion exchange and sorption processes

The unsaturated and saturated zones provide sufficient organic and inorganic material for the sorption of chemical constituents from the aqueous phase. Sorption (adsorption and absorption) is defined as a physical process where a mass transfer of ions from the aqueous to the solid phase takes place, resulting in a decrease in ion concentration in the aqueous and increase in the solid. Adsorption indicates that an ion adheres to the surface of the solid phase, whereas absorption is the incorporation of an ion into the crystal lattice. Thus, ion exchange processes describe the replacement of one ion for another at the surface of solids. In addition, ion exchange and adsorption processes determine the bio-availability of contaminants.

In the unsaturated and saturated zones, the most important sorption (or exchange) process is reflected by adsorption of ions on mineral surfaces (Lloyd & Heathcote, 1985) and organic material surfaces as referred to the solid phase. Sorption and exchange processes are limited by the sorption or exchange capacity of the solid phase. Solids such as clay minerals, organic matter and oxides/hydroxides have a certain exchange capacity for cations and anions. **Figure 4.3** shows the various sorption processes.

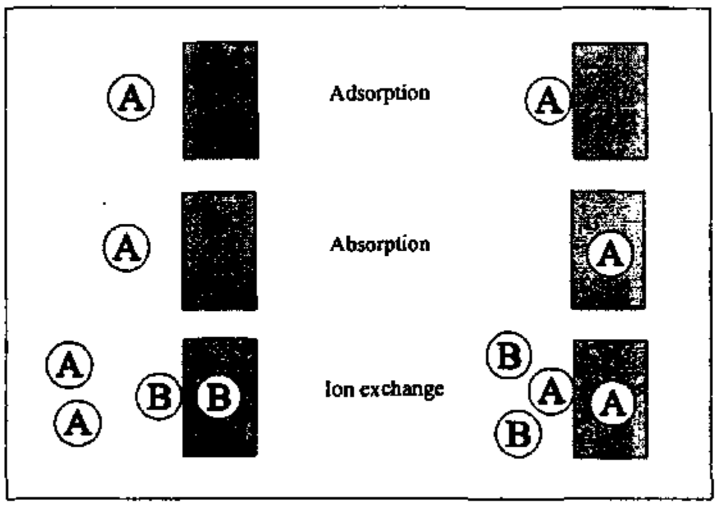


Figure 4. 3: Schematic description of various sorption processes (after Appelo & Postma, 1994).

Sorption and exchange processes are the main regulating mechanisms for the migration of contaminants in the unsaturated and saturated zone. Appelo & Postma (1994) state that the cation exchange process is a temporary buffer in non-steady state situations as a result of contamination, acidification or moving salt/fresh water interfaces. In case of the exploitation and pollution of aquifers, flow characteristics and water quality along pathways may vary, but cation exchange reflects former, displaced groundwater at sampling points and enables a better interpretation of the observed water quality.

A typical example for cation exchange processes in coastal aquifers is the intrusion of seawater into the fresh water aquifer system, resulting in the replacement of Na^+ by Ca^{2+} in the groundwater. Thus, the water quality change from a NaCl dominated water type to the $CaCl_2$ type. **Formula 4.6** represents such a cation exchange reaction:

$$Na^+ + \frac{1}{2}\,Ca\text{-}X_2 \Rightarrow Na\text{-}X + \frac{1}{2}\,Ca^{2+}, \qquad [4.6]$$

where X indicates the exchanger, Na^+ is adsorbed by the exchanger, and Ca^{2+} is released. However, if the groundwater system is polluted, it might be very difficult to distinguish between cation exchange processes (sorption) and other reactions such as precipitation and dissolution (Sposito, 1984).

Salomons & Stigliani (1995) report that heavy metals occur in different adsorbing phases in soils. These phases can be investigated by performing special leaching tests such as sequential extraction tests. The following adsorbing phases have been identified (Kabata-Pendias, 1994) for heavy metals and are illustrated in **Figure 4.4**:

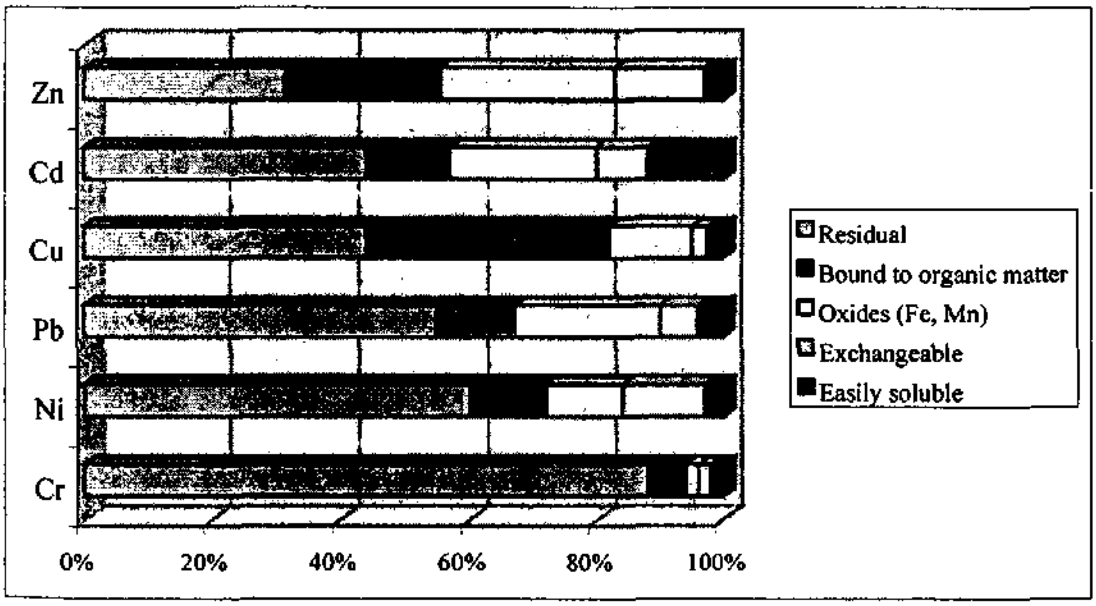


Figure 4. 4: Distribution of heavy metals over various sorption phases in the soil (after Kabata-Pendias, 1994).

Of those the residual fraction (HF and $HClO_4$ soluble) is the least mobile and does not partake in chemical reactions of soils, whereas the easily and exchangeable fractions are the most mobile and determine the bio-availability of a trace element. The actual mobility, and hence the bio-availability, of contaminants is additionally determined by the pH, redox conditions and the presence of dissolved organic matter. This is discussed in the following paragraphs. Detailed information about the behaviour of trace elements in soils is given in Kabata-Pendias (1992), Kabata-Pendias & Pendias (1992) and Alloway (1995).

4.2.5 Reduction and oxidation processes (redox reactions)

Reduction and oxidation processes, known as the redox potential (Eh), provide much information about the behaviour of metal contaminants in soils and groundwater systems. Redox reactions describe the electron transfer from one atom to another. Because these reactions are often very slow, kinetic aspects play a significant role (Appelo & Postma, 1994).

Only elements such as Cl and F are relatively insensitive to redox conditions, whereas almost all elements which are regulated by drinking water standards (e.g. As, Cr, Fe, Mn, U, S) have more than one possible oxidation state in surface and groundwater system (Freeze & Cherry, 1979). The redox state of an element can be of considerable interest, because it often controls the chemical and biological properties, including toxicity and mobility in the environment (Langmuir, 1997).

Table 4. 3: Selected elements that can occur in more than one oxidation state in groundwater systems (after Fetter, 1992).

Element	Valence State	Examples
Chromium (Cr)	+6	CrO_4^{2-}, $Cr_2O_7^{2-}$
	+3	Cr^{3+}, $Cr(OH)_3$
Copper (Cu)	+1	CuCl
	+2	CuS
Iron (Fe)	+2	Fe^{2+}, FeS
	+3	Fe^{3+}, $Fe(OH)_3$

Oxygen (O_2)	0	O
	-1	H_2O_2
	-2	H_2O, O^{2-}
Sulphur (S)	-2	H_2S, S^{2-}, PbS
	+2	$S_2O_3^{2-}$
	+5	$S_2O_6^{-2}$
	+6	SO_4^{2-}

Table 4.3 shows selected elements that can exist in more than one oxidation state (after Fetter, 1992).

Freeze & Cherry (1979) states that the soil has a certain capability to generate relatively large amounts of acid and to consume much or all of the available dissolved oxygen in the soil water. Geochemically, the most important acid produced in the soil zone is H_2CO_3, derived from the reaction of CO_2 due to the decay of organic matter and respiration of plant roots and H_2O.

Berner (1981) establishes a classification of various redox zones in relation to the solid phases which are expected to form in each zone of a groundwater system. The redox classification is shown in **Table 4.4** below:

Table 4. 4: Redox classification after Berner (1981) for different chemical environments together with formed solid phases.

Chemical environment	Solid phases
I. **Oxic milieu (Conc. $O_2 \geq 10^{-6}$)**	Haematite, goethite, MnO_2-type minerals; no organic matter
II. **Anoxic milieu**	
A. Sulphidic	Pyrite, marcasite, rhodochrosite, alabandite: organic matter
B. Non-sulphidic	
Post-oxic	Glauconite and other Fe^{2+}-Fe^{3+} silicates (also siderite, vivianite, rhodochrosite): no sulphide minerals; minor organic matter
Methanic	Siderite, vivianite, rhodochrosite, sulphide minerals formed earlier; organic matter.

Berner (1981) initially distinguishes between oxic and anoxic conditions, according to whether they contain measurable amounts of dissolved oxygen (O_2 conc. $\geq 10^{-6}$ M). Subsequently, anoxic environments are subdivided into post-oxic (dominated by reduction of nitrate, MnO-oxide and Fe-oxide), sulphidic (sulphate reduction) and finally methanic zones. It is important to note that not all zones need to occur in a reduction sequence and in many cases the groundwater system never achieves the post-oxic state. In other cases, the sulphidic zone may follow the oxic zone directly.

Figure 4.5 *shows the different redox zones which occur in the unsaturated and saturated* zones in relation to the formation of secondary minerals and other species (modified from Berner, 1981).

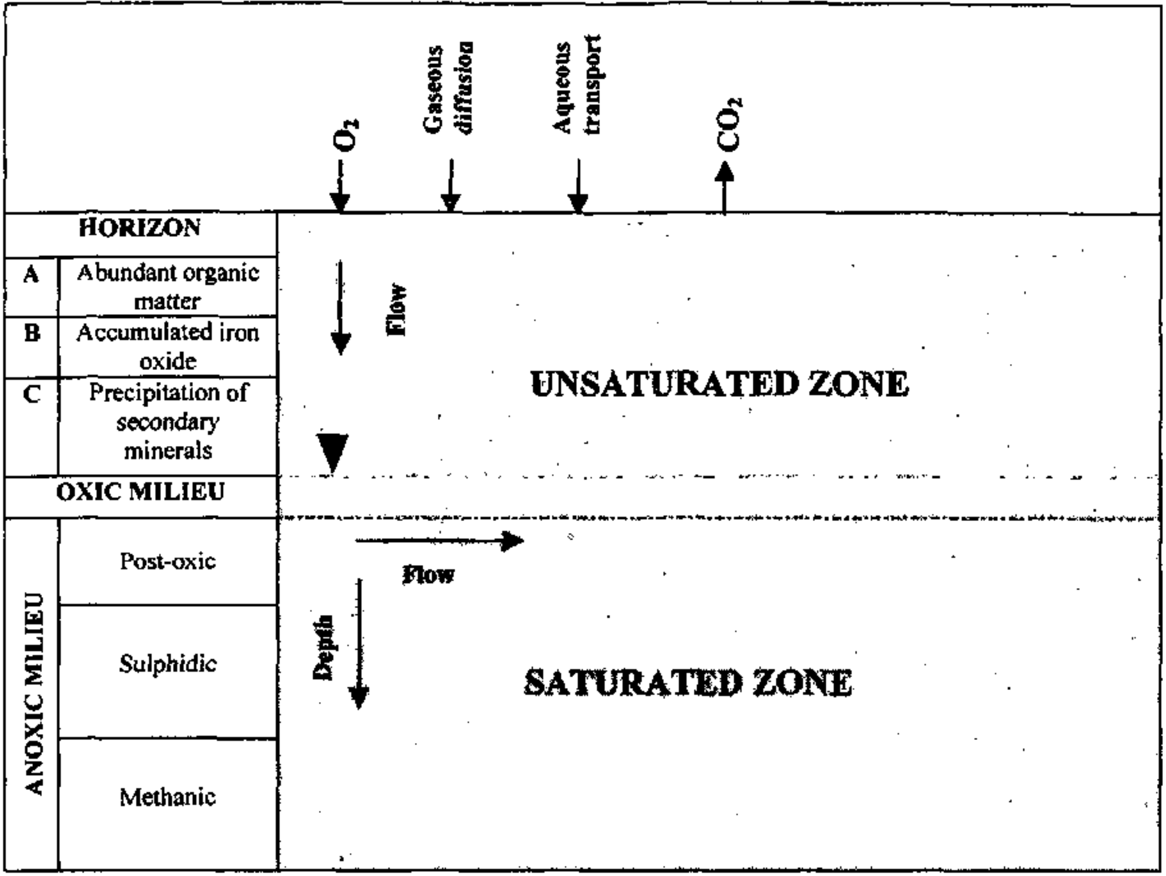


Figure 4. 5: Sequence of reduction processes with increasing depth in the unsaturated and saturated zones (modified after Berner, 1981).

Another environmental aspect is the usual release of protons or acidity, which is the origin of acid mine drainage (AMD) in surface and groundwater systems. In contrast, reduction reactions usually consume protons and thus result in a pH increase. Most of the negative environmental effects caused by redox reactions require the availability of an oxidising agent (a substance that accepts electrons) such as oxygen, oxo-anions, sulphate and nitrate, the latter typically released as a portion of a fertiliser during agricultural activities. Additionally, the disposal of mine wastes and the operation of mines often lead to drastic changes from reducing to oxidising conditions, and result in the release of various metal contaminants from the deposition area into the aquatic environment (Bourg, 1988).

In contrast, the addition of a reducing agent (a substance that donates an electron) such as downward leaching of dissolved organic matter (DOC) from soils or landfills, inorganic sulphides such as pyrite, and Fe (II) silicates can also be of importance with regard to pollution in groundwater systems. **Formula 4.7** shows the general half-formula for a reduction reaction:

$$\underbrace{aA + bB + n_{e^-}}_{\text{oxidised state}} = \underbrace{cC + dD}_{\text{reduced state}} \qquad [4.7]$$

where A, B, C and D reflect the reacting substances and a,b,c and d their stoichiometric coefficients, and n is the number of transferred electrons (e^-). The theoretical voltage which corresponds to the half-reaction above is expressed by the known Nernst reaction.

It should be emphasised that most of the recent literature prefers the use of pE instead of Eh (Stumm & Morgan, 1970 and Drever, 1988), which is the negative common logarithm of the electron concentration or pE = $-\log_{10} (_{e^-})$. Therefore, pE is related to Eh in the **Formula 4.8** below (after Langmuir, 1997):

$$pE = \frac{[nF]Eh}{2{,}303RT} = \frac{Eh(volts)}{0{,}05916} \qquad [4.8]$$

Although Eh-pH relations (displayed in pH-Eh diagrams, **Chapter 4.5.2**) provide a framework for a better understanding of the behaviour of redox-sensitive elements in groundwater, they cannot be used directly for the prediction of contaminant mobility in groundwater (Cherry et al., 1980). To identify the state of redox stability with regard to a particular contaminant that has entered a groundwater system, the pH, Eh, and major chemistry occurring within the contaminated zone must be predicted. Computer models such as PHREEQE (Parkhurst et al., 1990) are a useful tool for the prediction of equilibrium water chemistry. PHREEQE enables the prediction of pH and Eh, presuming that the initial condition and the mineral phases contained in the aquifer system are known.

Furthermore, where groundwater contamination occurs, dispersion can have a major influence on the redox state of the groundwater (Freeze & Cherry, 1979). Contaminated groundwater at waste disposal sites often has a much lower initial redox state than the ambient groundwater. Dispersion may cause a mixing of waters which have different chemical compositions and redox states, resulting in changes in the pH and Eh conditions. Subsequently, changes in the entire water chemistry occur, due to reactions such as dissolution or precipitation of solids (see **Figure 4.7**).

Oxidation states and the standard potential of the elements are listed in standard chemistry textbooks. A basic understanding of redox reactions is crucial for the discussion of the oxidation of sulphide minerals contained in mine tailings and is discussed in **Chapter 4.2.5**.

4.3 THE CONCEPT OF BACKGROUND VALUES

Many surface and groundwaters contain natural concentrations of chemical constituents which exceed drinking water standards. In some cases, this is even unrelated to the direct impact of human activities (Langmuir, 1997). To determine the extent of pollution in an aquatic system due to the heavy metal concentration in the aqueous and solid phase, it is important to define the natural level of these substances (pre-civilisation value), and then subtract it from existing values for metal concentrations, thereby deriving the total enrichment caused by anthropogenic impacts (Förstner, 1983).

Thornton (1983) and Runnels et al. (1992) found that many streams, springs and deeper groundwater show highly elevated natural ore metal concentrations caused by mineralisation processes. These natural effects are not caused by mining or other human activities.

In the literature, various concepts have been suggested to determine the natural background value in sediments and soils (Turekian & Wedepohl, 1961; Banks et al., 1995 and Lahermo et al., 1995).

A common approach is to sample river sediments upstream (similar geology) of the pollution source, where the water quality is presumably unaffected, and to compare the sediment concentrations with samples taken directly downstream of the pollution source. However, in especially highly populated and industrialised areas such as the Gauteng Province, it is often difficult to identify a sampling point in a river or aquifer where the sediment quality seems to be unaffected by human activities.

- Other methods make use of literature data such as those from White et al. (1963), who summarised typical compositions of groundwaters in relation to different rock types, or use databases such as WATSTORE from the US Geological Survey, which stores ± 30 000 chemical analyses of groundwater samples and related geological information from the United States (Barnes & Langmuir, 1978). These data are usually plotted in histograms and examples are given in Langmuir (1997).

- The most recent approach (Haan, 1977 and Levinson et al., 1987) is the construction of cumulative probability plots of all the data of an area of interest, where all the samples are classified into uncontaminated and contaminated groups, including an estimate of the statistical standard parameters (e.g. median, standard deviation) for each group.

- Soil background values can be obtained by sampling unaffected soils overlying similar geology compared to the polluted soils. This is the method used during the course of this study and is discussed in **Chapter 5**.

A summary for the determination of background values in stream sediments has been given in Förstner & Wittmann (1981).

A quantitative measure of the metal pollution in aquatic sediments has been introduced by Müller (1979), who established a geochemical load index which has been used in this study. The geochemical load index is explained in more detail in **Chapter 5.4.4.**

4.4 HYDROGEOCHEMICAL PROCESSES WITHIN MINE TAILINGS

4.4.1 Introduction

The uncontrolled release of acid mine drainage (AMD) is perhaps the most serious environmental impact of mining operations world-wide, according to Ferguson & Erickson (1988). Acid mine drainage (AMD) of metal mining operations is represented at low pH and high acidity and often contains high concentrations of dissolved heavy metals, salts and radionuclides which exceed drinking water standards up to a toxic level.

The first studies dealing with the AMD processes were conducted in the early 1980s in Elliot Lake in Canada (Cherry et al., 1980; Blair et al., 1980; Morin, 1983; Blowes, 1983; Dubrovsky et al. 1984a/b; Dubrovsky, 1986 and Morin et al. 1988a/b). Since then many researchers world-wide have focussed on the processes related to AMD.

The processes that generate AMD are natural, but they are accelerated by mining operations and can produce large quantities of contaminated leachates. AMD originates from the rapid oxidation of sulphide minerals such as pyrite and often occurs where sulphide minerals are exposed to oxygen.

Additionally, the oxidation of sulphide minerals is greatly enhanced by the catalytic activity of micro-organisms typically associated with sulphide-bearing ore residues and tailings. Mines such as coal and gold/uranium mines are the primary source of pollution, because economically recoverable concentrations of coal and metals often occur in association with enriched sulphide mineralisations in the ore body. Although the knowledge about the acid generating process is incomplete, several influence parameters are known to control the production of AMD and are discussed in the following paragraphs.

It is apparent that tailings dams represent extremely complex and variable systems, because the deposits differ in design, mineralogical composition and in geotechnical and hydraulical properties. Additionally, variations in the nature of tailings material occur between different zones within each tailings dam as a result of changes in the ore grade during mining operations and fluctuations in the metallurgical extraction efficiency. Other aspects which must be taken into consideration are the residence time of the deposited tailings material and the flux of water throughout the tailings dam, which have already been described in **Chapter 2.5**.

4.4.2 Sulphide oxidation and acid generation processes (AMD)

Hydrogeochemical studies have revealed that the release and migration of potentially toxic heavy metals and radionuclides are strongly dependent on the acidification process of tailings material. This results from the oxidation of sulphide minerals in the unsaturated zone of the tailings dams.

Ferguson & Erickson (1988) classify and describe the factors controlling AMD formation into primary, secondary and tertiary factors. The primary factors are those directly involved in the generation of acidity. Secondary factors control the consumption or alteration of the products from the acid generation reactions, while tertiary factors reflect the physical characteristics of the tailings material that influence acid production, migration and consumption. The authors also describe a downstream factor, which concerns the affected area underneath and downstream of the tailings dam.

4.4.2.1 Primary factors

The primary factors comprise the availability of sulphide minerals such as pyrite, oxygen, water, ferric iron, and catalysing bacteria, which act as accelerators in the acid production process.

The oxidation of pyrite, the most common sulphide mineral in tailings dams in South Africa, can be expressed in the following reaction:

$$FeS_2(s) + 7/2\ O_2 + H_2O \Rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \qquad [4.9]$$

This reaction releases Fe^{2+}, SO_4^{2-} and H^+ to the tailings pore water. Subsequently, Fe^{2+} released from the sulphide oxidation can be further oxidised to Fe^{3+} through the reaction expressed in **Formula 4.10** below:

$$Fe^{2+} + \frac{1}{4}\ O^2 + H^+ \Rightarrow Fe^{3+} + \frac{1}{2}\ H_2O \qquad [4.10]$$

The Fe^{3+} resulting from **Formula 4.10** may react to further oxidise pyrite:

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \Rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \qquad [4.11]$$

Alternatively the Fe^{3+} may be hydrolysed and precipitated as $Fe(OH)_3$ or a similar ferric hydroxide or hydroxy-sulphate (Blowes, 1995):

$$Fe^{3+} + 3\ H_2O \Leftrightarrow Fe(OH)_3 + 3\ H^+ \qquad [4.12]$$

The sequence of **Formulas 4.9-4.12** may consume most of the primary sulphide minerals in the upper unsaturated surface layer (up to 2-3 m depth) of the tailings dam. These reactions also result in the accumulation of secondary minerals of the ferric oxy-hydroxide group. These secondary minerals, most commonly amorphous ferric hydroxyde [$Fe(OH)_3$], goethite [α-FeOOH] and ferrihydrite [$Fe_5HO_8 \cdot 4\ H_2O$], usually replace the primary sulphide minerals, resulting in thick alteration rims which surround an inner core of unweathered sulphide minerals (Blowes, 1995). It is important to note that Fe and Mn co-precipitates can adsorb significant amounts of heavy metals such as Co, Cr, Cu, Mn, Niu, Mo, V and Zn (Alloway, 1995). **Figure 11** in **Appendix F** shows a ferricrete block, which consists of such Fe-minerals. Furthermore, these relatively slow reactions comprise the initial stage in the three-stage AMD production process described by Kleinmann et al. (1981):

Stage 1:	pH around the tailings particles is moderately acidic (pH > 4.5)
Stage 2:	pH declines and the rate of Fe hydrolysis (see **Formula 4.12**) decreases, providing ferric iron as an oxidant
Stage 3:	Rapid acid production by the ferric iron oxidant, which dominates at low pH, where ferric iron is more soluble (see **Formula 4.11**)

The replenishment of oxygen within the tailings material from the atmosphere is probably required to sustain the rapid oxidation rates catalysed by bacteria of stage 3 as described above. Hammack & Watzlaff (1990) state that the rate of pyrite oxidation at partial pressures above 8 % of oxygen is independent as long as catalysing bacteria are present. The oxidation rate drops significantly below 8 % oxygen partial pressure.

The rate of ferrous iron oxidation at low pH would be too slow to provide a sufficient concentration of oxidant, without catalysis of autotrophic micro-organisms such as *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* (Singer & Stumm, 1970). Consequently, the final stage of the AMD process only occurs when the micro-organisms become established, which requires a certain chemical milieu.

Abiotic and biotic oxidation of sulphide minerals is a function of the prevailing pH within the tailings dam. At pH > 5, biotic sulphide oxidation occurs at a slower rate than abiotic oxidation. At pH ≈ 3, the biotic oxidation dominates by being four times faster than the abiotic reaction. At pH ≤ 2.5, the reaction is considered to be fully biotic due to a maximum oxidation rate (Kölling, 1990) of *Thiobacillus ferrooxidans*, which can catalyse both iron and sulphur oxidation.

The bacteria *Thiobacillus thiooxidans* can only oxidise iron (Mitchell, 1978). The bacteria mentioned above can attack most sulphide minerals under suitable conditions (Duncan & Bruynesteyn, 1971 and Lundgren et al. 1972) and increase the oxidation rate up to several orders of magnitude (Singer & Stumm, 1970; Silver, 1980 and Brock & Madigan, 1991). Some reactions for bacteria and ferric ion with various sulphide minerals are summarised in Ferguson & Erickson (1988).

Favourable conditions for the growth and efficiency of such bacteria have been described as follows (after Mitchell, 1978 and Kölling, 1990):

- Optimal pH range: 2.4 - 3.5;
- Large specific surface area requiring a small particle size;
- Temperature between 30° – 35°C;
- Sufficient nutrients, e.g. for *Thiobacillus ferrooxidans*: organic carbon, iron sulphate, pyrite, calcium nitrate and ammonium sulphate;
- Sufficient oxygen flux;
- Drainage system to transport the reaction products.

Water is a key parameter in the generation of AMD, acting as a reactant, as a reaction medium, and as the transporting medium. The first two processes can be considered as primary factors, as discussed by Smith & Shumate (1970) and Morth et al. (1972). Thus, a controlling parameter for bacteriological activity is the moisture content within the tailings dam (Belly & Brock, 1974 and Kleinmann et al., 1981). Consequently, pore water or moisture provides the medium to transport large quantities of salts, heavy metals, radionuclides and other toxic substances into the subsurface underneath the tailings deposit.

Another aspect is the crystal structure of relevant sulphide mineral phase, because various structures (such as in pyrite, marcasite, phyrrhotite) result in different oxidation rates (Hawley, 1977). As a result, heavy metals and radionuclides can be released from the sulphide mineral by three different processes, according to Dutrizac & MacDonald (1974):

- Direct oxygen oxidation;
- Bacterial oxidation;
- Acidified ferric sulphate dissolution.

It should be stressed that sulphide minerals such as pyrite often contain significant concentrations of various toxic heavy metals, which were initially used to establish genetic relationships among different ore types (Vaughan & Craig, 1978) and can also be used as an indicator to trace AMD pollution.

Hallbauer (1986) reported average trace element contents for the Black Reef, which are discussed in **Chapter 4.4.3.**

4.4.2.2 Secondary factors

The most important secondary factors comprise the presence of buffer minerals such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), which neutralise the pH or acidity by alkalinity within the mine tailings material as well as in the underlying soil and aquifer material, if seepage occurs . The neutralisation by calcite of acidity produced by pyrite oxidation is presented in the **Formula 4.13** below (Williams et al., 1982):

$$FeS_2(s) + 2CaCO_3(s) + 15/4\ O_2(g) + 3\ H_2O \Rightarrow \quad [4.13]$$
$$Fe(OH)_3(s) + 2\ SO_4^{2-} + 2\ Ca^{2+} + 2\ CO_2(g)$$

As a result of **Formulas 4.9-4.12** the dissolved concentrations of sulphate and Fe correspond to the stoichiometry of the pyrite oxidation reaction, although most Fe is commonly precipitated as FeOOH (Appelo & Postma, 1994). Thus, 4 M of calcite is required for the neutralisation of 1 M pyrite in order to achieve a complete neutralisation of acidity. Assuming a pyrite content of 1 weight-% would result in 18 kg pyrite per ton mine tailings, which equals an amount of 72 kg calcite per ton for complete acid neutralisation. On average, the

Witwatersrand gold-bearing quartz conglomerates contain 30-50 kg pyrite per ton (Hallbauer, 1986).

The rapid equilibrium controlled dissolution of carbonate minerals (as shown in **Formula 4.13** above) results in alkalinity, which is controlled by four key parameters:

- Partial pressure of CO_2;
- Temperature;
- Mineral type;
- Concentration of dissolved constituents.

In contrast, the release and accumulation of acidity from the oxidation of sulphide minerals is a kinetically controlled process (Geidel, 1980).

The reaction rate of the interaction between sulphide and carbonate minerals determines the seepage water quality, which can range from high pH and low sulphate concentrations in carbonate dominated materials to low pH ($pH \approx 2$-3) and high sulphate concentrations (> 1000 mg/l) in a carbonate-deficient environment (Caruccio, 1968). The last scenario typically represents the AMD composition.

Other secondary factors comprise the weathering of oxidation products by further reactions. This includes ion exchange on clay surfaces, the precipitation of gypsum ($CaSO_4 \times 2\ H_2O$), and the acid-induced dissolution of other minerals (see **Figure 12** in **Appendix F**). Ferguson & Erickson (1988) found that these reactions change the quality of seepage, often by adding various trace elements (Al, Mn, Cu, Pb, Zn) and replacing Fe with Ca and Mg contained in carbonates.

4.4.2.3 Tertiary factors

Tertiary factors are characterised by the properties of the tailings material and the geohydrological conditions within the deposit. Important physical parameters are particle size, weathering tendency and the hydraulical characteristics of the tailings material. The rate of pyrite oxidation and thus, acid generation is a function of the particle size area, since this parameter reflects the amount of sulphide exposed for reaction (Ferguson & Erickson, 1988).

However, coarse-grained material is typically found in sand dumps (**Chapter 2.3.1**) and, as a result of greater oxidation depth, enables a greater oxygen flux and hence more material is exposed for active acid generation than in the fine-grained material contained in tailings dams. In very coarse material, typically found as rock dumps, oxygen transport is supported by wind speed, changes in barometric pressure and internal dump heating originating from the exo-thermodymical oxidation reaction (**Chapter 4.4.2.1**).

Another aspect is the physical weathering tendency (Ferguson & Erickson, 1988) of the tailings material. This factor may also support the control of hydraulic properties such as permeability and influences the oxygen and pore water migration. A decrease in permeability will result in a decrease in acid generation. However, experience in North America (e.g. Dubrovsky et al., 1984a/b; Blowes et al., 1988 and Mills, 1993), Europe (e.g. Ferguson & Erickson, 1988; Mende & Mocker, 1995) and South Africa (e.g. Förstner & Wittmann, 1976; SRK, 1988; Funke, 1990 and Cogho et al., 1992) has clearly shown that, even decades after decommission of mining operations, significant loads of salts, heavy metals and in some cases radionuclides have been released from such deposits, unless appropriate pollution control and rehabilitation measures took place.

A further tertiary factor is the pore water flow throughout the tailings dam. Water which infiltrates the tailings material has been already discussed as a primary factor in **Chapter 4.** Significant acid generation within the saturated zone may not occur because of limited oxygen flux (Ferguson & Erickson, 1988). However, a fluctuating phreatic surface level within the tailings dam, which is particularly common on operating tailings dams and may occur even after decommission in connection with rainfall events, may result in periodically wet and dry zones which allow further oxidation and acid generation during fluctuations in the water table.

Consequently, active acid generation in rock dumps may occur throughout the dump rather than being limited to the surface layer; whereas in tailings dams the active acid generation area is usually limited up to a depth of 2-3 m in South Africa (Marsden, 1986). It can also be concluded that seepage from open pits and underground mines is less contaminated than seepage from tailings dams, due to the smaller particle surface area of sulphide minerals exposed to oxygen.

4.4.2.4 Downstream factors

The acid generating process not only affects the mechanisms within the tailings dam, but also influences natural processes underneath and downstream of the pollution source.

Although many tailings dams originated from the recovery of gold have been reclaimed for further gold recovery in South Africa, over time AMD and related contaminants have migrated into the subsurface. The unsaturated zone is hereby considered to be a barrier between the pollution source (e.g. tailings dam) and the receiving groundwater system, because fluid movement and contaminant attenuation conditions can become favourable for mitigation pollutants, if sufficient neutralisation capacity is available and a low permeability is present. But once this barrier has become polluted and the natural neutralisation capacity is exhausted, it can also act as a continuous pollution source for further groundwater pollution.

Ferguson & Erickson (1988) found that the dissolved oxygen content and pH of the water may decrease downstream from tailings dams (regarded as the source of AMD). This is reflected in secondary minerals such as Fe precipitates in the river bed. Further downstream, the pH of the river will increase due to dilution effects and the presence of buffer material causing chemical speciation effects. At pH ranges between 5-6, most of the Fe and other metals precipitate as metal hydroxides and accumulate in the sediment. Further reactions with CO_2 and carbonates neutralise the pH in the water to 7-8. While most of the metals will precipitate under these pH conditions, salts such as sulphate remain dissolved in water and act as a conservative tracer. Thus, sulphate can be used as a pollution indicator of AMD generation and traced back to the pollution source, which is the tailings dam.

4.4.3 Chemistry and mineralogy of gold-mine tailings

Only limited geochemical and mineralogical information in respect of gold-mine tailings is available for South Africa. More data is available in studies in the United States and Canada.

Rösner (1996) analysed 36 samples from five different gold tailings dams in the East Rand for their major and trace element composition. All these samples were taken at depths of between 30-80 cm, within the oxidised surface zone of the tailings dams, and were dried and analysed using X-ray fluorescence spectrometry (XRF).

The following paragraphs present the ore body chemistry and mineralogy of the mined reefs and the origin of the tailings.

4.4.3.1 Background - Chemistry and mineralogy of the Witwatersrand Reefs

The gold-bearing conglomerate mined in the Witwatersrand area has a typical mineralogical composition of (after Förstner & Wittmann, 1976):

- Quartz (70-90 %);
- Phyllosilicates (10-30 %), consisting mainly of sericite;
- Primary minerals (1-2 %) such as uraninite, monazite, chromite and rutile.

De Jesus et al. (1987) reported high phyrophyllite (max. 16 %) and sericite (max. 2 %) as well as quartz contents of 80-90 % in tailings material.

Additionally, Feather & Koen (1975) provide more detailed mineralogical information for the Vaal Reef in Hartebeestfontein and the Ventersdorp Contact Reef (VCR) as shown in **Table 4.5** below:

Table 4. 5: Mean concentrations for significant minerals and uranium present in Vaal Reef and Ventersdorp Contact Reef (VCR) samples (after Feather & Koen, 1975)

Mineral / Element	Unit	Vaal Reef (Hartebeestfontein)	Ventersdorp Contact Reef (Venterspost)
Muscovite	%	4.4	3.0
Pyrophyllite	%	0.1	0.2
Chlorite	%	0.8	4.9
Quartz	%	88.3	88.9
Titanium	%	0.1	0.1
Zircon	%	0.1	0.2
Chromite	%	0.2	0.2
Pyrite	%	6.6	3.2
U_3O_8	mg/kg	50	44

More than 70 ore minerals have been determined in the reefs, the most important ones being listed above. Barton & Hallbauer (1996) reported average trace metal concentrations for the pyrite grains of the Black Reef Formation of the Transvaal Supergroup. A summary is listed in **Table 4.6** below:

Table 4. 6: Trace element contents (average maximum) of pyrites of the Black Reef Formation, Transvaal Supergroup (after Barton & Hallbauer, 1996)

Element	As mg/kg	Co mg/kg	Cu mg/kg	Cr mg/kg	Ni mg/kg	Mn mg/kg	Sr mg/kg	Ti mg/kg	Pb mg/kg	Zn mg/kg
	1394	1006	346	33	1930	16	3	98	844	90

4.4.3.2 Mineralogical composition of gold-mine tailings

A number of sixteen tailings samples have been selected for the determination of mineral distribution. Although a detailed quantification is very difficult (by using the X-ray diffraction (XRD) in combination with a semi-quantitative approach), it can provide a good indication of the mineralogical composition. **Figure 4.6** presents the result of these analyses.

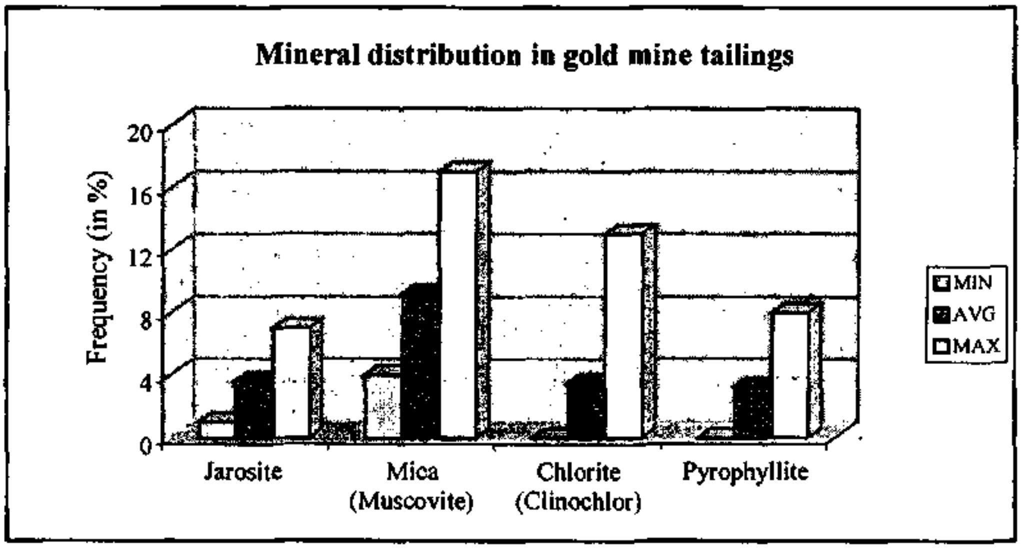


Figure 4. 6: Mineral distribution in gold-mine tailings at three different sites (n=16; excluding quartz)

Quartz (SiO_2) is the dominant mineral phase in tailings material ranging from 70-93 % with an average of 81 %. The high weathering resistance of quartz results in a relative enrichment compared to high weathering mineral phases. The sulphide mineral oxidation process results in the formation of secondary minerals such as gypsum ($CaSO_4 \times 2\ H_2O$) and jarosite ($KFe_3(SO_4)(OH)_6$). Gypsum and other secondary minerals are predominate on the outer toe wall of tailings impoundments and in surface areas close to the impoundment where seepage discharge takes place. Gypsum is formed as a result of evaporation of solutions supersaturated with respect to SO_4^{2-}, resulting in the precipitation of gypsum. In addition, primary mineral phases formed within the tailings are muscovite $[Kal_2(AlSi_3)O_{10}(OH)_2]$, clinochlor $[Cu_3(AsO_4)(OH)_3]$ and pyrophyllite $[AlSi_2O_5(OH)]$.

It is important to note that the solid phases in tailings impoundments control the pore water chemistry (equilibrium and kinetic reactions), thus affecting the chemical composition of AMD.

4.4.3.3 Chemical composition of gold-mine tailings

Table 4.7 indicates the variety of major elements found in tailings material samples. It is important to note that tailings dams differ in design (e.g. exposure to oxygen), mineralogical composition, geotechnical and hydraulical properties:

Table 4. 7: Summary of statistics for major element concentrations contained in tailings dam samples from the East Rand area (in % of dry material) according to Rösner (1996; n = 36)

	SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	P_2O_5 %	(SO_3) %	(Cl) %	(F) %	LOI %
AVG	81.60	0.46	7.61	3.57	0.01	0.63	0.30	0.19	1.80	0.03	0.07	0.03	0.01	3.36
MIN	73.42	0.2	4.2	1.62	0.005	0.1	0.05	0.09	0.71	0.019	0.01	0.002	0.01	1.73
MAX	89.86	0.63	12.66	5.82	0.021	1.07	0.86	0.43	3.45	0.06	0.43	0.081	0.05	6.17
STDEV	3.39	0.12	1.79	0.70	0.00	0.26	0.20	0.08	0.62	0.01	0.08	0.02	0.01	1.21

The main parameters causing these fluctuations in major element geochemistry are the following:

- Changing ore body geochemistry;
- Type of extraction process applied for the recovery of gold;
- Fluctuations in the efficiency of the metallurgical process;
- Development of the weathering process in the mine tailings.

While the first three parameters can be directly derived from the mining operation and extraction plant, the last parameter is a result of various geochemical processes throughout the tailings dam. These processes have been discussed in the previous paragraphs.

According to the chemical composition of the tailings material, the high SiO_2 values are clearly a result of the high quartz content in the mined ore (see **Table 4.7**). The high content of SiO_2 in the tailings material samples reflects the high erosion resistance of quartz during the gold recovery process.

As a result, quartz is relatively enriched towards other mineral phases, whereas the carbonates in the soluble phase reflected in CaO (0.05-0.86 %) in acidic environment show concentrations which are too low to provide sufficient acid neutralisation capacity. The other major elements also show low concentrations, which indicates that the bulk of the ore minerals dissolved during the extraction process or weathered after deposition on tailings dams.

The loss on ignition (LOI) as shown in **Table 4.7** usually reflects the total content of organic matter and volatile elements such as C, Cl, F, S and CN. It is highly unlikely that tailings contain any significant concentrations of organic material due to prevailing acidic conditions; in addition, the ore does not contain any organic matter. One explanation for the high loss on ignition could be CN, which dissociates at temperatures above 1000°C (Loubser, 1998) and is a common substance in tailings and seepage. Cyanide is used during the gold recovery process to dissolve the gold.

The pyrite content is also assumed to be extremely low, because all samples were taken from within the oxidised zone (2-3 m sampling depth) of the deposit (Marsden, 1986), where pyrite (FeS_2) reacted with oxygen to form sulphate and acid. Furthermore, none of the samples show clear trends when the macro-chemistry versus sampling depth was plotted.

Znatowicz (1993) reports elevated concentrations of CN and trace metals such as As, Cd, Co, Cu, Fe, Ni, Mn, Pb, Ra, U and Zn in seepage samples from gold-mines. However, very low U concentrations were found in samples which were collected from these seepage plumes down gradient and downwind of tailings dams in the East Rand, although significant radiometric anomalies were detected during airborne radiometric mapping surveys conducted by Coetzee & Szczesniak (1993). **Table 4.8** presents the concentrations of some of these contaminants, contained in samples from five different tailings dams in the East Rand area.

Table 4. 8: Summary of statistics for trace elements concentrations contained in tailings dam samples from the East Rand area (in mg/kg dry material) according to Rösner (1996; n = 36)

	As mg/kg	Co mg/kg	Cu mg/kg	Cr mg/kg	Ni mg/kg	Pb mg/kg	Zn mg/kg	Th mg/kg	U mg/kg
AVG	107	12	20	440	64	53	43	3	20
MIN	54.00	3.00	10.00	297.00	25.00	14.00	12.00	3.00	6.00
MAX	183.00	35.00	39.00	668.00	145.00	169.00	145.00	4.00	63.00
STDEV	31.25	9.55	9.08	94.41	29.56	44.94	33.22	0.23	16.54

The following parameters may influence the trace element concentration in the mine tailings:

- Fluctuations in the pyrite content of the mined ore;
- Dilution effect caused by the matrix;
- Metallurgical separation during the gold recovery process;
- Oxidation within the surface layer (2-3 m sampling depth) and migration into deeper zones of the impoundment.

A correlation matrix of all measured elements (major and trace elements) was produced and is presented in **Appendix B**. Significant correlation (r > 0.8, n=81) was found among the following pairs: K_2O/SiO_2 (r=0.81), U/Zn (r=0.84), Al_2O_3/SiO_2 (r=0.86), Ni/Co (r=0.90), U/Pb (r=0.92) and K_2O/Al_2O_3 (r=0.96). These correlation coefficients could be explained on a mineralogical basis. The secondary sheet silicate, muscovite ($K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$), which forms part of the mica group of minerals, accounts for the correlation coefficients between the K_2O-SiO_2-Al_2O_3 components, as indicated by the structural formula. U is often associated with sphalerite (ZnS), as well as galena (PbS), in Witwatersrand-type auriferous ores. Niccolite (NiAs) and Cobaltite (CoFeAsS) are rare minerals in Witwatersrand-type ores, but are closely related when they are present (Feather & Koen, 1975).

4.5 GEOCHEMICAL STABILITY OF CONTAMINANTS

4.5.1 Introduction

The geochemical stability of heavy metals, which occur in significant concentrations in tailings dams and in soils underneath the deposit, is of major importance for water quality downstream of the tailings dam. A fundamental issue is the concern that such seepage may transport elevated levels of dissolved contaminants, which could affect water quality in the downstream receiving surface and groundwater bodies. A comprehensive description of AMD prediction techniques such as acid base counting and column tests (steady state and kinetic) is given by Ferguson & Erickson (1988).

The previous paragraphs provided an introduction to the various mechanisms of geochemical, biological and physical processes affecting the migration behaviour of contaminants in groundwater systems. The following paragraphs focus on certain pollutants which are common in tailings dams in South Africa and summarise their chemical properties.

4.5.2 Geochemical stability

Znatowicz (1993) reported elevated concentrations of CN and trace metals such as As, Cd, Co, Cu, Fe, Ni, Mn, Pb, Ra, U and Zn in seepage samples from gold-mines. In an airborne gamma-ray survey in the Witwatersrand, Coetze (1995) shows that high gamma-activities emanating from immobile daughters such as ^{226}Ra of the U decay series in tailings dams pose a serious threat to the nearby environment due to dust erosion. ^{238}U itself is very soluble and hence, highly mobile in the aquatic environment while it becomes decoupled from the decay series, which results in disequilibrium conditions in the decay chain. The examples above have shown that the geochemical stability of a solution is mainly a function of pH and Eh conditions. (see **Chapter 4.3**).

The pH of a solution is a master variable for the control of mineral dissolution and precipitation reactions. The chemical characteristics such as precipitation and dissolution of many elements can be represented in Eh-pH phase or stability diagrams. The techniques involved in the development of such phase diagrams are described in detail by Garrels & Christ (1965).

Although stability diagrams are useful for understanding the equilibrium conditions of dissolved species such as sulphur, the redox reaction can be slow if bacteria are not catalysing the reaction (Fetter, 1992). Thus, it may take a long time for the system to attain the equilibrium state and a kinetic approach should be applied.

However, the Eh-pH diagram for the Fe-system provides a useful summary of the dissolution and precipitation reactions of the element in the aquatic environment. **Figure 4.7** shows the Eh-pH relationship for some common natural aquatic environments (after Garrels & Christ, 1965). The application of Eh-pH relationships is illustrated in Figure 4.8, where the stability relationships is shown between iron oxides, sulphides and carbonates in the aqueous phase (after Garrels & Christ, 1965).

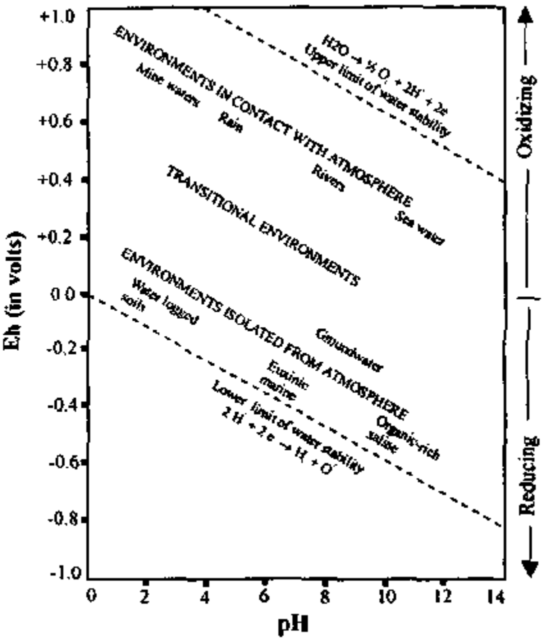


Figure 4. 7

Eh-pH fields for some common aquatic environments (after Garrels & Christ, 1965).

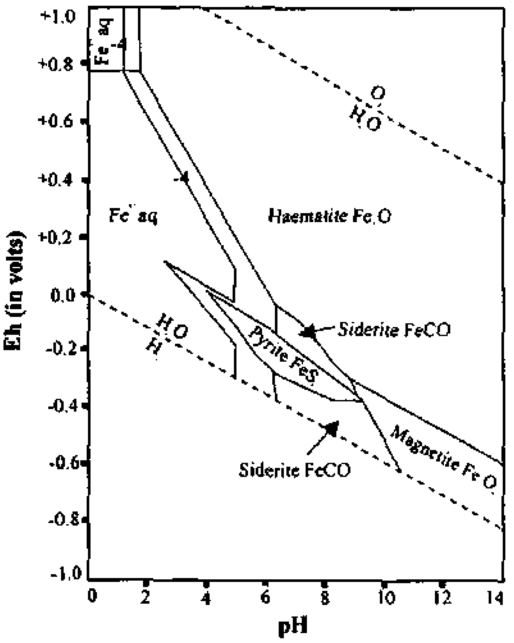


Figure 4. 8

Eh-pH stability relationships between iron oxides, sulphides and carbonates in the aqueous phase at 25°C and 1 atmosphere total pressure. Total dissolved sulphur = 10^{-6} mol/l; total dissolved carbonate = 10 mol/l. Solid lines show the boundaries plotted for concentrations (strictly activities) of dissolved species at 10^{-6} mol/l, fainter lines show boundaries at 10^{-4} mol/l (after Garrels & Christ, 1965).

Figure 4.7 clearly indicates that mine waters and groundwater show completely different Eh/pH-stability fields. Mine waters are characterised by low pH values and oxidising conditions, whereas groundwater shows a fairly neutral to alkaline pH range and reducing conditions.

Four different types of reactions have been identified in **Figure 4.8**:

1. Reactions as a function of pH, e.g. the precipitation of aqueous ferric ions as ferric oxide or haematite:

$2Fe^{3+}(aq) + 3\ H_2O(l) \Rightarrow Fe_2O_3(s) + 6H^+$ [4.14]

2. Reactions as a function of Eh, e.g. the oxidation of aqueous ferrous ions to ferric ions:

$Fe^{2+}(aq) \Rightarrow Fe^{3+}(aq) + e^-$ [4.15]

3. Reactions as a function of both Eh and pH, e.g. the oxidation of ferrous ions and their precipitation as ferric oxide (haematite):

$2Fe^{2+}(aq) + 3H_2O(l) \Rightarrow Fe_2O_3(s) + 6H^+(aq) + 2e^-$ [4.16]

4. Reactions as a function of the concentration of ionic species, and of Eh and/or pH, e.g. the precipitation of ferrous ions as siderite ($FeCO_3$). Note that diagrams have to be plotted for specific anion concentrations or activities:

$Fe^{2+}(aq) + CO_2(g) + H_2O(l) \Rightarrow FeCO_3(s) + 2H^+(aq)$ [4.17]

Under acidic conditions (e.g. AMD), Fe is stable as Fe^{2+} and Fe^{3+}, whereas Fe^{3+} dominates under oxidising conditions. Mineral precipitation is primarily induced by increasing pH, although the Fe^{3+}/Fe_2O_3 boundary can also be crossed by changes in Eh at constant pH. The stability fields of the ferrous minerals pyrite, siderite and magnetite are stable under conditions of negative Eh values (reducing conditions). This stability is mainly a function of the concentrations of total dissolved carbonate and sulphur.

Pyrite is precipitated even if the dissolved concentration of S is low, but siderite shows only a small stability field, although the concentration of total dissolved carbonate is six orders of magnitude greater, reflecting the much lower solubility product of FeS_2 (pyrite) compared with $FeCO_3$ (siderite).

It is also evident from the stability diagram that relatively small shifts in Eh or pH can have a major effect on the solubility of iron. Thus, when pyrite is exposed to oxygenated water, iron will be dissolved. This fact is of major importance to the formation of AMD from tailings.

4.5.3 Remobilisation of trace elements from gold-mine tailings

Solubility, mobility and hence, bio-availability of heavy metals are controlled by four main influence parameters, according to Förstner & Kersten (1988):

- *Increase in pH*, because acidity poses problems in all aspects of metal in the environment, e.g. toxicity of drinking water, growth and reproduction of aquatic organisms, increased leaching of nutrients from the soil resulting in reduction of soil fertility, increased availability and toxicity of metals in sediments (Fagerström & Jernelöv, 1972). On a regional scale, AMD is most probably the main parameter affecting the mobility of toxic metals in surface waters.

- *Increased salt concentrations* such as sulphate and chloride due to the effect of competition on sorption sites on solid surfaces and by the formation of soluble chloro-complexes with some heavy metals.

- *Changing redox conditions*, e.g. after surface deposition of anoxic mine tailings.

- *Increased occurrence of natural and synthetic complexing agents*, which can form soluble metal complexes with heavy metals that would usually be adsorbed to solid matter.

The predominance of simple mineral solution equilibria (see **Chapter 4.2.1**) explains the concentrations of major elements in the surface environment, but the hydrogeochemical properties are more complex and are also determined by other factors such as co-precipitation, sorption effects and interaction with organic phases, which were described in the previous paragraphs.

Plant & Raiswell (1983) and Förstner & Kersten (1988) provide a simple scheme for the estimation of these interactions in **Table 4.9**. The table indicates the relative geochemical mobility of elements in sediments and soils as a function of Eh and pH and provides a basic understanding for the interpretation of the chemistry of tailings and affected soils underneath tailings dams.

Table 4. 9: Relative mobilities of elements in sediments and soils as a function of Eh and pH (summarised from Plant & Raiswell, 1983 and Förstner & Kersten, 1988).

Relative Mobilities	Chemical environment			
	Oxidising	**Acid**	**Neutral to alkaline**	**Reducing**
Very low mobility	Al, Cr, Fe, Mn	Si	Al, Cr, Hg, Cu, Ni, Co	Al, Cr, Mo, V, U, Se, S, B
Low mobility	Si, K, P, Pb	K, Fe(III)	Si, K, P, Pb	Si, K, P, Ni
Medium mobility	Co, Ni, Hg, Cu, Zn, Cd	Al, Pb, Cu, Cr, V	Mn	Mn
High mobility	Ca, Na, Mg, Sr, Mo, V, U, Se	Ca, Na, Mg, Zn, Cd, Hg	Ca, Na, Mg, Cr	Ca, Na, Mg, Sr
Very high mobility	Cl, I, Br, B	Cl, I, Br, B	Cl, I, Br, S, B, Mo, V, U, Se	Cl, I, Br

Förstner & Kersten (1988) found that changes from reducing to oxidising conditions, which are typical for oxidation processes of sulphide minerals (**Chapter 4.4.2**), that result in acidic conditions, will increase the mobility of *chalcophylic* (enriched in sulphide minerals and ore) elements such as Hg, Zn, Pb, Cu and Cd. On the other hand, a decrease in the pH and oxidising conditions would lower the mobility of elements such as Mn and Fe.

Various element transformations under different geochemical milieus have been described in Hoeppel et al. (1978) and Salomons & Förstner (1988). It is also important to note that reactivity, mobility and bio-availability of metals for metabolic processes are closely related to their chemical species in both solid and aqueous phases (Förstner & Kersten, 1988).

4.6 TOXICITY

4.6.1 Introduction

Toxic substance or toxicants are defined as harmful if it shows harmful effects to living organisms because of its detrimental effects on tissues, organs, or biological processes. Here, substances are limited to the toxic group of heavy metals contained in mine tailings. A comprehensive overview of the characteristics of various toxic substances in air, water and solids is given in Moore & Ramamoorthy (1984) and Morel & Hering (1993).

The most important factor for the interpretation of environmental data in relation to hazards for man, animals and plants is bio-availability. Bio-availability describes how easily sorbed contaminants could become remobilised and therefore bio-available for living organisms via various pathways such as air, water and solids. Bio-availability is discussed in **Chapter 5.4.3**.

The information and data for the following paragraphs with regard to the toxicity of selected substances have been taken from the guidelines contained in *Water Quality Guidelines Series* published by DWAF (Second Edition Series a-f) in 1996. The paragraphs have been supplemented with information from Moore & Ramamoorthy (1984) and others.

4.6.2 Toxicity of selected contaminants

A number of contaminants such as salts, heavy metals and radionuclides, which occur in mine tailings and subsequently in the leachate entering the subsurface, have been described in more detail in the following chapters.

4.6.2.1 Sulphate(SO_4^{2-})

Most sulphate compounds are readily soluble in waters and thereby controlled by equilibrium chemistry. Dissolved sulphates in surface and groundwater often occur in combination with gold mining operations (pyrite oxidation) due to leachates from underground mines and/or seepage from tailings dams. High concentrations of sulphate (> 600 mg/l) predominantly affect health (diarrhoea). Sulphate concentrations of 200-400 mg/l also cause a salty and bitter taste in drinking water. The target water quality of sulphate ranges from 0-200 mg/l in waters for domestic use (DWAF, 1996a). The sulphate concentrations in borehole waters close to tailings dams (distance approximately < 300 m) can easily exceed more than 5000 mg/l. It is important to ensure that these polluted boreholes are not used as drinking water supplies or for other domestic and agricultural uses. However, there are no important links between the geochemistry of sulphate and human diseases (Crounse et al., 1983).

4.6.2.2 Arsenic (As)

Arsenic is not a heavy metal, although it is often grouped with these elements (Olson, 1983). Arsenic becomes remobilised under acidic conditions in water. Another important parameter is the redox potential (Eh value), which also controls inorganic arsenic species in aquatic systems. Arsenic causes chronic and acute poisoning. Chronic poisoning can result in fatal diseases such as cancer, whereas acute poisoning can even lead to nerve damage, subsequently resulting in death. The target water quality for arsenic is given as ≤ 10 μg/l. Concentrations of 200-300 μg/l can cause skin cancer in the long term, whereas concentrations above 1000 μg/l are considered to be lethal. It is recommended that concentrations of arsenic in water in potable water should never exceed 200 μg/l (DWAF, 1996a). However, high arsenic concentrations (> 5000 μg/l) have been observed in boreholes in close proximity to mining operations such as tailings dams (Moore & Ramamoorthy, 1984).

4.6.2.3 Cobalt (Co)

Cobalt is an essential element for humans, but its pathway through the food chain to man is very complex (Crounse et al., 1983). The chemical properties of cobalt are similar to iron and nickel. Unlike Fe (II), the Co (II) ion is stable in the oxidised form. Co (III) is also a strong oxidising agent and unstable in soil. The soil pH is the main parameter for the Co content in solution, the solubility increases with decreasing pH (DWAF, 1996d). Cobalt concentrations in the range of 0.1-5 mg/l have been found to be toxic to a variety of food crops when added to nutrient solutions. However, the occurrence of cobalt toxicity is not common under field conditions (DWAF, 1996d). Although no target water quality concentration for domestic use is available, a concentration of ≤ 0.05 mg/l is recommended in soils, according to DWAF (1996d).

4.6.2.4 Chromium (Cr)

Chromium is an element which is essential to animals and man and is often found in high concentrations in combination with nucleic acids (Crounse et al., 1983). Chromium occurs in two oxidation states in waters, Cr^{3+} and Cr^{6+} respectively, where Cr^{3+} is the most stable and important oxidation state. In well-oxygenated waters, Cr^{6+} is the thermodynamically stable species. However, Cr^{6+} is easily reduced by Fe^{2+}, dissolved sulphides, and certain organic compounds (Moore & Ramamoorthy, 1984). Due to these common conversions, it is desirable that the target water quality should be based on Cr(total) rather than on Cr^{6+}. The World Health Organisation (WHO) recommended a limit of 0.05 mg/l in drinking water (Bundesgesundheitsamt, 1993). Moore & Ramamoorthy (1984) report that chromium is transported primarily in the solid phase in streams.

4.6.2.5 Copper (Cu)

Copper is an essential element and the normal adult human contains about 100-150 mg Cu (Crounse et al., 1983). At neutral and alkaline pH, the concentration of copper in surface waters is usually low, whereas in acidic waters, copper readily dissolves and significant higher concentrations may occur. Copper is an essential trace element for almost all living organisms and can occur in three different oxidation states. Even low concentrations of copper give water a strongly astringent taste. The target water quality varies from 0-1 mg/l for domestic use and it is recommended that the concentration of copper in potable water should not exceed 30 mg/l, as this is the threshold for acute poisoning with nausea and vomiting (DWAF, 1996a). It is interesting to mention that a large proportion of the copper content in soils is not bio-available for plants (Thornton, 1983).

4.6.2.6 Iron (Fe)

Iron is an essential element for all living organisms and an average human adult contains about 4-5 g Fe, most of which is present in haemoglobin in the red blood cells (Crounse et al., 1983). Fe concentrations are dependent on the pH, Eh of suspended matter and the concentrations of other heavy metals (notably manganese). Fe accumulation in the body due to uptake can cause tissue damage. However, poisoning is rare, since very high concentrations of dissolved iron in natural water hardly ever occur. Chronic health effects in sensitive individuals can be expected by 10-20 mg/l. The target water quality for Fe for domestic use is given as ≤ 0.1 mg/l (DWAF, 1996a). Where significant acidification of the waters occurs (pH < 3.5), the dissolved iron concentration can be to the order of several hundred mg/l, as a result of AMD (DWAF, 1996a). Fe concentrations of more than 10 mg/l have commonly been observed by the authors in seepage waters from tailings dams in South Africa.

4.6.2.7 Nickel (Ni)

Nickel is readily remobilised during the weathering process, whereas precipitation occurs predominantly in the presence of Fe and Mn oxides (Alloway, 1995). On the other hand, Ni is strongly retained by soils (DWAF, 1996d), preferably in the fine particle size fraction (Moore & Ramamoorthy, 1984). Ni is not considered to be a significant, widespread contaminant, as it mainly occurs close to industrial sites such as smelters. Németh et al (1993) and Alloway (1995) reported that Ni is phytotoxic under acid soil conditions. A target water quality for domestic use is not available. However, the limit for agricultural use (irrigation) is given as ≤ 0.2 mg/l (DWAF, 1996d).

4.6.2.8 Manganese (Mn)

Manganese is essential to a wide variety of animals (Crounse et al., 1983). Mn shows a similar chemical behaviour to Fe. Both elements tend to dissolve from solids under aerobic conditions and reprecipitate under anaerobic conditions. Once Mn is dissolved, it is often difficult to remove it from solution except at high pH, where it precipitates as the hydroxide (DWAF, 1996a). Mn shows chronic toxic effects from ≥ 20 mg/l. However, it is less toxic than other metals (Crounse et al., 1983). The target water quality for Mn for domestic use is given as ≤ 0.05 mg/l (DWAF, 1996a).

4.6.2.9 Lead (Pb)

Lead in excess (above normal blood and tissue levels) is toxic to humans and animals. The properties of Pb in the aqueous phase are a combination of precipitation, equilibria and the generation of complexes with inorganic and organic ligands. The degree of mobility of Pb depends on the physiochemical state of the complexes formed and on the prevailing pH, Moore & Ramamoorthy (1984) reporting that Pb is almost sorbed at pH > 6. The chemical properties of Pb in soils are similar to that of Cd, Co, Ni, Zn and Pb and are mainly controlled by the prevailing pH in the soil. (DWAF, 1996d). The target water quality for Pb for domestic use is given as ≤ 10 µg/l (DWAF, 1996a). Significant health effects such as neurological damage can be expected from concentrations above 50 µg/l. It is important to note that Pb has many industrial applications and also shows significant concentrations in gold-mine tailings in South Africa, as shown in Rösner (1996) and Aucamp (1997).

4.6.2.10 Zinc (Zn)

Zinc is an essential element in a wide variety of animals (Olson, 1983). Zn occurs dissolved at a pH value less than neutral, whereas at pH > 8 it precipitates as the relatively stable Zn hydroxide $Zn(OH)_2$, according to Moore & Ramamoorthy (1984). DWAF (1996a) reported that Zn strongly interacts with Cd, which shows similar chemical properties. The target water quality for domestic use for Zn is given as ≤ 3 mg/l. Zn is less toxic than other heavy metals and shows only acute toxic effects at concentration levels above 700 mg/l (DWAF, 1996a).

4.6.2.11 Cyanide (CN)

Dissolved cyanide ions (CN^-) result from the reaction between water and the highly toxic hydrocyanic acid (HCN). Most of the aqueous cyanide is in the hydrocyanic acid form and is largely undissociated at pH values ≤ 8 (DWAF, 1996g). CN usually forms metal complexes (e.g. with Ni). The toxicity of cyanide depends on various factors such as pH, temperature, dissolved oxygen concentration salinity and the presence of other ions in solution. The target water quality for free cyanide in aquatic ecosystems is given as ≤ 1 μg/l. Chronic effects are expected at concentrations of about 4 μg/l and acute effects at concentrations above 11 μg/l (DWAF, 1996g)

4.6.2.12 Radioactive elements

Radioactivity in the environment occurs due to the presence of radioactive nuclides (radionuclides) or isotopes emitting α- and β- particles and γ-rays.

In mineral phases, U and its daughters (isotopes) often establish secular equilibrium, whereas the production of each isotope is balanced by its decay, and the ratios between the different isotopes remain constant and equal to their respective decay constants. Rock weathering and leaching of U tends to result in separation of the parent isotopes from its daughter products. This separation is mainly caused by varying mobilities and retardation due to different hydrogeochemical properties and half-lives. When one isotope in a radioactive decay chain is selectively mobilised from solid surfaces in the aquifer, disequilibrium is produced in both the solid and aqueous phase (Ivanovich & Harmon, 1992).

Radioactive isotopes present in tailings from the gold and uranium mines on the Witwatersrand are a potential source of contamination of soils, surface and groundwater. The following daughters (isotopes) of the decay chain are of special interest as regards environmental aspects of the surface and groundwater pathways:

- ^{238}U (uranium) as the parent isotope and the main component of the Witwatersrand ore, which can accumulate in waters and migrate over long distances even at pH > 7.5, because of its ability to form complexes such as $UO_2(CO_3)_3^{4-}$, $UO_2(CO)_2^{2-}$ and $UO_2(HPO_4)_2^{2-}$ (Bowie & Plant, 1983).

- ^{226}Ra (radium) is an immediate daughter of ^{238}U and dissolves only at low pH values. The migration of ^{226}Ra via seepage into the soil underneath 30-40 year old tailings dams has been reported, although ^{226}Ra becomes heavily retarded (1300-4500 times slower than water) by the clay mineral phyrophyllite within the deposit, according to De Jesus et al. (1987). If ^{226}Ra enters carbonate- or sulphate-containing surface and shallow groundwater systems, it forms insoluble precipitates such as $RaCO_3$ and $RaSO_4$ respectively (Ivanovich & Harmon, 1992). The physico-chemical properties and migration of ^{226}Ra released from uranium-bearing tailings have been discussed in detail in Benes (1984).

- ^{222}Rn (radon) is a very soluble inert gas with a short half-life of four years and is generated as long as ^{226}Ra (radium) occurs. Assuming ^{226}Ra in the tailings may result in ^{222}Rn escaping to the atmosphere. However, Bowie & Plant (1983) report that ^{222}Ra tends to accumulate in confined spaces such as poorly ventilated mine workings or houses, due to its density (9.73 g/l at NTP) and thus ^{222}Rn exerts a health risk for people ingesting ^{222}Rn.

- ^{214}Bi (bismut) is a very active gamma-ray emitter, which is used as the target isotope in gamma-ray investigations of the ^{238}U series.

- ^{232}Th (thorium) is invariably insoluble in soil and groundwater systems and is therefore not considered to be a main hazard (Ivanovich & Harmon, 1992).

- ^{40}K (potassium) is the most common radionuclide (β-emitter) found in water. ^{40}K is an essential intracellular mineral and is found in all living organisms and in all water supplies (DWAF, 1996a).

Soil samples collected at a reclaimed tailings dam site (case study F) indicate high uranium (measured as U_3O_8) concentrations, which can be derived from the ore processing plant.

Leaching rates of radionuclides from uranium-bearing tailing are mainly a function of tailings particle size, chemical composition of the leaching solution and pH/Eh conditions. (Waite et al., 1989 and Bush & Landa, 1990).

The toxicity of radionuclides is usually assessed in relation to dose rates of ionising radiation. In this study, samples were only analysed for U. A uranium concentration of 0.07 mg/l or 0.89 mBq/l should not be exceeded for human consumption. Concentrations above 0.284 mg/l indicate a cancer risk < 1 of 200 000, but a significant risk of chemical toxicity with renal damage. Concentrations above 1.42 mg/l cause an increased cancer risk for humans in the long term and an increased cancer risk of renal damage in the short term (DWAF, 1996a). In addition, target water quality range for agricultural use is given with > 0.1 mg/l for irrigation purposes only over the short-term on a site-specific base (DWAF, 1996d).

4.7 ENVIRONMENTAL HAZARDS FOR THE AQUATIC PATHWAY CAUSED BY AMD

4.7.1 Introduction

A basic background to the characteristics and various mechanisms of the unsaturated zone has been given in **Chapter 3** as well as in Martin & Koerner (1984). The oxidation of sulphide minerals (e.g. pyrite) releases various toxic heavy metals into the tailings pore water. Under the low pH conditions (AMD) present in the unsaturated zone (vadose), these heavy metals remain in solution and can migrate laterally and vertically through the mine tailings and subsequently through the unsaturated zone into the aquifer.

4.7.2 Impact of AMD and trace elements on the unsaturated and saturated zone

Dissolved heavy metals originating from AMD have the potential to contaminate the groundwater and the surface water beyond drinking water limits. However, when acidic tailings leachate enters a carbonate aquifer (e.g. dolomitic aquifer), pH buffering processes can cause the precipitation of a least some of these heavy metals (Me), thus immobilising them within the aquifer and preventing discharge into surface water systems.

When acidic solutions generated by oxidation of sulphide minerals interact with solids in the tailings or in the underlying unsaturated and saturated zone which contain carbonate or hydroxide, a series of chemical neutralisation reactions occurs. Initially, the most soluble mineral phases dissolve, consuming protons (H^+) expressed in the following representative reaction:

$$MeCO_3(s) + H^+ \Leftrightarrow Me^{2+} + HCO^{3-} \qquad [4.18]$$

The dissolution of these relatively soluble mineral phases may result in the precipitation of less soluble phases. For example, the buffering of H^+ by the dissolution of calcite ($CaCO_3$) releases bicarbonate (HCO_3^-) **(Formula 4.18)** to the pore water of the tailings and unsaturated zone, favouring the precipitation of less soluble carbonate minerals, such as siderite ($FeCO_3$) and other metal-containing carbonates and hydroxides. This process is described by the following reactions:

$$Me^{2+} + CO_3^{2-} \Leftrightarrow MeCO_3(s) \qquad [4.19]$$

$$Me^{n+} + {}_nOH^- \Leftrightarrow Me(OH)_n(s) \qquad [4.20]$$

These carbonate and hydroxide-generating reactions remove dissolved metals from the tailings leachate and can therefore act to mitigate groundwater contamination. Hence, in order to predict the effects of tailings on groundwater quality, it is necessary to determine the factors controlling the neutralisation mechanisms. An extensive description of these mechanisms has been given in the previous paragraphs.

In conclusion, the unsaturated zone is considered to be a geochemical and physical barrier between the pollution source (e.g. tailings dam) and the receiving groundwater system, because fluid movement and contaminant attenuation conditions can be favourable for mitigation of groundwater pollution. However, once this barrier zone has become polluted, it can also act as a continuous secondary pollution source for groundwater contamination. It must be stressed that metals are significantly retarded as they pass through the unsaturated zone. In contrast, the retention of salinity seems to be very low, which is reflected by high TDS values in the groundwater (Ca-Mg-SO_4 type).

CHAPTER 5

METHODOLOGY

5.1 DATA COLLECTION

A comprehensive literature study was undertaken in order to meet the research objective, namely, to evaluate and define the existing state of knowledge with regard to current and long-term environmental effects of mine residue deposits. Technical data and general information about the impact of mine deposits before and after reclamation have been accessed from various information sources. A brief summary of the information sources used in this study is shown below:

- Department of Water Affairs and Forestry (DWAF);
- Department of Minerals and Energy (DME);
- Council for Geoscience;
- Water Research Commission (WRC);
- Rand Water;
- Research institutions such as universities;
- Mining and reclamation companies.

The findings of the literature study have been incorporated into this report. During the course of the study, it became apparent that the information regarding water quality and gold tailings dams available in South Africa was very limited. Only a small number of mines and reclamation companies co-operated by providing useable information.

A field survey was initiated in March 1998 to close identified gaps in the data set. Samples from seven case study sites (sites A-G), were collected and analysed for their geotechnical, geochemical and mineralogical characteristics. The results of the case studies are described and discussed in **Chapter 6**.

The following data requirements have been identified as crucial for the impact assessment and are structured according to three categories as described by Parsons & Jolly (1994):

- Threat factor - *primary pollution source* (gold-mine tailings dam): mineralogy, geotechnical properties, geochemistry and hydraulical conditions.
- Barrier zone - *unsaturated zone* that may also become a secondary source of pollution: mineralogy, geotechnical properties and geochemistry.
- Resource Factor - *receptor* (groundwater and surface water systems): aquifer parameters (e.g. groundwater table, yield) and water quality.

The primary pollution source and barrier zone were investigated in detail during the field survey, whereas groundwater quality data had to be gathered by monitoring over long-term periods, a requirement which was outside the scope of this study. However, limited groundwater data were provided by mining companies. All relevant test site data have been entered into an internal database for further evaluation.

5.1.1 Development of a GIS-linked data base for gold-mine tailings dams

GIS technology (ArcView 3.0a) was chosen for the management and evaluation of data gathered during the course of this study. The use of a GIS system as a tool for the development of a mine residue deposit register has been discussed in **Chapter 2.8.1**. The following key parameters were selected to describe the environmental impact of gold-mine residue deposits.

- Name of the site;
- Index number of DME;
- Topographical sheet number (Scale: 1: 50 000);
- Type of gold-mine tailings dam;
- Area size covered by the gold-mine tailings dams (in km^2);
- Geological conditions beneath gold-mine tailings dams;
- Land use matrix describing land use in close proximity to the gold-mine tailings dam (distance < 1 km).

During the course of this study more than 270 mine residue deposits were identified, captured and investigated in terms of important environmental parameters. Note that it was not possible to identify all the key parameters for each gold-mine tailings dam owing to lack of information.

5.1.2 Field survey

Field investigations at the reclaimed test sites were carried out during March and April 1998. A total of 22 test pits (3 per site, except at site F where 4 test pits were investigated) were excavated by means of a Schaeff backactor mounted on a Mercedes Unimog truck (see **Appendix F, Figure 8**). The test pits were excavated up to a maximum depth of 2.40 m in order to determine depth to bedrock, underlying pedological conditions and the potential presence of a perched groundwater table. Samples for analyses (**Table 5.1**) were taken at various depths: topsoil to water table or maximum test pit depth.

All test pits were logged according to the MCCSSO method (moisture, colour, consistency, structure, soil type and origin), which was introduced by Jennings et al. (1973). Soil profiles are presented in the **Appendix A**.

Each site has been described according to the site characteristics (e.g. area size, vegetation, reclamation status, geology), geotechnical characteristics, geohydrological properties and contaminant assessment of the unsaturated and saturated zones. Additional information regarding land use in close proximity to the site was obtained from topographical maps, orthophotographs and a satellite image.

5.2 LABORATORY TESTING

Soil samples were analysed for the following elements: Fe_2O_3 (total), MnO_2, As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Rb, Th, U, V, Zn and Zr. **Table 5.1** below summarises laboratory testing and the methods applied:

Table 5.1: Summary of laboratory tests, the number of samples and the method applied.

	Total element analyses	Mineralogical composition	Soil extraction tests	Soil paste pH	Geotechnical properties
Tailings Samples	36	16	13	-	-
Soil Samples	81	-	16	54	57
Method	XRF	XRD	NH_4NO_3 and ICP-MS	Ref. ASTM (1990)	Standard foundation tests

As the majority of trace elements are accumulated in the clay-silt particle size range, the particle size < 75 µm was used for all sedimentological laboratory tests. Trace element analyses are more accurate, because the elements are concentrated above the detection limit of analytical methods such as XRF (X-ray fluorescence spectrometry) and ICP-MS (inductive coupled plasma mass spectrometry). The use of the silt particle size is recommended by various authors such as Förstner (1988) and Labusschagne et al. (1993).

In addition, the Council for Geoscience operated an extensive geochemical database which characterises the maximum, mean and minimum concentrations of various trace elements in topsoils in South Africa. These data have been used as background or baseline values.

Standard foundation tests comprise the following determinations:

- Atterberg limits;
- Grading analyses (clay-silt-sand-gravel fraction);
- Specific gravity;
- Void ratio;
- Dry density.

Total element analyses for gold-mine tailings material were obtained from Rösner (1996).

5.2.1 Soil extraction tests

Trace elements occur in the soil in various sorption phases (Salomons & Stigliani, 1995):

- Easily soluble phase (NH_4NO_3 soluble);
- Exchangeable phase (NH_4NO_3 soluble);
- Trace element bound to organic matter and oxides of Fe and Mn;
- Residual fraction (HF and $HClO_4$ soluble).

Of these phases, the residual fraction is the least mobile and does not partake in chemical reactions of soils, whereas the easily and exchangeable fractions are the most mobile and determine the bio-availability of a trace element, as discussed in **Chapter 4.2.4**.

Various leaching methods have been discussed in Förstner (1995) to estimate the concentration of an element in the easily soluble and exchangeable fraction. In this study simple salt solutions (e.g. 1 M NH_4NO_3) were used to estimate the bio-availability of trace elements in soils (particle size < 75 µm).

The NH_4NO_3 soil extraction method is an accepted method in the German Federal Environmental Agency (Umweltbundesamt) for conducting hazard assessments as part of risk assessments, and is likely to become an internationally recognised soil leaching method for environmental studies (Schloemann, 1994). The extracted solution stabilises in the acid range, thus ensuring that the leached element remains in solution. This method is simple to handle and rapid. Soil extraction methods using salt solutions such as NH_4NO_3 result in extracted concentrations that can be correlated with the amount of ions held on charged soil surfaces (e.g. clays, oxides and humus) and the concentration of these ions in the soil solution (Davies, 1983).

In this study, extracted concentrations were compared to the total concentration in the solid phase and to threshold values for NH_4NO_3 leachable trace elements, after Prüeß et al. (1991). Concentrations higher than the set threshold concentrations (TC) can result in a limitation of the soil function, according to Prüeß et al. (1991). The threshold concentrations for soils are listed in **Table 5.2** below:

Table 5.2: Extractable NH_4NO_3 threshold values for soils (in mg/kg dry material) after Prüß et al. (1991).

Element	*As* mg/kg	*Co* mg/kg	*Cr* mg/kg	*Cu* mg/kg	*Mo* mg/kg	*Ni* mg/kg	*Pb* mg/kg	*U* mg/kg	*V* mg/kg	*Zn* mg/kg
	0.1	0.5	0.1	2	1	1	2	0.04	1	10

SRK (1988) reported that extraction tests are not necessarily representative of the quantities of salts that will be leached out of the deposits after storm events, but only of the quantities of salts which are potentially available. Under natural conditions, the quality and quantity of the leachate will be dependent on many factors, which have been discussed in **Chapter 4.7.3.**

5.3 DATA EVALUATION

5.3.1 Background concentrations

An introduction into the establishment and evaluation of background values was provided in **Chapter 4.3.** The test pits of the seven reclaimed sites where field testing was conducted were excavated from soils or alluvial sediment belonging mostly to sedimentary rocks from the Vryheid Formation or dolomites of the Malmani Subgroup.

The trace element geochemistry of the soil samples retrieved from the investigated sites were compared with trace element concentrations from topsoil samples (particle size < 75 µm) of the Vryheid Formation and Malmani Subgroup in areas not affected by mining activities. These data were obtained from the geochemical database of the Council for Geoscience (Elsenbroek & Szczesniak, 1997 and Aucamp, 1998). Average background values (ABV) of selected trace metals of the Vryheid Formation and Malmani Subgroup are shown in **Table 5.3** below:

Table 5. 3: Average background values (ABV) in topsoils obtained from the Vryheid Formation, Karoo Supergroup (n= 21) and Malmani Subgroup, Transvaal Supergroup (n= 2148, particle size <75 µm). All values in mg/kg except Fe as Fe_2O_3 and Mn as MnO in %. Uranium concentrations were generally below the detection limit.

Element/ Geological Formation	Fe %	Mn %	As mg/kg	Co mg/kg	Cr mg/kg	Cu mg/kg	Mo mg/kg	Ni mg/kg	Pb mg/kg	U mg/kg	Zn mg/kg
Vryheid	4.40	0.08	22	14	130	35	23	45	15	-	103
Malmani	6.11	0.70	18	15	268	31	13	57	5	-	50

5.3.2 Environmental classification of case study sites

The case study sites were classified with respect to the:

- Current contamination impact;
- Future contamination impact (worst-case scenario).

Rating and index approaches such as the threshold exceedance ratio (TER) and the geochemical load index (pollution classes I-VI) were applied to assess the short- and long-term impacts. These approaches are discussed in the following paragraphs. The *implementation of a groundwater risk assessment procedure such as the* DRASTIC (*U.S.*-EPA, 1987b) approach failed due to a lack of relevant data.

5.3.3. Assessment of the current contamination impact

The current pollution impact was investigated by using the threshold exceedance ratio and the trace element mobility coefficient. The threshold exceedance ratio (TER) is calculated as follows:

$$TER = \frac{ExC}{TC} \qquad [5.2]$$

where TER is the threshold exceedance ratio for an element, ExC is the NH_4NO_3 (1 M) extractable concentration and TC is a given threshold concentration, after Prüeß et al. (1991). A concentration which is higher than the recommended maximum concentration can limit the functioning of the soil.

Table 5.4 indicates which of the soil functions is most threatened by a certain pollutant in order to assist in deciding on the appropriate countermeasures:

Table 5. 4: Recommended maximum NH_4NO_3 extractable threshold concentration (TC, in mg/kg) that should not be exceeded in the soil (Prüeß et al., 1991). Abbreviations for the ranking of concern if the maximum concentrations are not excessively exceeded: PC = primary concern, C = concern, INV = further investigations needed to assess risk. Limited soil functioning only if the maximum concentrations are excessively exceeded: X.

		Soil functions and ranking of concerns				
Element	**TC (mg/kg)**	Pollutant buffer with regard to plants for human consumption	Pollutant buffer with regard for animal consumption	Habitat for plants	Habitat for soil organisms	Pollutant filter with regard to groundwater
Arsenic	0.1	PC	X	C	X	C
Cobalt	0.5	X	C	C	X	X
Chromium	0.1	X	X	X	PC	C
Copper	2	X	C	C	PC	C
Molybdenum	1	X	PC	C	X	X
Nickel	1	X	X	C	X	X
Lead	2	PC	C	X	C	C
Vanadium	0.1	C	C	INV	X	X
Zinc	10	X	X	C	X	X
Uranium	40	X	X	X	X	INV

In addition, the mobility of trace elements (MOB) was derived by comparing the extractable ratio of an element to the total concentration by the following **Formula 5.2** below:

$$MOB\% = \frac{EC}{TotC} \qquad [5.2]$$

where MOB represents the percentage mobility of an element, EC is the NH_4NO_3 (1 M) extractable fraction and TotC is the total concentration measured in soil and sediment samples. MOB is similar to the distribution coefficient (K_d value) used in groundwater studies, but is easier to handle because bulk density data and the effective porosity values of the unsaturated or saturated zones are not required in this formula. The MOB value gives the percentage value of the concentration which could be remobilised and is thus bio-available in the soil.

It is important to note that TER and MOB values were only applied experimentally to samples of the case study site F and were then extrapolated to all the other samples from the remaining sites.

5.3.4 Assessment of the future contamination impact

The potential future pollution impact was assessed by implementing the geochemical load index introduced by Müller (1979). This index is represented in **Formula 5.3** below:

$$I_{geo} = \log_2 \frac{C_n}{B_n \times 1.5} \qquad [5.3]$$

where C_n ist the measured concentration of the element n in the sediment and B_n is the geochemical background value obtained from the geochemical database of the Council for Geoscience. The safety factor 1.5 is used to compensate for variation in the background data. The ratio is multiplied with a log to the base of 2. The index comprises six different classes (pollution class I-VI), which are shown in **Table 5.5** below.

Table 5. 5: Pollutant enrichment classes by using the geochemical load index (modified after Müller, 1979)

Geochemical Load Index I_{geo}	Pollution class	Level of pollution
>0-1	I	Non-polluted to moderately polluted
>1-2	II	Moderately polluted
>2-3	III	Moderately to predominantly high polluted (10-fold exceedance)
>3-4	IV	High polluted
>4-5	V	High to excessively polluted
>5	VI	Excessively polluted (100-fold exceedance)

The application of this index reflects the potential future pollution impact (worst-case scenario), assuming that the total concentration of contaminants contained in the solid phase (*sediment* or *soil*) can be remobilised and hence, are bio-available. It is evident that such a scenario is unlikely and only further field and laboratory testing would allow for more accurate predictions.

It is important to note that pollution class VI reflects an approximately 100-fold enrichment above the background concentration. The index has been successfully applied in various environmental studies in Germany, such as in the water quality monitoring program of the rivers Rhine and Elbe and in sludge deposits of the Hamburg harbour area (Förstner & Müller, 1975 and Förstner, 1982). The index was recently applied in the geochemical mapping of topsoils in the city of Berlin and in the Czech Republic, conducted by the German Federal Environmental Agency (Birke, 1998).

It is important to note that natural concentrations of elements in soils scatter over a wide range and concentration levels depend on the source rock type. Therefore, **Table 5.6** presents a range of expected concentrations for selected trace elements in soils, after Levinson (1974).

Table 5. 6: Average range for the abundance of selected trace elements in soils according to Levinson (1974; in mg/kg dry material). Arsenic data from Wedepohl (1969).

Element	As mg/kg	Co mg/kg	Cr mg/kg	Cu mg/kg	Mo mg/kg	N mg/kg	Pb mg/kg	Rb mg/kg	U mg/kg	Zn Mg/kg
Range	2-40	1-40	5-1000	2-100	2 n. a.	5-500	2-200	20-500	1 n. a.	20 n. a.

5.3.5 Estimation of saturated hydraulic conductivities

Saturated hydraulic conductivities for the samples were estimated according to the methods of Tavenas et. al. (1983) or by means of comparison to the permeability, after Mathewson, (1981) are summarised in **Table 5.7**. The geotechnical properties of the soil samples are listed in **Appendix A**.

Table 5. 7: Comparison of tables of the Unified Soil Classification Classes and related hydraulic conductivity (in m/s), after Mathewson, (1981). CH: Highly plastic clay. CL: Low plastic clay. MH: Highly plastic silt. ML: Low plastic silt. SP: Well sorted sand. SP: Poorly sorted sand. SM: Silt sand. SC: Clayey sand. GP: Well sorted gravel. GW: Poorly sorted gravel. GM: Silty gravel. GC: Clayey gravel.

Fraction	**Clay**		**Silt**		**Sand**				**Gravel**			
U. S. C. S. Class	CH	CL	MH	ML	SP	SW	SM	SC	GP	GW	GM	GC
Max K (m/s)	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-3}	10^{-3}	10^{-6}	10^{-7}	10^{-5}	10^{-4}	10^{-5}	10^{-6}
Min K (m/s)	10^{-11}	10^{-10}	10^{-9}	10^{-9}	10^{-7}	10^{-6}	10^{-8}	10^{-9}	0.01	0.01	10^{-8}	10^{-9}

Figure 5.1 shows the procedure after Tavenas et al. (1983) to estimate saturated hydraulic conductivity in a fine-grained soil:

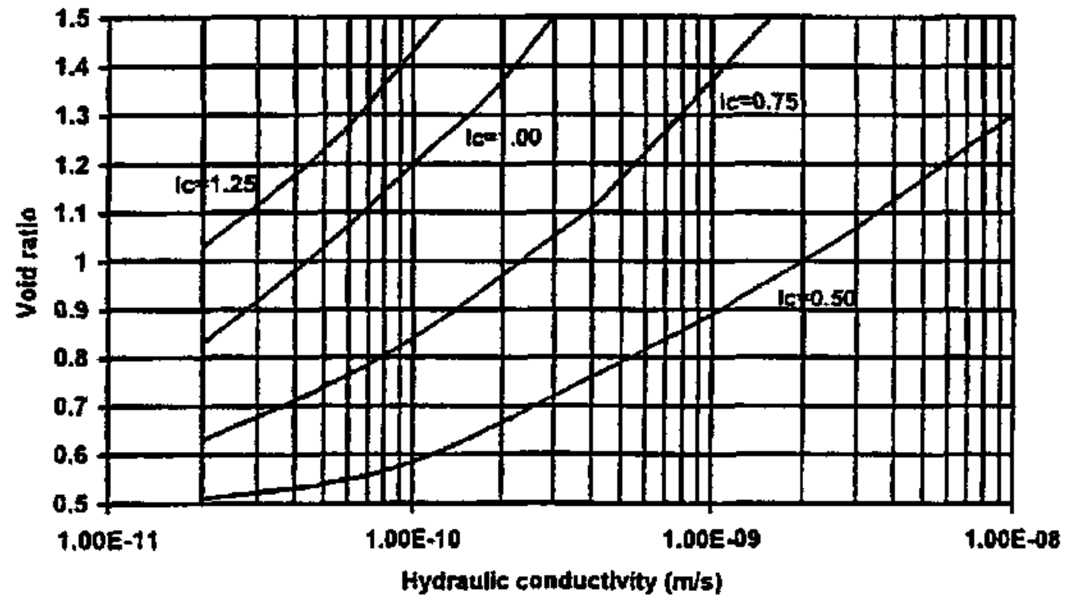


Figure 5. 1: Estimation of saturated hydraulic conductivity (m/s) in a fine-grained soil (after Tavenas et al., 1983).

The saturated hydraulic conductivity of a sample is estimated by comparing the void ratio to the clay fraction and the plasticity index of the entire solid sample.

5.3.6 Description of the soil types occurring in the study area

Soil types of the study area are *Avalon* (test pits A/2, A/3, C/1, G/1, G/2, G/3), *Glencoe* (test pit A/1), *Shortlands* (test pits B/1, B/2, C/2, D/1, F/1, F/2, F/3), *Willowbrook* (test pits B/3, C/3, D/2, D/3), *Katspruit* (test pit E/1) and *Rensburg* (test pits E/2, E/3).

The soil types are briefly discussed below:

- *Avalon* soil form consists of an orthic A, a yellow-brown apedal B and a soft plinthic B horizon.
- *Glencoe* soil form consists of orthic A, a yellow-brown apedal B and a hard plinthic B horizon.
- *Shortlands* soil form consists of orthic A overlying a red structured B horizon.
- *Willowbrook* soil form melanic A above a G horizon.
- *Katspruit* soil form orthic A above a G horizon.
- *Rensburg* soil form consists of a vertic A above a G horizon.

According to the Soil Classification Working Group (1991), an orthic A horizon is a surface horizon without significant organic material or clay content. A melanic A horizon is a soil unit with strongly developed structure without slickensides, while a vertic A horizon is a soil unit with strongly developed structure with slickensides. A yellow brown apedal soil horizon is a soil unit with a diagnostic yellow colour in the wet state and has a structure that is weaker than moderate blocky or prismatic when wet. A red structured B horizon has is diagnostically red when wet with strongly developed soil structure. A soft plinthic B horizon has undergone localized accumulation of iron and manganese oxides and has a loose to slightly firm consistency in the non-concretionary parts of the horizon while a hard plinthic B horizon consists of an indurated zone of accumulated iron and manganese oxides. A G-horizon is saturated with water for long periods and is dominated by grey colours on micro-void and ped surfaces.

CHAPTER 6

CASE STUDIES

6.1 INTRODUCTION

Eleven reclaimed tailings dams (sites A-K) were selected for further investigation. The sites A-G and I-J are situated in the East Rand area of the Gauteng Province and are partially or completely reclaimed. Site H is situated in the Northern Province and is completely reclaimed. Each site is characterised in terms of the following aspects:

1. *General site characterisation,* comprising the locality and site history, fieldwork conducted on site, topography and drainage, vegetation and geological conditions underneath the site.
2. *General soil profile and geotechnical characteristics,* describing important soil parameters such as saturated hydraulic conductivity and soil pH.
3. *Geohydrological characterisation of the unsaturated zone,* giving an indication for flow characteristics and mechanisms (e.g. preferential flow).
4. *Geohydrological characterisation of the saturated zone* (if data were available), comprising the aquifer type and geology and aquifer parameters (e.g. hydraulic conductivities, borehole yield).
5. *Contaminant assessment of the subsurface,* comprising a hydrogeochemical characterisation of the unsaturated and saturated zone with respect to the current pollution situation and the potential future pollution impact.

Field and laboratory testing was conducted on sites A-G from April to June 1988 by the project team, whereas for the sites H-K no field testing was required because of the sufficiency of available data to assess the extent of contamination.

6.2 AVAILABLE INFORMATION

Data and useful information were provided by various sources and were supplemented by a field study and laboratory testing. All the data were captured in a GIS-linked database. A list with various information sources such as from government departments and mining companies is given in **Chapter 2** and **5**. **Table 6.1** below represents a summary of the selected tailings dam sites with important features such ID, geology, area size and status of reclamation and rehabilitation:

Table 6. 1: Important features of the selected case study sites. Figures for reclamation status are estimates provided by the operator. Years of deposition are unknown, except case study site I: 1977-1984 (n.a. = information not available).

Case study	Type	Geology	Size ha	Reclamation status (in %)	Years of reclamation	Environ. Monitor.	Rehab.
A	Slime	Dwyka, Vryheid	50	50	Interrupted in 1996	n.a.	Paddocked
B	Slime	Oaktree, Dwyka	47	90	Late 1980s	None	Paddocked
C	Slime	Dwyka	28	100	1977-mid 1980s	None	All slime removed
D	Slime	Dwyka	71	100	1977-mid 1980s	None	All slime removed
E	Slime	Monte Christo, Vryheid	70	90	Early 1990s	Surface water	Outstanding
F	Slime	Dwyka	120	95	Late 1980s - early 1990s	None	Slime removal ongoing
G	Slime	Dwyka	13	95	1994-1995	None	Partly paddocked
H	Slime	Dolomite	4	100	1940s	Surface / groundwater	n.a.
I	Slime	Karoo, dolomite	1400	30	1996	Surface / groundwater	Some paddocks
J	Slime	Karoo	117	85	1985-present	Surface Water	Partly paddocked
K	Slime	Karoo, dolomite	111	15	Started 1997	Surface / groundwater	n.a.

Data for the period of deposition are generally lacking due to changing ownership. However, most of the tailings dams in Witwatersrand are 30-50 years old (Funke, 1990).

6.3 REGIONAL SETTING

The study area (see **Figure 6.1**) is located in the Blesbokspruit catchment system in the East Rand, approximately 50 km south of the centre of Johannesburg. The Blesbokspruit catchment system ultimately feeds into the Vaal Dam, a major dam known for its importance for the regional water supply to the Gauteng Province in South Africa. The region in which the study area is found was previously called the Witwatersrand. It is also known as the **Highveld Region**, since it is characterised by a high altitude of approximately 1600 m above sea level.

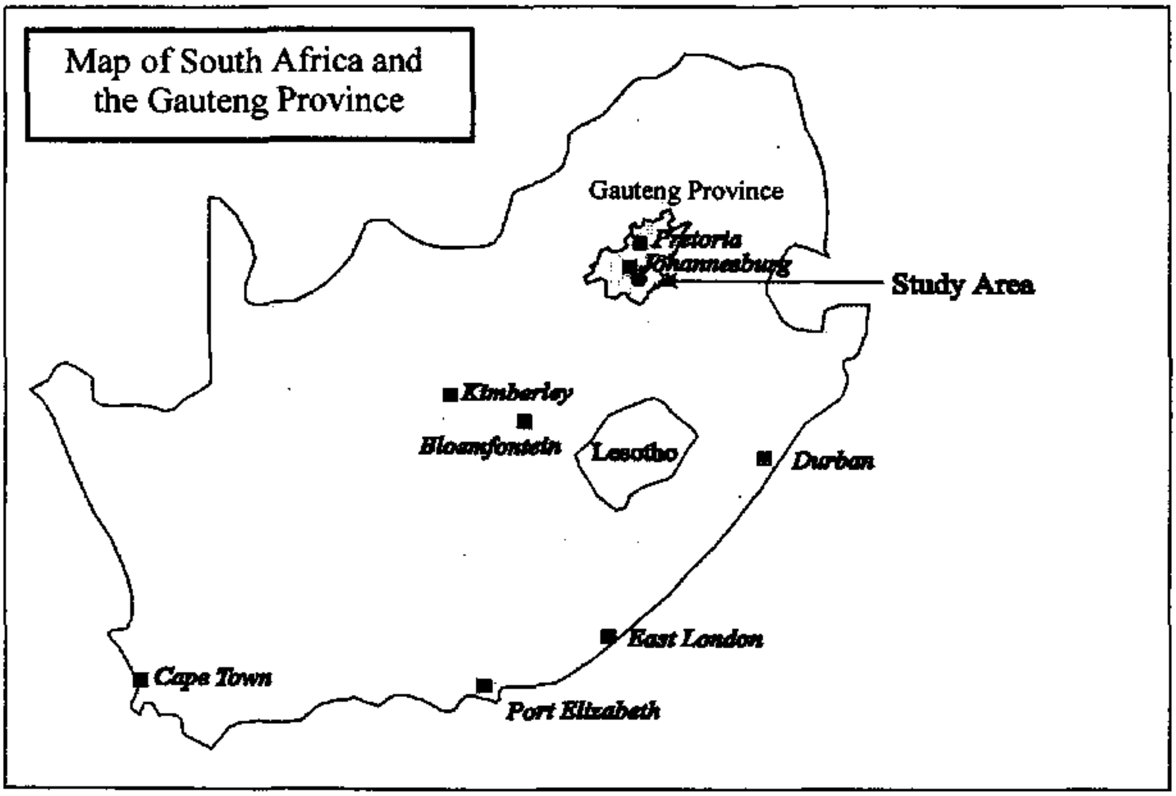


Figure 6. 1: Map of South Africa, showing the Gauteng Province, major cities, Lesotho and the location of the study area.

More than five million people live in Gauteng (mainly in Johannesburg and Pretoria) and population growth is fast (8.5 million in the year 2000, representing 40 % of the urban population in South Africa), resulting in an increasing demand on the water resources of the Vaal Barrage catchment (Van Rooy, 1996). In contrast, the Vaal River catchment produces only 8 % of the country's mean annual run-off (MAR). The combined annual run-off of

South Africa's rivers, calculated on a per capita basis, amounts to only 19 % of the global average (Huntley et al., 1989).

Although this demand is to some extent alleviated by water transfer schemes from other catchments, it is reasonable to assume that future management plans for regional water supply will also include strategies for the increased reuse of water. As the feasibility and cost of water reuse are inherently dependent on water quality, the success of future management plans for water supply from the Vaal Barrage may be influenced by the success in reducing the pollution load entering this catchment.

The reclaimed case study sites A-K were selected mainly because of the availability of site-specific data and the collaboration of a large mining company, which operates these sites. All sites are situated close to perennial streams, residential, industrial and/or agricultural areas.

6.3.1 Regional climate

No site-specific climatic data are available but the statistics for the closest station, the Johannesburg International Airport weather station, were used to describe the climate of the area. The investigation area occurs in the summer rainfall region (mainly between September and April), with the long-term average annual rainfall of 713 mm as shown in **Table 6.2** below:

Table 6. 2: The average monthly rainfall and maximum 24 hour rainfall for the Johannesburg International Airport and surroundings as well as average monthly A-pan equivalent evaporation data (Weather Bureau, 1995)

Month	Jan mm	Feb mm	Mar mm	Apr mm	May mm	Jun mm	Jul mm	Aug mm	Sep mm	Oct mm	Nov mm	Dec mm	Total mm
Rainfall AVG	125	90	91	54	13	9	4	6	27	72	117	105	713
Max. 24hr rainfall	108	56	92	50	70	31	17	21	62	110	55	102	-
Evaporation	222	182	172	135	129	109	123	107	217	246	223	231	2096

The high evaporation rates of the area imply a rainfall deficit during the entire year. **Table 6.3** below represents the average maximum and minimum temperature data for the study area:

Table 6.3: Average monthly maximum (MAX) and minimum (MIN) temperatures (°C) from the Johannesburg International Airport recording station and surroundings (Weather Bureau, 1995)

Month	Jan °C	Feb °C	Mar °C	Apr °C	May °C	Jun °C	Jul °C	Aug °C	Sep °C	Oct °C	Nov °C	Dec °C
MAX	25.6	25.1	24	21.1	10.9	16	16.7	19.4	22	23	24.2	25.2
MIN	14.7	14.1	13.1	10.3	7.2	4.1	4.1	6.2	9.3	11.2	12.7	13.9

The prevailing winds for the area are in a northerly to north-westerly direction, with wind speeds rarely exceeding 10.8 m/s. No rainfall occurred during the field survey period from March to April 1998.

6.4 CASE STUDIES

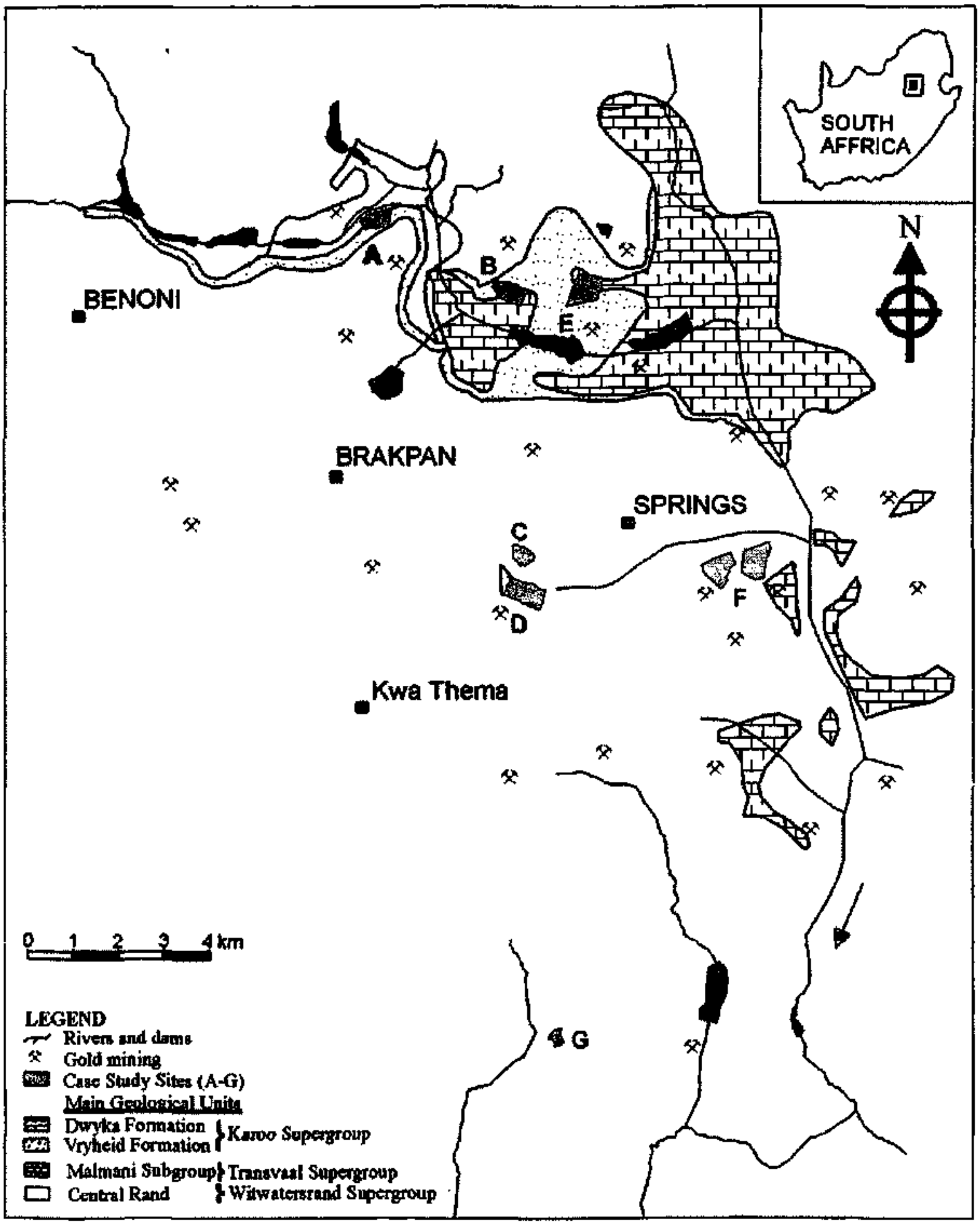


Figure 6.2: Locality map of the case study sites south of Johannesburg (Scale: 1:220 000) including subsurface conditions. Site H is situated approximately 130 kms west.

Sites A-K will be characterised and discussed in the following paragraphs. A site-specific summary with respect to all sites is provided at the end of this chapter. The case studies are discussed in terms of the associated environmental impact on a regional scale in **Chapter 7**. **Figure 6.2** shows a locality map of all investigated sites (A-G), except case study site H:

6.4.1 Case Study SITE A

Site characterisation

Site A is situated approximately 1 km east of the suburbs of Benoni and covers an area size of approximately 50 ha (see Appendix F, Figure 1). A residential area is located on the south-western border of the site. The site is located at an altitude of ±1630 m above sea level. Surface drainage direction is towards a non-perennial stream in the north.

Site A has not been completely reclaimed (reclamation status approximately 50 %) and no vegetation has been established on site except a grass cover and some trees on top of the toe wall. The oxidised zone in the remaining toe wall is clearly visible and reaches up to a depth of approximately 5 m. A paddock system has been established to prevent stormwater surface run-off from the site.

Three test pits (A/1, A/2 and A/3) were excavated and eleven soil samples were retrieved for geochemical analyses. In addition, the geotechnical characteristics of eight samples were determined.

Site A is underlain by sedimentary rocks of the Vryheid Formation, Karoo Supergroup, in the southern part of the site. The Dwyka Group of the Karoo Supergroup underlies the northern portion of the site.

General soil profile

The soils of the site A are of the Avalon (test pits A/2 and A/3) and Glencoe (test pits A/1) pedological soil forms. The following general soil profile occurs:

0.03 – 0.10 m	*Tailings*: Slightly moist, light grey banded pale yellow-brown, very soft, layered sandy silt.
0.20 – 0.55 m	*Colluvium*: Slightly moist, yellow-brown mottled dark brown, loose, slightly open textured clayey sand, stained pale yellow-brown on joints and cracks.
0.45 – 0.60 m	*Pebble marker horizon*: Abundant coarse-, medium- and fine-grained subrounded sandstone and quartz gravel and occasional sandstone boulders (up to 0,25 m in diameter) in slightly moist, yellow-brown mottled dark brown, open textured clayey sand. The overall consistency is very loose.
0.70 – 0.80 m	*Nodular ferruginous residual sandstone* (Vryheid Formation): Abundant coarse-, medium- and fine-grained angular to subrounded ferricrete gravel in slightly moist, yellow-brown, mottled red-brown and orange-brown clayey sand. The overall consistency is medium dense.
1.00 – 1.50 m	*Hardpan ferruginous residual sandstone* (Vryheid Formation): Slightly moist, orange-brown, mottled bright yellow-brown and stained brown, very dense, relic structured clayey sand.
1.30 m	*Sandstone saprolite*: Pale red-brown stained and mottled pale yellow-brown, highly weathered, coarse-grained, closely jointed and fractured, very soft rock sandstone of the Vryheid Formation.

Refusal occurred in test pits A/2 and A/3 on hard rock sandstone at between 1.30 and 1.40 m while test pit A/1 refused at 1.50 m on hardpan ferricrete. The nodular ferruginous soil unit is absent from test pit A/1.

Geotechnical characteristics

The *colluvium* (samples A1/1, A1/2, A2/2 and A3/2) is classified as a silty, clayey sand, a clayey sand or a clayey sand with gravel according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 8.45-15.82 % and a PI (whole sample) of 2.89-6.90 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1752.88-1816.08 kg/m^3 and a specific gravity of 2.72 were measured, which leads to a void ratio of 0.50-0.55 %. The unit has a pH of 3.1- 6.5. A saturated permeability of 1 x 10^{-9} m/s is predicted for the unit (Mathewson, 1981).

The *hardpan ferricrete* (samples A1/3, A2/4 and A3/4) is classified as a silty, clayey sand, or a clayey sand according to the U. S. C. S classification for soils (Howard, 1984). The unit has a clay content of 7.51-12.10 % and a PI (whole sample) of 5.94- 8.9 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1551.43 kg/m^3 and a specific gravity of 2.81 were measured, which leads to a void ratio of 0,81 %. The unit has a pH of 4.4- 6.9. A saturated permeability of 1 x 10^{-9} m/s is predicted for the unit (Mathewson, 1981).

The *nodular ferricrete* unit (sample A3/3) is classified as a clayey sand according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 11.31 % and a PI (whole sample) of 5.11 indicating low expansiveness (Van der Merwe, 1964). The unit has a pH of 6.9.

Geohydrological characterisation of the unsaturated zone

Vertical preferential flow occurs in the clayey sand, colluvial topsoil unit (0.20-0.55 m thickness) which has cracks stained pale yellow-brown. The coloration shows that displacement of the overlying tailings occurs within these structures. Lateral preferential flow may occur at between 0.45-0.60 m on the interface between the pebble marker (very loose consistency) and the underlying nodular ferricrete horizon (test pits A/2 and A/3) or the hardpan ferricrete unit present in test pit (test pit A/1 at 0.60 m). The hardpan ferricrete unit has zones of moist, brown, loose clayey sand within the matrix of very densely cemented clayey sand, through which preferential flow may occur.

However, the migration of metals such as Fe_2O_3 into deeper zones of the test pits indicates alternative flow routes such as preferential flow mechanisms. The ferricrete units in the profile suggest that seasonal perched groundwater tables are present in all test pits.

Contaminant assessment of the subsurface

Current contamination impact

All test pits show a significant trend for Fe_2O_3, where the concentration progressively increases from 3.5 % in the topsoil up to 18 % at 1.0 m depth. Manganese oxide shows a similar trend with 0.02 % in the topsoil and 0.07 % at 1.0 m depth in one of the test pits. The concentrations of MnO lie within ABV of the Vryheid formation given with 0.08 % (Table 5.3). In contrast, the concentration of Fe_2O_3 shows an average of 8.5 %, which is significantly higher than the ABV of 4.4 %, indicating the release of Fe during the pyrite oxidation process and the downward migration towards the groundwater table.

Chromium, Co, Cu and Ba and V concentrations show a clear positive trend to accumulate in the deeper part of the test pits, where As decreases significantly with depth, indicating a low geochemical mobility. However, elevated concentrations of up to 102 mg/kg occur in the topsoils, compared to ABV of 22 mg/kg. The high concentrations of As found in the topsoils and the negative correlation with depth strongly suggest the leaching of As from reclaimed tailings dam into the topsoil, whereupon As seems to be immediately immobilised on solid surfaces such as organic material. The low remobilisation and thus mobility of As has been confirmed by extraction tests. Average Cu concentrations of 64 mg/kg are almost twice as high as the ABV. In contrast, Ba, which typically occurs in feldspars, calcite and apatite, falls within the ABV.

However, elements such as Ni, Th and Pb indicate no significant trends occurring in the soil profiles. In two samples, measured U concentrations of 12 and 7 mg/kg are very low compared to site F, but still above the ABV. Levinson (1974) reports an average concentration of 20 mg Zn per kg in soils, whereas a maximum concentration of 282 mg/kg was found, thus indicating the potential leaching of Zn from the tailings dam into the subsurface.

The *current contamination impact* is represented by the threshold exceedance ratio, (TER) and the mobility of the solid phase (MOB). Arsenic does not show any exceedance of the TER, whereas Co, Ni and Zn exceed TER in all samples, resulting in a limited soil function. Chromium, Cu, Pb and Zn showed exceedance in only one sample. It is important to note that the extractable fraction of Ni is 28-fold higher than the recommended threshold value. The high TER value of Ni can be explained by a high mobility (MOB of 51 %). In contrast, Zn exceedance with regard to TER is not very high (maximum 3-fold); however, the mobility, calculated at 16 %, is particularly high.

Future contamination impact

Soil samples of the test pits A/1, A/2 and A/3 show none to moderate pollution with regard to the elements Ba and Ni, whereas As, Fe, Cr, Cu and Pb fall within pollution class II, reflecting moderate pollution. Only U occurs in concentrations which are classified as moderately to predominantly highly polluted due to a low ABV of 1 mg/kg.

6.4.2 Case Study SITE B

Site characterisation

Site B is situated in close proximity to a residential area on its eastern border, approximately two kilometres north of the outskirts of Springs (see Appendix F, Figure 2). The site covers an area size of approximately 47 ha. and is located at an altitude of ±1615 m above sea level. Surface drainage corresponds to the topographical gradient towards a wetland system in a south-westerly direction. A small squatter camp has been established in immediate vicinity to the reclaimed site.

Site B has been almost completely reclaimed (reclamation status approximately 90 %) except for minor amounts of tailings material still remaining. The site shows natural vegetation, consisting of a poor developed grass cover and some trees. Paddocks systems were established to prevent stormwater surface run-off.

Three test pits (B/1, B/2 and B/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of eight samples were determined.

The southern section of site B is located on dolomites of the Oaktree Formation, whereas the northern part is situated on Dwyka Formation of the Karoo Supergroup.

General soil profile

The soils of site B are of the Shortlands (test pits B1 and B2) and Willowbrook (test pit B/3) pedological soil forms (see Appendix F, Figure 3). The following two general soil profiles occur:

Test pits B1 and B2 (Shortlands soil form)

0.15	*Tailings*: Slightly moist, light grey banded pale yellow-brown, very soft, layered sandy silt (only present at B/2).
0.30 – 0.40 m	*Colluvium*: Slightly moist, dark red-brown, dense, open-structured, sandy silt (B/2) or silty sand (B/1) sand with abundant fine-grained gypsum crystals (up to 5 mm in diameter).
1.80 – 1.90 m	*Colluvium*: Moist, red-brown, firm, intact, sandy clay with occasional fine-grained gypsum crystals (up to 5 mm in diameter);
2.10 m	*Nodular ferruginous colluvium*: Moist, red-brown, firm, intact, sandy clay with numerous coarse-, medium- and fine-grained subrounded ferricrete nodules.

No refusal occurred and no water table was encountered.

Test pits B/3 (Willowbrook soil form)

0.30 m	*Tailings*: Slightly moist, light grey banded yellow brown, very soft, layered sandy silt,
0.50 m	*Colluvium*: Moist, dark grey, stiff, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter).
1.40 m	*Colluvium*: Moist, dark olive to dark yellow brown with depth, mottled dark grey or dark red-brown with depth, firm, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter).
2.10 m	*Nodular ferruginous colluvium*: Abundant medium- and fine-grained subrounded to subangular ferricrete gravel in very moist, light olive mottled black, dark red-brown and dark yellow brown sandy clay;. The overall consistency is stiff.

No refusal occurred and no water table was encountered.

Geotechnical characterisation

The *colluvium* (samples B1/1, B1/2, B2/1, B2/2, B3/1 and B3/2) is classified as a sandy clay of low plasticity, a silt with sand or an elastic silt according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 29.80-63.66 % and a PI (whole sample) of 11.28-19.63 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1619.22-1695.54 kg/m^3 and a specific gravity of 2.45-2.48 were measured which leads to a void ratio of 0.46-0.51 %. The unit has a pH of 3.53 - 6.63. A saturated permeability of 1 x 10^{-10} m/s is predicted for the unit (Mathewson, 1981).

The *nodular ferricrete* unit (sample B2/4 and B3/4) is classified as a clayey sand or an elastic silt according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 19.02-50.24 % and a PI (whole sample) of 8.21-25.67 indicating medium to low expansiveness (Van der Merwe, 1964). The unit has a pH of 5.7- 6.7.

Characterisation of the unsaturated zone

The open structured nature of the topsoil unit may facilitate preferential vertical infiltration, although the abundance of gypsum crystallisation could close up the pores and reduce vertical infiltration rates. Lateral preferential flow may occur at the contact of the nodular ferricrete unit with the overlying soil (between 1.40-1.90 m) as ferricrete formation entails precipitation of colloidal Fe-oxides that may close pores to reduce vertical permeability.

The nodular ferricrete units in the base of the profile suggest that seasonal high moisture contents are expected in all three test pits.

Contaminant assessment of the subsurface

Current contamination impact

In test pits B/1, B/2 and B/3, Fe_2O_3 shows a clear trend with increasing Fe_2O_3 concentrations towards the bottom at 2.10 m depth, whereas MnO indicates a positive trend with depth in one test pit only. Arsenic, Ni (except in test pit three) and Zn show a clear negative trend, thus enrichment occurs only in the topsoil, and lower concentrations were found towards the bottom part of the soil profile. Arsenic reaches an average concentration of 26 mg/kg in the topsoil compared to an ABV of 18 mg/kg. However, natural arsenic concentrations in soils depend on the source rock type, and concentrations up to 40 mg/kg were reported (Wedepohl, 1969). It can be assumed that As has migrated from the mine tailings into the topsoil, where it became readily immobilised. Extremely low remobilisation of As has also been confirmed by the extraction tests.

Average concentrations of Zn and Ni in the topsoils are enriched 2-3-fold compared to ABV of 50 m/kg for the dolomite formation. Rubidium and Zr show concentrations of between 70-100 mg/kg and 180-450 mg/kg respectively, i.e. natural concentratoions values. Both elements are considered to be lithogenic, thus not associated with any type of pollution. Rubidium common occurs in biotites, muscovite and alkali feldspars, whereas Zr is a frequent constituent of the silicate mineral zircon and occurs as a heavy mineral in sands and sedimentary rocks.

Test pit B/3 shows significantly lower concentrations for all measured elements than do the other two test pits B/1 and B/2, as a result of a higher pH which ranges from 6.2-6.7. It is important to note that a small shift in pH can cause a sharp increase or decrease in dissolved heavy metals. In contrast, pH values in test pit B/1 and B/2 are significantly lower (pH 3.6-5), indicating favourable leaching conditions for metals. Furthermore, acidic soils (reflected in low paste pH values) contain generally low concentrations of organic matter and thus have a lower sorption capacity. These factors, associated with preferential flow processes occurring within the soil profile, may promote the migration of pollutants towards the groundwater table.

The application of an extrapolated extractable fraction would result in a TER for Co of 38, indicating a limited soil function. Furthermore, an extrapolated extractable fraction for Ni would result in drastically TER values of up to 88. The TER is also high for Zn , up to 53. No significant threshold exceedance has been found for Cr, Pb and Fe.

Future contamination impact

Site B is moderately polluted by Ba, Cu and Ni, moderately to highly polluted by Co and highly polluted by Pb, reflecting 24-fold enrichment compared to the background. However, natural concentrations of Pb were found in the range between 2-200 mg/kg (Levinson, 1974).

6.4.3 Case Study SITE C

Site characterisation

The site covers an area size of approximately 71 ha and is located at an altitude of ± 1610 m above sea level. A golf course is situated in immediate proximity to the north-eastern border of the reclaimed site. General surface drainage direction is in a southerly direction towards a canal and dam.

Site C has been completely reclaimed and is sparsely covered by grass vegetation. No rehabilitation measures such as paddocks were found.

Three test pits (C/1, C/2 and C/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of nine samples were determined.

The reclaimed site is underlain by rocks of the Dwyka Formation, Karoo Supergroup.

General soil profiles

The soils of the site C are of the Avalon (test pit C/1), Shortlands (test pit C/2) and Willowbrook (test pit C/3) type. The following general soil profile occurs:

0.03 - 0.25 m	*Tailings*: Slightly moist, pale yellow, very soft, layered sandy silt.

0.20 - 0.60 m	*Colluvium*: Moist, dark brown (C/1) or dark grey (C/2 and C/3) mottled dark grey, stiff, open structured sandy clay sand with abundant fine-grained gypsum crystals (up to 5 mm in diameter).
1.10 - 1.40 m	*Colluvium*: Moist, yellow-brown (C/1) or red-brown (C/2) or dark grey (C/3), firm, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter).
1.60 - 2.40 m	*Nodular ferruginous colluvium*: Abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel in moist, light grey mottled yellow brown and black, clayey sand; The overall consistency is medium dense. (This unit is absent in C/3).
2.30 m	Moist, light grey mottled and stained yellow-brown and black, stiff, slickensided clay; residual shale of the Vryheid Formation. (This basal unit is only present in test pit C/3.)

Refusal only occurred in test pit C/1 at 1.60 m on hardpan ferricrete. No water table was encountered.

Geotechnical characteristics

The *colluvium* (samples C1/1, C1/2, C2/1, C2/2, C3/1 and C3/2) classifies as a sandy clay of low plasticity or a clayey sand according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 14.37-42.23 % and a PI (whole sample) of 6.09-14.55 which corresponds to a low to medium expansiveness index (Van der Merwe, 1964). A dry density of 1566.60-1684.51 kg/m^3 and a specific gravity of 2.61 - 2.64 were measured which leads to a void ratio of 0.55 - 0.69 %. The unit has a pH of 3.5-6.8. A saturated permeability of 9×10^{-9} m/s is predicted for the unit (Tavenas et. al., 1983).

The *ferruginous colluvial* unit (sample C1/4, C2/4 and C3/4) classifies as a clay with sand of low or high plasticity or a clayey sand according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 20.93-51.44 % and a PI (whole sample) of 9.36-30.32 indicating medium to low expansiveness (Van der Merwe, 1964). A dry density of 1553.81-1644.29 kg/m^3 and a specific gravity of 2.68 - 2.69 were measured which leads to a void ratio of 0.64-0.72 %. The unit has a pH of 6.29-6.78. A saturated permeability of 7×10^{-9} to 7.5×10^{-10} m/s is predicted for the unit (Tavenas et. al., 1983).

Characterisation of the unsaturated zone

The soils of the site C are of the Avalon (test pit C1), Shortlands (test pit C2) and Willowbrook (test pit C/3) type.

The soils of reclaimed site C exhibit an open soil structure to a maximum depth of 1.40 m. This soil structure should facilitate preferential vertical infiltration, although the abundance of gypsum crystallisation could close up the pores to reduce vertical infiltration rates. Lateral preferential flow may occur at 1.10 m on the boundary between the colluvium and nodular ferricrete units, as ferricrete formation entails precipitation of colloidal iron oxides that may close pores to reduce vertical permeability.

Lateral preferential flow may also occur at 1.40 m at test pit C/3 on the boundary between the ferruginous colluvium and the residual shale. Slickensides occur form 0.80 - 2.30 m and these features may be preferential vertical flow pathways. A hard pan ferricrete unit occurs at 1.60 m in test pit C/1 and lateral preferential flow may be induced on this layer.

Contaminant assessment of the subsurface

Current contamination impact

Iron oxide shows a clear positive trend with depth, whereas concentrations in the topsoils vary from 3.4-8.9 % and at the bottom of the test pit (2.30 m depth), 6.8-12.0 %. High Fe and Mn-oxide concentrations in the solid provide additional sorption surfaces, thus increasing the retention capacity and lowering the concentration of most of the dissolved heavy metals. Test pit C/3 shows generally significantly lower Fe_2O_3 and As concentrations than the two other test pits. The pH value in all topsoil samples varies from 3.5-3.8, thus indicating favourable leaching conditions of metals as a result of a lack of buffer minerals.

In contrast, a negative trend has been observed for As, with decreasing concentrations towards the bottom of the test pit. However, a comparison of As as well as Th values with ABV shows no significant enrichment in the investigated soil medium. In addition, elements such as Ba, Co, Cr, Mn, Mo, Ni, Pb, Sn, V, Zn, U and Th do not show any correlation with depth.

Extrapolated *extractable concentrations* for Co would result in TER values of 28 to 53 and 24 until 72 for Ni respectively. In contrast, Cr and Cu exceed the TC only slightly by a factor of 2 to 4 for Cu and 6 to 10 for Cr respectively. Zn and Pb extractable concentrations are within the TC, thus not exceeding TER.

Future contamination impact

Site C is moderately polluted by Fe, Mn, Cu, Ni, Pb and V while the site is moderately to highly polluted by Ba and Co. The site is highly polluted by Co.

6.4.4 Case Study SITE D

Site characterisation

Site D is situated adjacent to a highway and in close proximity to a large township (see Appendix F, Figure 4). It covers an area size of approximately 28 ha. and is located at an altitude of ±1610 m above sea level. Surface run-off may occur towards a canal in northern direction.

Site D has been completely reclaimed and poor grass vegetation covers the entire area. No land rehabilitation measures were found.

Three test pits (D/1, D/2 and D/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of nine samples were determined. Furthermore, a seepage sample was taken in test pit D2, indicating a perched groundwater table (see **Appendix F, Figure 10**).

Site D is mostly underlain by alluvial sediment deposited by a tributary of a perennial stream. The alluvium is underlain by sedimentary rocks of the Vryheid Formation of the Karoo Supergroup.

General soil profiles

The soil of the site D is colluvium of the Shortlands (test pit D/1) soil form and alluvium of the Willowbrook (test pits D/2 and D/3) soil form. The following two general soil profiles occur:

Alluvium: test pits D/2 and D/3 (Willowbrook soil form)

0.10 - 0.25 m	*Tailings*: Slightly moist, light greyish olive, very soft, intact sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter);
0.25 - 0.40m	*Alluvium:* Slightly moist, dark grey occasionally mottled and striped dark yellow brown, stiff, shattered sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter);
1.10 - 1.30 m	*Alluvium*: Slightly moist, yellow-brown (D/3) or dark grey (D/2) mottled and speckled dark yellow-brown and dark grey, firm, slightly shattered, sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter);
2.00 - 2.10 m	*Alluvium*: Slightly moist, yellow brown (D/3) or dark grey (D/2) mottled and speckled dark yellow brown, dark grey and light grey, stiff, slightly shattered, sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter);
2.40 m	*Alluvium*: Abundant coarse-, medium- and fine-grained, subrounded quartzite and sandstone gravel and occasional subrounded quartzite boulders (up to 0.10 m in diameter) in moist (D/3) or wet (D/2), light olive brown speckled and mottled dark yellow-brown to pale yellow-brown, sandy clay. The overall consistency is soft.

No refusal occurred. A perched water table occurs at 2.00 m in test pit D/2.

Colluvium: Test pits D/1 (Shortlands soil form)

0.60 m	*Tailings*: Slightly moist, pale yellow, firm, intact sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter);

1.20 m	*Colluvium*: Slightly moist, dark brown stained dark grey, firm, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter) and zones of moist, dark grey, soft, intact, sandy clay;
1.90 m	*Ferruginous colluvium*: Slightly moist, red-brown mottled and speckled dark red-brown and black, firm, intact sandy clay with abundant coarse, medium- and fine-grained, subrounded ferricrete gravel and with scattered fine-grained gypsum crystals (up to 5 mm in diameter);
2.30 m	*Ferruginous colluvium*: Slightly moist, red-brown mottled and stained light grey, yellow-brown and brown, stiff, intact sandy clay with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel.

No refusal occurred. No perched water table present.

Geotechnical characteristics

The *upper alluvial unit* (< 0.60 m thick) is represented by samples D2/1, D2/2, D3/1 and D3/2 and classifies as a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 24.58-38.41 % and a PI (whole sample) of 11.95-23.52 which corresponds to a low to medium expansiveness index (Van der Merwe, 1964). A dry density of 1700.96 kg/m^3 and a specific gravity of 2.40 were measured which leads to a void ratio of 0.41 %. The unit has a pH of 3.5- 6.1. A saturated permeability of 1 x 10^{-10} m/s is predicted for the unit (Mathewson, 1981).

The *deeper alluvial unit* (> 1.50 m in depth) is represented by samples D2/4 and D3/3 and classifies as a clayey sand with gravel or a clay with sand of high plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 19.51-48.66 % and a PI (whole sample) of 13.46-28.47 which corresponds to a medium expansiveness index (Van der Merwe, 1964). The unit has a pH of 7.4- 7.7.

The *colluvial unit* is presented by sample number D1/2 and the material classifies as a clay with sand of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 46.78 % and a PI (whole sample) of 14.26 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1602.09 kg/m^3 and a specific gravity of 2.61 were measured which leads to a void ratio of 0.63 %. The unit has a pH of 4.0. A saturated permeability of 8 x 10^{-10} m/s is predicted for the unit (Tavenas et. al., 1983).

The *ferruginous colluvial unit* is presented by sample numbers D1/3 and D1/4 and the material classifies as a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 28.90-34.33 % and a PI (whole sample) of 14.06-14.09 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1520.08 kg/m^3 and a specific gravity of 2.80 were measured which leads to a void ratio of 0.84 %. The unit has a pH of 3.8- 5.0. A saturated permeability of 9.5 x 10^{-8} m/s is predicted for the unit (Tavenas et. al., 1983).

Geohydrological characteristics of the unsaturated zone

Vertical preferential flow may occur between 0.10 - 2.10 m in the alluvial soils of test pits D/2 and D/3 as these soil units have a shattered structure (well aggregated soil). A perched water table occurs at 2.00 m in test pit D/2 that implies preferential lateral flow. Lateral preferential flow may occur at 1.20 m in the colluvial soils of test pit D/1 on the boundary between the colluvium and nodular ferricrete units.

The nodular ferricrete units in the base of the colluvial profile suggest that a seasonal high moisture content is expected in test pit D/1. A perched water table occurs in test pit D/2 at 2.00 m depth, a seepage sample was taken for chemical analyses.

Contaminant assessment of the subsurface

Current contamination impact

An increasing trend has been observed for Fe_2O_3, Cr and Zr, whereas MnO, Ni, Cu, As, Ba, Th, Pb, Co, Mo, V and Rb indicate no trend with depth. Average concentrations for Fe_2O_3 are twice as high compared to ABV for the Vryheid Formation, indicating the release of Fe from the pyrite oxidation process.

In addition, V, Co and Zn are 3-fold enriched compared to the ABV, and Cr and Ni are as twice as high as the ABV. Cu, As, Ba, Pb and Th concentration ranges are within the ABV. In one sample, U shows a concentration of 8 mg/kg. However, this concentration is very low compared to other sites, where concentrations above 1000 mg/kg were encountered.

The lithogenic elements Rb and Zr show no deviation in their concentrations from other sites. Measurements of pH indicate favourable leach conditions in test pits D/1 and D/3. However, almost neutral pH values were encountered towards the bottom of the test pits, indicating the effect of buffering minerals such as carbonates and/or fluctuations in a shallow groundwater table causing dilution effects.

The seepage analyses in test pit D/2 is shown in **Table 6.4** below. High alkalinity values reflecting the acid neutralisation capacity indicate the buffering of carbonate containing minerals and result in an almost neutral pH of 6.3.

Table 6. 4: Seepage analyses showing the macro chemistry of a water sample obtained from test pit D2. Alkalinity measured as total alkalinity ($CaCO_3$).

Parameter	pH	EC mS/m	TDS mg/l	Alk	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cl mg/l	NO_3 mg/l	HCO_3 mg/l	SO_4 mg/l
D2	6.3	3.09	2214	348	219	147	262	5.37	336	<0.1	348	1006

However, TDS values are relatively high and mainly caused by high salt concentrations such as sulphate and chloride. **Table 6.5** represents metal and cyanide concentrations. Arsenic, CN, Cu and Pb concentrations are below the detection limit. The concentrations of Fe, Mn, Ni and Zn are low compared to seepage samples of the sites G and F.

Table 6. 5: Seepage analyses showing the micro-chemistry of a water sample obtained from test pit D2.

Parameter	pH	As mg/l	Cu mg/l	CN mg/l	Fe mg/l	Mn mg/l	Ni mg/l	Pb mg/l	Zn mg/l
D2	6.3	<0.1	<0.01	<0.2	3.2	0.76	0.13	<0.01	0.05

Extrapolated extractable Ni concentrations result in TER varying from 19 to 40. In addition Co and Cr reach a TER of up to 44 and 18-fold respectively, indicating limited soil functioning. The extractable Zn concentration does not exceed significantly the TC.

Future contamination impact

Site D is moderately polluted by As, Co, Cr, Fe and V while the site is moderately to highly polluted by Pb and Ni. The site is highly polluted by Co, U and V.

6.4.5 Case Study SITE E

Site characterisation

Site E is situated approximately one kilometre to the north of the outskirts of Springs and is bordered by a dam on its western side. An industrial area is located on the eastern border of the reclaimed site. The reclaimed site E covers an area size of approximately 111 ha. and occurs at an altitude of ±1585 m above sea level. Surface drainage occurs towards a canal in a southerly direction. The canal feeds a dam further downstream.

The site has been completely reclaimed (reclamation status, 90%) and is sparsely covered by grass vegetation. Paddocks systems were established to prevent stormwater surface-run-off from the site (see **Appendix F, Figure 5**).

Three test pits (E/1, E/2 and E/3) were excavated and ten soil samples were retrieved for geochemical analyses. The geotechnical characteristics of seven samples were determined.

Site E is mostly underlain by alluvial sediments deposited by a tributary of a perennial stream. The alluvium is underlain in the northern section of the site by sedimentary rocks of the Dwyka Group of the Karoo Supergroup and by dolomitic rock of the Oaktree Formation of the Malmani Subgroup, Transvaal Supergroup in the southern portion of the site. Dolorite sill occurs in the central portion of the site.

General soil profiles

The soils of the site E are colluvium of the Katspruit (test pit E/1) soil form and alluvium of the Rensburg (test pit E/2 and E/3) soil form. The following two general soil profiles occur:

Alluvium: test pits E/2 and E/3 (Rensburg soil form)

0.20 - 0.30 m	*Fill:* Moist, red-brown, very loose, layered silty sand with abundant organic residue;
0.60 - 0.60 m	*Alluvium*: Moist, black, soft, intact clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter);
1.00 - 1.10 m	*Alluvium*: Moist, black, firm, slickensided clay (E/2) or sandy clay (E/3) with numerous coarse-, medium- and fine-grained subrounded quartz gravel and occasional fine-grained gypsum crystals (up to 5 mm in diameter);
1.30 - 1.50 m	*Alluvium*: Moist, blueish grey mottled dark yellow brown and dark grey, firm, slickensided clay with occasional coarse-, medium- and fine-grained calcrete and quartz gravel and scattered fine-grained gypsum crystals (up to 5 mm in diameter).

Refusal at 1.50 m (test pit E/2) and 1.30 m (E/3). No water table encountered.

Colluvium: Test pits E/1 (Katspruit soil form)

0.30 m	*Tailings*: Slightly moist, pale yellow brown mottled black and orange brown, very soft, layered sandy silt;
0.50 m	*Colluvium*: Moist, brown mottled dark grey and dark brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5mm in diameter);
1.30 m	*Colluvium*: Moist, light grey mottled yellow-brown and dark grey, stiff, slickensided sandy clay with occasional fine-grained gypsum crystals (up to 5 mm in diameter);
2.00 m	*Colluvium*: Moist, yellow-brown mottled light grey and dark grey, stiff, slickensided sandy clay with abundant fine-grained subrounded

	quartz gravel and sporadic rounded quartzite boulders (up to 0.40 m in diameter);
2.30 m	*Colluvium*: Abundant coarse-, medium and fine-grained subrounded quartz gravel and occasional ferricrete nodules in wet yellow-brown sandy clay; The overall consistency is firm.

No refusal. A perched water table exists at 2.00 m.

Geotechnical characteristics

The *alluvial soil* is represented by samples E2/1, E2/2, E2/3, E3/1 and E3/2 and classifies as a clay with sand of high plasticity or a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 35.02-46.55 % and a PI (whole sample) of 22.27-38.38 which corresponds to a medium to very high expansiveness index (Van der Merwe, 1964). A dry density of 1484.87-1535.06 kg/m^3 and a specific gravity of 2.68 was measured which leads to a void ratio of 0.75-0.80 %. The unit has a pH of 5.1-7.8. A saturated permeability of 9×10^{-9} to 8×10^{-10} m/s is predicted for the unit (Tavenas et al., 1983).

The *colluvial unit* is presented by sample numbers E1/2 and E1/3 and the material classifies as a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 33.29-40.06 % and a PI (whole sample) of 21.28-23.05 which corresponds to a medium expansiveness index (Van der Merwe, 1964). A dry density of 1535.78-1775.29 kg/m^3 and a specific gravity of 2.55-2.70 were measured which leads to a void ratio of 0.44-0.76 %. The unit has a pH of 6.7–7.0. A saturated permeability of 1×10^{-10} to 9.5×10^{-9} m/s is predicted for the unit after Mathewson (1981) and Tavenas et. al. (1983).

Geohydrological characterisation of the unsaturated zone

In the clayey alluvial soils of test pits E/2 and E/3, slickensides occur between 0.60 m and a maximum of 1.50 m and these features may be preferential vertical flow pathways. Both test pits refused on an alluvial boulder layer (at 1.50 m in test pit E/2 and 1.30 m in test pit E/3). This boulder layer may be a unit where lateral preferential flow occurs due to the relatively high permeability of this unit. A perched water table exists at 2.00 m in the colluvial soils of test pit E/1 that implies preferential lateral flow. Vertical preferential flow may occur between 0.50 m and 2.00 m in test pit E/1 as these soils are slickensided.

Contaminant assessment of the subsurface

Current contamination impact

Iron oxide, Cr, V, Rb and Zr show an increasing trend with depth, thus indicating the downward migration, whereas Zn and Pb indicate a contrasting trend. Iron oxide concentrations of most of the soil samples are within ABV of 6.1 %. All the other elements do not show any correlation with depth. However, Cr, Co, Cu, Ni, Pb, Th and V show higher concentrations than ABV, although Levinson (1974) reports concentrations for these metals exceeding the ABV by up to 10 times. In addition, U has not been detected in the soil samples.

No TER and past pH values are available for this site. However, aqueous extraction tests conducted on samples taken from three different test pits on site by the former operator of the reclaimed mine tailings indicate low pH values (2.4-4.1) in topsoil samples and fairly neutral pH values at depths between 6.9-7.4, thus indicating the presence of buffering minerals. Even after the fourth leaching test has been conducted, sulphate concentrations exceed the recommended maximum concentration of 600 mg/l (SABS, 1984). The high sulphate concentrations in the topsoil are a result of sulphide mineral oxidation of the reclaimed tailings dam and migration downwards into the unsaturated zone.

Future Contamination Impact

Site E is moderately polluted by Fe, Co, Pb and V, while the site is moderately to highly polluted by Pb and V. High SO_4^{2-} loads will remain in seepage water until sulphide minerals are consumed by the oxidation process.

6.4.6 Case Study SITE F

Site characterisation

Site F is situated approximately 1 km south of the outskirts of Springs adjacent to a highway and bordered to the east by a small township. Site F consists of two reclaimed tailings dams, which were located next to each other. The reclaimed sites cover a total area size of approximately 120 ha. The area seems to be affected by a former uranium processing plant which was located next to the site. High uranium oxide concentrations found in the topsoil indicate the deposition of radioactive waste material on this site. The site is located at an altitude of ±1585 m above sea level. Surface drainage is towards a perennial stream in the east.

Both sites have been reclaimed, but small volumes of tailings material still on site indicate the presence of the former tailings dam. Some vegetation has been developed on site and the mining company is in the process of removing the remaining tailings material (see **Appendix F, Figure 6**).

Four test pits (F/1, F/2, F/3 and F/4) were excavated on site and sixteen soil samples were retrieved for geochemical analyses. The geotechnical properties of twelve samples were determined. This site was identified as a problem area during the course of the literature study. Hence, investigations have been conducted in greater detail.

The majority of the site is underlain by rocks of the Vryheid Group, Karoo Supergroup, whereas a small proportion in the south-eastern section is underlain by sedimentary rocks of the Dwyka Formation, Karoo Supergroup.

General soil profile

The soils of site F are of the Shortlands soil form. The following general soil profiles occurs:

0.05 - 0.50 m	*Tailings*: Slightly moist, pale yellow-brown, very soft, layered sandy silt;
0.30 - 0.70 m	*Colluvium*: Slightly moist, dark red-brown, soft, open textured sandy clay with abundant fine-grained gypsum crystals (up to 0.05 m in diameter);
1.00 - 1.10 m	*Colluvium*: Moist, red-brown, soft, open textured sandy clay with abundant fine-grained gypsum crystals (up to 0.05 m in diameter, this horizon is absent from test pit F/4);
1.70 m	*Colluvium*: Abundant medium- to fine-grained subrounded chert gravel and occasional ferricrete nodules and occasional subangular chert boulders (up to 0.07 m in diameter) in moist, red-brown sandy clay; The overall consistency is stiff. (This unit is only present in test pit F/3);
2.00 - 2.20 m	*Colluvium*: Moist, dark red-brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 0.05 m in diameter);
2.40 m	*Nodular ferruginous colluvium*: Very moist, dark red-brown, stiff, intact sandy clay with abundant coarse-, medium- and fine-grained subangular ferricrete nodules;

Refusal only occurred in test pit F/3 at 1.70 m on chert boulders. No perched water table is present in any of the test pits.

Geotechnical characteristics

The *colluvial unit* is presented by sample numbers F1/1, F1/2, F1/3, F2/1, F2/2, F2/3, F3/1, F3/2, F4/1 and F4/2 and the material classifies as a sandy clay of low plasticity or a clay with sand of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 13.70-44.22 % and a PI (whole sample) of 6.64-14.33 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1661.44-1711.02 kg/m^3 and a specific gravity of 2.51-2.78 were measured which leads to a void ratio of 0.47-0.67 %. The unit has a pH of 3.7- 6.7. A saturated permeability of 6 x 10^{-9} to 1 x 10^{-10} m/s is predicted for the unit after Mathewson (1981) and Tavenas et. al. (1983).

The *nodular ferricrete unit* is presented by sample numbers F3/4 and F4/4 and the material classifies as a clayey sand with gravel or a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 19.72-39.56 % and a PI (whole sample) of 6.21-15.89 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1739.57 kg/m^3 and a specific gravity of 2.72 were measured which leads to a void ratio of 0.56 %. The unit has a pH of approximately 4.7. A saturated permeability of 6 x 10^{-10} m/s is predicted for the unit after Tavenas et. al. (1983).

Geohydrological characterisation of the unsaturated zone

The soils are open structured between a minimum of 0.05 m (test pit F/3) and a maximum of 2.40 m (test pit F/4). The open structured nature of this soil unit should facilitate preferential vertical infiltration, although the abundance of gypsum crystallisation could close up the pores to reduce vertical infiltration rates.

Lateral preferential flow may occur at the contact of the nodular ferricrete unit with the overlying soil (at a minimum of 1.00 m in test pit F/3 and a maximum of 2.20 m in test pit F/2) as ferricrete formation entails precipitation of colloidal Fe oxides that may close pores to reduce vertical permeability. Test pit F/3 refused at 1.70 m on chert boulders that may be a preferential lateral flow path due to the relative higher permeability of this unit.

No perched water tables were encountered but the basal nodular ferricrete unit present in most of the test pits are indicative of seasonal high moisture contents in the base of the profiles.

Geohydrological characterisation of the saturated zone

The site is underlain by a dolomitic aquifer. Repeated collapse during drilling, the recirculation of air during borehole development and the high transmissivity calculated from pumping tests indicate the presence of karstified features at shallow depth in this area. In addition, the high transmissivity of the dolomitic aquifer results in the immediate down gradient migration of contaminants away from the site, towards a perennial stream in the east.

A hydrocensus revealed the presence of 18 boreholes in close proximity to the site, which are used for irrigation of gardens and swimming pools. One monitoring borehole has been drilled on site and shows a groundwater yield of approximately 5 l/s. A groundwater table was determined at approximately 11 m below surface.

Contaminant assessment of the subsurface

Current contamination impact

The site shows relative low concentrations of some of the heavy metals such as MnO, Co, Pb, Zn compared to the ABV of the Vryheid Formation. However Fe_2O_3 shows higher concentrations than ABV, indicating the potential release of Fe during the pyrite oxidation process. Ni and As show 8-fold higher concentrations than the ABV, however their mobility is very low. Remarkable concentrations of U were found in six of sixteen samples, whereas three samples showed concentrations higher than 700 mg/kg, two of them collected from the topsoil. The U is likely to be released from the former uranium processing plant.

The extractable concentrations of trace elements of all soil samples were determined and extrapolated to the other sites A-E and G. The calculation of TER values revealed that Co, Ni and U exceed significantly TC. Co reaches a TER of up to 40, Ni of up to 72.5 and U of up to 118.75 due to a very high mobility of 6.4 % (MOB) at pH values between 3-4. Low TER values were found only Cu, Pb and Zn due to relatively low concentrations in the solid phase. However, MOB is significant high for these elements. The soil pH indicates in two test pits an increase of pH with depth from 4.4 to 6.3 and 4.5-5.2 respectively, whereas the two other test pits showed lowed pH values even at greater depths (maximum depth 2.4 m).

Various reasons can result in the lowering or increase of pH values at greater depths in the test pits. For instance a rise of the dolomitic groundwater table would result in dilution effects, thus increasing the pH. In contrast, a lack of buffer minerals in soils such as carbonates could lower the soil pH values.

Measured groundwater quality on site is presented in **Table 6.6**. The table indicates that groundwater underneath the reclaimed site is of poor quality and does not conform with specified drinking water limits with regard to Ca^{2+}, Mg^{2+}, SO_4^{2-} and NO_3^-. Groundwater shows a predominant Mg-Ca-SO_4 character, which becomes more pronounced with increasing TDS values. The pH is fairly neutral, although high concentrations of TDS occur indicating the acid neutralisation capacity of the groundwater in this particular area. Lower amounts of TDS and earth alkali metals respectively, can be explained with dilution effects as a result of net recharge to the aquifer.

Table 6.6: Groundwater quality at site F, measured in January, April and August 1996. RML means "Recommended Maximum Limit" according to Aucamp & Vivier (1987) and SABS* (1984).

Parameter / Sampl. Date	pH	TDS mg/l	Alk	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cl mg/l	SO_4 mg/l	NO^3 mg/l	CN mg/l
Jan 1996	6.7	2274	158	314	123	132	15	165	869	64	<1
Apr 1996	7.0	1328	162	184	69	102	0.1	216	729	3.5	<0.5
Aug 1996	7.3	1502	n/a	112	11	100	7.7	176	712	n. a.	n. a.
RML	6-9*	-	300	150	70	100	200	250	200	6	0.2

Future contamination impact

Site F is moderately polluted by Mn, As, Co, Ni and Th while the site is moderately to highly polluted by As and Ni, although As seems to have a very low mobility. In addition, the site is excessively polluted by U (pollution class VI). Important to note is, that U showed a high mobility, thus becoming easily bio-available to organisms. Groundwater quality indicates a significant impact from the reclaimed site, reflected by high TDS and SO_4^{2-} values.

6.4.7 Case Study SITE G

Site characterisation

The site situated approximately 4 km north east of the outskirts of Nigel. The site covers an area size of approximately 13 ha and is located at an altitude of ±1610 m above sea level. Surface drainage direction is towards a canal in western direction. Agricultural activities were found in immediate vicinity to the site.

The reclamation of tailings dam site G has been completed, except some rock material on the south-eastern border. However remaining tailings material in small volumes indicates the presence of the former tailings dam. No vegetation is presently developed except some pampersgras (prefers acidic conditions) and isolated trees.

Three test pits (G/1, G/2 and G/3) were excavated and eight soil samples were retrieved for geochemical analyses. The geotechnical characteristics of six samples were determined.

The reclaimed site G is underlain by sedimentary rocks of the Vryheid Formation, Karoo Supergroup.

General soil profile

The soils of the site G are of the Avalon soil form. The following general soil profiles occurs:

0.10 - 0.45 m	*Tailings*: Slightly moist, pale yellow, very soft, layered sandy silt;
0.35 - 0.80 m	*Colluvium*: Moist, dark grey (G/1), olive (G/2) or dark brown (G/3) stained black, medium dense, intact clayey sand;
0.70 - 0.80 m	*Ferruginous colluvium*: Moist, light grey stained pale yellow brown and occasionally mottled orange brown and black, medium dense, intact clayey sand with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel;
1.10 - 1.50 m	*Ferruginous colluvium*: Very moist, light grey mottled and stained orange brown and dark yellow brown, loose, intact clayey sand with abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel;

Refusal occurred at between 1.10 m and 1.50 m on hardpan ferricrete. Perched water tables were encountered in test pits G/2 and G/3 at 0.95 m and 1.30 m respectively.

Geotechnical characteristics

The *colluvial unit* is presented by sample numbers G1/1, G3/1 and G3/2 and the material classifies as a clayey sand according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 14.10-24.69 % and a PI (whole sample) of 5.78-8.27 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1786.21 kg/m^3 and a specific gravity of 2.64 were measured which leads to a void ratio of 0.48 %. The unit has a pH of 4.0-4.8. A saturated permeability of 1 x 10^{-9} m/s is predicted for the unit after Mathewson (1981).

The *nodular ferricrete* unit is presented by sample numbers G1/3, G2/2 and G3/3 and the material classifies as a clayey sand with gravel, a clayey sand or as a sandy clay of low plasticity according to the U.S.C.S classification for soils (Howard, 1984). The unit has a clay content of 22.63-31.45 % and a PI (whole sample) of 7.60-9.48 which corresponds to a low expansiveness index (Van der Merwe, 1964). A dry density of 1782.53 kg/m^3 and a specific gravity of 2.68 were measured which leads to a void ratio of 0.50 %. The unit has a pH of 6.30- 6.9. A saturated permeability of 1 x 10^{-9} m/s is predicted for the unit after Mathewson (1981).

Geohydrological characterisation of the unsaturated zone

Lateral preferential flow may occur on the hardpan ferricrete unit that caused refusal in all the test pits between 1.10 m and 1.50 m. A perched water table occurs at 0.95 m in test pits G/2. This is a zone of preferential lateral flow. Perched water tables were encountered in test pits G/2 and G/3 at 0.95 m and 1.30 m respectively.

Contaminant assessment of the subsurface

Current contamination impact

Most of the elements show no correlation with depth except Th, which has a positive correlation with depth. In contrast, As shows a negative correlation with depth due to a low mobility. Cobalt, Cu and Th exceed ABV slightly, whereas As shows significant concentrations in two topsoil samples with 52 and 56 mg/kg compared to an ABV of 22 mg/kg. In contrast Cr, Pb, V and Zn concentrations found in the soil samples are lower than ABV of the Vryheid Formation.

Low soil pH values (4.0-4.8) indicate favourable leaching conditions of dissolved metals. This is also reflected in one seepage sample collected in test pit G/2 and analysed for the macro and microchemistry. Seepage indicates a perched groundwater table. The macro chemistry is shown in **Table 6.7** below. Extreme high TDS values mainly caused by high sulphate concentrations and elevated concentrations of As, Fe and Mn under acidic pH conditions indicate the presence of AMD.

Table 6. 7: Seepage analyses showing the macro chemistry of a water sample obtained from test pit G2. Alkalinity measured as total alkalinity ($CaCO_3$).

Parameter	pH	EC mS/m	TDS mg/l	Alk	Ca mgl	Mg mg/l	Na mg/l	K mg/l	Cl mg/l	NO_3 mg/l	HCO_3 mg/l	SO_4 mg/l
G2	4.9	670	602	8	525	257	227	154	207	<0.1	8	4760

The microchemistry of the seepage sample is summarised in **Table 6.8** below:

Table 6. 8: Seepage analyses showing the micro chemistry from test pit G2.

Parameter	pH	As mg/l	Cu mg/l	CN mg/l	Fe mg/l	Mn mg/l	Ni mg/l	Pb mg/l	Zn mg/l
G2	4.9	0.12	0.1	<0.2	431	359	4.4	0.03	0.3

Potential future pollution impact

Site G is moderately polluted by Co and none to moderately polluted with As, Ni and Sn.

Pollution Status for the Other Sites

During the course of the literature study two sites have been identified, where a numerical groundwater model has been conducted in order to assess the present and future impact of the tailings dam on groundwater quality. Another two sites have been identified, where extensive testing has been conducted. The results of these sites are summarised below.

It is important to note that the summary below does not necessarily reflect the opinion of the authors and is only based on internal documents provided by the tailings dam operators.

6.4.8 Case Study SITE H

The investigation of this site has not been conducted as part of the WRC project, but data were provided from the Council for Geoscience. DME is currently investigating a rehabilitation plan for this site.

Site characterisation

The study area is located in the North West Province, west of Potchefstroom. The reclaimed investigated site covers an area of approximately 4 ha. Three other slimes dams and a rock dump are situated in close proximity to the investigated site (within a radius < 1 km). Gold mining activities in the investigated area started already in the 1930's. Mining proceeded actively until the early 1940's when the gold-mine was decommissioned. During this time four tailings dams were established, to deposit the residues of the gold recovery process. Subsequently to the closure of the mine one of the slimes dams has been reclaimed and approximately 4 ha of land has been exposed where a tailings dam was used to be. The remaining slimes dams were not stabilized, thus wind and water erosion (rainfalls) caused a downstream transport and deposition of fine slime material in a floodplain near a stream. Three auger holes (H/1, H/2 and H/3) have been drilled and sampling has been conducted at various profile depths. The area has a gentle sloping topography towards the south with an average height of 1379 m above sea level. The highest part of the mine boundary area is a hill located to the immediate west of the site at 1560 m above sea level. The southern section of the mine boundary is the Kromdraaispruit at an altitude of 1373 m above sea level. Predominant drainage mechanism of the site is sheetwash, which takes place in southerly direction. The drainage has resulted in portions of the floodplain being covered by fine slimes material originated from the tailings dams.

The vegetation cover of the site consists of pure developed grassveld made up of the Cymbogon-Themalda veld types according to Acocks (1988). Indigenous trees (species include Rhus and Combretum) are present in thickets, scattered across the mine area. Exotic trees (including Eucalyptus) occur around the old mine operations and on some of the tailings dams. The only vegetation present in the investigated area is unidentified grass and small shrubs, that occur sparsely in proximity to outcrop.

The area falls in the eastern boundary of the semi-arid climatic region of South Africa and receives on average up to 500 mm rain in the summer period (October – March), as showers and thunderstorms. The average maximum and minimum temperatures are approximately 31°C in summer and 17°C in the winter time. The prevailing wind direction of the area is north-westerly.

The area is underlain by dolomite of the Oaktree Formation of the Malmani Subgroup, Transvaal Supergroup.

Characterisation of the unsaturated zone

Three different dolomite residuum horizons were identified. A chert rich residual dolomite occurring in auger hole H/1 and H/2, a residual shale horizon occurring in auger hole H/1 and a rich ferricrete and poor chert horizon in auger holes H/2 and H/3.

The chert rich unit is approximately 1.50 m thick, consisting of abundant coarse-, medium and fine-grained, subrounded chert fragments in a matrix of slightly moist dark red-brown, specked and mottled white, clayey sand with abundant fine-grained, well-rounded ferricrete nodules. The residual shale horizon occurs at a depth of 1.50 m (auger hole H/1) and shows an average thickness of 0.50 m. The horizon consists of slightly moist, dark yellow-brown to dark olive-brown, speckled and mottled white sandy silt to sandy clay, with abundant to absent coarse-, medium and fine-grained ferricrete nodules. The rich ferricrete and poor chert unit consists of abundant to occasional medium to fine-grained, well rounded ferricrete nodules in slightly moist, dark brown silty clay in augerholes H/2 and H/3. The horizon is generally 1.50 and 2.50 m thick and occurs at a depth of 1.00 to 1.50 m.

Characterisation of the saturated zone

Limited groundwater data are available for this site, which were obtained from one borehole on site. A perched groundwater table was detected at a depth of about 7 m.

Contaminant assessment of the subsurface

Current pollution impact

Extraction tests (2 mm grain size fraction) were conducted to assess the current pollution impact. Bio-available concentrations of Ni, Zn and Cd in the soil increase where nodular ferricrete is more distinctly developed in the soil. The bio-available concentrations of Cr and Cu do not reflect a clear geochemical pattern. It can be concluded that Cd poses a hazard in the ferricrete, reflected by a threshold exceedance of almost 10. Copper, Ni and Zn pose a hazard in both their ferricrete poor soil and the ferricrete. Mercury does not pose a hazard, because bio-available concentrations of Hg are very low in all soil samples.

Two sets of groundwater measurements from one borehole on site are available and are presented in **Table 6.9.** below. High concentrations of SO_4^{2-} indicate the impact of AMD on groundwater quality. High concentrations of Ca^{2+} are reflected by dissolution reactions of the dolomitic aquifer material and result in neutral pH conditions.

Table 6. 9: Macro-chemistry from a groundwater sample.

Parameter / Sampl. date	pH	EC mS/m	NO_3 mg/l	SO_4 mg/l	HCO_3 mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
June 1998	7.7	338	145.5	2247	329.4	63.2	26.2	521	307
July 1998	7.7	328	-	2552	262.3	66.8	30.3	527	310

Potential future pollution impact

No background data for the 2 mm particle size fraction were available.

6.4.9 Case Study SITE I

Site characterisation

The site is located adjacent to the R23 (Old Heidelberg Road) between Brakpan and Heidelberg. The tailings dam comprises a southern compartment, which is currently reclaimed and retreated, and a northern compartment (active dam) where gold-mine tailings have been deposited (approximately 100000 t/day) by cycloning since 1985 (and are still being deposited). The maximum wall height of the current active dam is over 60 m and the dam has been in operation since 1985. The target height is anticipated to be approximately 85 m above lowest ground level. The current active dam covers an area of 870 ha, whereas the entire affected area, which includes the reclaimed area, results in an area size of approximately 1400 ha. A township is situated less than two kilometers east of the tailings dam and there is agricultural activity in the immediate surroundings. A perennial stream flows in a north-westerly direction and in a distance of less than a kilometer along the western boundary of the tailings dam through a wetland system.

The area slopes gently in a westerly direction towards a wetland system less than 1 km away. Surface run-off is controlled and limited by a drainage collection system surrounding the tailings dam. No vegetation is found at the reclaimed tailings dam (southern dam) due to the ongoing reclamation operation.

The tailings dam is surrounded by monitoring boreholes, which are sampled on a quarterly basis in order to determine groundwater quality (TDS, pH, EC, alkalinity, total hardness, major cations and anions, CN, As, Fe and Mn) at various depths and distances away from the tailings dam. An extensive geotechnical study was launched as part of the feasibility study for the northern tailings dam in the mid 1980s, which comprised core drilling, the excavation of a large number of test pits and a soil survey in the area now covered by the tailings dam. Pump testing has been conducted to assess the geohydrological properties of the aquifer underneath the site. As a result, detailed geological and geohydrological information were available, which were incorporated into the numerical model.

A vegetation cover is established on the slope walls to prevent wind erosion (see **Appendix F, Figure 7**).

The tailings dam is mainly underlain by andesitic lava of the Ventersdorp Supergroup and quartzite (Black Reef Formation) and dolomitic rocks (Oaktree and Monte Christo Formation of the Malmani Subgroup) of the Transvaal Supergroup, sandstone and mudstone (Dwyka and Vryheid Formation) of the Karoo Supergroup and post-Karoo doleritic intrusions. However, a large proportion of the area is covered by doleritic and dolomitic rocks.

Characterisation of the unsaturated zone

Three main groups of soils were identified during a study for the northern dam compartment (active dam):

- Red, apedal, medium textured soils associated with chert and mostly represented by Msinga Series.
- Small areas are covered by yellow, brown, apedal, medium textured soils associated with chert and Karoo sediments.
- Black and dark-coloured, structured, medium to heavy textured soils associated with dolerite and mostly represented by Rydalvale and Rosehill Series.

The surficial colluvial, alluvial and residual soils have permeabilities in a range of between 0.2 and 3.1 x 10^{-5} m/s. The deeper residual soils and weathered bedrock showed varying permeabilities of between 10^{-5}-10^{-7} m/s. Unweathered to slightly weathered bedrock indicated a permeability to the order of 10^{-8} m/s. A soil survey conducted at the reclaimed dam indicates the presence of soils of the Arcadia soil type.

Characterisation of the saturated zone

Groundwater flow occurs under unconfined to semi-confined conditions. Groundwater levels are shallow (mean between 1-2 m) and a significant groundwater mound has developed underneath and in close proximity to the tailings dam. The groundwater mound seems to be better developed where doleritic rocks, showing a lower permeability than dolomite, and clayey and silty weathered formations, are present. These areas are generally wet and thus, subjected to seepage (discharge areas).

Further away from the tailings dam, groundwater levels seem to reflect the topographical gradient towards the west. However, groundwater drainage takes place radially, in a westerly, north-westerly and northerly direction towards two rivers and with an average hydraulic gradient < 2 %.

Many boreholes close to the tailings dam are artesian, indicating that the tailings dam is hydraulically connected with deeper rock fracture systems underlying superficial soils and highly weathered bedrock. Monitoring boreholes drilled into the shallow and deeper aquifer system revealed slightly higher groundwater levels in the shallow boreholes and thus indicate seepage originated from the tailings dam and a higher transmissivity of the deeper fractured aquifer.

Contaminant assessment of the groundwater system

Current pollution impact

Generally, samples from the shallow boreholes show higher average electrical conductivities (EC), SO_4^{2-}, Na^+ and Cl^- concentrations than those obtained from the deeper monitoring boreholes. Thus, groundwater quality varies between moderate to poor due to high concentrations of total dissolved solids (TDS), reflected by high salt concentrations (SO_4^{2-} and Cl^-) as a result of contaminated seepage from the tailings dam. Thus, most of the groundwater samples obtained during the monitoring survey show a predominant Ca-Mg- SO_4 character, which is typical of water affected by AMD.

However, deeper monitoring boreholes further away from the tailings dam show a better groundwater quality than samples from the shallow boreholes, due to natural dilution effects in the area between the tailings dam and the main drainage features.

The shallow and deep boreholes in close proximity to the tailings dam exceed the crisis limits for SO_4^{2-} of 1200 mg/l (SABS, 1984), whilst those further away show concentrations which fall between maximum permissible of 600 mg/l and the crisis limit of 1200 mg/kg (SABS, 1984).

Heavy metal analyses were conducted on an irregular basis. Elevated concentrations of As, Cd, Co, Fe, Mn and Ni were found at almost neutral pH values (pH varies between 5.4-7.4) and indicate seepage draining from the tailings dam into the aquifer. It is important to note that similar contaminants were also found in elevated concentrations in soil samples at reclaimed sites (case study sites A-G).

Surface water samples taken along the adjacent river showed high concentrations of SO_4^{2-} at fairly neutral pH conditions (6.0-7.6), indicating AMD containing seepage.

A limited number of groundwater and surface water samples were analysed for radionuclides, indicating that surface water systems show far higher radioactivity than groundwater samples. However, concentrations and activities are low and are within the recommended concentrations (**Chapter 4.6.2.12**) of DWAF for domestic use (DWAF, 1996a) and agricultural use (DWAF, 1996d).

Geochemical analyses of soil samples taken at various depths resulted in low pH values ranging between 3.7-5.7, indicating the effect of AMD, despite relatively low sulphate concentrations varying between 370-760 mg/kg. Relatively low sulphate concentrations suggest the leaching into deeper zones of the soil. Heavy metal concentrations and pH values are shown in **Table 6.10** below.

Table 6. 10: Heavy metal concentration ranges and pH values from four different soil test pit samples of the southern situated reclaimed site l.

Parameter	pH	Cu mg/kg	Fe mg/kg	Mn mg/kg	Zn mg/kg
Site L	3.8-5.7	0.6-1.7	22.5-44.9	5.4-23.3	0.8-5.4

The calculation of sodium adsorption ratios (SAR) showed low ratios and thus there is no implication that the soil is becoming brackish.

Potential future pollution impact

A numerical two-dimensional finite element groundwater flow and mass transport model has been applied to assess the future pollution impact. The model supported the assumption of groundwater drainage radially away from the tailings dam and towards the surface drainage features. The model was run for 50 years, which represents 40 years after final rehabilitation and closure (scheduled for the year 2005).

A groundwater risk assessment (Monte-Carlo simulations) indicates a low impact on surface water resources downstream of the tailings dam. Salts contained in seepage from the tailings dam represent less than 0.5 % of the total salt load of the nearby river. It is estimated that salts in seepage would contribute less than 2.5 % to the total salt load after 50 years.

Groundwater in close proximity to the tailings dam has been polluted by seepage from the tailings dam, but groundwater quality further away suggests that drainage features such as the river have a much larger impact than the tailings dam.

6.4.10 Case Study SITE J

Site characterisation

Site J is located south of Brakpan, in immediate vicinity of a wetland system on its western border. The wetland area extends from the western border of site J along a non-perennial stream, and terminates at a confluence with another perennial stream, which eventually drains into the Vaal dam. A large township is located approximately two kilometres on the eastern border of the site. The site is currently in the process of reclamation and covers an area of approximately 120 ha.

A geochemical pollution study was conducted of the wetland system next to the tailings dam, indicating AMD escape from site J. Soil samples were taken at five different sampling points downgradient of the site. Twenty one vibracore holes were drilled up to a maximum depth of two metres along a traverse approximately 300 m long and adjacent to site J. From these boreholes, sediment and water samples were obtained and analysed for their contamination levels. Furthermore, a surface water sampling point of Rand Water is located downstream of the tailings dam and monitored for its water quality. In addition, the operator of the tailings dam drilled one borehole on the north-eastern border of the site to monitor groundwater quality and to conduct aquifer testing. The borehole remained dry even at a core depth of 40 m. As a result, no groundwater data are available for this site. However, a hydrocensus conducted by the operator resulted in groundwater quality data for one borehole upgradient of the site.

The tailings dam area is underlain by sedimentary rocks of the Karoo Supergroup.

Characterisation of the unsaturated zone

Information of the soils underlying the tailings dam area were obtained from a borehole log of the proposed monitoring borehole, drilled on the north-eastern border of the site J. The borehole log indicates a clayey, sandy material, which is considered to be the weathering product of the Karoo sediments underneath. The thickness of the clay layer in that particular borehole profile is approximately 7 m.

Soils downgradient of the site consist of yellow oxidised tailings sediment overlying moderate red to dark brown clayey soil (due to ferric oxides) containing abundant ferruginous concretions. The clay consists predominantly of kaolinite at shallow depths and montmorillonite at greater depths. Kaolinite is known to form under acidic conditions.

Characterisation of the saturated zone

No groundwater table was encountered up to a maximum drilling depth of 40 m. No aquifer information was available for the borehole approximately 300 m upgradient of site J. It is known that in close proximity to site J the groundwater table has been lowered to allow for underground mining. The water level has been maintained at approximately 1600 mbd at a pumping rate of approximately 70 ml/d. Pumping ceased in 1991 and since then the water level in the mine has been rising.

It is interesting to note that no minerals such as goethite, haematite and ferrihydrite were identified by XRD in sediments receiving AMD from the tailings dam.

Contaminant assessment of the subsurface

Current pollution status

Table 6.11 shows the average concentrations of macro and micro-chemistry from the Rand Water sampling point, approximately 1.5 km downstream of site J. It is evident that this water is affected by mining activities and the upstream position of the tailings dam strongly suggests the release of AMD and associated heavy metals (e.g. Fe, Mn and Ni) from this site.

Table 6. 11: Average values for selected water quality parameter measured by Rand Water approximately one km downstream site J. Measurements were taken in the period from October 1991 until September 1992.

Parameter	pH	EC mS/m	Hardness as $CaCO_3$	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	SO_4 mg/l
Site J	6.4	220	1907	559	124	242	42	1797

Table 6.12 below presents a selection of average heavy metal concentrations at the same sampling point. Cobalt, Mn and Ni (bold) exceed the crisis limit significantly and indicate the high mobility of these metals under nearly neutral pH conditions. Soil and sediment analyses obtained from samples downstream of the tailings dam contain significant concentrations of heavy metals and can act as a reservoir for the latter. These results are shown below in potential future pollution impact.

Table 6. 12: Average trace element concentrations at a Rand Water sampling point approximately one km downstream of site J. Measurements were taken in the period of October 1991 until September 1992. "Crisis limits" (maximum limit for low risk) were published by Aucamp & Vivier (1987).

Parameter	As mg/l	Cd mg/l	Co mg/l	Cr mg/l	Cu mg/l	Fe mg/l	Mn mg/l	Ni mg/l
Measured	0.0008	n/d	2.8	0.003	0.13	0.01	14	13.4
Crisis limit	0.6	0.04	1	0.4	2	2	2	1

Table 6.13 represents data from four different water quality sampling points which are approximately 2. 2.5. 5 and 7 km downstream of tailings dam site J, the latter value after the confluence with another perennial stream:

Table 6. 13: Surface water quality with increasing distances downstream of tailings dam site J.

Distance downstream	pH	Eh mV	EC mS/m	SO_4 mg/l	HCO_3 mg/l	Ca mg/l	Co mg/l	Fe mg/l	Mn mg/l	Zn mg/l
2 km (a)	5.8	94.4	3.2	1517	18.9	564	4	<1	21	16
2.5 km (b)	5.4	118.7	3.1	1428	15.7	561	4	<1	22	13
5.0 km (c) before confluence	6.6	48.7	2.1	759	91.1	289	<1	<1	6	<5
7.0 km (d) after confluence	7.4	5.8	2.0	893	116.3	273	<1	<1	<1	<5

The table above indicates the improvement in water quality with increasing distance to the tailings dam site J. Although the pH becomes fairly neutral at sampling point d, SO_4^{2-} concentrations still exceed the maximum allowable concentration of 600 mg/l (SABS, 1984) at all sampling points. Thus, water treatment has to be considered before using the water for domestic or agricultural purposes. High Ca^{2+} concentrations might be caused by lime treatment of slime and cause a rise of pH. Heavy metal concentrations of Mn and Zn improve significantly further downstream as a result of dilution effects.

A radiometric survey has shown that significant amounts of U and Th are leaving the tailings dam site J and entering the wetland system, where both seem to be partially adsorbed by peat as described below. Total α-activity was found to be almost 2 Bq/l downstream tailings dam site J and 0.4 Bq/l approximately 5 km downstream (similar to sampling point c above), thus indicating a significant decrease of concentration caused by dilution effects and adsorption by organic material such as peat.

Analysed peat samples obtained downstream of the tailings dam site J have shown very high concentrations of heavy metals such as Cd (25 mg/kg), Co (946 mg/kg), Cu (438 mg/kg), Pb (261 mg/kg), Zn (931 mg/kg), Th (110 mg/kg) and U (195 mg/kg), as a result of very high metal adsorption capacity.

Potential future pollution impact

It is apparent from **Table 6.14** below that As, Co, Cu, Cr, Ni, Pb and Zn occur in anomalous concentrations in soil samples affected by seepage from tailings dam site J.

Table 6. 14: Summary of statistics for trace element concentrations contained in soil and sediment samples in close proximity to site J (n = 53).

Element	As mg/kg	Co mg/kg	Cu mg/kg	Cr mg/kg	Ni mg/kg	Pb mg/kg	Zn mg/kg
MIN	1	15	4	35	42	17	23
MAX	204	6117	1071	713	17844	247	10516
AVG	455	582	274	340	1882	69	1095
STDEV	523	1096	290	194	2948	55	1744

Affected soils, sediments, peat and the wetland systems acts as a reservoir for a variety of heavy metals downstream of the tailings dam, because heavy metals seem to be immobilised under the given pH (fairly neutral) conditions. Acidic pH conditions due to the uncontrolled release of AMD and a lack of buffer capacity could result in dissolution reactions, thus increasing the metal content in waters downstream of the site drastically. However, dilution effects and the adsorption capacity of wetlands and peat may contribute to the mitigation of the metal content. Sulphate concentrations will remain high in surface waters affected by

AMD of the tailings dam, until the sulphide minerals occurring in tailings and affected soils are oxidised.

6.4.11 Case study SITE K

Site Characterisation

Site K is situated north of Springs in immediate vicinity to a large dam. The tailings dam was used for the disposal of liquid effluent during the period 1969 to 1994. Since 1994 the tailings dam has been in the process of reclamation. Groundwater sampling has been conducted to monitor the impact of contaminated seepage released from the tailings dam and draining towards the dam. A number of boreholes have been drilled to monitor the groundwater quality (quarterly) affected by contaminated seepage released from the tailings dam as well as to abstract contaminated groundwater downgradient of the site. The tailings dam covers an area size of approximately 111 ha. The tailings dam is situated at an altitude of ± 1600 m above sea level. Surface drainage follows the topographical gradient, which is reflected by a gentle slope towards the north, where the dam is situated.

No vegetation was found on site K.

The site is underlain by sedimentary rocks of the Karoo Supergroup, dolomites of the Transvaal Supergroup and intrusive dykes and sills of Karoo and post-Karoo age. The Karoo rocks, which lie unconformably over the dolomites, occur as localised pockets. Witwatersrand quarzites occur below the dolomites at depths exceeding about 300 m below surface. The northern part of the tailings dam is underlain by dolomites, whilst the southern part is underlain by Karoo sedimentary rocks. The thickness of Karoo rocks to the south of the tailings dam varies from 6-15 m. Two NW-SE trending dolerite dykes occur below the tailings dam. A third narrower dyke occurs towards the west of the site. A diabase sill, showing a thickness between 10-20 m, occurs at depths of about 20-40 m below the site, and outcrops to the north of the dam.

Characterisation of the unsaturated zone

Soil information is limited and all that is known is that the tailings dam is directly underlain by a zone of transported and residual clayey soils with a thickness of up to 5 m. In order to assess the role of the perched aquifer system a soil field survey was launched and a number of auger holes were drilled (depths between 2-5 m). Clayey sands dominate the unsaturated zone to a depth of a few metres. The perched aquifer generally occurs at a depth of 3 m. A permeability test conducted at a sample taken from a depth of 1.8 m above the perched aquifer indicated a low permeability in the order of 10^{-10} m/s. However, the permeability of the perched aquifer is likely to be significantly higher.

Characterisation of the saturated zone

Three different aquifers have been identified:

- Perched groundwater tables, occurring above shallow ferricrete or clay horizons at depths between 3-5 m below surface.

- Semi-confined weathered and fractured aquifer, occurring at depths of about 20-30 m. The base of the aquifer comprises less fractured dolomitic rocks. The semi-confined aquifer is hydraulically connected to the underlying fractured aquifers within the dolomite. Preferential flow paths are associated with zones of highly weathered/residual dolomite (wad) and highly fractured zones along dyke contacts and faults. Preferential flow paths, which are characterised by higher permeabilities, are likely to be the main zones of contaminant transport.

- Confined fractured aquifers, occurring at depths below 30 m in fractured zones within the unweathered hard rock dolomite, as well as along dyke and sill contact zones. Due to recharge from the semi-confined aquifers above the deeper aquifer, groundwater contamination is likely.

The presence of north-stretching dykes and fractures (zones of higher permeability) results in preferred contaminant migration towards the dam. Different groundwater tables around the north-west corner of the tailings dam suggest a compartmentalisation of the semi-confined aquifer by dyke systems.

Contaminant assessment of the groundwater system

Current pollution impact

Only limited groundwater quality data were obtained for the relevant site. High sulphate concentrations (varying between 1000-2800 mg/l) in abstraction and monitoring boreholes around and on the site indicate the impact of contaminated seepage released from the tailings dam. The pH values are neutral to slightly alkaline with a mean value of 7.9 in groundwater samples collected beneath the tailings dam, indicating the presence of buffer minerals and the effect of natural dilution as a result of net recharge. Cobalt, Cu, Fe, Ni, Mn, Zn concentrations measured from groundwater samples sampled from piezometers in the dolomitic aquifer are below the recommended maximum limits of the SABS (1984) for domestic use. Sulphate concentrations show concentrations ranging between 200-600 mg/l with a maximum concentration of > 2000 mg/l in one groundwater sample.

However, analyses conducted on effluent samples collected around the pond area show significantly higher concentrations with respect to Co, Cu, Fe, Ni and Mn than those sampled in the dolomitic aquifer. The pH is highly acidic (pH around 2) resulting in dissolution reactions of heavy metals. TDS concentrations are extremely high in these samples and reach a mean of 14600 mg/l mainly caused by high salt loads. Hence, the fairly neutral pH found in the groundwater samples is reflected by the high buffer capacity of the dolomitic groundwater in the area. It is anticipated that heavy metal concentrations are low under these pH conditions, despite high salt concentrations.

Potential future pollution impact

A numerical groundwater (pseudo three-dimensional finite element) flow and mass transport model (for sulphate) has been applied to assess the future pollution impact. The modelling exercise has indicated very small changes in groundwater quality after complete reclamation of the tailings dam. However, potential effects of removal, including remobilisation of contaminants or the seepage from residual paddocks, have not been included in the model. The impact of remobilisation of contaminants is considered to be likely to be short-term only, based on the results of the model. In contrast, the effects of paddocks on groundwater quality are not likely to result in large changes in concentration.

6.5 SUMMARY OF CONTAMINANT ASSESSMENTS

6.5.1 Case Study A

The site is situated approximately one km east of the outskirts of Benoni and covers an area size of approximately 50 ha. The site is located at an altitude of ±1630 m above sea level. Surface drainage direction is towards a non-perennial stream in the north. Site A has not been completely reclaimed (60-70 % reclamation) and no vegetation has been established on site except a grass cover and some trees on top of the toe wall. Three test pits (A/1, A/2 and A/3) were excavated and eleven soil samples were retrieved for geochemical analyses. In addition, the geotechnical characteristics of eight samples were determined. Site A is underlain by sedimentary rocks of the Vryheid Formation, Karoo Supergroup, in the southern part of the site. The Dwyka Group of the Karoo Supergroup underlays the northern portion of the site. The soils of the site A are of the Avalon (test pits A/2 and A/3) and Glencoe (test pits A/1) pedological soil forms. The depth to hard rock varies between 1.30 - 1.50 m. The soils have a clay content of 7.51 - 15.82 and are mainly composed of clayey sands. A saturated permeability of 1 x 10^{-9} m/s is predicted for all the soils. Soil pH in the topsoils varies between 3.06 - 6.05 while the subsoils have a pH of 4.36 - 6.90. Cobalt, Ni and Zn is predicted to pose the greatest current pollution hazard, while isolated elevated concentrations of Cr, Cu, Pb and U are predicted. As, Cr, Cu, Fe, Pb, V and U occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. No data are available regarding the quality of the water in the saturated zone.

6.5.2 Case Study B

Site B is situated in close proximity to a residential area on its eastern border approximately two kilometres north of the outskirts of Springs. The reclaimed site covers an area size of approximately 47 ha. and is located at an altitude of ±1615 m above sea level. Surface drainage follows the topographical gradient towards a wetland system in south-westerly direction. Rehabilitation measures were partially undertaken, as is evident from a paddocks system. Site B has been almost completely reclaimed except for small volumes of tailings material which remain on site. The site shows natural vegetation, consisting of a poor developed grass cover and some trees. No rehabilitation measures were found. Site B is underlain by dolomite of the Oaktree Formation in the south and by tillite and shale of the Dwyka Formation of the Karoo Supergroup to the north. The soils of the site B is of the

Shortlands (test pits B/1 and B/2) and Willowbrook (test pit B/3) pedological soil forms. Three test pits (B/1, B/2 and B/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of eight samples were determined. No rock was encountered in any of the test pits. The soils have a clay content of 19.02 - 63.66 and are mainly composed of sandy clays or silts. A saturated permeability of 1 x 10^{-10} m/s is predicted for all the soils. Soil pH in the topsoils varies between 3.53 - 6.63 while the subsoils have a pH of 5.74 - 6.66. Cobalt, Cr, Cu, Ni and Zn are predicted to pose the greatest current pollution hazard. Co, Cu, Ni and Pb occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. No data are available regarding the quality of the water in the saturated zone.

6.5.3 Case Study C

Site C is situated adjacent to a highway and in close proximity to a large township and covers an area size of approximately 28 ha. It is located at an altitude of ±1610 m above sea level. Surface run-off may occur in a northerly direction towards a canal. The site has been completely reclaimed and poor grass vegetation covers the entire area. No land rehabilitation measures were found. The reclaimed site is underlain by rocks of the Vryheid Formation, Karoo Supergroup. The soils of the site C are of the Avalon (test pit C/1), Shortlands (test pit C/2) and Willowbrook (test pit C/3) type. Three test pits (C/1, C/2 and C/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of nine samples were determined. No rock was encountered in any of the test pits although test pit C/1 refused on hardpan ferricrete at 1.60 m. The soils have a clay content of 14.37 - 51.44 and are mainly composed of sandy clays or clayey sands. A saturated permeability of 7 x 10^{-9} - 7.5 x 10^{-10} m/s is predicted for the soils. Soil pH in the topsoils varies between 3.47 - 6.00 while the subsoils have a pH of 3.89 - 6.78. Cobalt, Cr, Cu, Ni and Zn are predicted to pose the greatest current pollution hazard. Co, Cu, Fe, Mn, Ni, Pb and V occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. No data are available regarding the quality of the water in the saturated zone.

6.5.4 Case Study D

Site D covers an area size of approximately 71 ha and is located at an altitude of ± 1610 m above sea level. A golf course is situated in immediate proximity to the north-eastern border of the reclaimed site. General surface drainage direction is towards a canal and dam in the south.Site D has been completely reclaimed and is sparsely covered by grass vegetation. No rehabilitation measures were found. Site D is mostly underlain by alluvial sediment deposited by a tributary of a perennial stream. The alluvium is underlain by sedimentary rocks of the Vryheid Formation of the Karoo Supergroup. The soil of the site D is colluvium of the Shortlands (test pit D/1) soil form and alluvium of the Willowbrook (test pits D/2 and D/3) soil form. Three test pits (D/1, D/2 and D/3) were excavated and twelve soil samples were retrieved for geochemical analyses. The geotechnical characteristics of nine samples were determined. Furthermore, a seepage sample was taken in test pit D/2 indicating a perched groundwater table. No rock was encountered in any of the test pits. The alluvial soils have a clay content of 19.51 - 48.66 and are mainly composed of sandy, clayey sand or clay with sand. A saturated permeability of 1×10^{-10} - 1×10^{-11} m/s is predicted for the alluvial soils. Soil pH in the topsoils varies between 3.52 - 6.09 while the subsoils have a pH of 4.9 - 7.7. The colluvial soils have a clay content of 28.90 - 38.33 and are mainly composed of sandy clay or clay with sand. A saturated permeability of 9.5×10^{-6} - 8×10^{-8} m/s is predicted for the colluvial soils. Soil pH in the topsoil is 4.0 while the subsoil has a pH of 3.8 - 5.0. Cobalt, Cr, Cu, Ni and Zn are predicted to pose the greatest current pollution hazard, while isolated elevated concentrations of Pb and U is also predicted. As, Co, Cr, Fe, Pb, Ni, U and V occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. A sample of the perched water table in test pit D/2 indicates Mg^{2+}, Cl^-, and SO_4^{2-} as well as Fe, Mn occur in concentrations above the acceptable limit for domestic use.

6.5.5 Case Study E

Site E is situated approximately one kilometre to the north of the outskirts of Springs and is bordered by a dam on its western side. The reclaimed site E covers an area size of approximately 111 ha. Site E occurs at an altitude of ±1585 m above sea level. Surface drainage occurs in a southerly direction towards a canal. The canal feeds a dam further downstream. The site has been completely reclaimed and is sparsely covered by grass vegetation. Limited rehabilitation measures were undertaken by paddocking of a portion of the site. Site E is mostly underlain by alluvial sediments deposited by a tributary of perennial stream. The alluvium is underlain in the northern section of the site by sedimentary rocks of the Dwyka Group of the Karoo Supergroup and by dolomitic rock of the Oaktree Formation of the Malmani Subgroup, Transvaal Supergroup in the southern portion of the site. Dolorite sill occurs in the central portion of the site. The soils of the site E are colluvium of the Katspruit (test pit E/1) soil form and alluvium of the Rensburg (test pit E/2 and E/3) soil form. Three test pits (E/1, E/2 and E/3) were excavated and ten soil samples were retrieved for geochemical analyses. The geotechnical characteristics of seven samples were determined. Test pits E/2 and E/3 refused on alluvial boulders at 1.50 and 1.30 m respectively while a perched water table is present in test pit E/1 at 2.0 m. The alluvial soils have a clay content of 35.02 - 46.55 and are mainly composed of clay with sand or sandy clay. A saturated permeability of 9×10^{-9} - 8×10^{-10} m/s is predicted for the alluvial soils. Soil pH in the topsoils varies between 5.1 - 7.8 while the subsoils have a pH of 6.8 - 8.3. The colluvial soils has a clay content of 33.92 - 40.06 and are mainly composed of sandy clay. A saturated permeability of 9.5×10^{-9} - 1×10^{-10} m/s is predicted for the colluvial soils. Soil pH in the topsoil is 6.7 while the subsoil has a pH of 7.0. The soils have a paste pH above that of the mobility of metals, no prediction of the current pollution hazard was made. Cobalt, Cr, Cu, Ni and Zn are predicted to pose the greatest current pollution hazard, while isolated elevated concentrations of Pb and U is also predicted. Fe, Co, Pb and V occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. No data are available regarding the quality of the water in the saturated zone.

6.5.6 Case Study F

Site F is situated approximately 1 km south of the outskirts of Springs adjacent to a highway. The site is bordered to the east by a small township and consists of two reclaimed tailings dams, which were located next to each other. The reclaimed sites cover a total area size of approximately 120 ha. The area was formerly occupied by a uranium processing plant which was removed after decommission, subsequent to which the tailings dams were constructed. The site is located at an altitude of ±1585 m above sea level. Surface drainage is towards a perennial stream in the east. Both sites were completely reclaimed. No vegetation has developed on the site and rehabilitation measures were undertaken by removing the remaining tailings material. The majority of the site is underlain by rocks of the Vryheid Group, Karoo Supergroup, whereas a small proportion in the south-eastern part is underlain by sedimentary rocks of the Dwyka Formation, Karoo Supergroup. The soils of the site F is of the Shortlands soil form. Four test pits (F/1, F/2, F/3 and F/4) were excavated on site and sixteen soil samples were retrieved for geochemical analyses. The geotechnical properties of twelve samples were determined. Only test pit F/3 refused at 1.70 m on chert boulders. The soils have a clay content of 13.70 - 44.22 and are mainly composed of sandy clay or clay with sand. A saturated permeability of 6×10^{-9} - 6×10^{-10} m/s is predicted for the soils. Soil pH in the topsoils varies between 3.7 - 4.5 while the subsoils have a pH of 3.7 - 6.7. Ammonium nitrate leaching tests shows U, Co, Ni and Zn to pose a current pollution hazard. Extractable U concentrations were up to 1500 times in excess of guideline values. Isolated elevated concentrations of Cr and Cu also occur and may therefore pose a current pollution hazard. As, Co, Mn, Ni, Th and U occur in total concentrations that are elevated above the natural background, these elements may in future pose a hazard. Groundwater underneath the reclaimed site is of poor quality and does not conform with specified drinking water limits with regard to Ca^{2+}, Mg^{2+}, SO_4^{2-} and NO_3^-.

6.5.7 Case Study G

Site G is situated approximately 4 km north-east of the outskirts of Nigel. The site covers an area size of approximately 13 ha and is located at an altitude of ±1610 m above sea level. Surface drainage direction is towards a canal in western direction. Agricultural activities were found in immediate vicinity to the site. The reclamation of tailings dam site G has been completed although scattered tailings still occur on the site. No vegetation is present, apart from some isolated trees. No land rehabilitation measures were found. The reclaimed site G is underlain by sedimentary rocks of the Vryheid Formation, Karoo Supergroup and the soils of the site are of the Avalon soil form. Three test pits (G/1, G/2 and G/3) were excavated and eight soil samples were retrieved for geochemical analyses. The geotechnical characteristics of six samples were determined. Refusal occurred between 1.10 - 1.50 m and a perched water table is present in test pits G/2 and G/3 at 0.95 and 1.30 m respectively. A sample of the perched water table in test pit G/2 was taken. The soils have a clay content of 14.10 - 31.45 and are mainly composed of clayey sand or sandy clay. A saturated permeability of 1×10^{-9} m/s is predicted. Soil pH in the topsoils is approximately 4.0 while the subsoils have a pH of 4.8 - 6.9. Cobalt, Ni and Zn are predicted to pose the greatest current pollution hazard, while isolated elevated concentrations of Cr and Cu is also predicted. Cobalt occurs in total concentrations that are elevated above the natural background. Thus, Co may in future pose a hazard. A sample of the perched water table in test pit G/2 indicates Ca^{2+}, Mg^{2+} and SO_4^{2-} as well as Fe and Mn occur in concentrations above the acceptable limit for domestic use.

OTHER SITES

6.5.8 Case Study H

This site was not investigated as part of this Water Research Commission project; data were provided by the Council for Geoscience. The site is located in the North West Province, west of Potchefstroom. The reclaimed investigated site covers an area of approximately 4 ha. Three other slimes dams and a rock dump are situated in close proximity to the investigated site (within a radius < 1 km). Three auger holes (H/1, H/2 and H/3) were drilled and sampling was conducted at various profile depths. The area has a gentle sloping topography towards the south with an average height of 1379 m above sea level. The reclaimed area is underlain by dolomite of the Oaktree Formation of the Malmani Subgroup, Transvaal Supergroup. Limited groundwater data are available for this site, which were obtained from one borehole on site. A perched groundwater table has been detected at a depth of about 7 m. Bio-available concentrations of Ni, Zn and Cd exceeded guideline values. Groundwater beneath the reclaimed site is of poor quality and does not conform to specified drinking water limits with regard to Ca^{2+}, Mg^{2+}, SO_4^{2-} and NO_3.

6.5.9 Case Study I

The site is located adjacent to the R23 (Old Heidelberg Road) between Brakpan and Heidelberg. The tailings dam comprises of a southern compartment, which is currently reclaimed and retreated and a northern compartment (active dam) where gold-mine tailings have been deposited (approximately 100 000 t/day) by cycloning since 1985 (and are still being deposited). The current active dam covers an area of 870 ha, whereas the entire affected area which includes additionally the reclaimed area results in an approximate area size of 1400 ha. A township is situated less than two kilometres east of the tailings dam and there is evidence of extensive agricultural activy in the immediate surroundings. A perennial stream flows in a north-westerly direction and at a distance of less than a kilometer along the western boundary of the tailings dam through a wetland system. The area slopes gently in a westerly direction towards a wetland system less than 1 km away.

Surface run-off is controlled and limited by a drainage collection system surrounding the tailings dam. No vegetation occurs at the reclaimed tailings dam (southern dam) due to ongoing reclamation operation. The tailings dam is surrounded by monitoring boreholes, which are sampled on a quarterly basis for the determination of groundwater quality. The tailings dam is mainly underlain by andesitic lava of the Ventersdorp Supergroup and quartzite (Black Reef Formation) and dolomitic rocks (Oaktree and Monte Christo Formation of the Malmani Subgroup) of the Transvaal Supergroup, sandstone and mudstone (Dwyka and Vryheid Formation) of the Karoo Supergroup and post-Karoo doleritic intrusions. However, dolerite and dolomite cover a large proportion of the area.

The soils of the area are of the Msinga, Avalon, Rydalvale and Rosehill Series while the reclaimed area is composed of Arcadia soils. The surficial colluvial, alluvial and residual soils have permeabilities in the range between 0.2 and 3.1 x 10^{-5} m/s. The deeper residual soils and weathered bedrock showed varying permeabilities between 10^{-5}-10^{-7} m/s. Unweathered to slightly weathered bedrock indicated a permeabilities in the order of 10^{-8} m/s. Groundwater flow occurs under unconfined to semi-confined conditions. Groundwater levels are shallow (mean between 1-2 m) and a significant groundwater mound has developed beneath and in close proximity to the tailings dam.

Monitoring boreholes indicate seepage originating from the tailings dam and elevated concentrations of SO_4^{2-} occur as well as significant concentrations of As, Cd, Co, Fe, Mn and Ni. Radionuclide analyses revealed that surface water systems show far higher radioactivity than groundwater samples. All concentrations and activities are however within recommended concentrations. A groundwater risk assessment (Monte-Carlo simulations) indicates a low impact on surface water resources downstream of the tailings dam in future.

6.5.10 Case Study J

Site J is located south of Brakpan, in the immediate vicinity of a wetland system on its western border. A large township is located approximately two kilometres on the eastern border of the site. The site is currently in the process of reclamation and covers an area of approximately 120 ha. A geochemical pollution study of the wetland system next to the tailings dam has been conducted. The site is underlain by a clayey, sandy unit (> 7 m thick) consisting predominantly of kaolinite at shallow depths and montmorillonite at greater depths with an abundance of iron concretions. Concentrations of As, Co, Cu, Cr, Ni, Pb and Zn in the soils of the affected area occur in anomalous concentrations while peat samples in the wetland revealed high concentrations of Cd, Co, Cu, Pb, Zn, Th and U. No geohydrological data is available but surface water samples indicates Ca^{2+}, Mg^{2+} and SO_4^{2-} as well Co, Mn and Ni occur in concentrations above the acceptable limit for domestic use.

6.5.11 Case Study K

Site K is situated north of Springs in immediate vicinity to a large dam. The tailings dam has been undergoing reclamation since 1994. The tailings dam covers an area size of approximately 111 ha and is situated at an altitude of approximately 1600 m above sea level. Surface drainage is along a gentle slope towards the north. No vegetation cover exists on the site. The site is underlain by sedimentary rocks of the Karoo Supergroup, dolomites of the Transvaal Supergroup and intrusive dykes and sills of Karoo and post-Karoo age. The tailings dam is directly underlain by a zone of transported and residual clayey soils that have a permeability in the order of 10^{-10} m/s. A perched water table generally occurs at a depth of 3 m. Sulphate concentrations in the groundwater exceed recommended drinking water standards. Effluent samples collected around the pond area show significant higher concentrations with respect to Co, Cu, Fe, Ni and Mn than those sampled in the dolomitic aquifer. A mass transport model for sulphate indicated very small changes in groundwater quality after complete reclamation of the tailings dam.

CHAPTER 7

IMPACT ASSESSMENT

7.1 INTRODUCTION

The unsaturated zone is considered to be a geochemical and physical barrier between the primary pollution source (i.e. tailings dam) and the receiving groundwater system. Consequently, the unsaturated zones defines the aquifer vulnerability. Fluid movement and contaminant attenuation conditions have the potential to mitigate the contamination of the groundwater system. However, once this barrier has become polluted, it can also act as a continuous pollution source. **Figure 7.1** shows a conceptual model of the tailings dam and the affected subsurface:

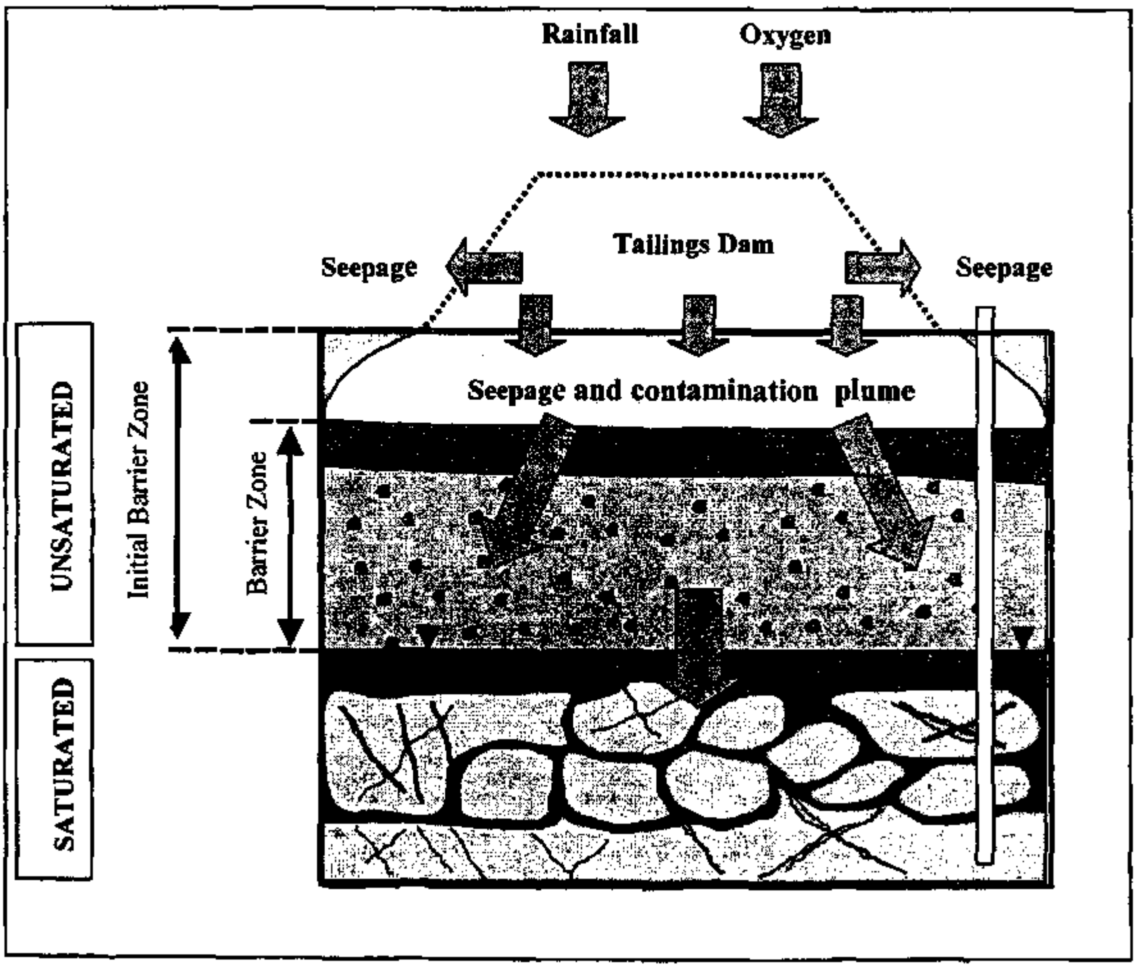


Figure 7. 1: Conceptual model of the pollution source (tailings dams) and the affected subsurface. Air-born pathway is not included.

The results of this project with regard to the various compartments such as pollution source, barrier zone and receiving groundwater system are discussed in the following paragraphs.

7.2 CHARACTERISATION OF THE PRIMARY POLLUTION SOURCE

The mobility (bio-availability) of various trace elements (As, Co, Cr, Cu, Fe, Mg, Mn, Ni, Pb, S and Zn) of 13 tailings samples has been investigated. Samples were collected at different gold-mine tailings dams within the oxidised zone up to a maximum depth of approximately one metre. It was found that gold-mine tailings contain significant concentrations of environmentally sensitive substances and are considered as potential pollution source for AMD, salts and associated trace elements (Rösner, 1996). The mechanisms and concentration levels have been discussed in detail in **Chapter 4**.

In addition, the average extractable concentration of each trace element is summarised in **Table 7.1** below. The table shows that all elements except As were highly extractable to concentrations exceeding their threshold concentration. These results confirm that gold-mine tailings are a potential source of contamination for the subsurface underneath the tailings dam.

Table 7.1 : Statistical parameters of the bio-availability by using the 1 M NH_4NO_3 extraction method for gold-mine tailings. Samples were obtained from five different tailings dams in the East Rand area (n=13). Extraction test data for tailings are summarised in Appendix B, Table 8.

Element	As mg/l	Co mg/l	Cr mg/l	Cu mg/l	Fe mg/l	Mg mg/l	Mn mg/l	Ni mg/l	Pb mg/l	S mg/l	Zn mg/l
MIN	n/d	n/d	n/d	n/d	n/d	7.5	0.5	n/d	n/d	32.3	n/d
MAX	0.3	30.0	5.0	22.5	105.0	1487.5	45.0	105.0	0.8	11262.5	80.0
AVG	-	13.8	2.3	8.9	36.4	513.9	19.4	44.9	0.6	3765.8	22.4

High concentrations of S (maximum > 10000 mg/l) indicate the oxidation and leaching of sulphide minerals (AMD).

All investigated reclaimed sites have shown elevated concentrations of contaminants in the soil, which are typically contained in tailings material. This indicates the escape of AMD and associated contaminants from the impoundment into the unsaturated and subsequently saturated zones.

In addition, Hahne et al. (1976) reported that Al is the predominant extractable cation in mine residue samples and is a prime hazard for the soils underneath mine deposits due to its toxicity to many plant species.

It is interesting to note that no correlation was found between concentration levels (absolute concentration) and sampling depth within the oxidised zone of three selected tailings dams in the East Rand area. Similar observations were reported by SRK (1988).

7.3 CURRENT POLLUTION IMPACT ON THE SUBSURFACE

7.3.1 Unsaturated zone (vadose zone)

The soil underneath reclaimed tailings dams has been polluted with various heavy metals and salts. The soil pH mostly varies between 4-6 (see **Figure 7.2**), thus acidic conditions are indicated. The threshold exceedance has been calculated in order to assess the effects on soil functioning (**Chapter 5.4.3**).

In addition, the bio-availability of heavy metals is determined by their mobility (MOB) or the ease with which they dissolve and migrate. Therefore, a mobility index was used to assess the bio-availability for certain heavy metals.

The threshold exceedance of various trace elements (As, Co, Cr, Cu, Ni, Pb, U and Zn) was determined for soil samples collected underneath reclaimed tailings dams. The exceedance is calculated by comparing extractable concentrations to threshold values from the literature. The results are presented in **Table 7.2** below:

Table 7.2: Threshold exceedance ratios (1M NH_4NO_3 extractable trace element concentrations) of the soils samples obtained from site F (n = 16). Cases mean the number of records, where a ratio of ≥ 0.1 is exceeded. Extraction test data for soils are summarised in Appendix B, Table 7.

Element	As	Co	Cr	Cu	Ni	Pb	U	Zn
MIN	0	0	0	0	0	0	0	0
MAX	0	40.0	12.5	3.8	77.5	0.5	1500.0	6.3
AVG	-	8.1	-	0.35	14.8	-	105.08	1.3
CASES	0	10	1	5	11	2	3	10

Extractable concentrations of Co, Ni and Zn exceed their threshold values in more than 50 % of the investigated samples. For each element, threshold concentrations are exceeded to the greatest extent in the topsoil samples. There is also a decrease in threshold exceedance with depth as a result of a reduced downward migration (contaminant attenuation).

Furthermore, Cr, Pb and U exceed their threshold concentrations for each analysis above the lower detection limit of the analytical technique. Uranium exceeds the threshold of 0.04 mg/l to the greatest extent, being 1500 times above the threshold concentration in one sample at site F. The high U concentrations can derived from radioactive waste material from an former uranium extraction and beneficiation plant. The radioactive material has been deposited on the site prior to the establishment of the tailings dam.

Extractable As concentrations were in all instances below the lower detection limit of the analytical technique and as such did not exceed the threshold value of 0.1 mg/l.

The mobility (bio-availability) of various trace elements was investigated by comparing the extractable ratio of an element to the total concentration in the solid phase (listed in **Appendix B**). The mobility of various trace elements in soil samples is shown in **Table 7.3** below:

Table 7.3: Trace element mobility (bio-availability) and main statistical parameters in soil samples obtained from site F. Extractable trace element concentrations expressed as a percentage of the total concentration (n=16). Average values were only calculated if more than two samples are > 0.1 %.

Element	As %	Co %	Cr %	Cu %	Fe %	Ni %	Pb %	U %	Zn %
MIN	0	0	0	0	0	0	0	0	0
MAX	0	66.67	0.47	8.33	19.34	50.70	12.50	6.44	39.12
AVG	-	14.90	-	0.94	1.76	8.59	-	-	11.4

Cobalt, Ni and Zn are the most mobile trace elements and the mobility decreases for each element as a function of depth due to attenuation. The elements are most mobile in the topsoil units of the test pits. This suggests that a significant portion of the Co, Ni and Zn amount in each soil sample is present in the mobile, easily soluble and exchangeable fractions as discussed in **Chapter 4. Figures 7.3-7.10** show the mobility of selected trace elements as a function of measured soil paste pH. It is evident that significant remobilisation only takes place at a pH < 4.

Figure 7.2 below shows the relation between soil depth and pH, where the soil pH bend back (dotted linear trend line) with increasing depth. This can be a result of buffering reactions by minerals such as carbonates or alternatively, by a fluctuating shallow groundwater table which causes a mixing and dilution effect with groundwater with a fairly neutral pH.

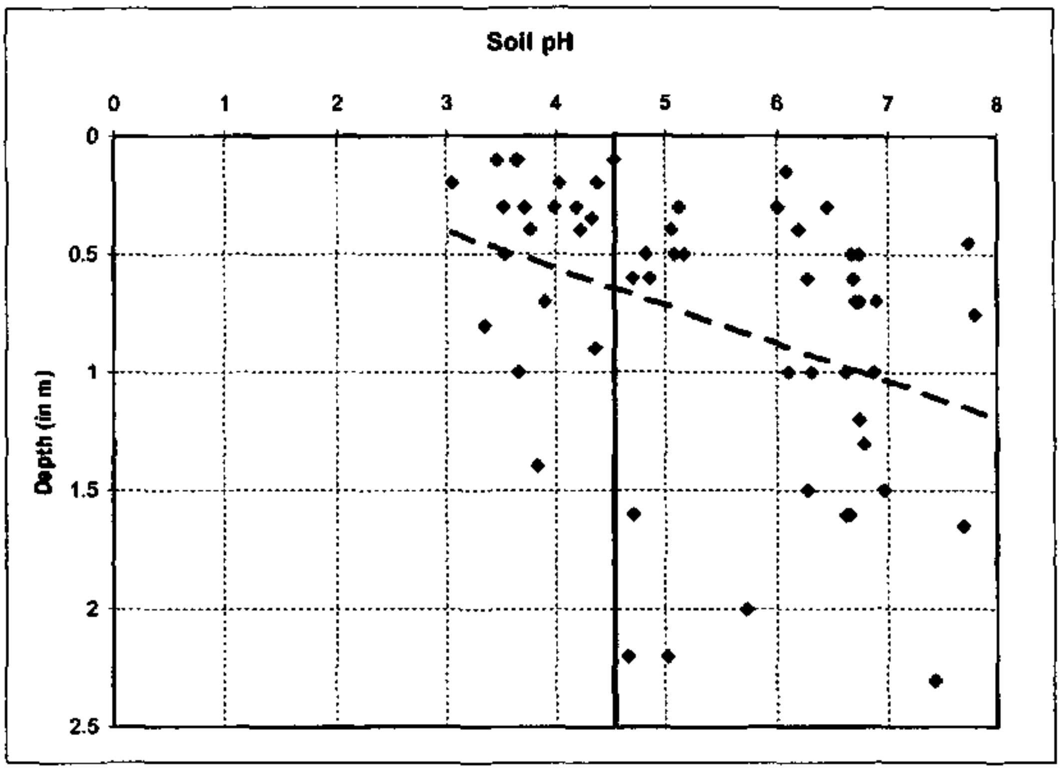


Figure 7. 2: Relation between soil depth and soil pH in the study area (n=54)

The vertical reference line indicates the pH boundary of approximately 4. Where the values are to the left of the boundary, main dissolution reactions of the solid phase (and thus remobilisation of contaminants) occurs.

The heavy metals as shown can be distinguished by their geochemical behaviour with respect to ease of solubility. One of the master variables for dissolution reactions is the soil pH. Co, Ni and Zn show increasing mobility with decreasing pH, whereas Cr, Pb and U seem to be insoluble. Furthermore, Cu shows a weak, but similar correlation to Co, Ni and Zn and Fe by a soil pH < 5.

An explanation of the low mobility of Cr, Cu, Fe, Pb and U could be, that a significant portion of these trace elements appears to be contained in the residual fraction and thus, is not bio-available. **Figures 7.3-7.10** present the element bioavailability of Co, Cu, Ni, U, Zn, Cr, Pb and Fe as a function of the soil pH.

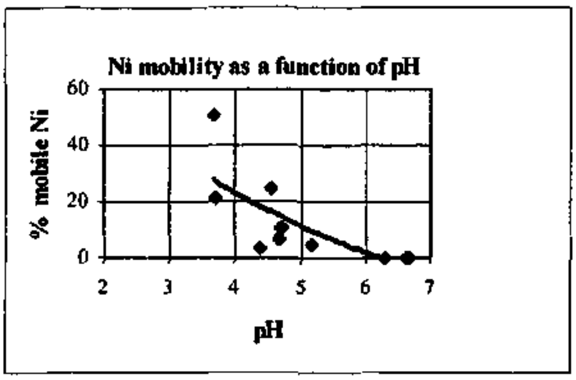


Figure 7. 3

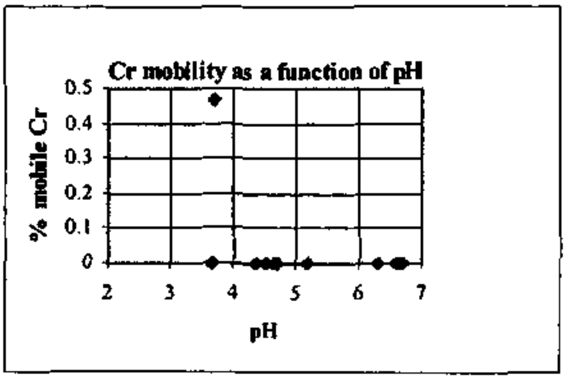


Figure 7. 4

Alloway (1995) reported similar findings for Cr (**Figure 7.4**), which is contained in the majority of soils and where the relative insoluble and less mobile Cr (III) form predominates and generally occurs as insoluble hydroxides and oxides. In addition, the acid character of AMD-affected soils suggests a rapid reduction from Cr (VI) to Cr (III). In addition, Alloway (1995) reports that above a soil pH of 5.5 complete precipitation of Cr (III) is likely. A comparison of the solubility of Cr and Ni is given in Brooks (1987), where Ni (**Figure 7.3**) is clearly more soluble than Cr. However, concentrations of Cr in plants growing on mine spoil and various types of chromium waste are commonly in the range of 10-190 mg/kg, but toxic concentrations may accumulate in plants growing on chromate waste in which the more soluble Cr (VI) form predominates (Alloway, 1995). Chromium concentrations in the soil samples collected at the reclaimed sites range from 97-622 mg/kg with an average of 237 mg/kg.

Under acid soil conditions, the most common secondary mineral or precipitation product of Ni is $NiSO_4$. Alloway (1995) report that over 50 % of Ni in soils may be associated with the residual fraction (HF and $HClO_4$ soluble), approximately 20 % with the Fe-Mn oxide fraction and the remainder is bound up with the carbonate fraction (extremely low in acid soils) leaving only a very small proportion for the exchangeable and thus, bio-available fraction. Significant vertical migration of Ni depends on the degree of soil acidification, certain texture conditions such as cracking (indicating preferential flow, **Chapter 3**) and the saturation status of the affected soil, as reported in Alloway (1995). In addition, it is well established that the Ni uptake by plants increases as the exchangeable fraction in soils increases as a result of the acidification caused by AMD. As a result, the concentration of Ni in plants can reflect the concentration of the element in the soil, although the relationship is more directly related to the concentration of soluble ions of Ni and the rate of replenishment of the mobile fraction (Alloway, 1995). Nickel concentrations in soil samples collected at the reclaimed sites range from 37-312 mg/kg with an average of 97 mg/kg.

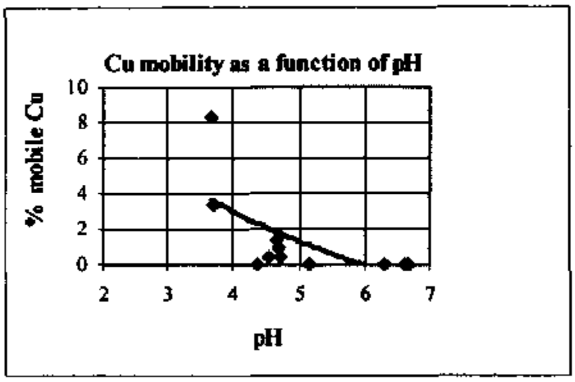


Figure 7. 5

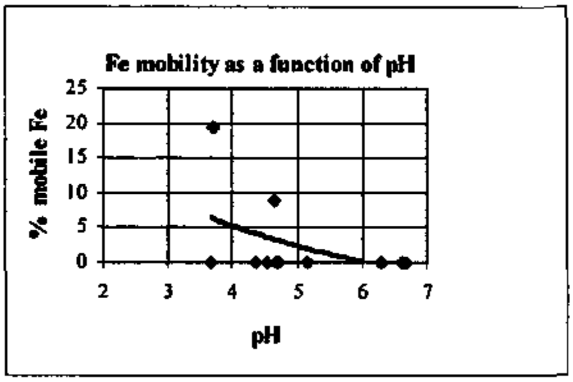


Figure 7. 6

Although Cu (**Figure 7.5**) is less mobile (between 1-2 % below pH 5) than Co, Ni and Zn it is important to note that concentration levels of 1.5 to 4.5 mg/kg for Cu damage or kill roots of growing plants (Alloway, 1995). Total Cu concentrations of AMD-affected soils in the study area range from 26-170 mg/kg with an average value of 60 mg/kg. Hence, plant toxicity plays an important role in the case of soil management regarding the introduction of recultivation measures (establishment of a vegetation cover).

Iron mobility (**Figure 7.6**) is very low and significant mobility was only found in two soil samples at a pH < 5. It is important to note that Fe-precipitates such as Fe-oxides provide additional adsorption surfaces for other metals within the soil system. Iron oxide (Fe_2O_3) concentrations found in soil samples of the study area range from 3-24 weight-% with an average of 8 weight-%.

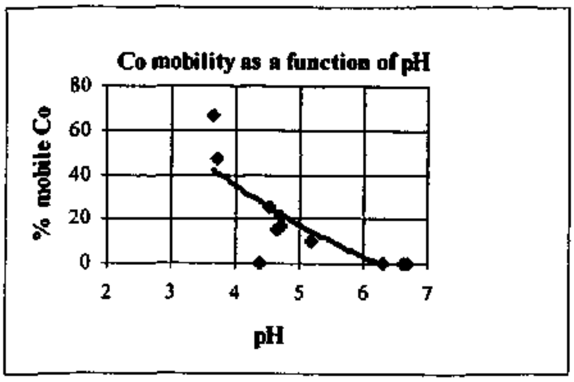


Figure 7. 7

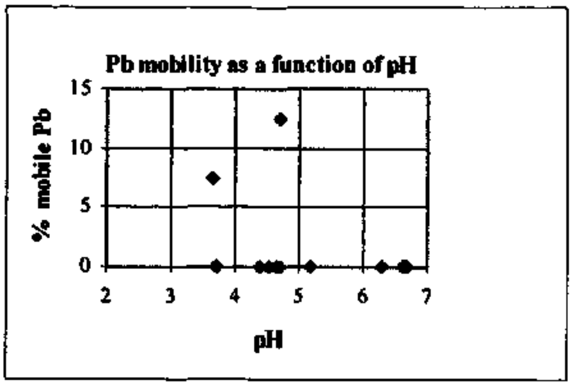


Figure 7. 8

Cobalt (**Figure** 7.7) shows a very high mobility (pH < 5) of up to 70 % compared to the solid phase. This would result in a higher plant uptake as also reported by Alloway (1995). Alloway (1995) found accumulation of Co in soil profiles in horizons rich in organic material and clay minerals. Furthermore, Co is often found in association with Mn-oxide minerals, which occur in the investigated soil samples at an average of 0,1 weight-%. The calculation of the correlation coefficient (Pearson approach) of MnO versus Co revealed a positive coefficient of r = 0.63 (n=81), which corresponds with the observation above.

Lead (**Figure** 7.8) shows a very low mobility in soils, and thus accumulation occurs within the surface horizon of the soils. Similar observations were made in Finland, Canada and England (Alloway, 1995). He found that soils affected by mining operations show higher accumulations of Pb in the surface horizon than in unaffected soils, suggesting a low mobility even under acid soil conditions.

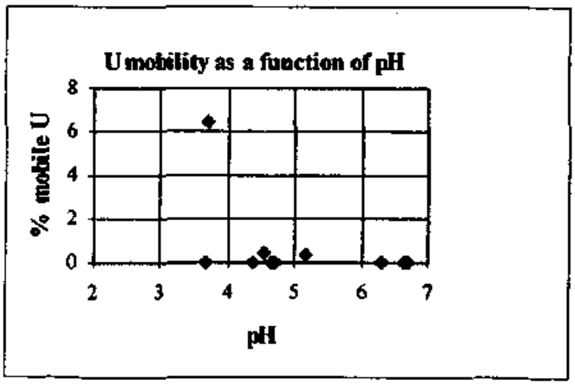


Figure 7. 9

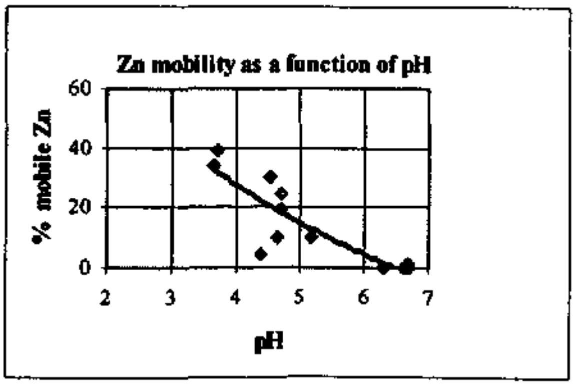


Figure 7. 10

The mobility of U (**Figure 7.9**) is very low, although three samples showed an elevated mobility which occurred only in the surface horizon of the soil. Remobilisation occurs at pH < 5, corresponding with other heavy metals such as Co, Ni and Zn. In case of elevated mobility the threshold value exceedance of U showed a range from 62-1500. However, the calculation of the correlation coefficient (Pearson approach) between U/As gave a positive coefficient of r = 0.74 (n=81), which is also reflected by the immobility of As. In contrast, Rose et al. (1979) and Förstner & Kersten (1988) described U as moderately to highly mobile under oxidising conditions across the entire pH range and immobile under reducing conditions. The formation of the cation UO_2^{2+} is most likely the reason for the solubility of U over a wide pH range. The low mobility of U found in the soil underneath reclaimed tailings deposits could be caused due to co-precipitation (secondary mineral) with HCO_3^{2-} or SO_4^{2-} in the soils, after U was released from the primary mineral after establishment of the tailings dam (Levin, 1998).

Zinc (**Figure 7.10**) shows a high mobility and the solubility increases with decreasing soil pH, corresponding with the findings of Kabata-Pendias (1994) for acid soils (pH <4). Zn activities in soils can be calculated based on the solubility products of the different Zn compounds (Lindsay, 1979). The extractable concentration (bio-availability) of Zn depends on the type of adsorbing phases, discussed in **Chapter 4.2.4.** Alloway (1995) distinguishes three different Zn forms in the soil: Free ions (Zn^{2+}) and organo-zinc complexes in the soil solution, adsorbed and exchangeable Zn in the colloidal fraction (see **Figure 4.4**) and Zn contained in secondary minerals and insoluble complexes in the solid phase of the soil. The distribution of Zn among these forms depends on the equilibrium constants (**Chapter 4.2.1**) of the corresponding reactions (precipitation and dissolution; complexation and decomplexation; adsorption and desorption), which are discussed in **Chapter 4**.

The concentrations of selected elements (As and Zn; n=81) in soils of the study area as a function of depth is shown in **Figure 7.11 and 7.12**:

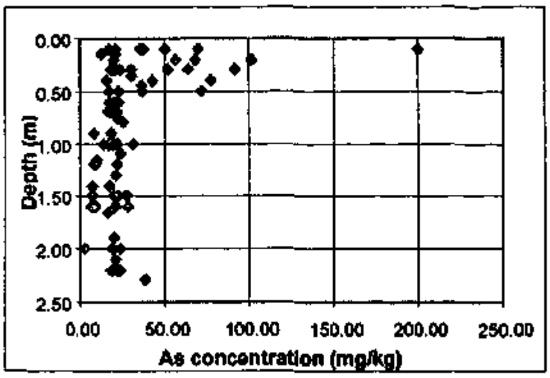


Figure 7.11

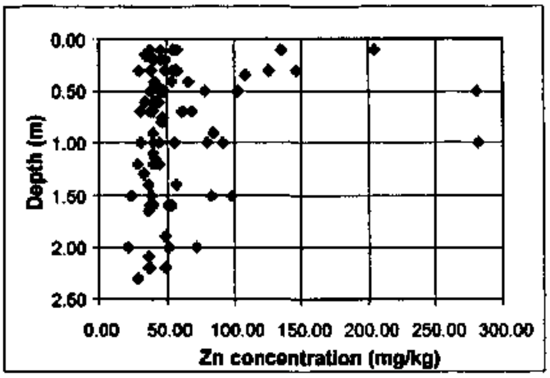


Figure 7.12

It is apparent that there is no clear relation between element concentrations and certain soil horizons throughout the study area. However, the highest concentrations seem to occur generally in the upper soil units and depth related element accumulations were found, if single test pits were considered. Additionally, although clay minerals have a much higher adsorption capacity for metals compared to coarser grain size fractions, no correlation was found between the occurrence of clays in soils and element concentrations. These observations correspond to the findings of Merrington & Alloway (1993), which investigated the behaviour of heavy metals in soils affected by old iron mines in England.

In conclusion, heavy metals exceeding threshold concentrations (e.g. Co, Cr, Cu, Ni, Zn and U) may limit soil functioning. The mobility of the trace elements is a function of soil pH. The majority of the topsoil samples were highly acidic (pH 3-4), whereas deeper samples showed generally higher pH-values (pH 5-7). The low pH value in soils underlying tailing dams is a direct result of the sulphide mineral oxidation and the associated generation of AMD. All of the investigated trace elements are most mobile when pH<4 and least mobile when a soil pH > 6. Co, Ni and Zn are the most mobile trace elements, which corresponds to the literature. In contrast, the mobility of Cr, Cu, Fe, Pb and U is lower, indicating that a significant portion of these trace elements are contained in the residual fraction. Arsenic concentrations were below the lower detection limit in all extraction tests. The potential hazard for land development and groundwater contamination posed by the trace elements can be summarised as U>>Co=Ni=Zn>Cr=Pb>>As. This potential hazard series is only a function of the degree and frequency with which a trace element exceeds the relevant threshold value. It is also important to note that such tests were only conducted at one site and further tests would be necessary to confirm and support these observations. Detailed information about the behaviour of trace elements in soils is given in Kabata-Pendias (1992), Kabata-Pendias & Pendias (1992) and Alloway (1995).

Furthermore, permeabilities derived from geotechnical properties (Mathewson, 1981 and Tavenas et al., 1983) and in-situ test data indicate a low to very low vertical conductivity (range between 10^{-7}–10^{-10} m/s) of the investigated soil profiles. Contaminants measured at greater depths would, however, require alternative migration mechanisms than percolation through the porous media. Soil conditions indicating preferential flow (bypass of the soil matrix) are observed in some test pit profiles, but attempts to identify dominating contaminant migration processes would be premature. Further investigations would be necessary to identify flow and subsequently mass transport mechanisms of contaminants.

Extraction tests on gold-mine tailings (**Table 7.1**) have shown high sulphur concentrations contained in the leachate. Hence, incomplete reclamation of tailings would result in tailings material remaining on the surface. This material provides an additional reservoir for acid generating processes and contaminant release.

There may be various reasons for the buffering and neutralisation of acid solutions at greater depths. A fluctuating groundwater table could cause dilution (mixing with groundwater having a neutral pH) or the presence of buffer minerals which mitigate AMD.

Finally, many countries such as the Netherlands Ministry of Housing, Physical Planning and Environment (1991) provide guidelines regarding soil quality standards for the assessment of soil contamination. However, these guidelines were established for the northern hemisphere, where humid climate conditions, which determine natural soil conditions, predominate. No guidelines are available for a semi-arid climate such as that experienced in South Africa.

7.3.2 Saturated zone (groundwater system)

7.3.2.1 Regional groundwater quality

Groundwater collected across the study area (East Rand area) can be characterised as two distinctive groundwater types (Kafri et al. 1986 and Scott, 1995):

- Ca-Mg-HCO_3;
- Ca-Mg-SO_4.

Piper diagrams representing these groundwater types are shown in Scott (1995). Groundwater quality showing a predominant Ca-Mg-HCO_3 character frequently indicates recharged waters associated with dolomitic aquifers. Such groundwater often shows low TDS values and a high total hardness. High Na^+ levels in some samples are probably reflected by ion exchange processes (Lloyd & Heathcote, 1985) preferably from the overlying Karoo strata (Scott, 1995). It is reported that high Ca^{2+} concentrations resulting from the dissolution of dolomite (and in some cases from lime treatment) and alkalinity may exceed drinking water standards in some areas.

In contrast, groundwater quality which is predominantly characterised by a Ca-Mg-SO_4 signature and high TDS concentrations indicates discharge areas (Palmer, 1992), but in the case of the study area, it is more likely to indicate AMD-related pollution emanating from mining activities. Although the relative proportions of anions in this groundwater remain similar to that of unaffected groundwater, the cation composition reflects the progressive dominance of SO_4^{2-} over HCO_3^- as the reaction products of the sulphide mineral (e.g. pyrite) oxidation are introduced into the groundwater system. In contrast, Scott (1995) reported that in some areas the ratios of main elements in surface and groundwater are very similar, particularly along less polluted portions of the Blesbokspruit, indicating that surface and groundwater are closely related across parts of the investigation area.

It is important to note that dolomites of the Oaktree (chert-poor dolomite) and Eccles (chert-rich dolomite) Formations occur within the study area. Kafri et al. (1986) reported that these dolomites contain occasionally considerable amounts of pyrite, which could contribute to metal and SO_4^{2-} pollution in groundwater. However, it is highly unlikely that the natural pyrite content could cause a SO_4-dominated water type in dolomitic aquifers.

7.3.2.2 Groundwater quality in the study area

Groundwater quality beneath and in close vicinity to the investigated tailings dams is dominated by the Ca-Mg-SO_4 type, although all sites with relevant groundwater data (sites H, I and K) are underlain by dolomitic rocks. In addition, high TDS (up to 8000 mg/l) values occur mainly because of high salinity (i.e. SO_4^{2-} and Cl^-) in the groundwater system. Groundwater pH values are fairly neutral in most of the samples due to the acid neutralisation capacity of the dolomitic rock.

In general, groundwater quality seems to improve further down-gradient of the tailings dams as a result of dilution effects and precipitation reactions caused by the high acid neutralisation capacity of the dolomitic aquifer. However, groundwater quality in close proximity to the sites is often characterised by elevated heavy metal (e.g. As, Cd, Co, Fe, Mn and Ni) and CN (total CN) concentrations, exceeding drinking water standards in some boreholes (SABS, 1984).

Sulphate concentrations are often very high in the immediate vicinity to the tailings dam (generally > 2000 mg/l, but up to 4000 mg/l) and decrease with increasing distance to the tailings dam because of dilution and solid speciation effects.

It must be stressed that agricultural activities often occur in immediate vicinity to tailings dams, and the use of such affected water for agricultural (e.g. irrigation) or domestic purposes should be avoided.

7.4 FUTURE POLLUTION IMPACT POTENTIAL ON THE SUBSURFACE

7.4.1 Impact on the unsaturated zone

The concentrations of Fe_2O_3 (total), MnO and various trace elements (As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Sn, Th, U, V and Zn) were compared to background soil concentrations of similar geology by using the geochemical load index system. This method has been discussed in **Chapter 5**. Based on the results of this comparison, a table listing contaminants of concern for each site was produced.

This methodology allows the assessment of trace element loads in the investigated soil profiles. A locality map of these sites is presented in **Figure 6.2**. Subsequently, **Table 7.4** below, showing contaminants of concern at the investigated sites, was produced:

Table 7. 4: .: Calculated geochemical load indexes for various trace elements of the case study sites in the East Rand. Geochemical load index system after Müller (1979).

	Geochemical load indexes (pollution classes I-VI)					
Case study	**Class I Non – mod. Polluted**	**Class II Mod polluted**	**Class III Mod – highly polluted**	**Class IV Highly polluted**	**Class V High – excessively polluted**	**Class VI Excessively polluted**
A	Ni, Zn	Fe, As, Cr, Cu, Pb, V	U	-	-	-
B	Fe, As, Cr, Mo, Th, V, Zn	Cu	Co, Ni	Pb	-	-
C	Mn, Cu, Th, V	Fe, As, Cr	Pb, Ni	Co, U, V	-	-
D	As, Cr	Fe, Mn, Cu, Ni, Pb, V	-	Co	-	-
E	As, Cr, Cu, Ni, Th, Zn	Fe, Co	Pb, V	-	-	-
F	Fe, Cr, Cu, Mo, V, Zn	Mn, Co, Th	As, Ni	-	-	(U)
G	As, Ni, Sn	Co	-	-	-	-

Significant pollution is reflected by a pollution class III (reflecting a 10-fold exceedance above the natural background and higher).

- *Moderately to highly polluted* (pollution class III): five sites with respect to the following trace elements: As, Co, Ni, Pb, V and U. Cobalt and Ni are known to be phytotoxic, thus having negative effects on plant growth (Alloway, 1995). High As concentration was only found in one case. However, As is less bio-available than other metals and thus, effects are negligible.

- *Highly polluted* (pollution class IV): only three sites with respect to Co, Pb, V and U. Vanadium is not a typical mine tailings contaminant, and enrichment caused by natural processes in association with ferricrete (Fe- hydrous-oxides and oxides, see **Appendix F, Figure 11**) is most likely (Németh et al., 1993 and Alloway, 1995). High U concentrations were found only at one site.

- One site has been classified with *excessively polluted* (pollution class VI) as a result of U (measured as U_3O_8) concentrations higher than 100-fold above the natural background. The high concentrations can be derived from the deposition of radioactive material generated at a former uranium extraction and beneficiation plant in close vicinity to the site. Thus, the high U concentrations found at this site can not be linked to gold-mine tailings dams. Uranium is highly mobile under alkaline pH conditions (pH 7.5) and can accumulate in waters and migrate over long distances even at $pH > 7.5$, because of the ability to form complexes such as $UO_2(CO_3)_3^{4-}$, $UO_2(CO)_2^{2-}$ and $UO_2(HPO_4)_2^{2-}$ (Bowie & Plant, 1983).

It can be concluded that the long-term impact of typical mine tailings contaminants (acidic seepage in association with high salinity and elevated levels of trace elements, radionuclides and other harmful substances) will mainly depend on the availability of minerals with a sufficient acid neutralisation capacity.

The application of the geochemical load index system is a conservative approach, assuming that the total contaminant load in the solid phase could be dissolved. However, studies by Kabata-Pendias (1994) have shown that only a minor portion of heavy metals are bio-available, as they are only contained in the easily soluble and exchangeable phase. A problem might be the ongoing production of SO_4^{2-} and acids as a result of sulphide mineral oxidation by remaining tailings material on the surface. The primary pollution source should be completely removed from the reclaimed sites in order to prevent further acid and salt generation. This measure would also support rehabilitation efforts with regard to vegetation establishment (recultivation). However, a risk assessment (discussed in **Chapter 8.6**) would be required to enable land development (e.g. housing).

7.4.2 Impact on the saturated zone

A limited number of tailings dams in South Africa have been investigated in detail with respect to the geohydrological conditions, including the application of numerical groundwater modelling (flow and mass transport modelling). Groundwater modelling has become an important supporting tool for groundwater risk assessment and is required to assess the future impact of contaminated sites on groundwater and surface water resources. Such a model can also assist in the development of strategies to achieve pollution reduction (e.g. hydrological barriers) and to assess aquifer vulnerability.

The disadvantage of the application of groundwater models is the large amount of input parameters required and the associated uncertainty in the predictions. Therefore, groundwater models have to be updated on a continuous basis by incorporating new monitoring data, which is cost intensive.

One mining company applied groundwater models to two tailings dams in the study area. Mass transport modelling of the sulphate load has been carried out because of its low retardation (conservative approach) within the aquifer system. The groundwater modelling exercises have shown that tailings dams continue to release seepage with high salinity for an extended time period (predictions were given for about 50 years) after decommissioning of tailings operations.

Acid and salt generation in tailings dams can only be avoided by preventing the oxygen flux into the impoundment (only achieved by cover systems), which would result in the stabilisation of sulphide minerals or a complete depletion of those. The models have also shown that deterioration of groundwater quality occurs only in the immediate vicinity of the impoundment. Groundwater quality will improve with increasing distance down-gradient of the tailings dam due to dilution and solid speciation effects. Seepage emanating from tailings dams is, however, likely to affect water quality negatively in nearby surface water systems due to discharge which would have an adverse impact on water users in that particular area (see **Appendix F, Figure** 9).

It is important to note that as a result of dewatering of underground mines, groundwater tables dropped across the study area, causing the Blesbokspruit to discharge water along permeable sections of the water course into the groundwater system. Mine closures and the limitations of mining activities resulted in a rapid groundwater table recovery of the dolomitic aquifers in the East Rand area (Scott, 1995) and might change water courses such as the Blesbokspruit to effluent rather than influent streams in future, characterised by recharge from the aquifers. The effect of groundwater recovery cannot be regarded in isolation from the release of AMD from tailings dams.

CHAPTER 8

PRELIMINARY REHABILITATION MANAGEMENT

8.1 INTRODUCTION

Rehabilitation is defined by the restoration of a disturbed land area to a land form and productivity which conforms with the land form and productivity of the locality before disturbance took place.

Section 38 of the Minerals Act (50/1991) determines the approach towards rehabilitation of the surface in a mining or prospecting environment. Within the context of the mining authorisation, rehabilitation measures must be carried out as follows:

- In accordance with the approved environmental management plan (EMP);
- As an integral part of the operations or prospecting progress;
- At the same time as the mining operations, unless otherwise determined by the Regional Director;
- To the satisfaction of the Regional Director.

Further details with respect to legal issues are discussed in **Chapter 2.**

Mining plays an essential role in the South African economy. However, there are growing cost implications involved in the disposal of mining wastes due to adverse effects on soils, surface and groundwater quality. The extent of these effects depends on the physical characteristics of the disposal site, mineralogy of the ore, the metallurgical process, the method of disposal, the climate and microbiological conditions within the disposal site and in the underlying subsurface.

In the case of reclaimed gold-mine tailings dams, the rehabilitation of the subsurface (soil and groundwater) is of major importance for the prevention of negative effects on the aquifer and to enable land development. As a result, waste rehabilitation efforts are heavily influenced by statutory and regulatory compliance and in some countries, such as the United States, waste rehabilitation is often dictated to by these regulations. Regulatory standards and guidelines are becoming increasingly prescriptive as regards procedural and technical requirements.

It is clearly preferable to prevent contamination problems at the outset by investigating contamination potentials at the mine planning stage, and deciding on the most appropriate metallurgical process and waste disposal. The success of rehabilitation measures depends on how effectively contamination has been eliminated and how sustainable the rehabilitation effort is in the long term (Van der Nest & Van Deventer, 1996).

Acid mine drainage (AMD) is recognised as a world-wide problem. At the 1998 Environmental Workshop of the Minerals Council in Australia have 17 international companies, representing about 40 % of the world's mining activity, agreed to join forces to control AMD. It is assumed that rehabilitation of AMD related environmental damages will cost an estimated US $ 550 million in Australia and US $ 35 billion in North America (Dorfling, 1998). The costs figures for South Africa to rehabilitate existing tailings dams and to mitigate such damages is currently unknown. Clean-up costs for contaminated soils (e.g. soil washing) range between US $ 100–200/ton (Daniel, 1993). This study has shown **(Chapter 8.2.1)** that at least 5.5 million tons of material would have to be treated in South Africa, if only the polluted topsoil (≤ 30 cm) underneath the reclaimed sites would have to be considered. Hence, only the topsoil clean-up would cost at least US $ 550 million, assuming the lower treatment cost scenario of US $ 100/ton. In addition, the following costs can be expected and would ad to this cost scenario:

- Risk assessments for each site or certain impact areas (including radiological risks);
- Treatment of contaminated soil material underneath the topsoil unit and/or at higher soil clean-up costs (> 100 US $/ton)
- Groundwater remediation;
- Removal and treatment of contaminated sediments in waterways;
- Rehabilitation of existing gold-mine tailings dams (e.g. cover systems) to prevent dust erosion and mitigate the generation of AMD;
- Rehabilitation of reclaimed sites (e.g. recultivation).

It is obvious that these rehabilitation costs cannot be afforded either by the South African government or by the mining industry. It is also questionable if the predicted costs for

Australia and North America will ever be spent, in order to rehabilitate. Thus, rehabilitation (including treatment of contaminated soils and groundwater) of large-scale polluted sites is uneconomical and this should only be applied at highly contaminated sites or areas determined by a risk assessment as high risk areas (delineation of risk zones). Rehabilitation options for contaminated soils and groundwater as well as the long-term environmental management of large-scale polluted sites is discussed in the following paragraphs.

8.2 REHABILITATION OPTIONS FOR CONTAMINATED SOILS

According to Pierzynski et al. (1994), two general strategies are used to deal with soils which are mainly contaminated by trace elements such as heavy metals:

- Treatment technologies;
- On-Site Management.

Treatment technologies refer to soil that has been physically removed (ex-situ) and processed in a certain way in an attempt to reduce the concentrations of trace elements or to reduce the extractable (bio-available) trace element concentration (TCLP, toxic characteristic leaching procedure) to an acceptable level. The TCLP is a protocol used by the U.S.-EPA, which dictates that materials should be leached under standard conditions. If the concentration of various substances exceeds some critical levels in the leachate, the material is classified as hazardous.

The second strategy is called on-site management (in-situ), which implies that soil is treated in-situ. There are two subcategories within the on-site management option:

- Isolation;
- Reduction of bio-availability.

Isolation is one of a number of processes by which a volume of soil is solidified, resulting in prevention of any further interaction with the environment. The second subcategory consists of methods for reducing the bio-availability of trace elements in the soil. The following chapters will provide a brief introduction of both rehabilitation strategies and their application potential for this type of contamination.

8.2.1 Treatment technologies

Clean-up methods make use of the specific differences between the properties of contaminants and soil particles. Soil contamination characteristics at which clean-up may be directed are volatility of the contaminants, solubility in water or in another liquid, adsorption and remobilisation characteristics, size, density, shape of contaminated particles, biodegradability and geochemical instability. The following aspects are of importance for the application of a clean-up technique:

- Soil type (properties of the inorganic and organic soil phases);
- Type and concentration levels of contaminants;
- Physical state of the contaminants (e.g. particulate pollutant, adsorbed, absorbed, liquid films around soil particles, contaminant as a liquid or solid phase in soil pores);
- Migration mechanisms of contaminants and the time interval between contamination and clean-up. Particularly in the case of in-situ treatment, it is important to know if the contaminated site is disturbed by mechanical processes or not.

Clean-up possibilities depend on the type and concentration of contaminants, which can vary significantly in the soil. Contamination caused by seepage leaving gold-mine tailings dams and entering the subsurface mainly consists of:

- Acidity;
- Salts (e.g. SO_4^{2-} and Cl^-);
- Trace elements (e.g. heavy metals and heavy metal compounds and radionuclides);
- Cyanides (free and complex cyanides).

Soils contaminated with heavy metals or heavy metal compounds are in general most resistant to clean-up (Rulkens et al., 1995), because metals and metal compounds cannot be destroyed, with the exception of volatile elements such as As and Hg. However, the volatilisation of As and Hg contaminants will only succeed at extremely high temperatures. In addition, heavy metals are usually found in soils accompanied by other types of contamination (e.g. organic compounds). The occurrence of organic substances can make the removal of metals from the soil substantially more complicated.

Five main principles are applied for the clean-up or decontamination of affected soils. These principles are discussed in detail by Rulkens et al. (1995) and listed below:

- Removal of contaminants by *molecular separation* (e.g. treatment by extraction and treatment by desorption or remobilisation);
- Removal of particulate contaminants by *phase separation* (e.g. classification with hydrocyclones, froth flotation and jig techniques);
- Removal of contaminants by *chemical/thermal destruction*;
- Removal of contaminants by *biodegradation* (e.g. land farming and biological slurry reactors, not applicable to heavy metals);
- Removal of contaminants by *biological adsorption* or *biological mobilisation*.

A large number of clean-up techniques have been developed on the basis of these principles. However, only a few approaches are presently successfully applied in practice (Rulkens et al., 1995).

In general, mining sites in South Africa are far too large to be cleaned up using the available technology at reasonable cost. Approximately 13 km^2 of land has been affected by gold-mine tailings dams, which have been reclaimed. If only the top 0.3 m of these areas were to be treated, this would imply that 3.9 million m^3 and hence, at least 5,5 million tons of material would have to be treated. This is a very conservative estimate, since treating the top 30 cm would not be sufficient - some contaminants have already reached the groundwater system, thus indicating downward migration in deeper parts of the unsaturated zone.

Areas affected by wind-blown tailings or contaminated sediments in waterways downstream of these deposits have not been considered in this example. Even with an effective treatment technology available, it would be cost prohibitive to treat the quantities of material necessary to address the problem. It can be concluded, therefore, that treatment technologies are confined to situations with very small volumes of soil are to be treated.

8.2.2 On-site management

The isolation subcategory of the on-site management includes in-situ approaches described under the treatment technologies option. All isolation approaches aim to isolate the contaminants from the surrounding environment by encapsulating them into a nonporous matrix.

Of major interest in the context of rehabilitation of land affected by mine tailings are the methods to lower the mobility and hence, to reduce the bio-availability of trace elements. These methods include the following aspects relevant for AMD affected soils:

- Altering soil pH;
- Increase sorption capacity;
- Precipitation of trace elements as some insoluble phase.

The influence of soil pH, cation exchange capacity (CEC), and adsorption mechanisms on trace element bio-availability are well studied and reported in soil literature (e.g. in Alloway, 1995), although generally not in association with a rehabilitation technique.

Of all the methods for reducing trace element bio-availability, increasing the soil pH by adding lime (generally to a pH of ≥ 6.5) is probably the most common approach applied. This is a result of the general tendency for most trace elements to precipitate as hydroxides at a pH ≥ 6.5 and of the fact that soil pH management is a routine measure of a fertility program. However, where more than one trace element is involved in the rehabilitation (common situation), changing the soil pH may reduce the mobility of some elements whilst mobilising others such as Mo (Pierzynski, 1994).

Studies have shown that the plant availability of some trace elements is influenced by the soil CEC, with availability decreasing as the exchange capacity increases. An increase in soil CEC can be achieved for instance by:

- Adding clays having a high CEC;
- Adding organic material (e.g. manures, sludges).

Other methods are aimed to reduce the bio-availability of trace elements such as:

- Adding large amounts of Fe and Al salts (increasing adsorption capacity for oxy-anions with a subsequent reduction in their bio-availability).
- Adding hydroxides, carbonate, phosphate, sulphate, or sulphide-containing salts can cause precipitation of the corresponding trace element-containing solid phase. If the solid phase then controls the activity of the trace element in the soil solution and this activity is lower than the initial level, the bio-availability will be reduced.
- Mixing the contaminated soil with uncontaminated material or materials such as coal fly ash, paper mill wastes, sewage sludge in order to dilute existing pollution levels (attenuation) in the contaminated soil.

Sutton & Dick (1984), as mentioned above, discusses many of these methods in detail with respect to soil treatment.

Another aspect is phytotoxicity, which can protect the human food chain. This phenomenon is called the *soil-plant barrier* and refers to the situation where a plant reacts phytotoxically to a trace element concentration below that which would be harmful if humans were to consume the plant as food.

The following elements might exert a lower risk to humans because of phytotoxic reactions of plants: Ag, Al, Au, Fe, Hg, Sn, Pb and Ti. However, some elements, such as Cd, Mn, Mo and Zn, are not affected by this phenomena, as a result of insolubility or strong retention of the element in the soil that prevent plant uptake (Pierzynski, 1994). Another mechanism is the low mobility in non-edible portions of plants that prevent movement into edible portions (e.g. roots versus above-ground portions), or phytotoxicity that occurs in concentrations in the edible portions of plants below a level at which they would be harmful to animals or humans. Detailed information about the effects of heavy metal pollution on plants is given in Hutchinson (1981).

It is important to note that direct ingestion of contaminated soil or dust (e.g. mine tailings) bypasses the soil-plant barrier and thus exerts a direct threat to human health.

8.2.2.1 Vegetation cover for reclaimed sites

A primary objective for the satisfactory rehabilitation of land affected by mine tailings is to establish a permanent self-sustaining vegetation cover (Sutton & Dick, 1984). This may have a beneficial effect, since it may reduce the amount of leachates.

However, the establishment of vegetation (recultivation) on land affected by mine tailings is often hindered due to the low availability of plant nutrients and soil moisture. Another primary factor is the low pH in soils (caused by AMD and a lack of buffer minerals) which prevents the establishment of vegetation. In addition, incomplete reclamation often results in tailings material remaining on the surface. The remaining tailings material provides an additional reservoir for AMD generation and associated contaminants and makes rehabilitation efforts even more difficult.

Although the acid and soluble salt amounts will decrease with time due to weathering and leaching processes, the underlying soil might remain too acid for plant growth. As a result, most of the areas covered by tailings dams which were reclaimed will remain without a vegetation cover for an extended period of time, if exposed to weathering.

Treatment options were discussed in **Chapter 8.2.2** and amelioration could be achieved by addition of soil amendments such as lime, sewage sludge and coal fly ash. Once the abandoned mined land shows vegetation growing on the surface, the initial regeneration of these areas towards future land development has begun. In addition, a vegetation cover on abandoned mined lands improves the aesthetics of the area (Sutton & Dick, 1984).

The land use capability, location, and objectives of the owner will determine the ultimate use of these areas. This would also include ecological aspects in respect of agriculture, forestry, wildlife, and recreation (Sutton & Dick, 1984).

8.3 REMEDIATION OF GROUNDWATER CONTAMINATED BY AMD AND ASSOCIATED CONTAMINANTS

Most of the remediation techniques are related to organic pollution such as petroleum from leaking underground tanks. However, limitations to remediation of contaminated groundwater became apparent in the mid 1980s as data from groundwater remediation projects in the US became available (U.S.-EPA, 1989; Mackay & Cherry, 1989 and Travis & Doty, 1990 and Kavanaugh, 1996). The most common groundwater remediation strategy in the US has been the pump-and-treat approach (P&T technology), where contaminated groundwater is pumped to the surface, treated and returned to the aquifer. Because of growing concerns in the US that this approach was not likely to achieve target levels in many cases, and that predictions of clean-up times had been seriously underestimated, an independent assessment of the issues was conducted by the US National Research Council in 1994 (NRC, 1994). A number of 77 remediated sites were investigated in the US with regard to clean-up success. The survey revealed that only 8 of the 77 sites reached the remediation clean-up level and in most cases the concentration of the target compounds in the extracted water had reached a constant level.

The low success of P&T technologies is not surprising, because even in the case of an optimal design of the P&T approach, restoration of groundwater is limited by four factors which are inherent to the problem of removing contaminants from the subsurface (Kavanaugh, 1996). These factors are:

- Compounds strongly adsorbed to aquifer solids (Mackay et al., 1989);
- Highly heterogeneous subsurface environments contain zones of low permeability (e.g. clay);
- Slow mass transfer of contaminants from aquifer solids to the bulk interstitial fluid (Brusseau & Rao, 1989);
- Wide spread presence of non-aqueous phase liquids (NAPL's), particularly those that are more dense than water (Mecer & Cohen, 1990). This factor does not account for inorganic trace element pollution.

Alternative remediation techniques such as semi-reactive walls and bio-remediation approaches are not applicable to groundwater, if heavily affected by salt and heavy metal contamination. Thus, remediation efforts should focus on pollution control of the pollution source (e.g. vegetation cover, liner systems) and, if contamination in the subsurface occurs, on limiting the bio-availability of contaminants within the unsaturated zone. Clean-up technologies have been reviewed by the U.S.-EPA (1987a).

The long term management of the contaminated subsurface will be discussed in the following paragraph.

8.4 LONG-TERM ENVIRONMENTAL MANAGEMENT FOR LARGE-SCALE CONTAMINATED SITES

Large-scale sites, such as the area covered by gold-mine tailings dams, are too large to be cleaned up economically. However, since the unsaturated zone (vadose zone) underneath the mine tailings is expected to be contaminated for a long time, it is necessary to understand the mobility of contaminants and the capacity of the unsaturated zone to retain contaminants in the long term. In a number of cases, contaminants have already migrated into the groundwater system, thus causing a deterioration in the groundwater quality.

The parameters, which control the balance between retention and mobility of contaminants in soils and sediments and can be called master variables (i.e. pH, redox conditions and the presence of complexing agents such as dissolved organic matter and inorganic anions). These parameters have been discussed extensively in **Chapter 4** and also by Salomons & Stigliani. (1995). For a *short-term risk assessment* (time period of 5-10 years) it is sufficient to understand how these master variables are associated with mobility and hence, bio-availability of contaminants. A great deal of information is available in the literature on this subject (Salomons & Stigliani, 1995).

However, there is less information available which deals with the mechanisms which determine the master variables. This is not important for short-term processes, which determine the current pollution status of soils and sediments and their immediate impact on the environment. Salomons & Stigliani (1995) found that in a number of cases the present impact may be slight; however, this may increase if the retention capacity of soils for contaminants changes or when the master variables controlling the interaction between the soil and the soil solution change. This could be a result of the consumption of minerals which provide acid neutralisation capacity. These changes are of a *long-term nature* and are caused by the dynamic geochemical behaviour of the master variables and the major element cycles in the soil-sediment system. **Figure 8.1** illustrates the relationship between the master variables, the major element cycles and contaminants:

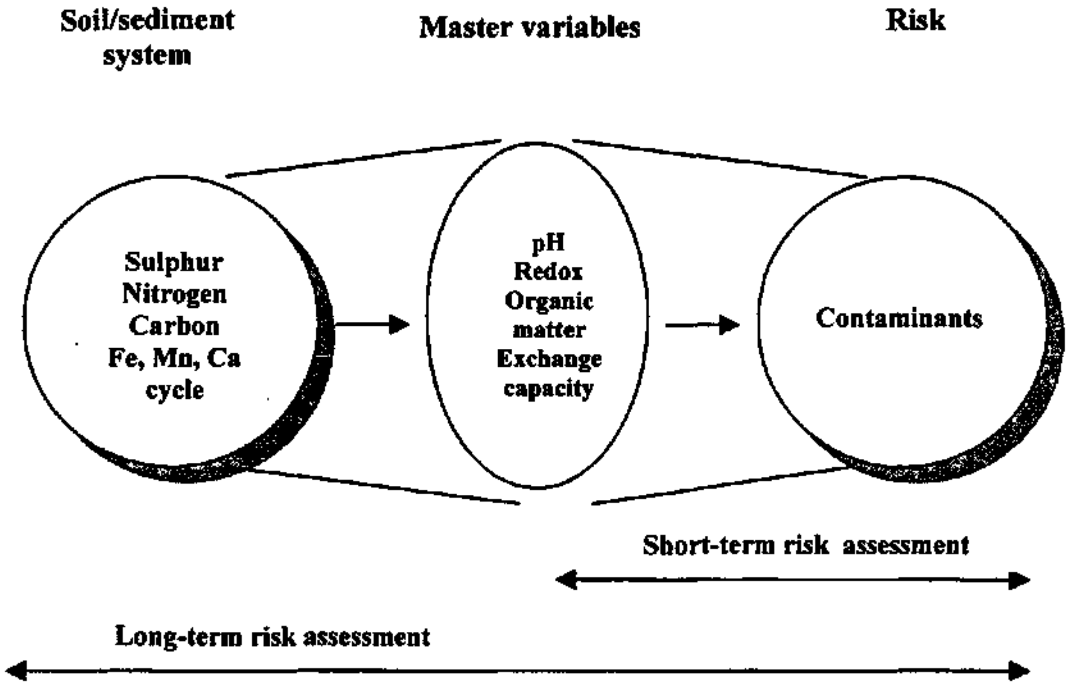


Figure 8. 1: Association between the master variables, the major element cycles and contaminants (modified after Salomons & Stigliani, 1995).

It is important to understand that these changes in contaminant concentrations in the soil solution show a non-linear relationship, in particular for inorganic pollutants (such as heavy metals). Changes in the pH or Eh conditions can cause sharp increases in concentrations over a short time period (Salomons & Stigliani, 1995). This could be a result of changing land use (e.g. deposition and reclamation of tailings dams), continued acid deposition and changes in hydrology.

Although the previous discussion has focused on the chemical properties and behaviour of contaminants in the soil, it is important to realise that other disciplines must be taken into account for a complete understanding of this complex system and in order to be able to perform predictive long-term modelling (e.g. kinetic geochemical models). Hence, it is important to assess the significance of increased mobility on transport, plant uptake and impact on the soil ecosystem as part of a risk assessment. Integration of these aspects would allow one to establish eco-toxicological guidelines, sustainable agriculture, changing land-use and long-term protection of groundwater resources for certain target areas such as land affected by reclaimed gold-mine tailings.

8.5 MONITORING AS AN INTEGRAL PART OF REHABILITATION MANAGEMENT

The success of rehabilitation is determined by how effectively contamination can be mitigated and how sustainable the rehabilitation effort is under long-term conditions.

Consequently, the only available tool to measure the success of rehabilitation at a specific site is monitoring (after-care). Only monitoring ensures that improvement occurs as a direct result of the rehabilitation measure. Monitoring would also justify the use of a specific rehabilitation method for further applications under similar conditions. Therefore, monitoring serves as a quality control procedure (QA/QC) for rehabilitation management and thus, forms an integral part of a risk assessment.

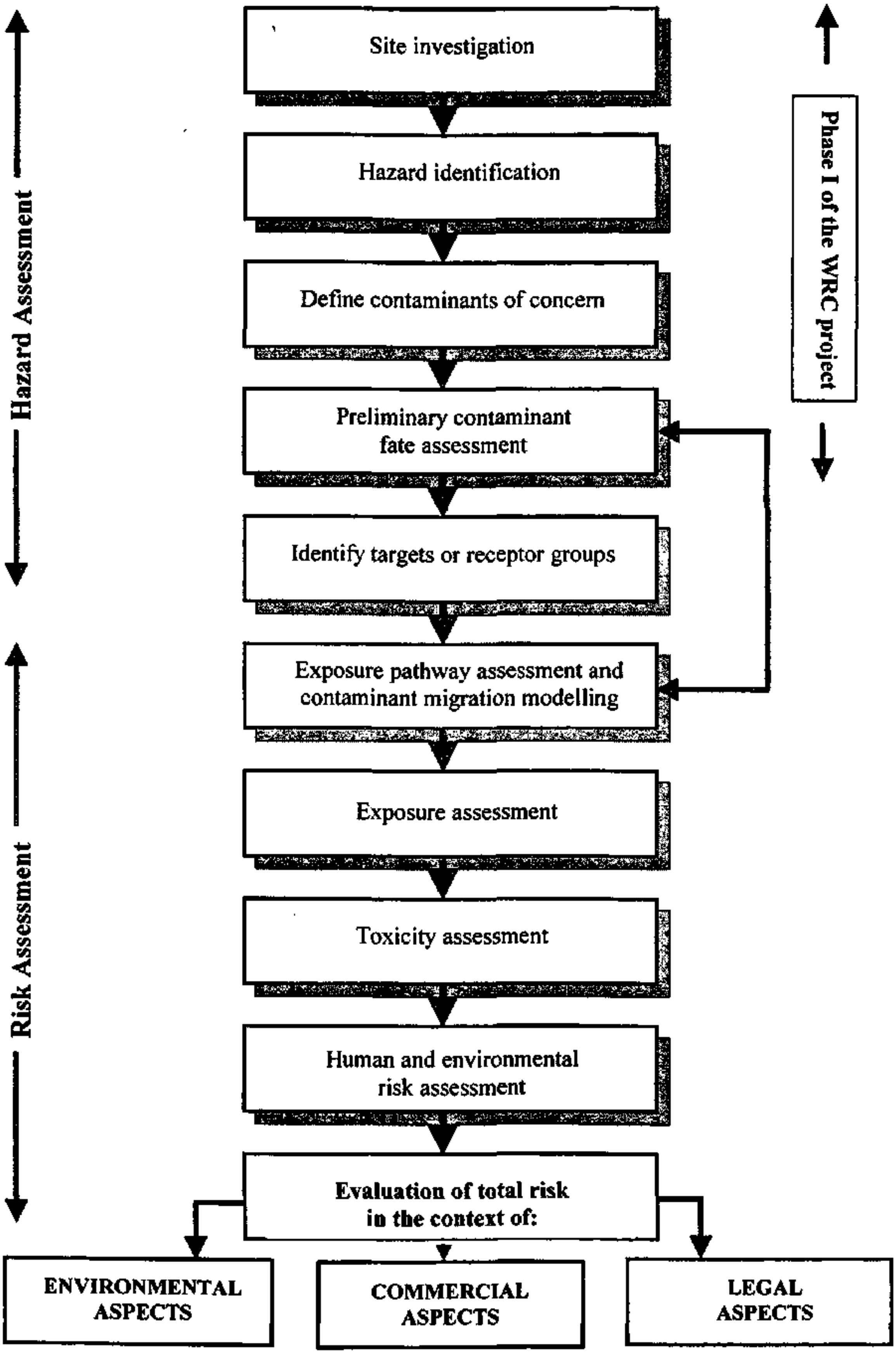
The type and extent of monitoring, however, would depend on the site-specific conditions and could comprise the monitoring of the vadose zone, surface and/or groundwater systems. The latter monitoring technique would consist of the establishment of boreholes suitable for groundwater sampling up and down-gradient of the site. A hydrocensus would allow the sampling of already established boreholes (such as private boreholes on farms or in gardens) and could drastically decrease costs related to water quality monitoring. Groundwater monitoring approaches are discussed in detail in textbooks such as Palmer (1992), Daniel (1993), and by Mulvey (1998). In addition, minimum requirements for monitoring at waste management facilities are presented by DWAF (1994).

In addition, the use of satellite images could provide an important tool for the monitoring of reclamation activities of mining companies as well as of the nearby environment (fast-growing residential areas such as townships and illegal land use) of tailings dams. Radiometric surveys would allow the identification of pollution plumes leaking from such deposits on the surface (wind-blown tailings material and surface water systems).

8.6 RISK ASSESSMENT

This study serves as a preliminary investigation of a risk assessment procedure, which is aimed at achieving a risk reduction to acceptable levels by implementation of rehabilitation measures. **Figure 8.2** summarises the various steps of a risk assessment procedure.

Figure 8. 2: Stages in a risk assessment procedure (after Ellis & Rees, 1995)



This project (Phase I) covers the first four steps of a risk assessment procedure: the site investigations, hazard identification, definition of contaminants of concern (high bio-availability) and the preliminary contaminant fate assessment respectively.

The evaluation of the total risk is usually conducted for three various aspects as shown in **Figure 8.2:**

- Environmental aspects;
- Commercial aspects;
- Legal aspects.

This project (Phase I) and the continuation in Phase II will only deal with environmental aspects such as:

- Groundwater;
- Surface water;
- Impact on users;
- Vegetation.

The aim of such a risk assessment approach is the understanding of the interaction between the master variables, which control the balance between retention and dissolution of contaminants. Only if these mechanisms are fully understood will it be possible to quantify certain risks caused by the impact of tailings on certain receptors (e.g. groundwater, surface water, soils and boreholes).

The incorporation of a risk assessment into the environmental management of waste disposal facilities such as tailings dams is required according to DWAF (1994). Risk assessment procedures for water quality management in South Africa are presented by Skivington (1997).

CHAPTER 9

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

9.1 DISCUSSION

Large volumes of mine waste such as tailings have been generated as a result of intensive gold-mining activities in South Africa. To date, more than 200 tailings dams have been constructed to store these fine-grained tailings. Most of the tailings dams are situated south of Johannesburg within the highly populated Gauteng Province (currently 7.7 million people increasing to estimated 8.5 million in the year 2000) and were deposited some 30 to 50 years ago. Up to 1998 70 tailings dams were reclaimed throughout the East Rand area in order to extract the gold, still present in economically viable concentrations (currently approximately 0.40 g/ton). Once the tailings material has been completely reclaimed, the land has a certain potential for development. However, it is important to realise that the reclaimed tailings material leaves a contaminated subsurface (footprint).

It is known that gold-mine tailings are prone to the generation of acid mine drainage (AMD), which is recognised as a world wide problem. It is estimated that the remediation of environmental damages related to AMD will cost about US $ 500 million in Australia and US $ 35 billion in the United States and Canada. The cost figure for South Africa to rehabilitate existing tailings dams and to mitigate damages in the unsaturated and saturated zone is currently unknown. Clean-up costs for contaminated soil material (e.g. soil washing) range from US $ 100-200/ton. This study has shown that at least 5.5 million tons of material would have to be treated in South Africa, if only the polluted topsoil ($\leq$ 30 cm) underneath the reclaimed sites would have to be considered. Hence, only the topsoil treatment would cost at least US $ 550 million, assuming the lower treatment cost scenario of US $ 100/ton. Additional rehabilitation measures such as cover systems for present mine-residue deposits, recultivation of reclaimed land or groundwater remediation were not taken into account for this cost senario. It is obvious that these rehabilitation costs cannot be afforded either by the South African government or by the mining industry. It is also questionable if the predicted costs figures for Australia and North America will ever be spent, in order to rehabilitate such sites. Thus, rehabilitation (including treatment of soils and groundwater) of large-scale polluted sites is uneconomical and this should only be applied at highly contaminated sites or areas determined by a risk assessment as high risk areas (delineation of risk zones). It is important to realise that the understanding of the short- and long term behaviour of contaminants in the subsurface zone affected by such mining operations, forms an integral part of a risk assessment.

Eleven selected reclaimed tailings dam sites (gold-mining), situated in the Gauteng Province and North-West Province of South Africa, were investigated in this study. All reclaimed sites were analysed in terms of their current pollution status, and conservative predictions were also attempted to assess the future pollution impact. In addition, the pollution source (i.e. tailings dam) was geochemically and mineralogically characterised. Field and laboratory tests were conducted on samples taken from seven reclaimed selected sites within the unsaturated zone and from a shallow groundwater table. Further groundwater data of the investigated sites was obtained from mining companies, various government departments and associated institutions. Rating and index systems were applied to assess the level of contamination contained in the unsaturated zone underneath reclaimed gold-mine tailings dams.

9.2 CONCLUSIONS

In conclusion, this study has shown that pollution occurs in the subsurface underlying former gold-mine tailings. However, based on the findings of this study, it is premature to quantify this impact and to incorporate it into a risk assessment approach. This investigation therefore provides a first step towards a risk assessment and serves as a hazard assessment/identification. It is important to understand that slight changes in the pH or Eh conditions of the soil (e.g. by land use, climate) can cause mobilisation of large amounts of contaminants, which are characterised by a geochemical behaviour that is time-delayed and non-linear. Additional field and laboratory testing would be obligatory for the in-depth understanding of the long-term dynamic aspects of these contaminant processes, which pose a serious threat to the vulnerable groundwater resources (i.e. dolomite aquifers) and land development. Salomons & Stigliani (1995) described these processes as "… precisely the kind of response that catches policymakers, the public, and even scientists by surprise".

The main findings of this investigation regarding reclaimed gold-mine residue deposits and existing deposits affecting the unsaturated and saturated zones (short- and long-term effects) are summarised below:

- Groundwater quality beneath and in close vicinity to the investigated tailings dams is dominated by the Ca-Mg-SO_4 type, indicating acidic seepage, although all sites with relevant groundwater data (sites H, I and K) are underlain by dolomitic rocks. In addition, high TDS (up to 8000 mg/l) values occur mainly as a result of high salt loads (SO_4^{2-} and Cl^-) in the groundwater system. In most of the samples, groundwater pH values are fairly neutral due to the acid neutralisation capacity of the dolomitic rock aquifer. There is a tendency for groundwater quality to improve further down-gradient of the tailings dams as a result of *dilution effects and precipitation reactions caused by the high acid neutralisation capacity of* the dolomitic aquifer. These observations have been confirmed with the application of numerical groundwater models. However, groundwater quality in close proximity to the sites is often characterised by elevated trace element (e.g. As, Cd, Co, Fe, Mn and Ni) and total CN concentrations, exceeding drinking water standards in some boreholes.

- Elevated trace element concentrations in the soils affected by AMD and the high mobility of phytotoxic elements such as Co and Ni complicate rehabilitation and recultivation attempts. The most commonly applied remediation method involves the addition of lime. However, *where more than one trace element is involved in the rehabilitation (common situation)*, changing the soil pH may reduce the mobility of some elements whilst mobilising others such as Mo (under alkaline conditions).

- Preliminary tests indicate that the extractable trace element concentration of the selected reclaimed site shows greater exceedance ratios in the unsaturated zone and, furthermore, shows a variable spatial contaminant distribution. For example, Uranium exceeds the threshold value (0.04 mg/l) by three orders of magnitude. Cobalt, Ni and Zn exceed their threshold concentrations of 0.5, 1 and 10 mg/l, respectively. Chromium and Pb also exceed threshold values. Extractable As concentrations, and occasionally Pb and Cr, did not exceed the lower analytical detection limits.

- The mobility of trace elements is dependent on a number of parameters, including pH. All the trace elements examined are most mobile when the soil pH < 4, and least mobile when a soil pH > 6. Cobalt, Ni and Zn are the most mobile trace elements for the selected reclaimed site. Chromium, Cu, Fe, Pb and U are less mobile compared to the above elements, indicating that a significant portion of the latter trace elements is contained in the residual fraction of the solid phase.

- The potential hazard posed by the trace elements at the selected reclaimed site can be summarised as U>>Co=Ni=Zn>Cr=Pb>>As in the soil. This potential hazard series is a function of the degree and frequency with which a trace element exceeds the relevant threshold values.

- The application of the geochemical load index for the assessment of the future pollution potential at seven sites, classified three sites as moderately to highly polluted (pollution class III), three sites as highly polluted (pollution class IV) and one site as excessively polluted (pollution class IV). It should be noted that pollution class VI reflects a 100-fold exceedance above the background value.

- Soil conditions indicating preferential flow (bypass of the soil matrix) were observed in some test pit profiles. However, the identification of dominant contaminant migration processes would be premature owing to the lack of in situ tests.

- International guidelines such as the soil quality standards of the Netherlands are not directly applicable to South African conditions. The predominantly humid climate conditions in Europe do not correspond with South African conditions in the areas where the bulk of mining activities take place. Major difficulties which occur when different studies are compared could be avoided through the use of standardised approaches to analytical testing (e.g. extraction tests) and the establishment of background or baseline values.

- The extractable concentrations of Co, Cr, Cu, Ni and Zn found in gold-mine tailings samples exceed threshold concentrations. This confirms that gold-mine tailings are a source of trace element pollution. In addition, tailings dams continue to release significant salt loads contained in seepage for an extended time period after termination of mining operations. Seepage emanating from tailings dams also has a negative effect on water quality in nearby surface water systems, which impacts adversely on water users in those areas as a result. High sulphur concentrations are contained in the leachate. Consequently, incomplete reclamation of tailings would result in tailings material remaining on the surface. Such material provides an additional reservoir for acid generating processes and contaminant release.

9.3 RECOMMENDATIONS

The following recommendations for further studies emanated from this research project and are summarised in terms of the following categories:

Investigate gold-mine tailings dams:

- **Field and laboratory testing**: to sample at various depths of the deposit, mineralogical composition, acid base accounting, total and extractable or bio-available concentrations of toxic metals and selected radionuclides.
- **Water balance modelling**: to characterise the flow-conditions within a deposit and quantify seepage volumes of deposits under certain scenarios (deposition technologies, soil cover, vegetation, climate effects).
- **Geochemical modelling**: to predict seepage quality under different scenarios (no rehabilitation, cover systems, vegetation, climate effects).

Investigate the unsaturated zone underneath the gold-mine tailings deposit and in prevailing wind-direction:

- **Field and laboratory testing**: to sample at various depths, mineralogical composition, acid base accounting, total and extractable or bio-available concentrations of toxic metals and selected radionuclides including sequential extraction tests, in-situ infiltration tests, soil moisture and water retention tests.
- **Unsaturated zone modelling**: to predict seepage quantities and qualities entering the groundwater system under different rehabilitation scenarios (e.g. no rehabilitation, liming, addition of clay or fly ash to the contaminated soils, recultivation).

Investigate the saturated zone affected by seepage emanating from gold-mine tailings dams:

- **Field and laboratory testing**: to monitor groundwater quality (including toxic metals and selected radionuclides) up and down gradient of selected tailings dam sites, in-situ measurements by using a flow cell. Aquifer testing (if necessary).

- **Flow and mass transport modelling**: to predict velocity of contamination plume under various scenarios (e.g. no groundwater remediation option and hydraulic barriers).

General recommendation:

- Develop rehabilitation guidelines for land affected by seepage emanating from gold-mine tailings dams by using a risk assessment procedure (including radiological risks). This would enable to identify certain levels of land development, after tailings reclamation took place.

Please note that the majority of the above mentioned recommendations will be addressed in Phase II of this research project, which will commence in January 1999.

In addition, the following general recommendations are made:

- Develop soil quality standards and background values;

- Develop remote sensing technologies (e.g. satellite images) in connection with GIS applications to monitor the expansion of residential areas towards mine facilities and to assess environmental parameters such as dust erosion emanating from tailings dams;
- Develop guidelines for certain laboratory procedures for soils (such as the South African acid rain test or EPA leaching approaches such as the TCLP approach for waste dumps).

CHAPTER 10

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APPENDIX A

Geotechnical Profiles

Geotechnical & Geochemical Descriptions
of the Test Pits

Summary of all Geotechnical Results

SUMMARY OF ALL GEOTECHNICAL RESULTS

SAMPLE DESCRIPTION			GRADING ANALYSES				ATTERBERG LIMITS					INSITU PROPERTIES				PERMEABILITY
TEST PIT and Sample No.	DEPTH (m)	UNIFIED SOIL CLASSIFICATION	% Clay	% Silt	% Sand	% Gravel	LL	LS	PI	PI ws	Exp	pH	Dry density (Kg/m³)	SG	e %	K (cm/s)
Reclaimed site 5L7																
A/1/1	0,20	SC-SM Silty, Clayey SAND	13,15	23,50	62,50	0,50	18,75	2,06	5,98	4,80	low	3,06	1752,88	2,72	0,55	1 x 10^{-7}
A/1/2	0,40	SC Clayey SAND	15,82	20,38	54,60	9,20	20,98	3,77	9,81	6,90	low	4,22	1816,08	2,72	0,50	1 x 10^{-7}
A/1/3	1,00	SC-SM Silty, Clayey SAND	7,51	25,49	53,00	14,00	21,01	2,79	5,94	3,85	low	6,11	-	-	-	-
A/2/2	0,35	SC Clayey SAND with gravel	10,62	15,48	51,20	22,70	23,05	5,27	9,30	4,03	low	4,33	-	-	-	-
A/2/4	0,90	SC Clayey SAND	8,54	21,96	57,30	12,20	26,23	5,21	8,26	3,55	low	4,36	1551,43	2,81	0,81	1 x 10^{-7}
A/3/2	0,30	SC Clayey SAND with gravel	8,45	8,45	52,20	30,90	28,70	7,22	12,25	2,89	low	6,45	-	-	-	-
A/3/3	0,70	SC Clayey SAND	11,31	28,39	56,00	4,30	25,69	5,58	9,34	5,11	low	6,90	-	-	-	-
A/3/4	1,00	SC Clayey SAND	12,10	31,40	45,80	10,70	25,24	5,49	8,99	5,65	low	6,87	-	-	-	-
Reclaimed site 6L3																
B/1/1	0,10	CL Sandy CLAY of low plasticity	29,80	24,60	45,60	0,00	28,00	7,28	13,07	11,79	low	3,64	1695,54	2,48	0,46	1 x 10^{-8}
B/1/2	0,50	CL Sandy CLAY of low plasticity	34,68	21,82	43,50	0,00	29,32	8,18	13,01	11,73	low	3,53	1619,22	2,45	0,51	1 x 10^{-8}
B/2/1	0,30	ML SILT with sand	50,92	26,18	22,90	0,00	48,40	10,91	19,17	16,54	low	4,19	-	-	-	-
B/2/2	0,50	MH Elastic SILT	63,66	23,54	12,40	0,40	50,31	11,13	20,64	19,63	low	5,09	-	-	-	-
B/2/4	2,00	MH Elastic SILT	50,24	43,46	6,30	0,00	57,83	11,82	26,00	25,67	med	5,74	-	-	-	-
B/3/1	0,40	CL Sandy CLAY of low plasticity	31,71	29,59	38,50	0,20	28,78	7,42	12,74	11,28	low	6,19	-	-	-	-
B/3/3	1,00	CL Sandy CLAY of low plasticity	41,80	28,00	30,10	0,10	33,41	8,97	14,82	13,65	low	6,63	1665,46	-	-	-
B/3/4	1,60	SC Clayey SAND	19,02	21,68	50,30	9,00	34,84	8,36	15,61	8,21	low	6,66	-	-	-	-
Reclaimed site 6L5																
C/1/2	0,80	CL CLAY with sand of low plasticity	46,78	28,42	24,80	0,00	32,72	8,93	15,10	14,26	low	3,95	1602,09	2,61	0,63	8 x 10^{-8}
C/1/3	1,40	CL Sandy CLAY of low plasticity	28,90	32,40	38,60	0,10	38,33	8,89	18,61	14,06	low	3,82	1520,08	2,80	0,84	9,5 x 10^{-6}
C/1/4	2,20	CL Sandy CLAY of low plasticity	34,33	32,77	30,70	2,20	35,52	9,03	17,43	14,09	low	5,01	-	-	-	-
C/2/1	0,15	CL Sandy CLAY of low plasticity	35,37	30,53	43,70	0,40	45,01	7,73	25,13	21,10	med	6,09	-	-	-	-
C/2/2	0,40	CL Sandy CLAY of low plasticity	35,75	21,15	42,60	0,50	48,06	10,38	28,01	23,52	med	5,05	-	-	-	-
C/2/4	2,30	SC Clayey SAND with gravel	19,51	13,09	50,80	16,60	44,86	10,93	26,68	13,46	med	7,44	-	-	-	-
C/3/1	0,30	CL Sandy CLAY of low plasticity	24,58	36,62	38,80	0,00	29,89	6,97	13,03	11,95	low	3,52	-	-	-	-
C/3/2	0,60	CL Sandy CLAY of low plasticity	38,41	27,79	33,60	0,20	34,53	9,14	16,50	15,20	low	4,85	1700,96	2,40	0,41	1 x 10^{-8}
C/3/3	1,65	CH CLAY with sand of high plasticity	48,66	26,64	23,70	1,00	52,85	8,93	31,38	28,47	med	7,69	1738,90	2,57	0,48	1 x 10^{-8}
Reclaimed site 6L6																
D/1/1	0,10	CL Sandy CLAY of low plasticity	27,77	27,33	44,90	0,00	28,18	7,84	13,39	11,75	low	3,65	1684,51	2,61	0,55	9 x 10^{-7}
D/1/2	0,30	CL Sandy CLAY of low plasticity	41,64	25,46	32,90	0,00	31,92	8,69	14,70	13,49	low	6,00	1566,60	2,64	0,69	9 x 10^{-7}
D/1/4	1,30	SC Clayey SAND	20,93	23,57	48,30	7,20	32,38	8,04	15,72	9,36	low	6,78	1644,29	2,69	0,64	7 x 10^{-7}
D/2/1	0,40	CL Sandy CLAY of low plasticity	31,33	24,67	44,00	0,00	34,09	9,88	16,48	14,55	low	3,76	-	-	-	-

LL: Liquid limit, LS: Linear shrinkage, PI: Plasticity Index, PI ws: Plasticity index of whole sample. Exp: Expansiveness SG: Specific gravity e: void ratio. K: Estimated saturated hydraulic conductivity

SAMPLE DESCRIPTION			GRADING ANALYSES				ATTERBERG LIMITS					INSITU PROPERTIES				PERMEABILITY
TEST PIT and Sample No.	DEPTH (m)	UNIFIED SOIL CLASSIFICATION	% Clay	% Silt	% Sand	% Gravel	LL	LS	PI	PI ws	Exp	pH	Dry density (Kg/m³)	SG	e %	K (cm/s)
Reclaimed site 6L6 (continued)																
D/2/2	0,70	CL Sandy CLAY of low plasticity	42,23	25,67	32,10	0,00	37,13	10,73	15,73	14,38	low	3,89	-	-	-	-
D/2/4	0,60	CL CLAY with sand of low plasticity	35,00	35,70	29,30	1,00	40,93	9,97	19,20	16,90	low	6,29	-	-	-	-
D/3/1	0,10	SC Clayey SAND	14,37	28,83	55,80	0,00	20,48	3,52	7,20	6,09	low	3,47	-	-	-	-
D/3/2	0,50	CL Sandy CLAY of low plasticity	34,73	22,67	39,50	3,10	32,68	9,14	15,53	13,07	low	6,75	-	-	-	-
D/3/4	1,90	CH CLAY with sand of high plasticity	51,44	25,96	22,50	0,10	55,87	11,09	32,28	30,32	med	-	1553,81	2,68	0,72	$7,5 \times 10^{-8}$
Reclaimed site 6L12																
E/1/2	0,70	CL Sandy CLAY of low plasticity	33,29	23,21	42,70	0,80	45,57	7,83	27,43	23,05	med	6,72	1775,29	2,55	0,44	1×10^{-6}
E/1/3	1,50	CL Sandy CLAY of low plasticity	40,06	22,34	37,50	0,10	46,19	7,28	26,31	21,28	med	6,97	1535,78	2,70	0,76	$9,5 \times 10^{-7}$
E/2/1	0,45	CH CLAY with sand of high plasticity	37,39	23,61	37,40	1,60	56,54	11,67	32,58	28,91	high	7,74	1484,87	2,68	0,80	9×10^{-7}
E/2/2	0,75	CH CLAY with sand of high plasticity	35,02	20,38	36,20	8,40	52,32	11,32	27,65	22,27	med	7,79	-	-		-
E/2/3	1,15	CH CLAY with sand of high plasticity	46,55	24,65	28,30	0,50	64,10	11,15	37,23	34,27	v high	8,31	1535,06	2,68	0,75	8×10^{-8}
E/3/1	0,30	CH CLAY with sand of high plasticity	38,38	30,02	31,00	0,60	56,02	9,84	32,59	38,38	high	5,12	-	-	-	-
E/3/2	0,70	CL Sandy CLAY of low plasticity	39,19	29,61	31,00	0,00	48,69	7,30	28,31	26,88	high	6,75	-	-	-	-
Reclaimed site 6L18																
F/1/1	0,60	CL Sandy CLAY of low plasticity	40,16	28,54	31,30	0,00	30,12	8,81	13,60	12,73	low	6,69	1709,29	2,51	0,47	1×10^{-6}
F/1/2	1,00	CL Sandy CLAY of low plasticity	28,23	28,07	43,70	0,00	24,79	7,04	11,11	9,90	low	3,66	1711,02	2,71	0,58	6×10^{-7}
F/1/3	1,60	CL Sandy CLAY of low plasticity	40,82	28,28	30,60	0,30	29,52	8,30	13,01	12,09	low	6,62	-	-	-	-
F/2/1	0,20	CL Sandy CLAY of low plasticity	30,05	24,80	44,70	0,00	26,10	6,92	11,32	10,09	low	4,37	-	-	-	-
F/2/2	0,50	CL Sandy CLAY of low plasticity	40,34	21,46	38,20	0,00	30,69	7,98	12,94	11,82	low	6,67	-	-	-	-
F/2/3	1,50	CL CLAY with sand of low plasticity	44,22	26,78	29,00	0,00	33,32	8,55	15,22	14,33	low	6,29	-	-	-	-
F/3/1	0,10	CL Sandy CLAY of low plasticity	25,56	28,74	45,70	0,00	23,72	6,12	10,66	9,41	low	4,53	-	-	-	-
F/3/2	0,50	CL Sandy CLAY of low plasticity	30,96	24,94	44,10	0,00	25,99	7,67	10,98	9,78	low	5,17	1661,44	2,78	0,67	6×10^{-7}
F/3/4	1,60	CL Clayey SAND with gravel	19,72	16,48	43,30	20,50	29,67	7,81	12,91	6,21	low	4,70	-	-	-	-
F/4/1	0,30	CL Sandy CLAY of low plasticity	13,70	37,00	49,30	0,00	21,32	4,32	7,45	6,64	low	3,70	-	-	-	-
F/4/2	0,60	CL Sandy CLAY of low plasticity	29,24	23,56	47,20	0,00	25,48	7,85	11,23	10,04	low	4,71	-	-	-	-
F/4/4	2,20	CL Sandy CLAY of low plasticity	39,56	26,84	33,20	0,40	31,55	8,83	17,23	15,89	low	4,65	1739,57	2,72	0,56	6×10^{-8}
Reclaimed site 7L14																
G/1/1	0,30	SC Clayey SAND	14,10	26,80	58,10	0,30	19,39	4,36	7,54	5,78	low	3,99	1786,21	2,64	0,48	1×10^{-7}
G/1/3	1,00	SC Clayey SAND with gravel	23,61	23,99	35,60	16,80	29,26	7,79	14,76	9,48	low	6,89	-	-	-	-
G/2/2	1,00	SC Clayey SAND	22,63	25,37	43,50	8,50	24,21	6,23	10,75	7,60	low	6,31	1782,53	2,68	0,50	1×10^{-7}
G/3/1	0,20	SC Clayey SAND	18,74	28,06	53,20	0,00	22,90	6,42	10,37	8,27	low	4,03	-	-	-	-
G/3/2	0,50	SC Clayey SAND	24,69	32,61	41,30	1,40	23,18	6,98	10,03	7,90	low	4,83	-	-	-	-
G/3/3	1,20	CL Sandy CLAY of low plasticity	31,45	21,15	34,60	12,80	30,85	8,60	11,54	8,23	low	6,74	-	-	-	-

LL: Liquid limit, LS: Linear shrinkage, PI: Plasticity Index, PI ws: Plasticity index of whole sample. Exp: Expansiveness SG: Specific gravity e: void ratio. K: Estimated saturated hydraulic conductivity

Test Pit Log

Test pit number: E/1

		Profile description	**Sample number**	**Geotechnical description**						**Geochemical description**															
				% Clay	**PI ws**	**Dry density**	**SG**	**e**	**K cm/s**	**pH**	**Fe**	**Mn**	**As**	**Ba**	**Co**	**Cr**	**Cu**	**Mo**	**Ni**	**Pb**	**Sn**	**Th**	**U**	**V**	**Zn**
0 0,30	▥	Slightly moist, pale yellow brown mottled black and orange brown, very soft, layered sandy silt, Tailings																							
0,50	▨	Moist, brown mottled dark grey and dark brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5mm in diameter); Colluvium.	E1/1	-	-	-	-	-	-	-	5.9	0.14	21	248	36	279	26	16	106	14	0	15	0	111	58
	▨		E/1/2	33,29	23	1775,29	2,55	0,44	1×10^{-8}	6,72	6.1	0.27	17	533	47	294	31	15	70	21	0	16	0	134	37
1 1,30	▨	Moist, light grey mottled yellow brown and dark grey, stiff, slickensided sandy clay with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.																							
2	▨	Moist, yellow brown mottled light grey and dark grey, stiff, slickensided sandy clay with abundant fine-grained subrounded quartz gravel and sporadic rounded quartzite boulders (up to 0,40 m in diameter); Colluvium.	E/1/3	40,06	21	1535,78	2,70	0,76	$9,5 \times 10^{-7}$	6,97	12.2	0.07	7	194	20	403	38	10	88	25	0	15	0	261	24
2,30	▨	Abundant coarse-, medium and fine-grained subrounded quartz gravel and occasional ferricrete nodules in wet yellow brown sandy clay; Colluvium. The overall consistency is firm.	E/1/4	-	-	-	-	-	-	-	18.8	0.07	24	271	47	498	57	0	135	41	0	0	0	581	22
3		**Notes** 1. No refusal 2. Perched water table at 2,00 m 3. Stable sidewalls																							
meter																									

Date: ###### **Locality:** Case Study Site E

Elevation: 1585 m

Profiled by: P Aucamp & T Rösner

Test Pit Log

Test pit number: E/2

0
0,30
0,60
1,00
1,50
2
3
meter

Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Moist, red brown, very loose, layered silty sand with abundant organic residue; Fill.																							
Moist, black, soft, intact clay with abundant *fine-grained gypsum crystals* (up to 5 mm in diameter); Alluvium.	E/2/1	37,39	29	1484,87	2,68	0,80	9×10^{-7}	7,74	6.6	0.08	36	191	24	258	52	9	69	0	0	8	0	99	43
Moist, black, firm, slickensided clay with numerous coarse-, medium- and fine-grained subrounded quartz gravel and occasional fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.	E/2/2	35.02	22.27	-	-	-	-	7,79	6.9	0.07	22	274	17	285	54	14	66	2	0	12	0	113	47
Moist, blueish grey mottled dark yellow brown and dark grey, firm, slickensided clay with occasional coarse-, medium- and fine-grained calcrete and quartz gravel and scattered *fine-grained gypsum crystals* (up to 5 mm in diameter); Alluvium.	E/2/3	46,55	34	1535,06	2,68	0,75	6×10^{-8}	8,31	7.8	0.10	10	266	25	305	58	14	78	11	0	15	0	161	41

Notes

1. Refusal at 1,50 m on alluvial boulders (quartzite and chert)
2. No water table encountered
3. Stable sidewalls

Date: ###### **Locality:** Case Study Site E **Elevation:** 1580 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: E/3

meter		Profile description	Sample number	Geotechnical description						Geochemical description															
0				% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0,20	░	Moist, red brown, very loose, layered silty sand with abundant organic residue; Fill.																							
0,60	▨	Moist, black, soft, intact clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium	E/3/1	38.38	38	-	-	-	-	5,12	4.5	0.02	19	138	23	235	31	15	65	15	0	18	0	102	57
1 1,10	▨	Moist, black, firm, stickensided sandy clay with numerous coarse-, medium- and fine-grained subrounded quartz gravel and occasional fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium	E/3/2	36.19	26.88	-	-	-	-	6,75	4.7	0.02	19	118	18	297	33	16	68	12	0	19	0	147	68
1,30	▨		E/3/3	-	-	-	-	-	-	-	3.6	0.02	23	109	14	287	27	19	61	10	0	17	0	118	83
2		Moist, blueish grey mottled dark yellow brown and dark grey, firm, intact clay with occasional coarse-, medium- and fine-grained calcrete and quartz gravel and scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.																							
3																									

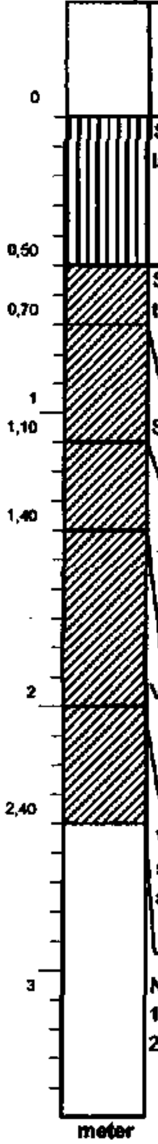
Notes

1. Refusal at 1,30 m on alluvial boulders (quartzite and chert)
2. No water table encountered
3. Stable sidewalls

Date: ###### Locality: Case Study Site E **Elevation:** 1606 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: F/1



Depth (m)	Profile description	Sample number
0–0,50	Slightly moist, pale yellow brown, very soft, layered sandy silt, Tailings	
0,50–1	Slightly moist, dark red brown, soft, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium	F/1/1
1–1,40	Slightly moist, red brown, soft, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter) Colluvium.	F/1/2
1,40–	Moist, dark red brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/1/3
–2,40	Very moist, dark red brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium	F/1/4
2,40–	Very moist, dark red brown, stiff, intact sandy clay with abundant coarse-, medium- and fine-grained subangular ferricrete gravel Ferrugenised colluvium.	

Notes

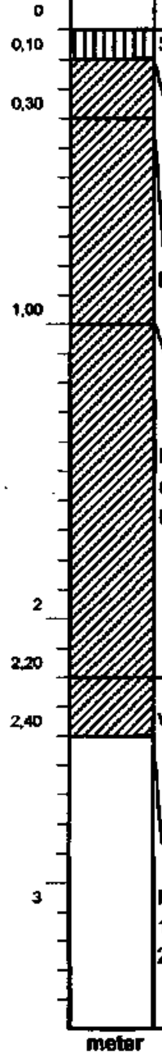
1. No refusal
2. No water table encountered

Sample number	Geotechnical description						Geochemical description															
	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
F/1/1	40,16	13	1709,29	2,51	0,47	1 x 10^{-8}	6,69	8.6	0.16	20	188	5	178	53	22	76	11	0	21	0	139	43
F/1/2	28,23	10	1711,02	2,71	0,58	6 x 10^{-7}	3,66	7.3	0.19	31	222	30	170	90	22	143	10	0	18	57	127	80
F/1/3	40.82	12.01	-	-	-	-	6,62	8.3	0.12	21	182	4	169	49	23	68	11	0	20	0	134	40
F/1/4	-	-	-	-	-	-	-	8.2	0.09	21	178	3	200	43	24	62	9	0	21	0	133	36

Date: 21/4/1998 **Locality: Case Study Site F** **Elevation:** 1583 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: F/2



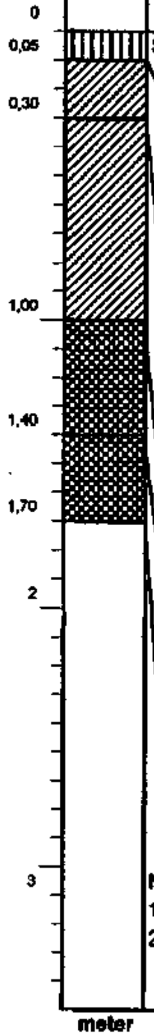
Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, pale yellow brown, very soft, layered sandy silt, Tailings	F/2/1	30.05	10.09	-	-	-	-	4,37	8.5	0.44	20	235	9	202	68	22	83	11	0	18	0	135	46
Slightly moist, dark red brown mottled dark brown, very stiff, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/2/2	40.34	12	-	-	-	-	6,67	9.3	0.18	17	214	5	208	68	20	88	12	0	18	0	152	46
Moist, red brown, stiff, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium																							
Moist, red brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/2/3	44.22	14	-	-	-	-	6,29	9.6	0.11	20	196	4	199	63	21	78	10	0	20	0	154	39
Very moist, dark red brown, stiff, intact sandy clay with abundant coarse-, medium- and fine-grained subangular ferricrete gravel; Ferrugenised colluvium.	F/2/4	-	-	-	-	-	-	-	9.0	0.11	18	186	4	209	54	23	66	7	0	20	0	144	37

Notes
1. No refusal
2. No water table encountered

Date: 21/4/1998 **Locality:** Case Study Site F **Elevation:** 1587 m **Profiled by:** P Aucamp T Rösner

Test Pit Log

Test pit number: F/3



		Geotechnical description						Geochemical description															
Profile description	Sample number	% Clay	PI	Dry density	SG	e	K	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, pale grey, very soft, layered sandy silt, Tailings	F/3/1	25.56	9	-	-	-	-	4,53	5.4	0.04	200	194	60	179	55	24	312	0	0	0	1175	125	205
Slightly moist, dark red brown occasionally mottled red brown, stiff, open textured sandy clay sand with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/3/2	30,96	10	1661,44	2,78	0,67	6×10^{-7}	5,17	6.6	0.04	72	183	51	178	56	36	301	3	0	13	704	131	281
Moist, red brown, firm, open testured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/3/3	-	-	-	-	-	-	-	7.2	0.06	24	179	14	291	47	15	83	10	0	16	9	129	40
Abundant medium- to fine-grained subrounded ferricrete nodules and chert gravel in moist, red brown clayey sand; Ferrugenised colluvium. The overall consistency is dense.	F/3/4	19.72	6	-	-	-	-	4,70	7.6	0.06	28	170	15	292	52	14	96	4	0	15	50	142	51
Abundant medium- to fine-grained subrounded chert gravel and occasional ferricrete nodules and occasional subangular chert boulders (up to 0,07 m in diameter) in moist, red brown clayey sand; Ferrugenised colluvium. The overall consistency is dense.																							
Notes 1. Gradual refusal on hard rock chert. 2. No water table encountered																							

Date: 21/4/1998 **Locality: Case Study Site F**

Elevation: 1585 m

Profiled by: P Aucamp & T Rösner

Test Pit Log

Test pit number: F/4

meter	Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0 – 0,20	Slightly moist, pale grey, very soft, layered sandy silt, Tailings.																							
0,20 – 0,50	Slightly moist, dark red brown occasionally mottled red brown, stiff, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/4/1	13.7	7	-	-	-	-	3,70	5.2	0.03	92	188	32	267	74	43	187	0	0	50	932	118	147
0,50		F/4/2	29,24	10	-	-	-	-	4,71	8.1	0.05	21	179	12	174	53	21	92	9	0	19	0	132	41
1,00	Moist, red brown, stiff, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	F/4/3	-	-	-	-	-	-	-	7.2	0.04	27	201	25	181	58	23	147	8	0	17	100	135	98
2	Moist, red brown, firm, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.																							
2,10 – 2,40	Moist, red brown, firm, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter) and numerous medium- to fine-grained ferricrete gravel; Ferrugenised colluvium.	F/4/4	39,56	16	1739,57	2,72	0,56	6×10^{-7}	4,65	8.5	0.06	19	191	5	199	53	21	78	7	0	19	0	138	49
3																								

Geotechnical description: % Clay, PI, Dry density, SG, e, K. Geochemical description: pH to Zn.

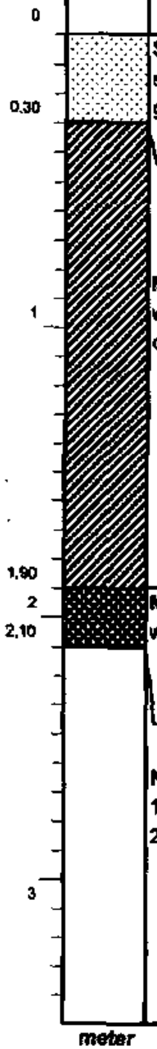
Notes

1. No refusal.
2. No water table encountered.

Date: 21/4/1998 **Locality: Case Study Site F** **Elevation:** 1580 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: B/1



Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s
Slightly moist, dark red brown, dense, open structured, silty sand with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/1/1	29,80	12	1695,54	2,48	0,46	1×10^{-5}
Moist, red brown, firm, intact, sandy clay with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/1/2	34,68	12	1619,22	2,45	0,51	1×10^{-8}
	B/1/3	-	-	-	-	-	-
Moist, red brown, firm, intact, sandy clay with numerous coarse-, medium- and fine-grained subrounded ferricrete gravel; Ferrugenised colluvium.	B/1/4	-	-	-	-	-	-

Geochemical description

Sample number	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
B/1/1	3,64	9.8	0.06	17	281	27	232	87	19	173	13	0	16	0	156	135
B/1/2	3,53	9.6	0.06	17	259	18	226	89	20	153	14	0	17	0	158	102
B/1/3		10.1	0.06	17	231	8	230	79	20	115	13	0	18	0	165	91
B/1/4		10,4	0.07	19	236	7	246	87	21	106	10	0	19	0	172	72

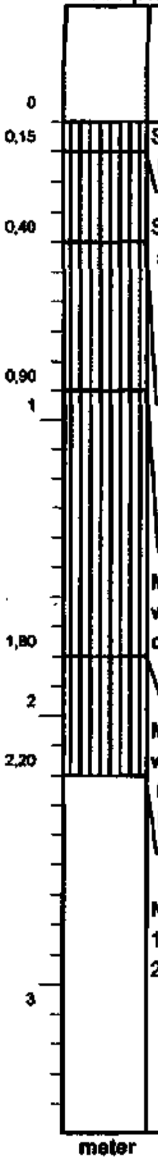
Notes

1. No refusal.
2. No water table encountered.

Date: 21/4/1998 **Locality: Case Study Site B** **Elevation:** 1609 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: B/2



Profile description

Slightly moist, pale yellow brown, very soft, layered sandy silt, Tailings.

Slightly moist, dark red brown, dense, open structured, sandy silt with abundant fine-grained gypsum crystals (up to 5 mm in diameter) and subrounded quartzite boulders (up to 0,20 m in diameter); Colluvium.

Moist, red brown, firm, intact, sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.

Moist, dark red brown, firm, intact, silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.

Moist, dark red brown, firm, intact, silt with occasional coarse-, medium- and fine-grained subrounded ferricrete gravel; Ferrugenised colluvium

Notes

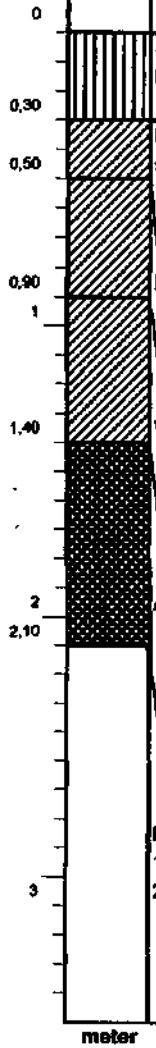
1. No refusal.
2. No water table encountered.

Sample number	Geotechnical description						Geochemical description															
	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
B/2/1	50.92	17	-	-	-	-	4,19	13.2	0.10	18	286	76	372	135	9	241	15	0	15	0	207	126
B/2/2	63.66	20	-	-	-	-	5,09	12.9	0.10	23	247	51	344	143	10	190	6	0	14	0	202	78
B/2/3	-	-	-	-	-	-	-	13.6	0.06	17	293	10	374	130	14	139	4	0	16	0	197	57
B/2/4	50.24	26	-	-	-	-	5,74	15.1	0.06	3	400	16	485	170	12	140	6	0	15	0	203	51

Date: 21/4/1998 **Locality:** Case Study Site B **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: B/3



Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, light grey banded yellow brown, very soft, layered sandy silt, Tailings.																							
Moist, dark grey, dense, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/3/1	31.71	11	-	-	-	-	6,19	6.0	0.04	43	230	19	211	48	12	85	0	0	12	0	89	53
	B/3/2	-	-	-	-	-	-		6.2	0.03	22	204	13	163	46	20	78	9	0	21	0	96	40
Moist, dark olive mottled dark grey, firm, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/3/3	41.6	14	-	-	-	-	6,63	7.2	0.04	19	197	9	230	51	19	85	13	0	23	0	113	44
Very moist, dark yellow brown occasionally mottled dark red brown, firm, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/3/4	19.02	8.21	-	-	-	-	6,66	8.7	0.47	6	1018	124	204	67	4	126	83	0	8	0	163	39
Abundant medium- and fine-grained subrounded to subangular ferricrete gravel in very moist, light olive mottled black, dark red brown and dark yellow brown sandy clay; Ferrugenised colluvium. The overall consistency is stiff.																							

Notes

1. No refusal.
2. No water table encountered.

Date: 21/4/1998 **Locality: Case Study Site B** **Elevation:** 1613 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

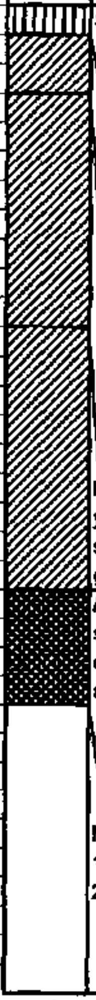
Test pit number: C/1

		Profile description	Sample number	Geotechnical description						Geochemical description															
				% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0	▥	Slightly moist, pale yellow, firm, intact sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Tailings.	C/1/1	-	-	-	-	-	-	-	7.1	0.03	68	205	13	170	44	8	77	0	0	7	0	112	49
0,60 1	▨	Slightly moist, dark brown stained dark grey, firm, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter) and zones of moist, dark grey soft, intact, sandy clay; Colluvium.	C/1/2	46,78	14	1602,09	2,61	0,63	8×10^{-8}	3,92	8.5	0.04	25	212	14	191	50	18	79	8	0	21	0	126	47
1,20	▨	Slightly moist, red brown mottled and speckled dark red brown and black, firm intact sandy clay with abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel and with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Ferrugenised colluvium.	C/1/3	28,90	14	1520,08	2,80	0,84	$9,5 \times 10^{-6}$	3,82	14.2	0.06	7	526	33	369	67	0	76	118	0	0	0	254	36
1,90 2	▨	Slightly moist, red brown mottled and stained light grey, yellow brown and brown stiff, intact sandy clay with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.	C/1/4	34.33	14	-	-	-	-	5,01	10.6	0.11	22	511	25	220	54	16	65	10	0	17	0	167	38
2,30 3		Notes 1. No refusal. 2. No water table encountered.																							
meter																									

Date: ####### **Locality:** Case Study Site C **Elevation:** 1605 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: C/2



Depth (meter)	Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0																								
0,10	*Slightly moist, pale yellow brown, very soft* intact sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Tailings.	C/2/1	35.37	21	-	-	-	-	6,09	6.91	0.05	13	370	20	223	32	16	51	14	0	17	0	99	34
0,25		C/2/2	35.75	24	-	-	-	-	5,05	7.1	0.07	15	363	28	230	32	15	72	15	0	17	0	107	41
1	*Slightly moist, dark grey occasionally* mottled and striped dark yellow brown, stiff shattered sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.																							
1,10	Moist, dark grey occasionally mottled dark yellow brown, soft, intact sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.	C/2/3	-	-	-	-	-	-	-	7.1	0.03	21	406	16	270	27	14	56	17	0	19	0	166	33
2	Moist, grey mottled and speckled dark yellow brown, soft, intact sandy clay with sporadic course-grained, subangular quartz gravel; Alluvium.																							
2,40	Abundant coarse-, medium- and fine-grained subanguler ferricrete and quartz gravel in wet orange brown speckled and mottled black and dark yellow brown, clayey sand. Ferrugenised alluvium. The overall consistency is soft.	C/2/4	19.51	27	-	-	-	-	7,44	23.9	0.17	38	428	188	622	89	0	282	8	0	0	0	937	28
3																								

Geotechnical description: % Clay, PI ws, Dry density, SG, e, K cm/s. Geochemical description: pH to Zn.

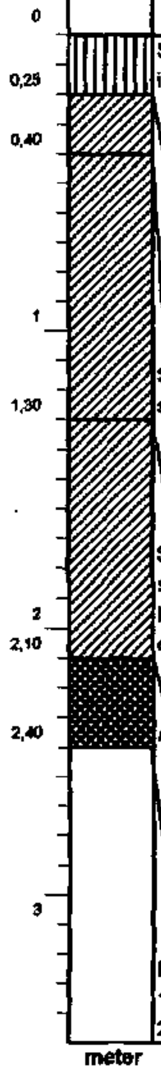
Notes

1. No refusal.
2. Perched water table at 2,00 m.

Date: ####### **Locality:** Case Study Site C **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: C/3



Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, light greyish olive, very soft intact sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Tailings.	C/3/1	24.58	12	-	-	-	-	3,52	4.09	0.03	30	193	22	166	46	23	53	5	0	20	8	98	29
Slightly moist, dark grey occasionally mottled and striped dark yellow brown, stiff shattered sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.	C/3/2	38,41	15	1700,96	2,40	0,69	1 x 10^{-8}	4,85	6.9	0.10	23	237	40	201	39	18	76	19	0	18	0	146	34
Slightly moist, yellow brown mottled and speckled dark yellow brown and dark grey firm slightly shattered, sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.	C/3/3	48,66	28	1738,90	2,57	0,64	1 x 10^{-9}	7,69	10.4	0.15	16	539	44	247	47	8	75	29	0	16	0	220	36
Slightly moist, yellow brown mottled and speckled dark yellow brown, dark grey and light grey, stiff, slightly shattered, sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Alluvium.																							
Abundant coarse-, medium- and fine-grained subrounded quartzite and sandstone gravel and occasional subrounded quartzite boulders (up to 0,10 m in diameter) in moist light olive brown speckled and mottled dark yellow brown to pale yellow brown, sandy clay; Alluvium. The overall consistency is soft.	C/3/4	-	-	-	-	-	-	-	7.3	0.10	24	292	42	213	42	14	65	7	0	18	0	178	36

Notes

1. No refusal.
2. No water table encountered.

Date: ###### **Locality:** Case Study Site C **Elevation:** 1608 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: D/1

Depth (meter)	Profile description	Sample number	Geotechnical description						Geochemical description															
			% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0 0,03 0,20	Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.	D/1/1	27,77	12	1684,51	2,61	0,55	9 x 10^{-7}	3,65	6.15	0.04	50	207	21	155	51	14	82	0	0	8	0	100	54
0,60	Moist, dark brown mottled dark grey stiff, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	D/1/2	41,64	13	1566,60	2,64	0,69	9 x 10^{-7}	6,00	7.1	0.02	21	188	15	159	62	19	77	6	0	18	0	112	49
		D/1/3	-	-	-	-	-	-	-	7.4	0.03	18	196	23	161	51	21	79	4	0	19	0	120	40
1 1,10	Moist, yellow brown, firm, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.																							
1,60	Moist, yellow brown occasionally mottled red brown, firm, open structured sandy clay with occasional fine-grained gypsum crystals (up to 5mm in diameter); Colluvium.	D/1/4	20,93	9	1644,29	2,69	0,64	7 x 10^{-7}	6,78	10.2	0.37	9	1252	90	195	78	10	99	46	0	8	0	199	38
2 3	Abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel in moist, light grey mottled yellow brown and black, clayey sand; Ferrugenised colluvium. The overall consistency is medium dense.																							

Notes

1. Gradual refusal at 1,60 m on hardpan ferricrete.
2. No water table encountered.

Date: 21/4/1998 **Locality:** Case Study Site D **Elevation:** 1605 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: D/2

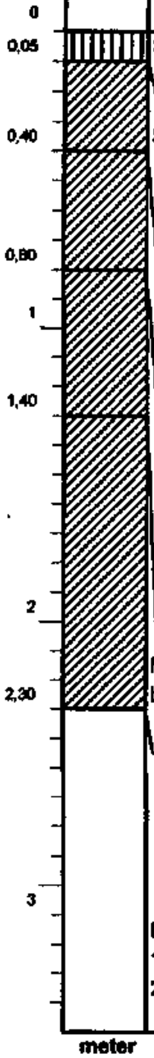
Depth (meter)		Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
				Geotechnical description						**Geochemical description**															
0	▥	Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.																							
0,25	▨	Moist, dark brown mottled dark grey, stiff open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	D/2/1	-	-	-	-	-	-	-	8.9	0.06	64	342	23	189	93	6	109	0	0	1	0	150	55
0,60	▨	Moist, red brown occasionally mottled yellow brown and dark brown, firm, open structured sandy clay with scattered fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	D/2/2	42.23	14	-	-	-	-	3,89	9.4	0.08	16	312	40	192	97	15	142	10	0	15	0	164	61
1,10	▩	Abundant coarse-, medium- and fine-grained subrounded ferricrete gravel in moist, light grey mottled red brown, yellow brown and black, clayey sand with numerous coarse-medium- and fine-grained subangular quartz gravel; Ferrugenised colluvium. The overall consistency is medium dense	D/2/3	-	-	-	-	-	-	-	10.5	0.46	9	1698	295	181	96	7	157	62	0	5	0	213	40
			D/2/4	35	17	-	-	-	-	6,29	11.7	0.41	8	716	99	246	116	18	120	21	0	15	0	199	53
2,40		**Notes** 1. No refusal. 2. No water table encountered.																							

Depth scale: 0, 0,25, 0,60, 1, 1,10, 2, 2,40, 3 meter

Date: 21/4/1998 **Locality:** Case Study Site D **Elevation:** 1604 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: D/3



Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.	D/3/1	14.37	6	-	-	-	-	3,47	3.4	0.04	35	195	25	113	33	22	48	0	0	14	0	61	37
Slightly moist, dark grey occasionally mottled yellow brown, firm, open structured sandy clay with numerous fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	D/3/2	34.73	14	-	-	-	-	6,75	6.7	0.05	17	305	23	175	42	17	70	6	0	18	0	90	48
Slightly moist, dark grey mottled yellow brown, firm, open structured sandy clay with sporadic fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	D/3/3	-	-	-	-	-	-	-	9.0	0.10	8	707	30	146	35	20	59	9	0	16	0	108	28
Moist, dark grey mottled yellow brown and light grey, firm, occasionally slickensided sandy clay with abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.	D/3/4	51,44	30	1553,81	2,68	0,72	$7{,}5 \times 10^{-8}$	-	6.8	0.03	20	228	10	196	50	17	75	1	0	19	0	85	49
Moist, light grey mottled and stained yellow brown and black, stiff, slickensided clay; Residual mudrock of the Vryheid Formation.																							

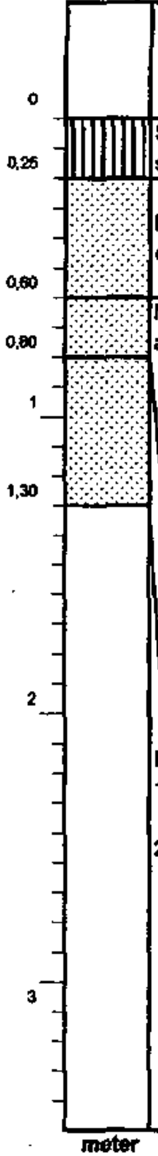
Notes

1. No refusal.
2. No water table encountered.

Date: 21/4/1998 **Locality: Case Study Site D** **Elevation:** 1606 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: G/1



Profile description	Sample number	Geotechnical description						Geochemical description															
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.																							
Moist, dark grey stained black, medium dense, intact clayey sand; Colluvium.	G/1/1	14,10	6	1786,21	2,64	0,48	1×10^{-7}	3,99	3.1	0.02	52	176	47	122	41	19	103	0	0	9	0	47	39
Moist, light grey stained pale yellow brown and occasionally mottled orange brown and black, medium dense, intact clayey sand with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.	G/1/2	-	-	-	-	-	-	-	5.3	0.01	23	185	8	141	43	18	70	4	0	17	0	58	44
	G/1/3	23.61	9	-	-	-	-	6,89	4.2	0.03	22	178	12	126	39	22	66	2	0	20	0	41	40
Very moist, light grey mottled and stained orange brown and dark yellow brown, loose intact clayey sand with abundant coarse- medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.																							

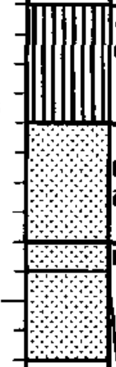
Notes

1. Gradual refusal at 1,30 *m* on hardpan ferricrete.
2. No water table encountered.

Date: ####### **Locality: Case Study Site G** **Elevation:** 1610 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: G/2



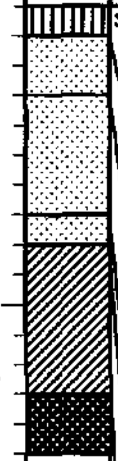
			Geotechnical description						Geochemical description																
	Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0 0,45	Slightly moist, pale yellow banded and mottled yellow brown and orange, very soft layered sandy silt, Tailings.																							
0,80	Moist, olive stained pale yellow brown, loose intact clayey sand; Colluvium.	G/2/1	-	-	-	-	-	-	-	4.1	0.02	21	190	14	125	39	26	56	0	2	17	0	54	35
0,95 1 1,10	Moist, light olive occasionally mottled dark olive and brown, loose, intact clayey sand with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.	G/2/2	22,63	8	1728,53	2,68	0,50	1×10^{-7}	6,31	5.4	0.05	22	192	18	159	47	24	73	3	0	19	0	74	56
2	Very wet, light olive occasionally mottled dark olive and brown, soft, intact clayey sand with abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.																							
3 meter	Notes 1. Gradual refusal at 1,10 m on hardpan *ferricrete.* 2. Perched water table at 0,95 m.																							

Date: *######* *Locality:* *Case Study Site G* *Elevation:* *1607 m* **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: G/3

0
0,10
0,35
0,70
0,85
1
1,30
1,50
2
3
meter



Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
		Geotechnical description						**Geochemical description**															
Slightly moist, pale yellow banded and mottled yellow brown and orange, very soft layered sandy silt, Tailings.	G/3/1	18.74	8	-	-	-	-	4,03	2.9	0.03	56	209	21	97	33	14	67	0	0	8	0	31	40
Slightly moist, dark brown mottled and stained orange brown (root stains), medium dense, intact clayey sand; Colluvium.	G/3/2	24.69	8	-	-	-	-	4,83	3.3	0.02	36	224	12	104	34	19	55	0	0	15	0	34	38
Slightly moist, brown mottled and stained orange brown (root stains), medium dense intact clayey sand; Colluvium.																							
Moist, light grey mottled dark grey, loose intact clayey sand; Colluvium.	G/3/3	31.45	8	-	-	-	-	6,74	3.9	0.03	22	206	22	121	42	19	73	7	0	20	0	41	44
Moist, light grey mottled orange brown soft, intact sandy clay with occasional coarse-, medium- and fine-grained, subrounded ferricrete gravel; Ferrugenised colluvium.																							
Abundant coarse-, medium- and fine-grained, subrounded ferricrete gravel in wet light grey silty clay; Ferrugenised colluvium. The overall consistency is soft.																							

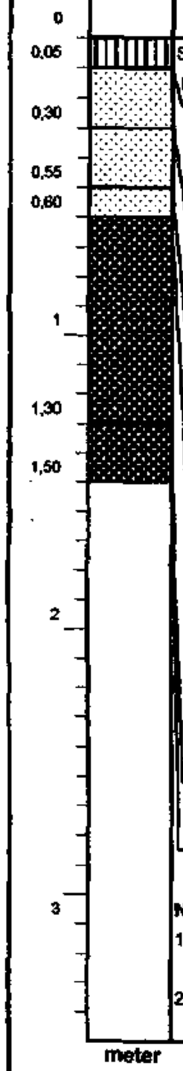
Notes

1. Gradual refusal at 1,50 m on hardpan ferricrete.
2. No water table encountered.

Date: ####### **Locality:** Case Study Site G **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: A/1



Profile description	Sample number	% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, light grey banded pale yellow brown, very soft, layered sandy silt, Tailings.	A/1/1	13,15	4,8	1752,88	2,72	0,55	1×10^{-7}	3,06	3.8	0.02	102	188	10	197	43	3	55	0	0	0	0	62	41
Slightly moist, dark brown, loose, slightly open textured clayey sand stained pale yellow brown on joints and cracks. Colluvium.	A/1/2	15,82	6,9	1816,08	2,72	0,50	1×10^{-7}	4,22	4.3	0.02	77	194	11	202	43	9	62	0	6	1	0	70	66
Slightly moist, yellow brown mottled dark brown, loose, slightly open textured clayey sand stained pale yellow brown on joints and cracks. Colluvium.	A/1/3	7,51	3,85	1892,52	2,81	0,81	1×10^{-7}	6,11	7.9	0.02	14	408	17	341	48	9	37	7	0	12	0	143	282
Slightly moist, yellow brown mottled dark brown, loose, slightly open textured clayey sand with occasional coarse-, medium- and fine-grained, subrounded quartz gravel; Pebble marker horizon.																							
Slightly moist, orange brown mottled bright yellow brown and stained brown, medium dense, relic structured clayey sand with zones of moist, brown, loose, open structured clayey sand; Hardpan ferruge = nised residual sandstone of the Vryheid Formation.																							
As above but very dense																							

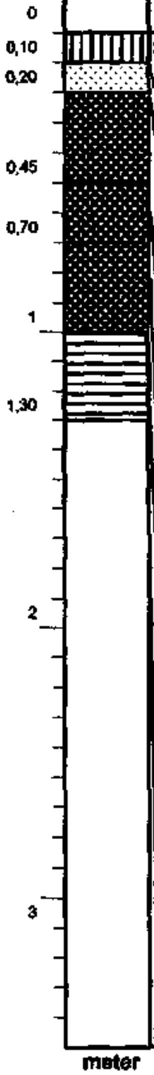
Notes

1. Gradual refusal at 1,50 m on hardpan ferricrete.
2. No water table encountered.

Date: ####### **Locality: Case Study Site A** **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: A/2



Profile description	Sample number	Geotechnical description						Geochemical description																
		% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
Slightly moist, light grey banded pale yellow brown, very soft, layered sandy silt, Tailings.	A/2/1	-	-	-	-	-	-	-	4.1	0.02	70	175	12	246	54	10	60	0	0	2	0	76	58
Slightly moist, yellow brown mottled dark brown, loose, slightly open textured clayey sand stained pale yellow brown on joints and cracks. Colluvium.	A/2/2	10.62	4	-	-	-	-	4,33	7.6	0.03	30	263	14	310	94	19	85	0	9	14	12	117	108
	A/2/3	-	-	-	-	-	-	-	9.1	0.02	17	314	5	360	93	18	62	2	0	15	7	180	40
Abundant course-, medium- and fine-grained subrounded sandstone and quartz gravel and occasional sandstone boulders (up to 0,25 m in diameter) in slightly moist yellow brown mottled dark brown, open textured clayey sand. Pebble marker horizon The overall consistency is very loose.	A/2/4	8,54	3,55	1551,43	2,81	0,81	1×10^{-7}	4,36	18	0.05	8	362	4	494	106	4	78	60	0	2	0	327	84
Abundant course-, medium- and fine-grained angular to subrounded ferricrete gravel in slightly moist, yellow brown mottled red brown and orange brown clayey sand. Nodular ferrugenised residual sandstone of the Vryheid Formation. The overall consistency is medium dense.																							
Slightly moist, orange brown mottled bright yellow brown and stained brown, very dense, relic structured clayey sand; Hardpan ferrugenised residual sandstone.																							
Pale red brown stained and motteled pale yellow brown, highly weathered, coarse-grained, closely jointed and fractured, very soft rock sandstone of the Vryheid Formation.																							

Notes
1. Gradual refusal at 1,50 m on hard rock sandstone of the Vryheid Formation.
2. No water table encountered.

Date: ####### **Locality:** Case Study Site A **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: A/3

Depth (meter)	Profile description	Sample number	Geotechnical description						Geochemical description															
0			% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe	Mn	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0,03 0,20	Slightly moist, light grey banded pale yellow brown, very soft, layered sandy silt, Tailings.	A/3/1	-	-	-	-	-	-	-	3.9	0.02	37	144	11	152	39	26	58	0	0	14	0	59	45
0,60	Slightly moist, yellow brown mottled dark brown, loose, slightly open textured clayey sand stained pale yellow brown on joints and cracks. *Colluvium.*	A/3/2	8.45	12	-	-	-	-	6,19	7.5	0.02	24	200	16	266	55	20	94	2	0	19	0	132	58
0,80	Abundant course-, medium- and fine-grained subrounded sandstone and quartz gravel and occasional sandstone boulders (up to 0,35 m in diameter) in slightly moist yellow brown mottled dark brown, open textured clayey sand. Pebble marker horizon The overall consistency is very loose.	A/3/3	11.31	5	-	-	-	-	6,63	12.2	0.04	20	204	7	351	57	17	67	9	0	17	0	279	31
1		A/3/4	12.1	6	-	-	-	-	6,66	15.1	0.07	16	302	22	341	70	12	65	28	0	12	0	332	31
1,40 2	Abundant course-, medium- and fine-grained angular to subrounded ferricrete gravel in slightly moist, yellow brown *mottled red brown and orange brown clayey* sand. Nodular ferrugenised residual sandstone of the Vryheid Formation. The overall consistency is medium dense.																							
	Slightly moist, orange brown mottled yellow brown and stained brown, very dense, relic structured clayey sand with scattered course-, medium and fine-grained well rounded quartz gravel; Hardpan *ferrugenised residual sandstone of the* Vryheid Formation.																							
3																								

Notes

1. Gradual refusal at 1,50 m on hard rock sandstone of the Vryheid Formation.
2. No water table encountered.

meter

Date: ####### **Locality: Case Study Site A** **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

APPENDIX B

Summary of Geochemical Soil Analyses (XRF)

Background Values for Vryheid Formation

Correlation matrices for the Tailings and Soil Analyses

Results of the Extraction Tests (Tailings and Soil)

Table A1 XRF analyses of the soils of the investigated reclaimed sites

	TiO2%	MnO%	Fe_2O_3t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
5L7/1/1	0.94	0.02	3.64	11	62	197	10	55	43	41	102	68	16	14	519	13	3	0	0	188	7	0	0	0
5L7/1/2	0.98	0.02	4.26	14	70	202	11	62	43	66	77	78	19	21	509	16	9	6	0	194	10	0	1	0
5L7/1/3	0.57	0.02	7.95	16	143	341	17	37	48	282	14	95	41	18	273	16	9	0	0	408	6	7	12	0
5L7/2/1	0.89	0.02	4.08	11	76	246	12	60	54	58	70	62	21	9	522	15	10	0	0	175	5	0	2	0
5L7/2/2	1.02	0.03	7.61	20	117	310	14	85	94	108	30	78	23	17	485	21	19	9	0	263	6	0	14	12
5L7/2/3	0.81	0.02	9.08	21	180	360	5	62	93	40	17	78	23	15	414	19	18	0	0	314	7	2	15	7
5L7/2/4	0.86	0.05	18.05	31	327	494	4	78	106	84	8	49	15	6	346	15	4	0	19	362	4	60	2	0
5L7/3/1	0.99	0.02	3.9	13	59	152	11	58	39	45	37	70	22	24	612	22	26	0	0	144	8	0	14	0
5L7/3/2	1.04	0.02	7.52	19	132	266	16	94	55	58	24	90	26	27	432	23	20	0	0	200	7	2	19	0
5L7/3/3	1.06	0.04	12.15	25	279	351	7	67	57	31	20	58	25	18	439	22	17	0	0	204	6	9	17	0
5L7/3/4	1.11	0.07	15.09	28	332	341	22	65	70	31	16	47	24	15	432	21	12	0	0	302	4	28	12	0
	TiO2%	MnO%	Fe_2O_3t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
6L3/1/1	1.21	0.06	9.75	25	156	232	27	173	87	135	17	85	23	35	429	22	19	0	0	281	7	13	16	0
6L3/1/2	1.2	0.06	9.61	24	158	226	18	153	89	102	17	85	22	33	428	23	20	0	0	259	7	14	17	0
6L3/1/3	1.22	0.06	10.11	24	165	230	8	115	79	91	17	82	22	28	431	23	20	0	0	231	6	13	18	0
6L3/1/4	1.3	0.07	10.44	26	172	246	7	106	87	72	19	77	21	23	444	25	21	0	0	236	8	10	19	0
6L3/2/1	0.92	0.1	13.18	32	207	372	76	241	135	126	18	79	22	29	200	17	9	0	0	286	4	15	15	0
6L3/2/2	0.92	0.1	12.87	30	202	344	51	190	143	78	23	76	23	22	200	18	10	0	0	247	5	6	14	0
6L3/2/3	1.05	0.06	13.61	35	197	374	10	139	130	57	17	64	26	26	251	19	14	0	0	293	6	4	16	0
6L3/2/4	0.95	0.06	15.14	41	203	485	16	140	170	51	3	72	35	35	186	17	12	0	0	400	5	6	15	0
6L3/3/1	1.05	0.04	5.97	16	89	211	19	85	48	53	43	90	35	31	421	21	12	0	0	230	8	0	12	0
6L3/3/2	1.12	0.03	6.22	18	96	163	13	78	46	40	22	96	35	33	437	25	20	0	0	204	7	9	21	0
6L3/3/3	1.18	0.04	7.2	19	113	230	9	85	51	44	19	101	31	29	418	26	19	0	0	197	6	13	23	0
6L3/3/4	1.22	0.47	8.65	21	163	204	124	126	67	39	6	89	42	26	409	19	4	0	0	1018	5	83	8	0
	TiO2%	MnO%	Fe_2O_3t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
6L5/1/1	1.03	0.03	7.14	18	112	170	13	77	44	49	68	96	16	17	405	18	8	0	0	205	6	0	7	0
6L5/1/2	1.1	0.04	8.54	21	126	191	14	79	50	47	25	107	20	30	388	24	18	0	0	212	7	8	21	0
6L5/1/3	1.06	0.06	14.23	27	254	369	33	76	67	36	7	74	19	9	361	12	0	0	0	526	3	118	0	0
6L5/1/4	1.05	0.11	10.55	21	167	220	25	65	54	38	22	93	30	21	397	22	16	0	0	511	5	10	17	0
6L5/2/1	0.99	0.05	6.91	15	99	223	20	51	32	34	13	70	57	31	405	22	16	0	0	370	5	14	17	0
6L5/2/2	0.96	0.07	7.07	16	107	230	28	72	32	41	15	71	53	33	378	22	15	0	0	383	6	15	17	0
6L5/2/3	1.03	0.03	7.05	17	166	270	16	56	27	33	21	57	57	24	359	23	14	0	0	406	6	17	19	0
6L5/2/4	0.84	0.17	23.86	36	937	622	188	282	89	28	38	43	30	115	246	10	0	0	64	428	10	8	0	0
6L5/3/1	1.31	0.03	4.09	14	98	166	22	53	46	29	30	67	26	28	537	27	23	0	0	193	8	5	20	8
6L5/3/2	1.18	0.1	6.85	17	146	201	40	76	39	34	23	78	28	32	444	24	18	0	0	237	6	19	18	0
6L5/3/3	1.02	0.15	10.44	23	220	247	44	75	47	36	16	72	35	24	303	21	8	0	0	539	5	29	16	0
6L5/3/4	1.01	0.1	7.32	19	178	213	42	65	42	36	24	64	35	30	378	23	14	0	0	292	7	7	18	0

Table A1 XRF analyses of the soils of the investigated reclaimed sites

	TiO2%	MnO%	Fe$_2$O$_3$t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
6L6/1/1	1.11	0.04	6.15	17	100	155	21	82	51	54	50	97	20	26	465	20	14	0	0	207	7	0	8	0
6L6/1/2	1.03	0.02	7.1	19	112	159	15	77	62	49	21	105	26	30	396	22	19	0	0	188	6	6	18	0
6L6/1/3	1.11	0.03	7.44	19	120	161	23	79	51	40	18	96	24	27	443	23	21	0	0	196	6	4	19	0
6L6/1/4	1.13	0.37	10.21	21	199	195	90	99	78	38	9	89	47	25	433	18	10	0	0	1252	4	46	8	0
6L6/2/1	1.24	0.06	8.86	22	150	189	23	109	93	55	64	95	22	27	434	16	6	0	0	342	5	0	1	0
6L6/2/2	1.1	0.08	9.44	23	164	192	40	142	97	61	16	104	25	34	356	21	15	0	0	312	5	10	15	0
6L6/2/3	1.21	0.46	10.53	23	213	181	295	157	96	40	9	85	89	23	377	16	7	0	0	1696	5	62	5	0
6L6/2/4	1.43	0.41	11.73	28	199	246	99	120	116	53	8	92	42	33	419	22	18	0	0	716	5	21	15	0
6L6/3/1	1.14	0.04	3.43	10	61	113	25	48	33	37	35	75	33	21	571	22	22	0	0	195	7	0	14	0
6L6/3/2	1.05	0.05	6.67	19	90	175	23	70	42	48	17	129	43	29	403	22	17	0	0	305	6	6	18	0
6L6/3/3	1.14	0.1	9.04	19	108	146	30	59	35	28	8	87	55	24	482	23	20	0	0	707	7	9	16	0
6L6/3/4	1.02	0.03	6.79	19	85	196	10	75	50	49	20	101	46	26	380	23	17	0	0	228	6	1	19	0
	TiO2%	MnO%	Fe$_2$O$_3$t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
6L12/1/1	1.06	0.14	5.89	16	111	279	36	106	26	58	21	68	32	36	448	22	16	0	0	248	6	14	15	0
6L12/1/2	1.09	0.27	6.11	17	134	294	47	70	31	37	17	61	33	32	438	23	15	0	0	533	7	21	16	0
6L12/1/3	1.11	0.07	12.15	24	261	403	20	88	38	24	7	62	22	31	359	22	10	0	0	194	4	25	15	0
6L12/1/4	0.93	0.07	18.76	31	581	498	47	135	57	22	24	50	18	29	255	11	0	0	85	271	5	41	0	0
6L12/2/1	0.9	0.08	6.62	17	99	258	24	69	52	43	36	60	52	18	351	17	9	0	0	191	5	0	8	0
6L12/2/2	0.95	0.07	6.89	20	113	285	17	66	54	47	22	60	54	16	349	19	14	0	0	274	3	2	12	0
6L12/2/3	0.99	0.1	7.84	20	161	305	25	78	58	41	10	49	39	32	332	20	14	0	0	266	5	11	15	0
6L12/3/1	0.96	0.02	4.49	13	102	235	23	65	31	57	19	66	39	44	393	23	15	0	0	138	6	15	18	0
6L12/3/2	1.08	0.02	4.71	15	147	297	18	68	33	68	19	58	31	39	420	24	16	0	0	118	8	12	19	0
6L12/3/3	1.07	0.02	3.62	13	118	287	14	61	27	83	23	58	29	30	480	24	19	0	0	109	8	10	17	0
	TiO2%	MnO%	Fe$_2$O$_3$t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
6L18/1/1	1.16	0.16	8.59	22	139	178	5	76	53	43	20	89	25	24	462	25	22	0	0	188	6	11	21	0
6L18/1/2	1.12	0.19	7.33	20	127	170	30	143	90	80	31	88	21	37	484	24	22	0	0	222	8	10	18	57
6L18/1/3	1.18	0.12	8.28	21	134	169	4	68	49	40	21	81	23	18	498	25	23	0	0	182	6	11	20	0
6L18/1/4	1.18	0.09	8.16	20	133	200	3	62	43	36	21	77	24	17	506	25	24	0	0	178	8	9	21	0
6L18/2/1	1.07	0.44	8.46	21	135	202	9	83	68	46	20	82	27	28	462	22	22	0	0	235	6	11	18	0
6L18/2/2	1.04	0.18	9.34	24	152	208	5	88	68	46	17	87	24	24	422	22	20	0	0	214	7	12	18	0
6L18/2/3	1.13	0.11	9.6	24	154	199	4	78	63	39	20	77	22	21	439	23	21	0	0	196	6	10	20	0
6L18/2/4	1.11	0.11	9.04	22	144	209	4	66	54	37	18	70	23	19	469	23	23	0	0	186	5	7	20	0
6L18/3/1	1.06	0.04	5.44	18	125	179	60	312	55	205	200	79	13	35	479	35	24	0	0	194	12	0	0	1175
6L18/3/2	1.07	0.04	6.61	20	131	178	51	301	56	281	72	91	21	46	474	36	36	0	0	183	9	3	13	704
6L18/3/3	0.87	0.06	7.22	18	129	291	14	83	47	40	24	68	28	16	379	20	15	0	0	179	7	10	16	9
6L18/3/4	0.87	0.06	7.58	18	142	292	15	96	52	51	28	68	28	17	355	21	14	0	0	170	6	4	15	50
6L18/4/1	1.05	0.03	5.17	18	118	267	32	187	74	147	92	77	24	23	518	41	43	0	0	188	9	0	50	932
6L18/4/2	1.06	0.05	8.07	21	132	174	12	92	53	41	21	83	22	23	462	23	21	0	0	179	7	9	19	0
6L18/4/3	1.05	0.04	7.23	19	135	181	25	147	58	98	27	84	24	35	462	24	23	0	0	201	8	8	17	100
6L18/4/4	1.16	0.06	8.51	22	138	199	5	78	53	49	19	77	22	21	482	24	21	0	0	191	7	7	19	0

Table A1 XRF analyses of the soils of the investigated reclaimed sites

	TiO2%	MnO%	Fe_2O_3t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
7L14/1/1	1.06	0.02	3.08	13	47	122	47	103	41	39	52	84	19	28	545	19	19	0	0	176	8	0	9	0
7L14/1/2	0.98	0.01	5.27	16	58	141	8	70	43	44	23	113	21	25	405	21	18	0	0	185	7	4	17	0
7L14/1/3	1.12	0.03	4.18	16	41	126	12	66	39	40	22	104	20	26	479	24	22	0	0	178	7	2	20	0
7L14/2/1	1.03	0.02	4.06	14	54	125	14	56	39	35	21	86	22	21	549	22	26	2	0	190	7	0	17	0
7L14/2/2	1.13	0.05	5.44	16	74	159	18	73	47	56	22	93	20	34	516	23	24	0	0	192	8	3	19	0
7L14/3/1	1.16	0.03	2.93	14	31	97	21	67	33	40	56	91	21	31	497	20	14	0	0	209	9	0	8	0
7L14/3/2	1.15	0.02	3.31	14	34	104	12	55	34	38	36	106	23	32	488	22	19	0	0	224	6	0	15	0
7L14/3/3	1.12	0.03	3.89	14	41	121	22	73	42	44	22	119	23	27	414	24	19	0	0	206	6	7	20	0

Table A1 XRF analyses of the background concentrations in top soils developed on the Vryheid Formation.

	TiO2%	MnO%	Fe_2O_3t%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
SBV 1	1.06	0.14	6.44	16	99	157	18	61	43	68	26	89	36	31	492	21	20	0	0	246	8	12	15	0
SBV 2	1.08	0.05	3.3	12	41	93	12	33	28	48	18	84	33	29	623	24	30	2	0	266	8	5	18	0
SBV 3	1.01	0.1	4.99	13	69	123	18	51	46	125	25	89	37	29	494	20	18	0	0	270	8	15	12	0
SBV 4	0.96	0.04	4.48	13	55	130	10	38	24	41	24	97	45	31	443	21	19	0	0	257	6	5	18	0
SBV 5	0.95	0.11	4.6	12	68	117	18	42	33	136	17	78	25	22	553	18	19	0	0	267	6	33	8	0
SBV 6	0.92	0.08	2.58	8	36	83	12	29	26	205	18	72	36	23	609	20	25	0	0	183	10	17	12	0
SBV 7	0.99	0.06	2.63	10	34	107	10	26	24	230	14	73	32	23	656	21	28	2	0	177	9	14	14	0
SBV 8	0.95	0.08	4.31	12	61	115	15	44	33	142	19	76	29	26	616	20	25	0	0	196	6	20	12	0
SBV 9	0.96	0.1	5.05	15	75	139	15	53	46	199	22	72	102	28	591	18	21	7	0	277	7	25	12	0
SBV 10	1.01	0.12	4.59	12	67	145	18	41	34	80	15	80	29	27	579	20	22	1	0	279	8	15	12	0
SBV 11	0.91	0.13	5.85	15	97	175	21	46	37	74	20	70	27	26	579	18	22	0	0	341	8	16	10	0
SBV 12	0.89	0.08	4.8	14	67	132	13	50	41	145	22	83	29	25	502	17	17	0	0	192	7	30	8	0
SBV 13	0.95	0.07	4.37	13	66	134	13	50	36	93	27	79	27	28	603	21	28	0	0	161	8	10	15	0
SBV 14	0.97	0.07	4.44	14	67	132	14	51	37	87	25	81	26	28	555	21	24	1	0	169	9	8	16	0
SBV 15	1	0.06	4.67	13	73	149	13	55	37	79	20	83	25	27	542	21	23	2	0	171	7	10	15	0
SBV 16	0.91	0.05	3.77	12	59	136	12	48	35	60	28	68	26	24	520	19	20	1	0	153	7	20	12	0
SBV 17	1	0.08	4.96	15	79	130	15	56	39	67	24	79	23	25	528	21	23	0	0	174	7	14	14	0
SBV 18	0.84	0.06	3.13	10	44	96	10	38	29	49	23	69	24	24	560	20	27	6	16	145	8	3	15	0
SBV 19	0.91	0.08	5.62	16	106	223	15	59	39	78	31	82	35	22	532	19	21	0	0	251	7	11	14	0
SBV 20	0.89	0.06	2.51	9	37	80	11	32	21	56	21	50	22	21	793	20	39	0	0	85	8	4	15	0
SBV 21	0.99	0.09	5.1	14	74	131	15	54	38	108	26	80	34	30	549	20	22	0	0	214	14	17	13	0
Average:	**0.96**	**0.08**	**4.40**	**13**	**65**	**130**	**14**	**46**	**35**	**103**	**22**	**78**	**33**	**26**	**568**	**20**	**23**	**1**	**1**	**213**	**8**	**14**	**13**	**0**

Table 1: Summary of geochemical soil analyses (XRF). All element concentrations in mg/kg (cont.).

Site	Sample-No.	TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
A	1/1	0.94	0.02	3.64	11	62	197	10	55	43	41	102	68	16	14	519	13	3	0	0	188	7	0	0	0
A	1/2	0.98	0.02	4.26	14	70	202	11	62	43	66	77	78	19	21	509	16	9	6	0	194	10	0	1	0
A	1/3	0.57	0.02	7.95	16	143	341	17	37	48	282	14	95	41	18	273	16	9	0	0	408	6	7	12	0
A	2/1	0.89	0.02	4.08	11	76	246	12	60	54	58	70	62	21	9	522	15	10	0	0	175	5	0	2	0
A	2/2	1.02	0.03	7.61	20	117	310	14	85	94	108	30	78	23	17	485	21	19	9	0	263	6	0	14	12
A	2/3	0.81	0.02	9.08	21	180	360	5	62	93	40	17	78	23	15	414	19	18	0	0	314	7	2	15	7
A	2/4	0.86	0.05	18.05	31	327	494	4	78	106	84	8	49	15	6	346	15	4	0	19	362	4	60	2	0
A	3/1	0.99	0.02	3.9	13	59	152	11	58	39	45	37	70	22	24	612	22	26	0	0	144	8	0	14	0
A	3/2	1.04	0.02	7.52	19	132	266	16	94	55	58	24	90	26	27	432	23	20	0	0	200	7	2	19	0
A	3/3	1.06	0.04	12.15	25	279	351	7	67	57	31	20	58	25	18	439	22	17	0	0	204	6	9	17	0
A	3/4	1.11	0.07	15.09	28	332	341	22	65	70	31	16	47	24	15	432	21	12	0	0	302	4	28	12	0
B	1/1	1.21	0.06	9.75	25	156	232	27	173	87	135	17	85	23	35	429	22	19	0	0	281	7	13	16	0
B	1/2	1.2	0.06	9.61	24	158	226	18	153	89	102	17	85	22	33	428	23	20	0	0	259	7	14	17	0
B	1/3	1.22	0.06	10.11	24	165	230	8	115	79	91	17	82	22	28	431	23	20	0	0	231	6	13	18	0
B	1/4	1.3	0.07	10.44	26	172	246	7	106	87	72	19	77	21	23	444	25	21	0	0	236	8	10	19	0
B	2/1	0.92	0.1	13.18	32	207	372	76	241	135	126	18	79	22	29	200	17	9	0	0	286	4	15	15	0
B	2/2	0.92	0.1	12.87	30	202	344	51	190	143	78	23	76	23	22	200	18	10	0	0	247	5	6	14	0
B	2/3	1.05	0.06	13.61	35	197	374	10	139	130	57	17	64	26	26	251	19	14	0	0	293	6	4	16	0
B	2/4	0.95	0.06	15.14	41	203	485	16	140	170	51	3	72	35	35	186	17	12	0	0	400	5	6	15	0
B	3/1	1.05	0.04	5.97	16	89	211	19	85	48	53	43	90	35	31	421	21	12	0	0	230	8	0	12	0
B	3/2	1.12	0.03	6.22	18	96	163	13	78	46	40	22	96	35	33	437	25	20	0	0	204	7	9	21	0
B	3/3	1.18	0.04	7.2	19	113	230	9	85	51	44	19	101	31	29	418	26	19	0	0	197	6	13	23	0
B	3/4	1.22	0.47	8.65	21	163	204	124	126	67	39	6	89	42	26	409	19	4	0	0	1018	5	83	8	0
C	1/1	1.03	0.03	7.14	18	112	170	13	77	44	49	68	96	16	17	405	18	8	0	0	205	6	0	7	0
C	1/2	1.1	0.04	8.54	21	126	191	14	79	50	47	25	107	20	30	388	24	18	0	0	212	7	8	21	0
C	1/3	1.06	0.06	14.23	27	254	369	33	76	67	36	7	74	19	9	361	12	0	0	0	526	3	118	0	0
C	1/4	1.05	0.11	10.55	21	167	220	25	65	54	38	22	93	30	21	397	22	16	0	0	511	5	10	17	0
C	2/1	0.99	0.05	6.91	15	99	223	20	51	32	34	13	70	57	31	405	22	16	0	0	370	5	14	17	0
C	2/2	0.96	0.07	7.07	16	107	230	28	72	32	41	15	71	53	33	378	22	15	0	0	383	6	15	17	0
C	2/3	1.03	0.03	7.05	17	166	270	16	56	27	33	21	57	57	24	359	23	14	0	0	406	6	17	19	0
C	2/4	0.84	0.17	23.86	36	937	622	188	282	89	28	38	43	30	115	246	10	0	0	64	428	10	8	0	0
C	3/1	1.31	0.03	4.09	14	98	166	22	53	46	29	30	67	26	28	537	27	23	0	0	193	8	5	20	8
C	3/2	1.18	0.1	6.85	17	146	201	40	76	39	34	23	78	28	32	444	24	18	0	0	237	6	19	18	0

Table 1: Summary of the geochemical soil analyses (XRF). *All element concentrations in mg/kg (cont.).*

Site	Sample-No.	TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
C	3/3	1.02	0.15	10.44	23	220	247	44	75	47	36	16	72	35	24	303	21	8	0	0	539	5	29	16	0
C	3/4	1.01	0.1	7.32	19	178	213	42	65	42	36	24	64	35	30	378	23	14	0	0	292	7	7	18	0
D	1/1	1.11	0.04	6.15	17	100	155	21	82	51	54	50	97	20	26	465	20	14	0	0	207	7	0	8	0
D	1/2	1.03	0.02	7.1	19	112	159	15	77	62	49	21	105	26	30	396	22	19	0	0	188	6	6	18	0
D	1/3	1.11	0.03	7.44	19	120	161	23	79	51	40	18	96	24	27	443	23	21	0	0	196	6	4	19	0
D	1/4	1.13	0.37	10.21	21	199	195	90	99	78	38	9	89	47	25	433	18	10	0	0	1252	4	46	8	0
D	2/1	1.24	0.06	8.86	22	150	189	23	109	93	55	64	95	22	27	434	16	6	0	0	342	5	0	1	0
D	2/2	1.1	0.08	9.44	23	164	192	40	142	97	61	16	104	25	34	356	21	15	0	0	312	5	10	15	0
D	2/3	1.21	0.46	10.53	23	213	181	295	157	96	40	9	85	89	23	377	16	7	0	0	1696	5	62	5	0
D	2/4	1.43	0.41	11.73	28	199	246	99	120	116	53	8	92	42	33	419	22	18	0	0	716	5	21	15	0
D	3/1	1.14	0.04	3.43	10	61	113	25	48	33	37	35	75	33	21	571	22	22	0	0	195	7	0	14	0
D	3/2	1.05	0.05	6.67	19	90	175	23	70	42	48	17	129	43	29	403	22	17	0	0	305	6	6	18	0
D	3/3	1.14	0.1	9.04	19	108	146	30	59	35	28	8	87	55	24	482	23	20	0	0	707	7	9	16	0
D	3/4	1.02	0.03	6.79	19	85	196	10	75	50	49	20	101	46	26	380	23	17	0	0	228	6	1	19	0
E	1/1	1.06	0.14	5.89	16	111	279	36	106	26	58	21	68	32	36	448	22	16	0	0	248	6	14	15	0
E	1/2	1.09	0.27	6.11	17	134	294	47	70	31	37	17	61	33	32	438	23	15	0	0	533	7	21	16	0
E	1/3	1.11	0.07	12.15	24	261	403	20	88	38	24	7	62	22	31	359	22	10	0	0	194	4	25	15	0
E	1/4	0.93	0.07	18.76	31	581	498	47	135	57	22	24	50	18	29	255	11	0	0	85	271	5	41	0	0
E	2/1	0.9	0.08	6.62	17	99	258	24	69	52	43	36	60	52	18	351	17	9	0	0	191	5	0	8	0
E	2/2	0.95	0.07	6.89	20	113	285	17	66	54	47	22	60	54	16	349	19	14	0	0	274	3	2	12	0
E	2/3	0.99	0.1	7.84	20	161	305	25	78	58	41	10	49	39	32	332	20	14	0	0	266	5	11	15	0
E	3/1	0.96	0.02	4.49	13	102	235	23	65	31	57	19	66	39	44	393	23	15	0	0	138	6	15	18	0
E	3/2	1.08	0.02	4.71	15	147	297	18	68	33	68	19	58	31	39	420	24	16	0	0	118	8	12	19	0
E	3/3	1.07	0.02	3.62	13	118	287	14	61	27	83	23	58	29	30	480	24	19	0	0	109	8	10	17	0

Table 1: Summary of the geochemical soil analyses (XRF). All element concentrations in mg/kg.

Site	Sample-No.	TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
F	1/1	1.16	0.16	8.59	22	139	178	5	76	53	43	20	89	25	24	462	25	22	0	0	188	6	11	21	0
F	1/2	1.12	0.19	7.33	20	127	170	30	143	90	80	31	88	21	37	484	24	22	0	0	222	8	10	18	57
F	1/3	1.18	0.12	8.28	21	134	169	4	68	49	40	21	81	23	18	498	25	23	0	0	182	6	11	20	0
F	1/4	1.18	0.09	8.16	20	133	200	3	62	43	36	21	77	24	17	506	25	24	0	0	178	8	9	21	0
F	2/1	1.07	0.44	8.46	21	135	202	9	83	68	46	20	82	27	28	462	22	22	0	0	235	6	11	18	0
F	2/2	1.04	0.18	9.34	24	152	208	5	88	68	46	17	87	24	24	422	22	20	0	0	214	7	12	18	0
F	2/3	1.13	0.11	9.6	24	154	199	4	78	63	39	20	77	22	21	439	23	21	0	0	196	6	10	20	0
F	2/4	1.11	0.11	9.04	22	144	209	4	66	54	37	18	70	23	19	469	23	23	0	0	186	5	7	20	0
F	3/1	1.06	0.04	5.44	18	125	179	60	312	55	205	200	79	13	35	479	35	24	0	0	194	12	0	0	1175
F	3/2	1.07	0.04	6.61	20	131	178	51	301	56	281	72	91	21	46	474	36	36	0	0	183	9	3	13	704
F	3/3	0.87	0.06	7.22	18	129	291	14	83	47	40	24	68	28	16	379	20	15	0	0	179	7	10	16	9
F	3/4	0.87	0.06	7.58	18	142	292	15	96	52	51	28	68	28	17	355	21	14	0	0	170	6	4	15	50
F	4/1	1.05	0.03	5.17	18	118	267	32	187	74	147	92	77	24	23	518	41	43	0	0	188	9	0	50	932
F	4/2	1.06	0.05	8.07	21	132	174	12	92	53	41	21	83	22	23	462	23	21	0	0	179	7	9	19	0
F	4/3	1.05	0.04	7.23	19	135	181	25	147	58	98	27	84	24	35	462	24	23	0	0	201	8	8	17	100
F	4/4	1.16	0.06	8.51	22	138	199	5	78	53	49	19	77	22	21	482	24	21	0	0	191	7	7	19	0
G	1/1	1.06	0.02	3.08	13	47	122	47	103	41	39	52	84	19	28	545	19	19	0	0	176	8	0	9	0
G	1/2	0.98	0.01	5.27	16	58	141	8	70	43	44	23	113	21	25	405	21	18	0	0	185	7	4	17	0
G	1/3	1.12	0.03	4.18	16	41	126	12	66	39	40	22	104	20	26	479	24	22	0	0	178	7	2	20	0
G	2/1	1.03	0.02	4.06	14	54	125	14	56	39	35	21	86	22	21	549	22	26	2	0	190	7	0	17	0
G	2/2	1.13	0.05	5.44	16	74	159	18	73	47	56	22	93	20	34	516	23	24	0	0	192	8	3	19	0
G	3/1	1.16	0.03	2.93	14	31	97	21	67	33	40	56	91	21	31	497	20	14	0	0	209	9	0	8	0
G	3/2	1.15	0.02	3.31	14	34	104	12	55	34	38	36	106	23	32	488	22	19	0	0	224	6	0	15	0
G	3/3	1.12	0.03	3.89	14	41	121	22	73	42	44	22	119	23	27	414	24	19	0	0	206	6	7	20	0

0 indicates below detection limit

Table 2: Main statistical parameters of the Sites A-G

		TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
MIN		0.57	0.01	2.93	10	31	97	3	37	26	22	3	43	13	6	186	10	0	0	0	109	3	0	0	0
MAX		1.43	0.47	23.86	41	937	622	295	312	170	282	200	129	89	115	612	41	43	9	85	1696	12	118	50	1175
STDEV		0.12	0.10	3.74	5.82	117.55	96.59	41.00	54.09	28.14	46.09	27.05	17.05	12.37	12.44	82.92	4.64	7.21	1.21	11.90	239.52	1.57	18.67	7.24	181.86
AVG		1.06	0.09	8.17	20.17	151.65	237.52	29.49	96.63	60.10	59.51	28.59	80.02	29.12	27.01	420.59	21.57	16.37	0.21	2.07	299.63	6.41	12.32	14.73	37.70

Table 3: Background values for the Vryheid Formation. All element concentrations in mg/kg (n=21).

No.	TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
1	1.06	0.14	6.44	18	99	157	18	61	43	68	26	89	36	31	492	21	20	0	0	246	8	12	15	0
2	1.08	0.05	3.3	12	41	93	12	33	28	48	18	84	33	29	623	24	30	2	0	266	8	5	18	0
3	1.01	0.1	4.99	13	69	123	18	51	46	125	25	89	37	29	494	20	18	0	0	270	8	15	12	0
4	0.96	0.04	4.48	13	55	130	10	38	24	41	24	97	45	31	443	21	19	0	0	257	6	5	18	0
5	0.95	0.11	4.6	12	68	117	18	42	33	136	17	78	25	22	553	18	19	0	0	267	6	33	8	0
6	0.92	0.08	2.58	8	36	83	12	29	26	205	18	72	36	23	609	20	25	0	0	183	10	17	12	0
7	0.99	0.06	2.63	10	34	107	10	26	24	230	14	73	32	23	656	21	28	2	0	177	9	14	14	0
8	0.95	0.08	4.31	12	61	115	15	44	33	142	19	76	29	26	616	20	25	0	0	196	6	20	12	0
9	0.96	0.1	5.05	15	75	139	15	53	46	199	22	72	102	28	591	18	21	7	0	277	7	25	12	0
10	1.01	0.12	4.59	12	67	145	18	41	34	80	15	80	29	27	579	20	22	1	0	279	8	15	12	0
11	0.91	0.13	5.85	15	97	175	21	46	37	74	20	70	27	26	579	18	22	0	0	341	8	16	10	0
12	0.89	0.08	4.8	14	67	132	13	50	41	145	22	83	29	25	502	17	17	0	0	192	7	30	8	0
13	0.95	0.07	4.37	13	66	134	13	50	36	93	27	79	27	28	603	21	28	0	0	161	8	10	15	0
14	0.97	0.07	4.44	14	67	132	14	51	37	87	25	81	26	28	555	21	24	1	0	169	9	8	16	0
15	1	0.06	4.87	13	73	149	13	55	37	79	20	83	25	27	542	21	23	2	0	171	7	10	15	0
16	0.91	0.05	3.77	12	59	136	12	48	35	60	28	68	26	24	520	19	20	1	0	153	7	20	12	0
17	1	0.08	4.96	15	79	130	15	56	39	67	24	79	23	25	528	21	23	0	0	174	7	14	14	0
18	0.84	0.06	3.13	10	44	96	10	38	29	49	23	69	24	24	560	20	27	6	16	145	8	3	15	0
19	0.91	0.08	5.62	16	106	223	15	59	39	78	31	82	35	22	532	19	21	0	0	251	7	11	14	0
20	0.89	0.06	2.51	9	37	80	11	32	21	56	21	50	22	21	793	20	39	0	0	85	8	4	15	0
21	0.99	0.09	5.1	14	74	131	15	54	38	108	26	80	34	30	549	20	22	0	0	214	14	17	13	0

Table 4: Background values for the Vryheid Formation. All element concentrations in mg/kg (data compiled by P. Aucamp)

	TiO2%	MnO%	Fe2O3T%	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Ba	W	Pb	Th	U
MIN	0.84	0.04	2.51	8	34	80	10	26	21	41	14	50	22	21	443	17	17	0	0	85	6	3	8	0
MAX	1.08	0.14	6.44	18	106	223	21	61	46	230	31	97	102	31	793	24	39	7	16	341	14	33	18	0
STDEV	0.1	0.0	1.1	2.4	20.1	31.9	3.1	10.0	7.1	54.7	4.4	9.6	16.7	3.0	72.6	1.5	5.0	2.0	3.5	60.7	1.7	8.0	2.7	0.0
AVG	1.0	0.1	4.4	12.9	65.4	129.9	14.2	45.6	34.6	103.3	22.1	77.8	33.4	26.1	567.6	20.0	23.5	1.0	0.8	213.0	7.9	14.5	13.3	0.0

Table 5: Correlation matrix for selected major and trace elements in solid tailings samples from five different tailings dams situated in the East Rand area (Rösner, 1996; n=36).

	SiO_2	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**As**	**Co**	**Cu**	**Cr**	**Ni**	**Pb**	**Zn**	**Th**	**U**
SiO_2	1	0.55	0.86	0.67	0.26	0.40	0.11	0.03	0.81	0.30	0.14	0.3	0.26	0.44	0.36	0.12	0.10	0.07	0.08
TiO_2		1	0.74	0.03	0.33	0.58	0.28	0.10	0.82	0.26	0.16	0.45	0.30	0.66	0.57	0.01	0.14	0.15	0.16
Al_2O_3			1	0.41	0.22	0.47	0.40	0.02	0.96	0.31	0.10	0.42	0.30	0.60	0.45	0.08	0.15	0.11	0.14
Fe_2O_3				1	0.33	0.20	0.08	0.26	0.27	0.52	0.06	0	0.02	0.07	0.03	0.09	0.01	0.05	0.01
MnO					1	0.22	0.51	0.18	0.12	0.49	0.16	0.01	0.07	0.02	0.09	0.10	0.17	0.04	0.06
MgO						1	0.15	0.17	0.39	0.30	0.02	0.22	0.24	0.32	0.38	0.01	0.19	0.17	0.07
CaO							1	0.14	0.46	0.02	0.19	0.49	0.35	0.48	0.36	0.46	0.48	0.17	0.54
Na_2O								1	0.07	0.08	0.10	0.07	0.02	0.03	0.12	0.27	0.08	0.26	0.05
K_2O									1	0.27	0.18	0.47	0.32	0.70	0.51	0.07	0.13	0.15	0.16
P_2O_5										1	0.12	0.10	0.19	0.11	0.09	0.26	0.55	0.07	0.38
As											1	0.30	0.45	0.32	0.24	0.32	0.06	0.17	0.24
Co												1	0.72	0.48	0.90	0.36	0.56	0.38	0.66
Cu													1	0.45	0.76	0.12	0.24	0.19	0.30
Cr														1	0.62	0.12	0.60	0.27	0.19
Ni															1	0.15	0.43	0.33	0.50
Pb																1	0.72	0.15	0.84
Zn																	1	0.18	0.92
Th																		1	0.28
U																			1

r = 1 maximum positive correlation between two variables;

r = 0 no correlation between two variables;

r = -1 maximum negative correlation between two variables.

Table 6: Correlation matrix for selected trace elements in soils of the sites A-G (n = 81).

	As	Ba	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Th	U	Zn
As	1	0.23	0	0.13	0.08	0.24	0.25	0.08	0.41	0.34	0.25	0.74	0.26
Ba		1	0.78	0.14	0.30	0.34	0.73	0.40	0.17	0.58	0.25	0.08	0.13
Co			1	0.23	0.31	0.37	0.63	0.35	0.51	0.40	0.29	0.10	0.05
Cr				1	0.56	0.83	0.04	0.59	0.41	0.24	0.17	0.01	0.13
Cu					1	0.68	0.25	0.33	0.59	0.13	0.07	0.05	0
Fe						1	0.26	0.56	0.49	0.38	0.20	0.08	0.20
Mn							1	0.19	0.16	0.48	0.12	0.09	0.12
Mo								1	0.11	0.42	0.63	0.37	0.32
Ni									1	0.02	0.09	0.60	0.25
Pb										1	0.33	0.13	0.03
Th											1	0.15	0.06
U												1	0.46
Zn													1

r = 1 maximum positive correlation between two variables;
r = 0 no correlation between two variables;
r = -1 maximum negative correlation between two variables.

Table 7: Correlation of selected trace elements with the clay content in the soil.

	As	Ba	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Th	U	Zn
Clay	0.3	0.02	0.03	0.10	0.24	0.12	0.12	0.01	0.10	0.03	0.23	0.15	0.18

Table 7: Results of the extraction of soils at tests of site F (in mg/kg).

Sample-No.	As	Ca	Co	Cr	Cu	Fe	Mg	Mn	Ni	Pb	S	U	Zn
F1/1	n/d	315.00	n/d	n/d	n/d	n/d	587.50	447.50	n/d	n/d	797.50	n/d	n/d
F1/2	n/d	162.50	20.00	n/d	7.50	n/d	110.00	1325.00	72.50	0.75	121.25	n/d	27.50
F1/3	n/d	375.00	n/d	n/d	n/d	n/d	402.50	260.00	n/d	n/d	557.50	n/d	n/d
F1/4	n/d	427.50	n/d	n/d	n/d	n/d	295.00	270.00	n/d	n/d	515.00	n/d	n/d
F2/1	n/d	437.50	n/d	n/d	n/d	n/d	405.00	1020.00	2.50	n/d	620.00	n/d	2.00
F2/2	n/d	607.50	n/d	n/d	n/d	n/d	277.50	347.50	n/d	n/d	450.00	n/d	0.50
F2/3	n/d	490.00	n/d	n/d	n/d	n/d	292.50	205.00	n/d	n/d	405.00	n/d	n/d
F2/4	n/d	460.00	0.75	n/d	n/d	n/d	262.50	342.50	0.25	n/d	495.00	n/d	1.50
F3/1	n/d	495.00	15.00	n/d	n/d	n/d	30.00	15.00	77.50	n/d	497.50	4.75	62.50
F3/2	n/d	660.00	5.00	n/d	n/d	n/d	12.50	5.00	15.00	n/d	405.00	2.50	27.50
F3/3	n/d	655.00	2.00	n/d	n/d	n/d	10.00	122.50	2.50	n/d	342.50	n/d	2.00
F3/4	n/d	745.00	2.50	n/d	0.50	n/d	32.50	120.00	10.00	1.75	585.00	n/d	10.00
F4/1	n/d	162.50	15.00	1.25	2.50	1.00	92.50	10.00	40.00	1.00	1440.00	60.00	57.50
F4/2	n/d	597.50	2.50	n/d	0.25	n/d	17.50	10.00	10.00	n/d	552.50	n/d	10.00
F4/3	n/d	562.50	1.00	n/d	n/d	n/d	12.50	5.00	2.00	n/d	365.00	n/d	n/d
F4/4	n/d	422.50	0.75	n/d	0.75	0.75	15.00	12.50	5.00	n/d	32.25	n/d	5.00
MIN		**162.50**	**0.75**	**1.25**	**0.25**	**0.75**	**10.00**	**5.00**	**0.25**	**0.75**	**32.25**	**2.50**	**0.50**
MAX		**745.00**	**20.00**	**1.25**	**7.50**	**1.00**	**587.50**	**1325.00**	**77.50**	**1.75**	**1440.00**	**60.00**	**62.50**
AVG		**473.44**	**6.45**		**2.30**	**0.88**	**178.44**	**282.34**	**21.57**		**511.31**		**18.73**

Table 8: Results of the extraction tests of gold-mine tailings samples, collected at three different gold-mine tailings dams in the East Rand (in mg/kg)

Sample No.	As	Ca	Co	Cr	Cu	Fe	Mg	Mn	Ni	Pb	S	U	Zn
1	n/d	1574.50	0.50	n/d	2.50	0.75	7.50	1.25	1.25	n/d	1257.50	n/d	0.25
2	n/d	660.00	1.00	n/d	2.50	2.50	72.50	2.50	2.50	n/d	697.50	n/d	1.50
3	n/d	202.50	n/d	n/d	n/d	0.50	17.50	0.50	n/d	n/d	60.00	n/d	0.25
4	n/d	860.00	n/d	n/d	0.25	n/d	10.00	0.50	n/d	n/d	650.00	n/d	n/d
5	n/d	1082.50	10.00	1.75	12.52	50.00	460.00	15.00	32.50	n/d	3090.00	n/d	7.50
6	n/d	500.00	17.50	1.25	17.50	87.50	687.50	22.50	57.50	0.50	3712.50	n/d	10.00
7	0.25	1362.50	25.00	1.75	22.50	105.00	802.50	25.00	77.50	0.50	5097.00	n/d	12.50
8	n/d	1770.00	30.00	2.25	22.50	60.00	927.50	27.50	105.00	0.75	6132.50	n/d	15.00
9	n/d	1342.50	2.50	1.00	1.50	25.00	290.00	10.00	10.00	0.25	2510.00	n/d	10.00
10	n/d	2185.00	15.00	0.50	2.50	7.50	312.50	42.50	45.00	0.50	4837.50	n/d	80.00
11	n/d	2182.50	15.00	5.00	7.50	55.00	955.00	35.00	47.50	0.50	4820.00	n/d	40.00
12	n/d	1750.00	10.00	2.50	5.00	37.50	650.00	25.00	35.00	0.50	4827.50	n/d	27.50
13	n/d	3020.00	25.00	5.00	10.00	5.00	1487.50	45.00	80.00	0.75	11262.50	n/d	60.00
MIN	**0.25**	**202.50**	**0.50**	**0.50**	**0.25**	**0.50**	**7.50**	**0.50**	**1.25**	**0.25**	**60.00**		**0.25**
MAX	**0.25**	**3020.00**	**30.00**	**5.00**	**22.50**	**105.00**	**1487.50**	**45.00**	**105.00**	**0.75**	**11262.50**		**80.00**
AVG		**1422.46**	**13.77**	**2.33**	**8.90**	**36.35**	**513.85**	**19.40**	**44.89**	**0.53**	**3765.73**		**22.04**

APPENDIX C

Mineralogical Analyses
of Tailings Samples (XRD)

Council for Geoscience JOB 98-325, XRD results for P.Aucamp, CGS 28-07-1998

Sample	Lab No	Jarosite	Gypsum	Quartz	Mica	Chlorite	Pyrophyllite
7L8 1/30	1	1	-	70	17	11	1
7L8 1/60	2	2	-	71	13	13	1
7L8 1/80	3	1	-	78	11	10	-
7L8 2/30	4	3	-	74	12	11	-
7L8 3/30	5	2	-	71	15	11	trace
7L15 1/40	6	3	-	74	15	8	-
7L15 1/50	7	6	-	72	16	7	-
7L15 1/60	8	6	-	74	13	6	-
7L15 1/70	9	7	-	73	14	6	-
NIGEL 1/40	10	2	-	79	9	2	8
NIGEL 1/60	11	3	-	85	8	-	4
NIGEL 1/70	12	1	-	93	4	-	2
NIGEL 1/80	13	2	2	87	5	-	3
NIGEL 2/30	14	3	-	88	5	-	5
NIGEL 3/30	15	2	-	83	6	9	-
15 1/50	16	6	-	73	14	-	7

No	Sampling depth (cm)	Jarosite	Gypsum	Quartz	Muscovite	Clinochlor	Pyrophyllite	TOTAL (%)
1	30	1	0	70	17	11	1	100
2	60	2	0	71	13	13	1	100
3	80	1	0	78	11	10	0	100
4	30	3	0	74	12	11	0	100
5	30	2	0	71	15	11	0	100
6	40	3	0	74	15	8	0	100
7	50	6	0	72	16	7	0	100
8	60	6	0	74	13	6	0	100
9	70	7	0	73	14	6	0	100
10	40	2	0	79	9	2	8	100
11	60	3	0	85	8	0	4	100
12	70	1	0	93	4	0	2	100
13	80	2	2	87	5	0	3	100
14	30	3	0	88	5	0	5	100
15	30	2	0	83	6	9	0	100
16	50	6	0	73	14	0	7	100

MIN		1	0	70	4	0	0
MAX		7	2	93	17	13	8
AVG		3	0	78	11	6	2

APPENDIX D

Register for Mine Residue Deposits in South Africa

MINE RESIDUE DEPOSIT REGISTER

Explanation of abbreviations

Abbreviation	Name
BGM	
BLY	
CD	
CM	Crown Mines
CMR	
DOORN	
DRD	
ECH	
ERGO	East Rand Gold and Uranium Mining Company
ERPM	
FSG	
GFMD	
GGM	Glencairn Gold Mine
GMC	
HART	
Iscor	
Kloof	
Knights	
LIB	
LPV	
NVR	
PRESS	
RB	
REGM	
RL	
RM	
RMT	
ROSE	
SAL	Sallies Mine
SG	
SR	
SR	
STIL	
VM	
VMH	
VPOS	
VR	
WAGM	
WDL	
WDRIE	
WH	

WWN

TD	Tailings dam
Agr	Agricultural areas (land use)
Res	Residential areas (lad use)
Ind	Industrial areas (land use)
Rec	Recreational areas (land use)
Nat	Natural areas (land use)
Old ID	Gold Index Number
N/a	No information available

Please note: 0 and 1 indicates the none-presence or presence of mine residue deposits in a radius < 1 km related to different land use types. Statistics on the register data are presented in **Chapter 2.7**. Abbreviations for geological units are explained in **Table 2.5** of **Chapter 2**. are as follows:

DMEA INDEX	OWNER	Map No	Type	Size (sqkm)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2626DC/L/?	n/a	2626 DC	TD	0.12	R-Vr	0	1	0	0	1		
2626DC/L/?	n/a	2626 DC	TD	0.36	R-Vr	0	0	0	0	0		
2626DC/L/?	n/a	2626 DC	TD	0.85	R-Vr	0	0	0	0	1		West & West Extension
2626DC/L/7	VR	2626 DC	TD	4.12	R-Vr	1	0	0	0	1		New Western Extension
2626DD/L/?	n/a	2626DC	TD	0.18	Vmd	0	0	0	0	0		No. 7
2626DD/L/?	n/a	2626DD		1.61	Vmd	0	0	0	0	1		
2626DD/L/10	BGM	2626DD	TD	1.14	Vmd	0	0	0	0	0		6
2626DD/L/12	BGM	2626DD	TD	1.04	Vmd	0	0	0	0	0		
2626DD/L/12	BGM	2626DD	TD	0.05	Vmd	0	0	0	0	0		
2626DD/L/14	BGM	2626DD	TD	0.02	Vmd	0	1	0	0	0		
2626DD/L/8	VR	2626DD	TD	1.72	Vmd	0	0	0	0	0		Southern Residue
2626DD/L/6	HART	2626DD	TD	0.76	Vmd	0	0	0	0	0		No. 5 SD
2626DD/L/7	HART	2626DD	TD	2.13	Vmd	0	0	1	0	0		No. 4 SD
2626DD/L/?	n/a	2626DD		0.21	Vmd	0	0	1	0	0		
2626DD/L/?	n/a	2626DD	TD	0.05	Vmd	0	0	0	0	1		Springvale Goldmine
2626DD/L/2	STIL	2626DD	TD	2.01	Vmd	0	0	0	0	0		No. 5
2626DD/L/1	STIL	2626DD	TD	1.06	Vmd	0	0	0	0	0		No.4
2626DD/L/3,4	STIL	2626DD	TD	1.75	Vmd	0	1	0	0	0		No.3,No.2
2626DD/L/5	n/a	2626DD	TD	0.19	Vmd	0	0	0	0	0		
2626DD/L/12	BGM	2626DD	TD	0.99	Vmd	0	0	0	0	0		1
2627AD/L/28	n/a	2627AD	TD	2.61	Vdl, Vf	0	1	1	0	1		
2627AD/L/24	n/a	2627AD		0.86	Vmd, Vr	0	1	1	0	1		
2627AD/L/?	n/a	2627AD	TD	0.95	Vmd	0	0	0	0	1		No. 1 SD
2627AD/L/13	WDL	2627AD	TD	1.72	Vmd	1	0	0	0	1		No. 7 Compartment
2627AD/L/14	WDL	2627AD	TD	0.81	Vmd	0	0	0	0	0		No. 5 Compartment
2627AD/L/16	WDL	2627AD	TD	1.93	Vmd	0	1	0	0	0		No. 3,2,1
2627AD/L/15	WDL	2627AD	TD	0.76	Vmd	0	0	0	0	0		No. 7 SD
2627AD/L/26	WDRIE	2627AD	TD	0.77	Vmd	0	1	1	0	1		No. 3, No. 1 SD
2627AD/L/6,7,8,9	BLY	2627AD	TD	0.79	Vmd	0	0	0	0	0		o. 5, 4, 3,2
2627AD/L/10	BLY	2627AD	TD	0.1	Vmd	0	0	0	0	0		No. 4 SD
2627AD/L/10	BLY	2627AD	TD	0.25	Vmd	0	0	0	0	0		No. 4 SD
2627AD/L/?	n/a	2627AD	TD	0.36	Vmd	1	1	1	0	0		No. 2 SD - W
2627AD/L/7	n/a	2627AD	TD	1.11	Vmd	1	1	1	0	0		No. 2 SD - W
2627AD/L/7	n/a	2627AD	TD	1.08	Vmd	1	0	1	0	0		
2627AD/L/?	n/a	2627AD		0.14	Vmd	0	0	0	0	0		
2627AD/L/7	n/a	2627AD	TD	1.85	Vmd	0	0	0	0	0		
2627AD/L/5	DOORN	2627AD	TD	0.69	Vmd	1	0	0	0	1		No. 3 SD
2627AD/L/4	DOORN	2627AD	TD	0.59	Vmd	0	0	0	0	0		No. 1 SD
2627AD/L/3	DOORN	2627AD	TD	0.42	Vmd	1	0	0	0	1		NO. 2 SD
2627BA/L/?	n/a	2627BA	TD	0.74	Vmd	1	0	0	0	1		COOKE 1
2627BA/L/7	n/a	2627BA	TD	0.16	Vbr	0	1	0	0	1		Randfontein
2627BA/L/?	n/a	2627BA	TD	0.45	Vbr	0	0	0	0	0		S9
2627BA/L/1,2	REGM	2627BA	TD	1.45	Vbr, Vmd	1	0	0	0	1		
2627BA/L/4,5	REGM	2627BA	TD	2.12	RG	0	0	1	1	0		
2627BB/L/72	RM	2627BB	TD	1.42	Rt	0	1	1	0	1		
2627BB/L/74	RM	2627BB	TD	0.83	Rt	0	1	0	0	1		
2627BB/L/69	CM	2627BB	TD	1.39	Rt	0	0	0	0	1		
2627BB/L/70	CM	2627BB	TD	0.32	Rt	0	0	0	0	1		
2627BB/L/70	SR	2627BB	R	0.16	Rt	0	0	0	0	0		
2627BB/L/60	n/a	2627BB	TD	0.19	Rt	0	0	0	0	0		
2627BB/L/64	CMR	2627BB	TD	0.11	Rt	0	0	0	0	0		
2627BB/L/61	CMR	2627BB	TD	0.4	Rt	0	1	0	0	1		
2627BB/L/62	CMR	2627BB	TD	0.25	Rjo	0	1	0	0	1		
2627BB/L/65	CMR	2627BB	TD	0.12	Rjo	0	0	1	0	1		
2627BB/L/66	CMR	2627BB	TD	0.05	Rjo	0	0	0	0	1		
2627BB/L/52	RL	2627BB	TD	1.4	Rt	0	1	0	0	1		
2627BB/L/57	RL	2627BB	TD	0.12	Rt	0	0	0	0	0		
2627BB/L/55	n/a	2627BB	TD	0.49	Rt	0	0	0	0	0		
2627BB/L/51	DRD	2627BB	TD	0.44	Rt	0	0	0	0	0		One, Two and Three
2627BB/L/48	DRD	2627BB	TD	0.04	Rjo	0	0	0	1	0		
2627BB/L/49	n/a	2627BB	TD	0.05	Rjo	0	0	0	1	0		
2627BB/L/46	n/a	2627BB	TD	0.08	Rjo	0	0	0	0	0		
2627BB/L/41	DRD	2627BB	TD	0.1	Rjo	0	0	0	0	0		Six and Seven
2627BB/L/36	DRD	2627BB	R	0.04	Rjo	0	0	1	0	1		No. 8
2627BB/L/35	RMT	2627BB	TD	2.12	Vmd	0	0	0	0	1		X1
2627BB/L/?	n/a	2627BB	TD	0.96	Vmd	1	0	0	0	1		
2627BB/L/7-10	LPV,GMC	2627BB	TD	0.57	Vmd	0	0	0	0	0		
2627BB/L/22	REGM	2627BB	TD	1.93	Vmd	0	0	1	0	1		Doornkop
2627BB/L/7	n/a	2628BA	TD	0.02	Vbr	0	0	0	0	0		
2627BB/L/16,18,1	RB,RM	2627BB	TD	1.02	Rg	0	0	0	0	0		2L29 D&E
2627BB/L/2-5	WRC	2627BB	SA/TD	1.61	Vbr, Rjo	0	1	0	0	1		No.1/No.3
2627BB/L/20	DRD	2627BB	TD	0.17	Rjo	0	1	0	0	0		
2627BB/L/24	DRD	2627BB	R	0.07	Rjo	0	0	1	0	0		
2627BB/L/31	SR	2627BB	TD	0.2	Rg	0	0	1	0	1		
2627BB/L/15	DRD	2627BB	R	0.02	Rjo	0	0	0	0	1		H
2627BB/L/77	CM	2627BB	R	0.03	Rj	0	0	1	0	0		
2627BB/L/79	CM	2627BB	R	0.02	Rj	0	0	1	0	0		
2627BB/L/76	CM	2627BB	R	0.05	Rjo	0	0	0	0	1		
2627BB/L/78	CM	2627BB	R	0.04	Rjo	0	0	0	0	1		
2627BB/L/?	n/a	2627BB	R	0.08	Rt	0	0	0	0	1		
2627BB/L/2	n/a	2627BB	R	0.11	Rt	0	0	0	0	1		
2627BB/L/7	n/a	2627BB	R	0.07	Rjo	0	1	0	1	0		
2627BB/L/63	CMR	2627BB	R	0.09	Rj	0	1	0	0	0		
2627BB/L/67	CMR	2627BB	R	0.14	Rj	0	0	1	1	0		
2627BB/L/?	ECH	2627BB	R	0.18	Rj	0	0	1	1	0		
2627BB/L/68	CMR	2627BB	R	0.14	Rj	0	0	0	1	1		
2627BB/L/?	RL	2627BB	R	0.04	Rt	0	0	0	0	1		Lake Dump
2627BB/L/38	LPV	2627BB	R	0.04	Rjo	0	0	0	0	0		No. 8
2627BC/L/2	VPOS	2627BC	TD	1.1	Vmd	0	1	1	1	0		Northern SD
2627BC/L/3	VPOS	2627BC	TD	0.43	Vmd	0	0	0	0	0		No. 1
2627BC/L/4	LIB	2627BC	TD	1.32	Vmd	1	1	1	0	1		No.4a-4c
2627BC/L/10,11	VPOS	2627BC	TD	1.64	Vf	0	1	1	0	1		1. / 2. Shaft
DMEA INDEX	OWNER	Map No	Type	Size (sqkm)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2627BC/L/8,9	WAGM	2627BC	TD	0.6	Vdr, Vt	1	0	1	0	1		

2627BC/L/5	Kloof	2627BC	TD	1.03	Vf	1	0	0	0	1		No. 1 SD
2627BC/L/8	Kloof	2627BC	TD	0.89	Vt	1	1	0	0	1		No. 2 SD
2627BC/L/10	WAGM	2627BC	TD	1.14	Vmd	0	1	1	0	1		3
2627BC/L/1	DRIE	2627BC	TD	0.4	Vmd	1	1	1	1	0		No. 2 SD - E
2627BC/L/?	Kloof	2627 BC	R	0.66	Vmd	1	1	0	0	1		
2627BC/L/?	Kloof	2627 BC	TD	0.37	Vmd	1	1	0	0	1		
2627BC/L/?	Kloof	2627 BC	R	0.91	Vmd	1	1	0	0	0		
2627CA/L/1	Kynoch	2627	TD	0.22	Vmd	0	1	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.14	Pv	0	0	0	0	1		
2627DB/L/?	Iscor	2627 DB	TD	0.82	Qs	0	0	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.34	Qs	0	0	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.99	Qs	0	0	0	0	0		
28AA/L/84, 85, 89	ERPM	2628AA	TD	2.53	Rt, Rk	0	0	0	1	1		Elsburg SD No. 1
2628AA/L/86	ERGO	2628AA	TD	0.24	Pv	0	0	0	0	0		Elsburg No. 2, 4
2628AA/L/80	ERPM	2628AA	R	0.19	Rt	0	0	1	0	1		
2628AA/L/81	ERGO	2628AA	R	0.14	Rb	0	1	0	0	1		4L24
2628AA/L/?	n/a	2628AA	TD	0.03	Rv	0	0	1	0	1		
2628AA/L/71	ERGO	2628AA	R	0.03	Rjo	0	0	0	0	1		
2628AA/L/60	SG	2628AA	R	0.06	Rjo	0	1	1	0	1		
2628AA/L/53	n/a	2628AA	TD	0.12	Rt	0	1	1	0	1		
2628AA/L/53	ERGO	2628AA	TD	0.19	Rt	0	1	1	0	1		4L9
2628AA/L/52	n/a	2628AA	TD	0.24	Rt	0	0	1	1	1		
2628AA/L/48	CM	2628AA	TD	0.21	Rt	0	0	1	1	1		
2628AA/L/48	CM	2628AA	TD	0.2	Rt	0	0	1	1	1		
2628AA/L/50	SGM	2628AA	R	0.04	Rjo	0	1	1	0	0		
2628AA/L/41	n/a	2628AA	TD	0.22	Rt	0	1	1	0	1		
2628AA/L/38	CD	2628AA	TD	0.32	Rt	0	0	1	0	0		
2628AA/L/40	CD	2628AA	TD	0.37	Rjo	0	0	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.12	Rt	0	1	1	1	0		
2628AA/L/?	n/a	2628AA	TD	0.15	Rt	0	1	1	1	0		
2628AA/L/?	n/a	2628AA	TD	0.19	Zm	0	1	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.1	Zm	0	1	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.07	Zh	0	1	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.14	Zh	0	1	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.22	Zh	0	1	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.18		0	0	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.01	Rt	0	0	0	0	0		
2628AA/L/92	ERPM	2628AA	R	0.01	Rt	0	0	0	0	1		Cinderella, 4L46
2628AA/L/91	ERPM	2628AA	R	0.25	Pv	0	1	1	0	0		Cason
2628AA/L/90	ERPM	2628AA	R	0.05	Jd	0	1	0	0	0		Angelo East
2628AA/L/87	ERGO	2628AA	R	0.15	Jd	0	1	0	0	0		Driefontein, 4L4
2628AA/L/82	ERGO	2628AA	R	0.18	Rt, Rb	0	0	1	0	0		
2628AA/L/77	n/a	2628AA	R	0.27	Rt, Rb	0	0	0	0	1		
2628AA/L/76	ERGO	2628AA	R	0.07	Rjo	0	0	1	1	1		
2628AA/L/70	ERGO	2628AA	R	0.49	Rjo	0	0	1	0	0		
2628AA/L/75	ERGO	2628AA	R	0.03	Rjo	0	1	0	0	1		
2628AA/L/67	ERGO	2628AA	R	0.03	Rjo	0	1	0	0	0		
2628AA/L/?	n/a	2628AA	R	0.32	Pv	0	0	1	0	0		
2628AA/L/63	ERGO	2628AA	R	0.09	Pv	0	0	0	0	0		Ginsberg, 4L41
2628AA/L/?	n/a	2628AA	R	0.04	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.03	Rjo	0	0	1	0	0		
2628AA/L/69	GGM	2628AA	R	0.01	Rjo	0	0	1	0	0		
2628AA/L/66	SG	2628AA	R	0.46	Rjo	0	1	1	0	0		
2628AA/L/65	ROSE	2628AA	R	0.22	Rjo	0	1	1	0	0		
2628AA/L/60	SG	2628AA	TD	0.03	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA		0.04	Rjo	0	0	0	0	0		Primrose, 4L28
2628AA/L/56	SG	2628AA	R	0.19	Rj	0	0	0	0	0		
2628AA/L/46	n/a	2628AA	R	0.32	Rt	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	SA/R	0.06	Rjo	0	0	0	0	0		Rietfontein No.
2628AA/L/?	n/a	2628AA	R	0.13	Rjo	0	0	0	0	1		Mennels Dump
2628AA/L/35	CD	2628AA	R	0.06	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.12	Rjo	0	0	1	0	0		Meyer & Charlton
2628AA/L/?	n/a	2628AA	R	0.01	Rjo	0	0	1	0	0		
2628AA/L/28	CD	2628AA	R	0.26	Rb, Rt	0	0	1	0	0		4A Dam and 4 Dam
2628AA/L/26,29	VM	2628AA	R	0.19	Rt	0	0	1	0	0		3 Dam
2628AA/L/25	n/a	2628AA	R	0.05	Rt	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.04	Rjo	0	0	1	0	0		
2628AA/L/23	CM,VM	2628AA	R	0.05	Rjo	0	0	0	0	0		
2628AA/L/16	RD	2628AA	R	0.6	Pv	0	1	0	0	0		
2628AA/L/15	n/a	2628AA	R	0.1	Rjo	0	1	0	0	0		
2628AA/L/10	n/a	2628AA	R	0.07	Rjo	0	0	1	0	0		
2628AA/L/12	n/a	2628AA	R	0.06	Rt	0	0	1	0	0		
2628AA/L/9	n/a	2628AA	R	0.09	Rt	0	0	1	0	0		
2628AA/L/8	n/a	2628AA	R	0.15	Rt	0	0	0	0	0		
2628AA/L/5	CM	2628AA	R	0.12	Rt	0	1	1	0	0		
2628AA/L/10	n/a	2628AA	R	0.06	Rt	0	0	0	0	0		
2628AA/L/2,3	CM	2628AA	R	0.07	Rt	0	0	1	0	0		
2628AB/L/16	n/a	2628AB	TD	0.33	Pv	0	1	0	0	0		
2628AB/L/8	n/a	2628AB	TD	0.5	Pd, Rb, R	0	1	1	0	0	5L4	
2628AB/L/2-4	ERGO, SAL	2628AB	TD	0.12	C-Pd, Rjo	0	0	0	0	1	5L3	
2628AB/L/5	NVR,CMM,	2628AB	TD	0.33	C-PD, Rjo	0	0	0	0	1	5L1	
2628AB/L/23	ERGO	2628AB	TD	0.37	C-Pd, Rjo	0	1	0	0	1	5L23	
2628AB/L/22	CMM	2628AB	TD	0.07	Rjo	0	0	0	0	0	5L22	
2628AB/L/25	ERGO	2628AB	TD	0.36	Rjo, C-Pd	0	0	0	0	1	5L24	
2628AB/L/26	ERGO	2628AB	TD	0.42	Rb, Rt	0	1	0	1	1	5L26	

DMEA INDEX	OWNER	Map No	Type	Size (sq km)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2628AB/L/30	ERGO	2628AB	TD	0.47	C-Pd	1	1	0	0	1	6L3	
2628AB/L/?	ERGO	2628AB	TD	1.07	Vmd	0	0	0	0	1		Grootvlei
2628AB/L/39	ERGO	2628AB	TD	1.02	Vmd	1	0	0	0	0		
2628AB/L/38	ERGO	2628AB	TD	0.76	Vmd	1	0	0	0	1		No. 3
2628AB/L/35	ERGO	2628AB	TD	1.11	Vmd	1	0	1	0	0	6L13	6L13
2628AB/L/36	ERGO	2628AB	TD	0.59	Vmd	1	0	0	0	0		
2628AB/L/40	RM	2628AB	TD	0.15	Vmd, C-Pd	1	0	0	0	0	6L48	
2628AB/L/15	ERGO	2628AB		0.09	Pv	1	1	0	0	0		
2628AB/L/9	n/a	2628AB	TD	0.19	Pv	0	1	0	0	0		
2628AB/L/34	ERGO	2628AB	TD	1	Vmd	1	0	0	0	0		
2628AB/L/32	ERGO	2628AB	TD	0.7	Pv, C-Pd	0	1	0	0	0		
2628AB/L/31	ERGO	2628AB	R	1.02	Pv	0	1	0	0	0		
2628AB/L/28	ERGO	2628AB	R	1.07	Pv, C-Pd	0	1	0	0	1		
2628AB/L/27	ERGO	2628AB	R	0.91	Vmd	0	0	0	0	1	6L27/5A10	
2628AB/L/31	ERGO	2628AB	R	0.89	Pv	0	1	0	0	0		
2628AB/?	ERGO	2628AB	TD	0.19	Pv	0	0	1	0	0	5L10	
2628AB/?	ERGO	2628AB	TD	0.09	Pv	0	0	1	0	0	5L11	
2628AB/?	ERGO	2628AB	TD	0.06	Pv	0	0	1	0	0	5A2	
2628AB/?	ERGO	2628AB	TD	0.05	Pv	0	0	0	1	0	5A12	5L12
2628AD/L/1	GFMD	2628AD	TD	1.33	Pv, C-Pd	1	0	0	0	1	5L29	
2628AD/L/4	ERGO	2628AD	TD	1.17	Pv	1	0	1	0	1	5L31	Sallies No. 1
2628AD/L/5-6	ERGO	2628AD	TD	0.57	Pv, C-Pd	1	0	0	0	0	5L32	Sallies No. 2
2628AD/L/8	ERGO	2628AD	TD	0.71	Pv	0	0	0	1	0		Springs No. 1
2628AD/L/7	ERGO	2628AD	TD	0.28	Pv	0	0	0	1	0		Springs No. 2
2628AD/L/7	ERGO	2628AD	TD	0.64	Pv	0	0	0	1	1		Springs No. 3
2628AD/L/10	ERGO	2628AD	TD	0.39	Pv	0	0	0	1	0		Springs No. 4
2628AD/L/11	ERGO	2628AD	TD	0.18	Pv	0	0	0	1	0		Springs No. 5
2628AD/L/12	ERGO	2628AD	TD	0.26	Pv	0	0	0	1	0		Springs No. 6
2628AD/L/13	VGM	2628AD	TD	0.59	Pv	1	0	0	0	0	7L15	No. 2-3 Slimes D
2628AD/L/23	EDM	2628AD	TD	1.23	Pv	1	0	0	0	1		
2628AD/L/28	EDM	2628AD	TD	0.63	Pv	1	0	0	0	0		Nigel No. 1 SD
2628AD/L/21	EDM	2628AD	TD	0.68	Pv	1	0	0	0	0		
2628AD/L/22	EDM	2628AD	TD	1.05	Vmd	1	0	0	0	0	6L20	
2628AD/L/1	ERGO	2628BC	TD	0.93	Pv	0	0	0	0	0		
2628AD/L/18	GFMD	2628AD	TD	0.32	C-Pd	1	0	0	0	0	7L8	
2628AD/L/19	GFMD	2628AD	TD	0.54	C-Pd	0	0	0	0	0	7L9	
2628AD/L/25-26	GFMD	2628AD	TD	0.14	Rt	0	0	0	0	0		C Shaft SD
2628AD/L/28	EDM	2628AD	TD/R	0.11	Pv, C-Pd	0	0	0	0	0		Nigel No 2 D
2628AD/L/3	ERGO	2628AD	TD	14.51	Vmd, Jd	1	0	0	0	1		Withok
2628AD/L/2	Knights		TD	1,3	Vmd	1	0	0	0	1		Knights Tailings
2628AD/L/?	n/a			0.46	Pv	0	0	0	0	0		
2628AD/L24	VMH	2628AD	TD	0.75	Vmd	1	0	1	0	0		1,2 & 3
2628AD/L/14	SNGM	2628AD	TD	0.22	Pv	0	0	0	0	0		Sub Nigel New Sl
2628AD/L/15	NGM	2628AD	TD	0.8	Rt	1	0	0	0	0		Southgo Slimes D
2628AD/L/16	GFMD	2628AD	TD	0.13	Pv	1	0	0	0	0		Spaarwater Slime
2628AD/L/17	WWN	2628AD	TD	0.42	Pv	1	0	0	0	1		No 7 Shaft Dam
2628AD/L/?	n/a	2628AD	TD	0.09	Rt	1	0	0	0	0		
2628AD/L/?	n/a	2628 AC	TD	0.41	Rt	0	1	0	0	0		
2628AC/L/?	n/a	2628 AC		0.15		0	1	0	0	0		
2628AC/L/?	n/a	2628 AC	TD	0.52	Vmd	0	0	0	0	1		
2628AC/L/?	n/a	2628AD	TD	0.19	Pv, C-Pd	0	0	0	0	0		
2628AD/L/6	ERGO		TD	0.33	Pv, C-Pd	1	0	0	0	0		Calcine Dam
2628BA/L/1	SIH	2628 BA	TD	0.04	Vmd	0	0	0	0	0		No 4 Slimes Dam
2628BC/L/6	ERGO	2628BC	TD	4.46	Pv	1	0	0	0	1		Daggafontein
2628BC/L/2	ERGO	2628BC	TD	0.75	Pv	1	0	0	0	1		
2628BC/L/3	ERGO	2628BC	TD	0.18	Pv	0	0	0	0	0		
2628BC/L/4	VMH	2628BC	TD	0.46	Pv	1	0	0	0	1		
2628BC/L/5	ERGO	2628BC	TD	0.35	Pv	0	0	1	0	1		
2628BC/L1	ERGO	2628 BC	TD	0.75	Pv	1	0	1	0	1		
2628CB/L/1	WWN	2628 CB	TD	0.22	Rt	1	1	0	0	0		1 Shaft Slimes D
2629AC/L/1	n/a	2629 AC	TD	1.74	Jd	0	1	0	0	0		
2629AC/L?	n/a	2629 AC	TD	1,53	Jd	0	0	0	0	0		
2629AC/L/?	n/a	2629 AC	TD	2.29	Jd	0	1	0	0	0		
2629CA/L/1	n/a	2629CA	TD	3.44	Jd, Pv	0	0	0	0	0		
2629CA/L/2,3	n/a	2629CA	TD	2.14	Jd, Pv	1	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	1.63	Jd, Pv	1	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	0.62	Jd, Pv	1	0	1	0	0		
2629CA/L/?	n/a	2629CA	TD	0.4	Jd, Pv	0	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	0.5	Jd, Pv	0	0	1	0	0		
2629CA/L/?	n/a	2629CA	TD	0.81	Jd, Pv	1	0	0	0	0		
2726DC/L/7	FSG	2726 DC	TD	2.07		1	0	1	0	0		Rheedersdam
2726DC/L/8	WH	2726 DC	TD	2.27		0	0	1	0	1		No 1 Slimes Dam
2726DC/L/5	FSG	2726 DC	TD	0.89		1	0	1	0	1		3 Shaft Slimes D
2726DC/L/3	FSG	2726 DC	TD	1.1		1	0	1	0	1		9 Shaft Slimes D
2726DC/L/2	LGM	2726 DC	TD	2.08		1	0	0	0	0		Loraine GM Slime
2726DD/L/1	WH	2726 DD	TD	2.57		1	0	1	1	1		No 3 Slimes Dam
2826BB/L/7	PRESB	2826 BB	TD	0.62		0	0	1	0	0		No 1 Slimes Dam
2826BB/L/4	PRESB	2826 BB	TD	1.32		0	0	0	1	1		No 2 Slimes Dam
2826BB/L/1	PRESB	2826 BB	TD	2.68		0	0	1	0	1		Low Grade Dam
2826BB/L/3	PRESB	2826 BB	TD	1.43		0	0	0	0	0		Final Dam
2826BB/L/21	HGM	2826 BB	TD	2.53		0	0	1	0	0		Harmony No 3
2826BB/L/14	WH	2826 BB	TD	0.24		1	0	0	0	0		No 4 Slimes Dam
2826BB/15-18	WH	2826 BB	TD	1.01		0	0	1	0	0		No 1-3 Slimes Da
2826BB/L/19	WH	2826 BB	TD	0.83		0	0	0	0	0		No 5a Slimes Dam
2826BB/L/22	HGM	2826 BB	TD	1.33		1	0	0	0	0		Harmony
2826BB/L/31	HGM	2826 BB	TD	0.88		0	0	1	0	1		No 2 and 3
2826BB/L/32	HGM	2826 BB	TD	1		0	0	0	1	1		Merriespruit No
2826BB/L/30	HGM	2826 BB	TD	1.06		1	0	0	0	0		No 4a and 10
2826BB/L/28	HGM	2826 BB	TD	0.07		0	0	0	0	0		No 9 Calcine Dam
2826BB/L/?	n/a	2826 BB	TD	0.18		0	0	0	0	1		
2826BB/L/27	HGM	2826 BB	TD	0.41		0	0	0	0	1		No 1, 2a, 2b Cal
2826BB/L/26	HGM	2826 BB	TD	0.05		0	0	0	0	1		No 1a, 1b Calcin
DMEA INDEX	OWNER	Map No	Type	Size (sq km)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2826BB/L/?	n/a	2826 BB	TD	0.07		0	0	0	0	1		

2826BB/L/7	n/a	2826 BB	TD	0.16		0	0	0	0	1		

DMEA INDEX	OWNER	Map No	Type	Size (sqkm)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2626DC/L/?	n/a	2626 DC	TD	0.12	R-Vr	0	1	0	0	1		
2626DC/L/?	n/a	2626 DC	TD	0.36	R-Vr	0	0	0	0	0		
2626DC/L/?	n/a	2626 DC	TD	0.85	R-Vr	0	0	0	0	1		West & West Extension
2626DC/L/7	VR	2626 DC	TD	4.12	R-Vr	1	0	0	0	1		New Western Extension
2626DD/L/?	n/a	2626DC	TD	0.18	Vmd	0	0	0	0	0		No. 7
2626DD/L/?	n/a	2626DD		1.61	Vmd	0	0	0	0	1		
2626DD/L/10	BGM	2626DD	TD	1.14	Vmd	0	0	0	0	0		5
2626DD/L/12	BGM	2626DD	TD	1.04	Vmd	0	0	0	0	0		
2626DD/L/12	BGM	2626DD	TD	0.06	Vmd	0	0	0	0	0		
2626DD/L/14	BGM	2626DD	TD	0.02	Vmd	0	1	0	0	0		
2626DD/L/8	VR	2626DD	TD	1.72	Vmd	0	0	0	0	0		Southern Residue
2626DD/L/6	HART	2626DD	TD	0.76	Vmd	0	0	0	0	0		No. 5 SD
2626DD/L/7	HART	2626DD	TD	2.13	Vmd	0	0	1	0	0		No. 4 SD
2626DD/L/?	n/a	2626DD		0.21	Vmd	0	0	1	0	0		
2626DD/L/?	n/a	2626DD	TD	0.05	Vmd	0	0	0	0	1		Springvale Goldmine
2626DD/L/2	STIL	2626DD	TD	2.01	Vmd	0	0	0	0	0		No. 5
2626DD/L/1	STIL	2626DD	TD	1.06	Vmd	0	0	0	0	0		No.4
2626DD/L/3,4	STIL	2626DD	TD	1.75	Vmd	0	1	0	0	0		No.3,No.2
2626DD/L/5	n/a	2626DD	TD	0.19	Vmd	0	0	0	0	0		
2626DD/L/12	BGM	2626DD	TD	0.99	Vmd	0	0	0	0	0		1
2627AD/L/28	n/a	2627AD	TD	2.61	Vdl, Vf	0	1	1	0	1		
2627AD/L/24	n/a	2627AD		0.86	Vmd, Vr	0	1	1	0	1		
2627AD/L/?	n/a	2627AD	TD	0.95	Vmd	0	0	0	0	1		No. 1 SD
2627AD/L/13	WDL	2627AD	TD	1.72	Vmd	1	0	0	0	1		No. 7 Compartment
2627AD/L/14	WDL	2627AD	TD	0.81	Vmd	0	0	0	0	0		No. 5 Compartment
2627AD/L/16	WDL	2627AD	TD	1.93	Vmd	0	1	0	0	0		No. 3,2,1
2627AD/L/15	WDL	2627AD	TD	0.76	Vmd	0	0	0	0	0		No. 7 SD
2627AD/L/26	WDRIE	2627AD	TD	0.77	Vmd	0	1	1	0	1		No. 3, No. 1 SD
2627AD/L/6,7,8,9	BLY	2627AD	TD	0.79	Vmd	0	0	0	0	0		o. 5, 4, 3,2
2627AD/L/10	BLY	2627AD	TD	0.1	Vmd	0	0	0	0	0		No. 4 SD
2627AD/L/10	BLY	2627AD	TD	0.25	Vmd	0	0	0	0	0		No. 4 SD
2627AD/L/?	n/a	2627AD	TD	0.36	Vmd	1	1	1	0	0		No. 2 SD - W
2627AD/L/?	n/a	2627AD	TD	1.11	Vmd	1	1	1	0	0		No. 2 SD - W
2627AD/L/?	n/a	2627AD	TD	1.08	Vmd	1	0	1	0	0		
2627AD/L/?	n/a	2627AD		0.14	Vmd	0	0	0	0	0		
2627AD/L/?	n/a	2627AD	TD	1.85	Vmd	0	0	0	0	0		
2627AD/L/5	DOORN	2627AD	TD	0.89	Vmd	1	0	0	0	1		No. 3 SD
2627AD/L/4	DOORN	2627AD	TD	0.59	Vmd	0	0	0	0	0		No. 1 SD
2627AD/L/3	DOORN	2627AD	TD	0.42	Vmd	1	0	0	0	1		NO. 2 SD
2627BA/L/?	n/a	2627BA	TD	0.74	Vmd	1	0	0	0	1		COOKE 1
2627BA/L/?	n/a	2627BA	TD	0.16	Vbr	0	1	0	0	1		Randfontein
2627BA/L/?	n/a	2627BA	TD	0.45	Vbr	0	0	0	0	0		S9
2627BA/L/1,2	REGM	2627BA	TD	1.45	Vbr, Vmd	1	0	0	0	1		
2627BA/L/4,5	REGM	2627BA	TD	2.12	RG	0	0	1	1	0		
2627BB/L/72	RM	2627BB	TD	1.42	Rt	0	1	1	0	1		
2627BB/L/74	RM	2627BB	TD	0.83	Rt	0	1	0	0	1		
2627BB/L/69	CM	2627BB	TD	1.39	Rt	0	0	0	0	1		
2627BB/L/70	CM	2627BB	TD	0.32	Rt	0	0	0	0	1		
2627BB/L/70	SR	2627BB	R	0.16	Rt	0	0	0	0	0		
2627BB/L/60	n/a	2627BB	TD	0.19	Rt	0	0	0	0	0		
2627BB/L/64	CMR	2627BB	TD	0.11	Rt	0	0	0	0	0		
2627BB/L/61	CMR	2627BB	TD	0.4	Rt	0	1	0	0	1		
2627BB/L/62	CMR	2627BB	TD	0.25	Rjo	0	1	0	0	1		
2627BB/L/65	CMR	2627BB	TD	0.12	Rjo	0	0	1	0	1		
2627BB/L/66	CMR	2627BB	TD	0.05	Rjo	0	0	0	0	1		
2627BB/L/52	RL	2627BB	TD	1.4	Rt	0	1	0	0	1		
2627BB/L/57	RL	2627BB	TD	0.12	Rt	0	0	0	0	0		
2627BB/L/55	n/a	2627BB	TD	0.49	Rt	0	0	0	0	0		
2627BB/L/51	DRD	2627BB	TD	0.44	Rt	0	0	0	0	0		One, Two and Three
2627BB/L/48	DRD	2627BB	TD	0.04	Rjo	0	0	0	1	0		
2627BB/L/49	n/a	2627BB	TD	0.05	Rjo	0	0	0	1	0		
2627BB/L/46	n/a	2627BB	TD	0.08	Rjo	0	0	0	0	0		
2627BB/L/41	DRD	2627BB	TD	0.1	Rjo	0	0	0	0	0		Six and Seven
2627BB/L/38	DRD	2627BB	R	0.04	Rjo	0	0	1	0	1		No. 8
2627BB/L/35	RMT	2627BB	TD	2.12	Vmd	0	0	0	0	1		X1
2627BB/L/?	n/a	2627BB	TD	0.96	Vmd	1	0	0	0	1		
2627BB/L/7-10	LPV,GMC	2627BB	TD	0.57	Vmd	0	0	0	0	0		
2627BB/L/22	REGM	2627BB	TD	1.93	Vmd	0	0	1	0	1		Doornkop
2627BB/L/?	n/a	2628BA	TD	0.02	Vbr	0	0	0	0	0		
2627BB/L/16,18,1	RB,RM	2627BB	TD	1.02	Rg	0	0	0	0	0		2L29 D&E
2627BB/L/2-5	WRC	2627BB	SA/TD	1.61	Vbr, Rjo	0	1	0	0	1		No.1/No.3
2627BB/L/20	DRD	2627BB	TD	0.17	Rjo	0	1	0	0	0		
2627BB/L/24	DRD	2627BB	R	0.07	Rjo	0	0	1	0	0		
2627BB/L/31	SR	2627BB	TD	0.2	Rg	0	0	1	0	1		
2627BB/L/15	DRD	2627BB	R	0.02	Rjo	0	0	0	0	1		H
2627BB/L/77	CM	2627BB	R	0.03	Rj	0	0	1	0	0		
2627BB/L/79	CM	2627BB	R	0.02	Rj	0	0	1	0	0		
2627BB/L/76	CM	2627BB	R	0.05	Rjo	0	0	0	0	1		
2627BB/L/78	CM	2627BB	R	0.04	Rjo	0	0	0	0	1		
2627BB/L/7	n/a	2627BB	R	0.08	Rt	0	0	0	0	1		
2627BB/L/2	n/a	2627BB	R	0.11	Rt	0	0	0	0	1		
2627BB/L/?	n/a	2627BB	R	0.07	Rjo	0	1	0	1	0		
2627BB/L/63	CMR	2627BB	R	0.09	Rj	0	1	0	0	0		
2627BB/L/67	CMR	2627BB	R	0.14	Rj	0	0	1	1	0		
2627BB/L/?	ECH	2627BB	R	0.18	Rj	0	0	1	1	0		
2627BB/L/68	CMR	2627BB	R	0.14	Rj	0	0	0	1	1		
2627BB/L/?	RL	2627BB	R	0.04	Rt	0	0	0	0	1		Lake Dump
2627BB/L/38	LPV	2627BB	R	0.04	Rjo	0	0	0	0	0		No. 8
2627BC/L/2	VPOS	2627BC	TD	1.1	Vmd	0	1	1	1	0		Northern SD
DMEA INDEX	OWNER	Map No	Type	Size (sqkm)	Geo	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2627BC/L/3	VPOS	2627BC	TD	0.43	Vmd	0	0	0	0	0		No. 1
2627BC/L/4	LIB	2627BC	TD	1.32	Vmd	1	1	1	0	1		No.4a-4c
2627BC/L/10,11	VPOS	2627BC	TD	1.84	Vf	0	1	1	0	1		1. / 2. Shaft
2627BC/L/8,9	WAGM	2627BC	TD	0.6	Vdr, Vt	1	0	1	0	1		

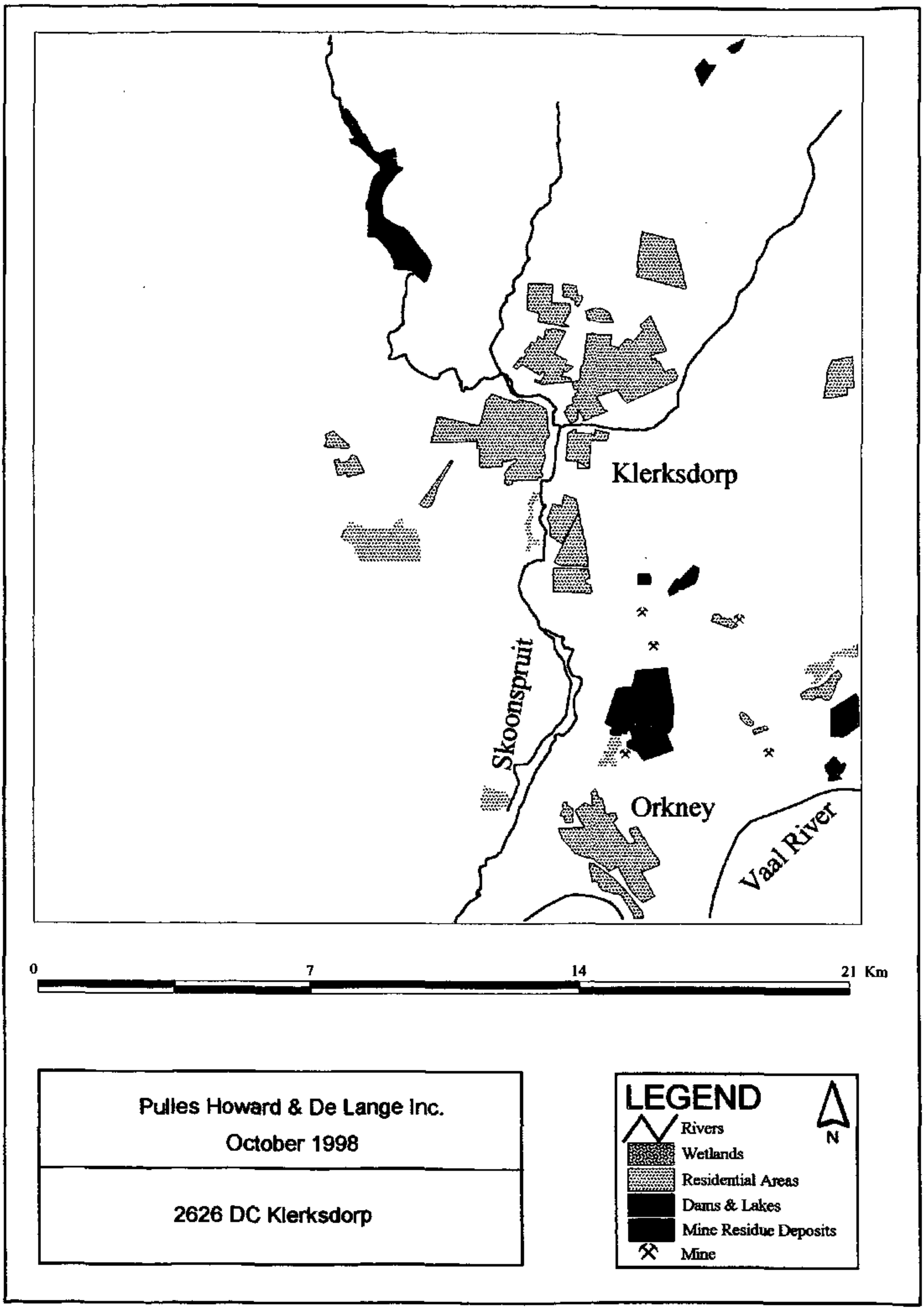
2627BC/L/5	Kloof	2627BC	TD	1,03	Vf	1	0	0	0	1		No. 1 SD
2627BC/L/6	Kloof	2627BC	TD	0.89	Vf	1	1	0	0	1		No. 2 SD
2627BC/L/10	WAGM	2627BC	TD	1.14	Vmd	0	1	1	0	1		3
2627BC/L/1	DRIE	2627BC	TD	0.4	Vmd	1	1	1	1	0		No. 2 SD - E
2627BC/L/?	Kloof	2627 BC	R	0.66	Vmd	1	1	0	0	1		
2627BC/L/?	Kloof	2627 BC	TD	0.37	Vmd	1	1	0	0	1		
2627BC/L/?	Kloof	2627 BC	R	0.81	Vmd	1	1	0	0	0		
2627CA/L/1	Kynoch	2627	TD	0.22	Vmd	0	1	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.14	Pv	0	0	0	0	1		
2627DB/L/?	Iscor	2627 DB	TD	0.82	Qs	0	0	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.34	Qs	0	0	0	0	0		
2627DB/L/?	Iscor	2627 DB	TD	0.99	Qs	0	0	0	0	0		
28AA/L/84, 85, 88	ERPM	2628AA	TD	2.53	Rt, Rk	0	0	0	1	1		Elsburg SD No. 1
2628AA/L/86	ERGO	2628AA	TD	0.24	Pv	0	0	0	0	0		Elsburg No. 2, 4
2628AA/L/80	ERPM	2628AA	R	0.19	Rt	0	0	1	0	1		
2628AA/L/81	ERGO	2628AA	R	0.14	Rb	0	1	0	0	1		4L24
2628AA/L/?	n/a	2628AA	TD	0.03	Rv	0	0	1	0	1		
2628AA/L/71	ERGO	2628AA	R	0.03	Rjo	0	0	0	0	1		
2628AA/L/60	SG	2628AA	R	0.06	Rjo	0	1	1	0	1		
2628AA/L/53	n/a	2628AA	TD	0.12	Rt	0	1	1	0	1		
2628AA/L/53	ERGO	2628AA	TD	0.19	Rt	0	1	1	0	1		4L9
2628AA/L/52	n/a	2628AA	TD	0.24	Rt	0	0	1	1	1		
2628AA/L/48	CM	2628AA	TD	0.21	Rt	0	0	1	1	1		
2628AA/L/48	CM	2628AA	TD	0.2	Rt	0	0	1	1	1		
2628AA/L/50	SGM	2628AA	R	0.04	Rjo	0	1	1	0	0		
2628AA/L/41	n/a	2628AA	TD	0.22	Rt	0	1	1	0	1		
2628AA/L/38	CD	2628AA	TD	0.32	Rt	0	0	1	0	0		
2628AA/L/40	CD	2628AA	TD	0.37	Rjo	0	0	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.12	Rt	0	1	1	1	0		
2628AA/L/?	n/a	2628AA	TD	0.15	Rt	0	1	1	1	0		
2628AA/L/?	n/a	2628AA	TD	0.19	Zm	0	1	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.1	Zm	0	1	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.07	Zh	0	1	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.14	Zh	0	1	0	0	1		
2628AA/L/?	n/a	2628AA	TD	0.22	Zh	0	1	1	0	1		
2629AA/L/?	n/a	2628AA	TD	0.19		0	0	1	0	1		
2628AA/L/?	n/a	2628AA	TD	0.01	Rt	0	0	0	0	0		
2628AA/L/92	ERPM	2628AA	R	0.01	Rt	0	0	0	0	1		Cinderella, 4L46
2628AA/L/91	ERPM	2628AA	R	0.25	Pv	0	1	1	0	0		Cason
2628AA/L/90	ERPM	2628AA	R	0.05	Jd	0	1	0	0	0		Angelo East
2628AA/L/87	ERGO	2628AA	R	0.15	Jd	0	1	0	0	0		Driefontein, 4L4
2628AA/L/82	ERGO	2628AA	R	0.18	Rt, Rb	0	0	1	0	0		
2628AA/L/77	n/a	2628AA	R	0.27	Rt, Rb	0	0	0	0	1		
2628AA/L/76	ERGO	2628AA	R	0.07	Rjo	0	0	1	1	1		
2628AA/L/70	ERGO	2628AA	R	0.49	Rjo	0	0	1	0	0		
2628AA/L/75	ERGO	2628AA	R	0.03	Rjo	0	1	0	0	1		
2628AA/L/67	ERGO	2628AA	R	0.03	Rjo	0	1	0	0	0		
2628AA/L/?	n/a	2628AA	R	0.32	Pv	0	0	1	0	0		
2628AA/L/83	ERGO	2628AA	R	0.09	Pv	0	0	0	0	0		Ginsberg, 4L41
2628AA/L/?	n/a	2628AA	R	0.04	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.03	Rjo	0	0	1	0	0		
2628AA/L/69	GGM	2628AA	R	0.01	Rjo	0	0	1	0	0		
2628AA/L/68	SG	2628AA	R	0.46	Rjo	0	1	1	0	0		
2628AA/L/65	ROSE	2628AA	R	0.22	Rjo	0	1	1	0	0		
2628AA/L/60	SG	2628AA	TD	0.03	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA		0.04	Rjo	0	0	0	0	0		Primrose, 4L28
2628AA/L/56	SG	2628AA	R	0.19	Rj	0	0	0	0	0		
2628AA/L/45	n/a	2628AA	R	0.32	Rt	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	SA/R	0.06	Rjo	0	0	0	0	0		Rietfontein No.
2628AA/L/?	n/a	2628AA	R	0.13	Rjo	0	0	0	0	1		Mennels Dump
2628AA/L/35	CD	2628AA	R	0.09	Rjo	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.12	Rjo	0	0	1	0	0		Meyer & Charlton
2628AA/L/?	n/a	2628AA	R	0.01	Rjo	0	0	1	0	0		
2628AA/L/28	CD	2628AA	R	0.26	Rb, Rt	0	0	1	0	0		4A Dam and 4 Dam
2628AA/L/26,29	VM	2628AA	R	0.19	Rt	0	0	1	0	0		3 Dam
2628AA/L/25	n/a	2628AA	R	0.05	Rt	0	0	1	0	0		
2628AA/L/?	n/a	2628AA	R	0.04	Rjo	0	0	1	0	0		
2628AA/L/23	CM,VM	2628AA	R	0.05	Rjo	0	0	0	0	0		
2628AA/L/16	RD	2628AA	R	0.6	Pv	0	1	0	0	0		
2628AA/L/15	n/a	2628AA	R	0.1	Rjo	0	1	0	0	0		
2628AA/L/10	n/a	2628AA	R	0.07	Rjo	0	0	1	0	0		
2628AA/L/12	n/a	2628AA	R	0.08	Rt	0	0	1	0	0		
2628AA/L/9	n/a	2628AA	R	0.09	Rt	0	0	1	0	0		
2628AA/L/8	n/a	2628AA	R	0.15	Rt	0	0	0	0	0		
2628AA/L/5	CM	2628AA	R	0.12	Rt	0	1	1	0	0		
2628AA/L/10	n/a	2628AA	R	0.08	Rt	0	0	0	0	0		
2628AA/L/2,3	CM	2628AA	R	0.07	Rt	0	0	1	0	0		
2628AB/L/16	n/a	2628AB	TD	0.33	Pv	0	1	0	0	0		
2628AB/L/8	n/a	2628AB	TD	0.5	Pd, Rb, R	0	1	1	0	0	5L4	
2628AB/L/2-4	ERGO, SAL	2628AB	TD	0.12	C-Pd, Rjo	0	0	0	0	1	5L3	
2628AB/L/5	NVR,CMM,	2628AB	TD	0.33	C-PD, Rjo	0	0	0	0	1	5L1	
2628AB/L/23	ERGO	2628AB	TD	0.37	C-Pd, Rjo	0	1	0	0	1	5L23	
2628AB/L/22	CMM	2628AB	TD	0.07	Rjo	0	0	0	0	0	5L22	
2628AB/L/25	ERGO	2628AB	TD	0.36	Rjo, C-Pd	0	0	0	0	1	5L24	
2628AB/L/26	ERGO	2628AB	TD	0.42	Rb, Rt	0	1	0	1	1	5L26	

DMEA INDEX	OWNER	Map No	Type	Size (sq km)	Geo.	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2628AB/L/30	ERGO	2628AB	TD	0.47	C-Pd	1	1	0	0	1	6L3	
2628AB/L/7	ERGO	2628AB	TD	1.07	Vmd	0	0	0	0	1		Grootvlei
2628AB/L/39	ERGO	2628AB	TD	1.02	Vmd	1	0	0	0	0		
2628AB/L/38	ERGO	2628AB	TD	0.75	Vmd	1	0	0	0	1		No. 3
2628AB/L/35	ERGO	2628AB	TD	1.11	Vmd	1	0	1	0	0	6L13	6L13
2628AB/L/36	ERGO	2628AB	TD	0.59	Vmd	1	0	0	0	0		
2628AB/L/40	RM	2628AB	TD	0.16	Vmd, C-Pd	1	0	0	0	0	6L48	
2628AB/L/15	ERGO	2628AB		0.09	Pv	1	1	0	0	0		
2628AB/L/9	n/a	2628AB	TD	0.19	Pv	0	1	0	0	0		
2628AB/L/34	ERGO	2628AB	TD	1	Vmd	1	0	0	0	0		
2628AB/L/32	ERGO	2628AB	TD	0.7	Pv, C-Pd	0	1	0	0	0		
2628AB/L/31	ERGO	2628AB	R	1.02	Pv	0	1	0	0	0		
2628AB/L/28	ERGO	2628AB	R	1.07	Pv, C-Pd	0	1	0	0	1		
2628AB/L/27	ERGO	2628AB	R	0.91	Vmd	0	0	0	0	1	5L27/5A10	
2628AB/L/31	ERGO	2628AB	R	0.89	Pv	0	1	0	0	0		
2628AB/?	ERGO	2628AB	TD	0.19	Pv	0	0	1	0	0	5L10	
2628AB/?	ERGO	2628AB	TD	0.09	Pv	0	0	1	0	0	5L11	
2628AB/?	ERGO	2628AB	TD	0.06	Pv	0	0	1	0	0	5A2	
2628AB/?	ERGO	2628AB	TD	0.05	Pv	0	0	0	1	0	5A12	5L12
2628AD/L/1	GFMD	2628AD	TD	1.33	Pv, C-Pd	1	0	0	0	1	5L29	
2628AD/L/4	ERGO	2628AD	TD	1.17	Pv	1	0	1	0	1	5L31	Sallies No. 1
2628AD/L/5-6	ERGO	2628AD	TD	0.57	Pv, C-Pd	1	0	0	0	0	5L32	Sallies No. 2
2628AD/L/8	ERGO	2628AD	TD	0.71	Pv	0	0	0	1	0		Springs No. 1
2628AD/L/7	ERGO	2628AD	TD	0.28	Pv	0	0	0	1	0		Springs No. 2
2628AD/L/7	ERGO	2628AD	TD	0.64	Pv	0	0	0	1	1		Springs No. 3
2628AD/L/10	ERGO	2628AD	TD	0.39	Pv	0	0	0	1	0		Springs No. 4
2628AD/L/11	ERGO	2628AD	TD	0.18	Pv	0	0	0	1	0		Springs No. 5
2628AD/L/12	ERGO	2628AD	TD	0.26	Pv	0	0	0	1	0		Springs No. 6
2628AD/L/13	VGM	2628AD	TD	0.59	Pv	1	0	0	0	0	7L15	No. 2-3 Slimes D
2628AD/L/23	EDM	2628AD	TD	1.23	Pv	1	0	0	0	1		
2628AD/L/26	EDM	2628AD	TD	0.63	Pv	1	0	0	0	0		Nigel No. 1 SD
2628AD/L/21	EDM	2628AD	TD	0.69	Pv	1	0	0	0	0		
2628AD/L/22	EDM	2628AD	TD	1.05	Vmd	1	0	0	0	0	6L20	
2628AD/L/1	ERGO	2628BC	TD	0.93	Pv	0	0	0	0	0		
2628AD/L/18	GFMD	2628AD	TD	0.32	C-Pd	1	0	0	0	0	7L8	
2628AD/L/19	GFMD	2628AD	TD	0.54	C-Pd	0	0	0	0	0	7L9	
2628AD/L/25-26	GFMD	2628AD	TD	0.14	Rt	0	0	0	0	0		C Shaft SD
2628AD/L/28	EDM	2628AD	TD/R	0.11	Pv, C-Pd	0	0	0	0	0		Nigel No 2 D
2628AD/L/3	ERGO	2628AD	TD	14.51	Vmd, Jd	1	0	0	0	1		Withok
2628AD/L/2	Knights		TD	1.3	Vmd	1	0	0	0	1		Knights Talings
2628AD/L/?	n/a			0.46	Pv	0	0	0	0	0		
2628AD/L24	VMH	2628AD	TD	0.75	Vmd	1	0	1	0	0		1,2 & 3
2628AD/L/14	SNGM	2628AD	TD	0.22	Pv	0	0	0	0	0		Sub Nigel New Sl
2628AD/L/15	NGM	2628AD	TD	0.8	Rt	1	0	0	0	0		Southgo Slimes D
2628AD/L/16	GFMD	2628AD	TD	0.13	Pv	1	0	0	0	0		Spaarwater Slime
2628AD/L/17	WWN	2628AD	TD	0.42	Pv	1	0	0	0	1		No 7 Shaft Dam
2628AD/L/?	n/a	2628AD	TD	0.09	Rt	1	0	0	0	0		
2628AD/L/?	n/a	2628 AC	TD	0.41	Rt	0	1	0	0	0		
2628AC/L/?	n/a	2628 AC		0.15		0	1	0	0	0		
2628AC/L/?	n/a	2628 AC	TD	0.52	Vmd	0	0	0	0	1		
2628AC/L/?	n/a	2628AD	TD	0.19	Pv, C-Pd	0	0	0	0	0		
2628AD/L/6	ERGO		TD	0.33	Pv, C-Pd	1	0	0	0	0		Calcine Dam
2628BA/L/1	StH	2628 BA	TD	0.04	Vmd	0	0	0	0	0		No 4 Slimes Dam
2628BC/L/6	ERGO	2628BC	TD	4.46	Pv	1	0	0	0	1		Daggafontein
2628BC/L/2	ERGO	2628BC	TD	0.75	Pv	1	0	0	0	1		
2628BC/L/3	ERGO	2628BC	TD	0.18	Pv	0	0	0	0	0		
2628BC/L/4	VMH	2628BC	TD	0.46	Pv	1	0	0	0	1		
2628BC/L/5	ERGO	2628BC	TD	0.35	Pv	0	0	1	0	1		
2628BC/L1	ERGO	2628 BC	TD	0.75	Pv	1	0	1	0	1		
2628CB/L/1	WWN	2628 CB	TD	0.22	Rt	1	1	0	0	0		1 Shaft Slimes D
2629AC/L/1	n/a	2629 AC	TD	1.74	Jd	0	1	0	0	0		
2629AC/L?	n/a	2629 AC	TD	1.53	Jd	0	0	0	0	0		
2529AC/L/?	n/a	2629 AC	TD	2.29	Jd	0	1	0	0	0		
2629CA/L/1	n/a	2629CA	TD	3.44	Jd, Pv	0	0	0	0	0		
2629CA/L/2,3	n/a	2629CA	TD	2.14	Jd, Pv	1	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	1.53	Jd, Pv	1	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	0.62	Jd, Pv	1	0	1	0	0		
2629CA/L/?	n/a	2629CA	TD	0.4	Jd, Pv	0	0	1	0	1		
2629CA/L/?	n/a	2629CA	TD	0.5	Jd, Pv	0	0	1	0	0		
2629CA/L/?	n/a	2629CA	TD	0.61	Jd, Pv	1	0	0	0	0		
2726DC/L/7	FSG	2726 DC	TD	2.07		1	0	1	0	0		Rheedersdam
2726DC/L/8	WH	2726 DC	TD	2.27		0	0	1	0	1		No 1 Slimes Dam
2726DC/L/5	FSG	2726 DC	TD	0.89		1	0	1	0	1		3 Shaft Slimes D
2726DC/L/3	FSG	2726 DC	TD	1.1		1	0	1	0	1		9 Shaft Slimes D
2726DC/L/2	LGM	2726 DC	TD	2.08		1	0	0	0	0		Loraine GM Slime
2726DD/L/1	WH	2726 DD	TD	2.57		1	0	1	1	1		No 3 Slimes Dam
2826BB/L/7	PRESB	2826 BB	TD	0.62		0	0	1	0	0		No 1 Slimes Dam
2826BB/L/4	PRESB	2826 BB	TD	1.32		0	0	0	1	1		No 2 Slimes Dam
2826BB/L/1	PRESB	2826 BB	TD	2.68		0	0	1	0	1		Low Grade Dam
2826BB/L/3	PRESB	2826 BB	TD	1.43		0	0	0	0	0		Final Dam
2826BB/L/21	HGM	2826 BB	TD	2.53		0	0	1	0	0		Harmony No 3
2826BB/L/14	WH	2826 BB	TD	0.24		1	0	0	0	0		No 4 Slimes Dam
2826BB/15-18	WH	2826 BB	TD	1.01		0	0	1	0	0		No 1-3 Slimes Da
2826BB/L/19	WH	2826 BB	TD	0.83		0	0	0	0	0		No 5a Slimes Dam
2826BB/L/22	HGM	2826 BB	TD	1.33		1	0	0	0	0		Harmony
2826BB/L/31	HGM	2826 BB	TD	0.88		0	0	1	0	1		No 2 and 3
2826BB/L/32	HGM	2826 BB	TD	1		0	0	0	1	1		Merriespruit No
2826BB/L/30	HGM	2826 BB	TD	1.06		1	0	0	0	0		No 4a and 10
2826BB/L/28	HGM	2826 BB	TD	0.07		0	0	0	0	0		No 9 Calcine Dam
DMEA INDEX	OWNER	Map No.	Type	Size (sq km)	Geo.	Agri	Res	Ind	Rec	Nat	Old ID	NAME
2826BB/L/?	n/a	2826 BB	TD	0.18		0	0	0	0	1		
2826BB/L/27	HGM	2826 BB	TD	0.41		0	0	0	0	1		No 1, 2a, 2b Cal
2826BB/L/26	HGM	2826 BB	TD	0.05		0	0	0	0	1		No 1a, 1b Calcin
2826BB/L/?	n/a	2826 BB	TD	0.07		0	0	0	0	1		

2826BB/L/7	n/a	2826 BB	TD	0.18		0	0	0	0	1		

APPENDIX E

GIS-based Maps of the Mine Residue Deposit Register



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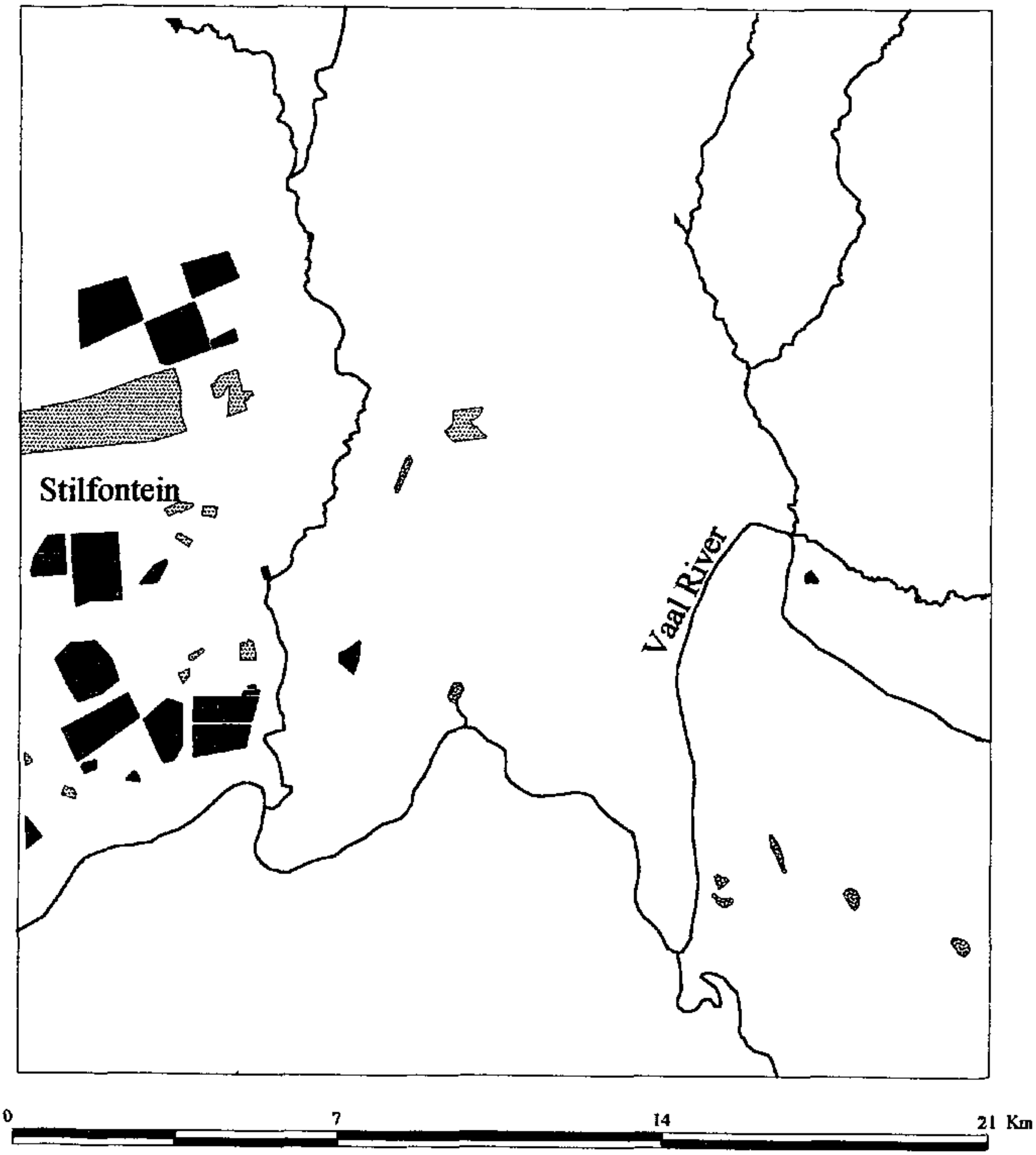
October 1998

2626 DC Klerksdorp



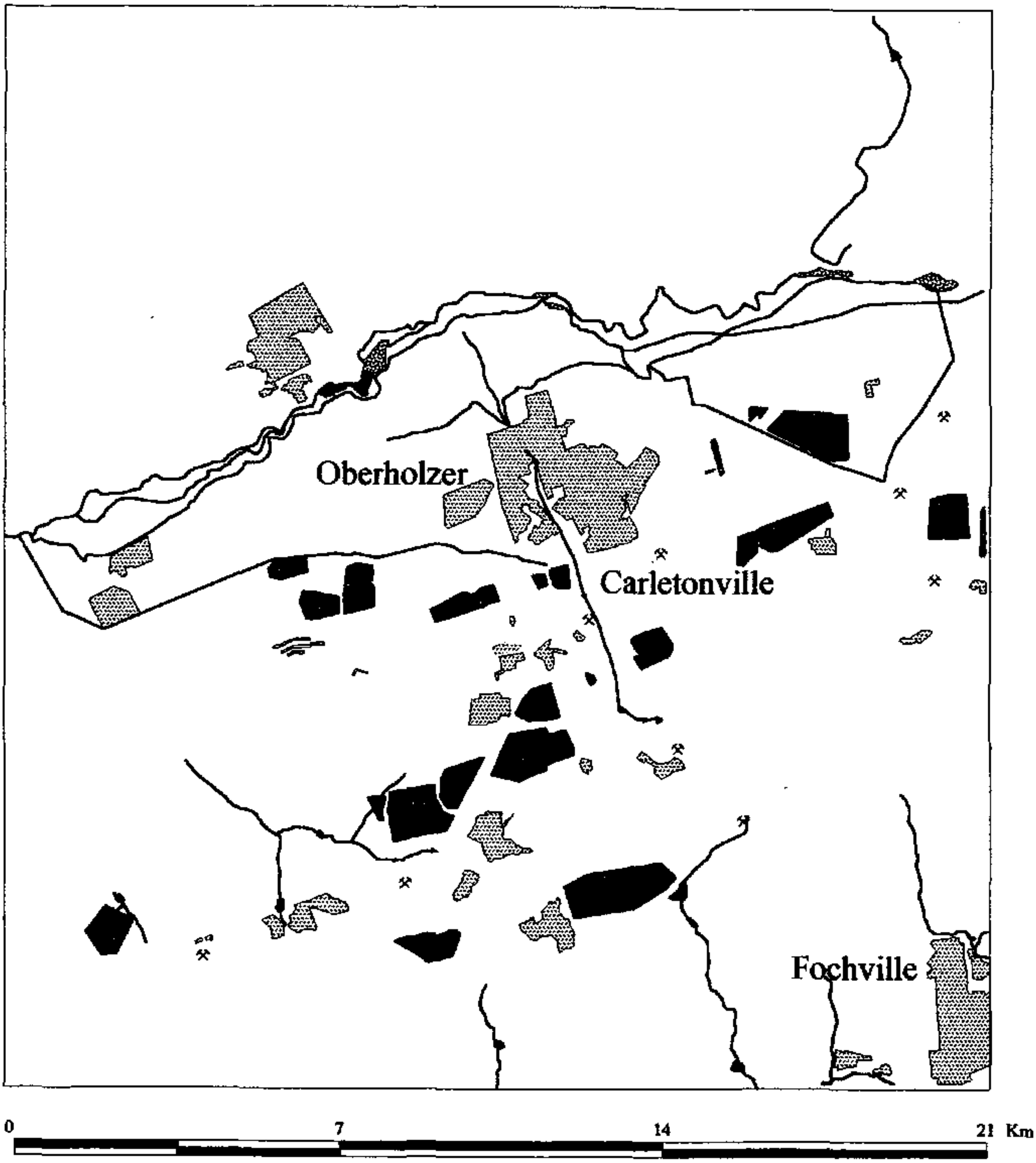
Pulles Howard & De Lange Inc.
October 1998

2626 DD Stilfontein

LEGEND

N

- Rivers
- ▩ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



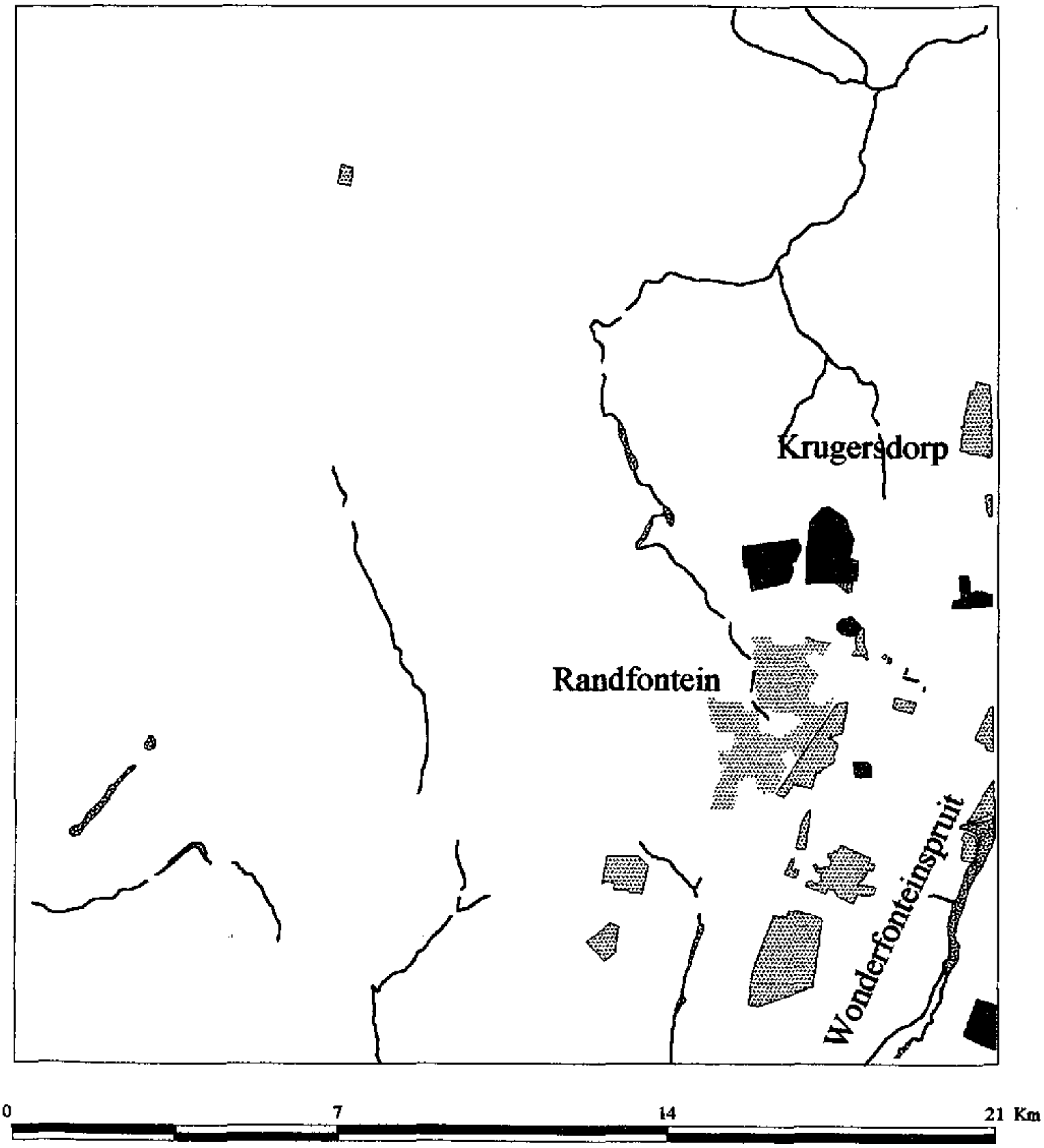
Pulles Howard & De Lange Inc.
October 1998

2627 DA Carletonville

LEGEND

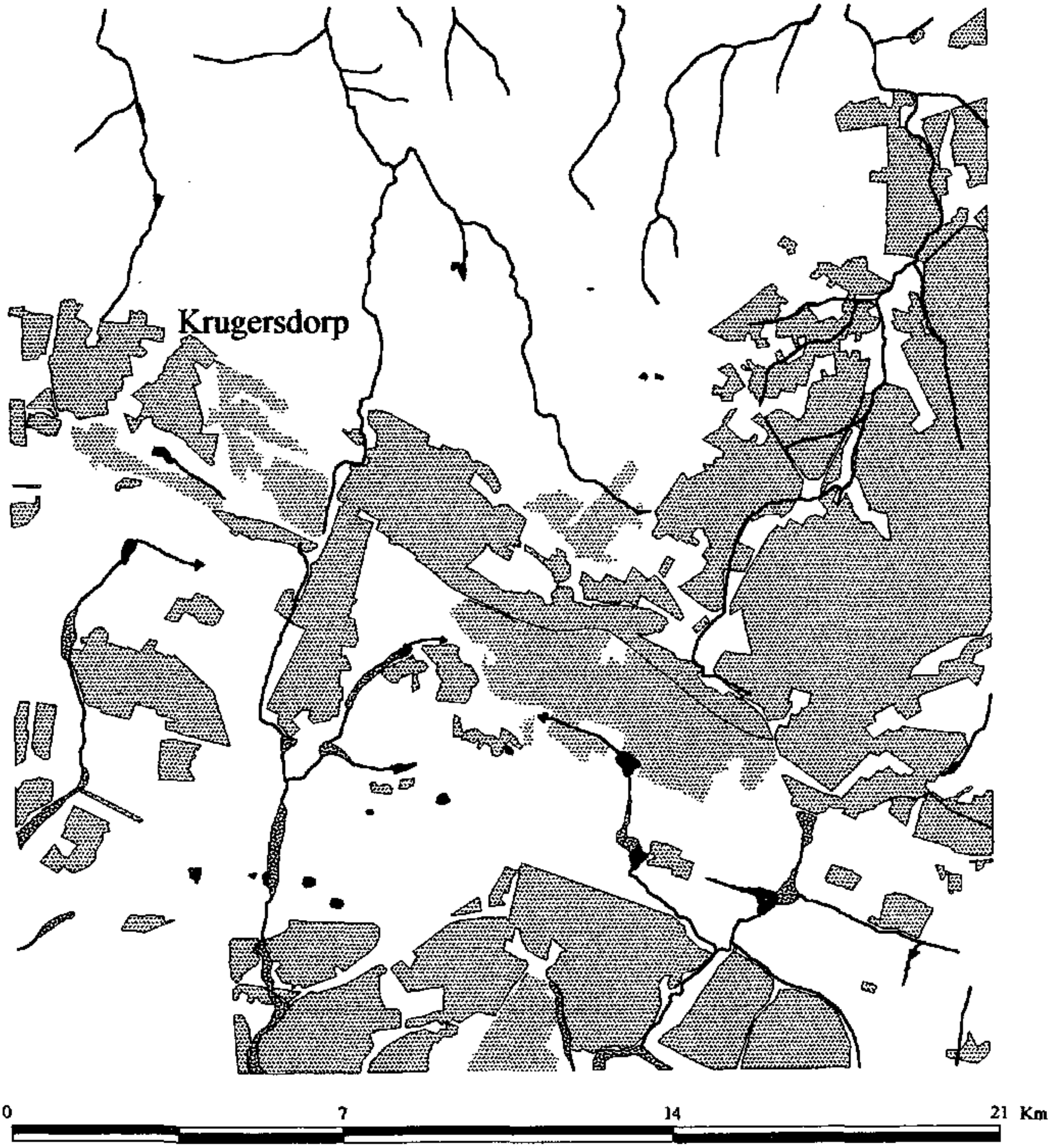
N

- ⋀ Rivers
- ▩ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



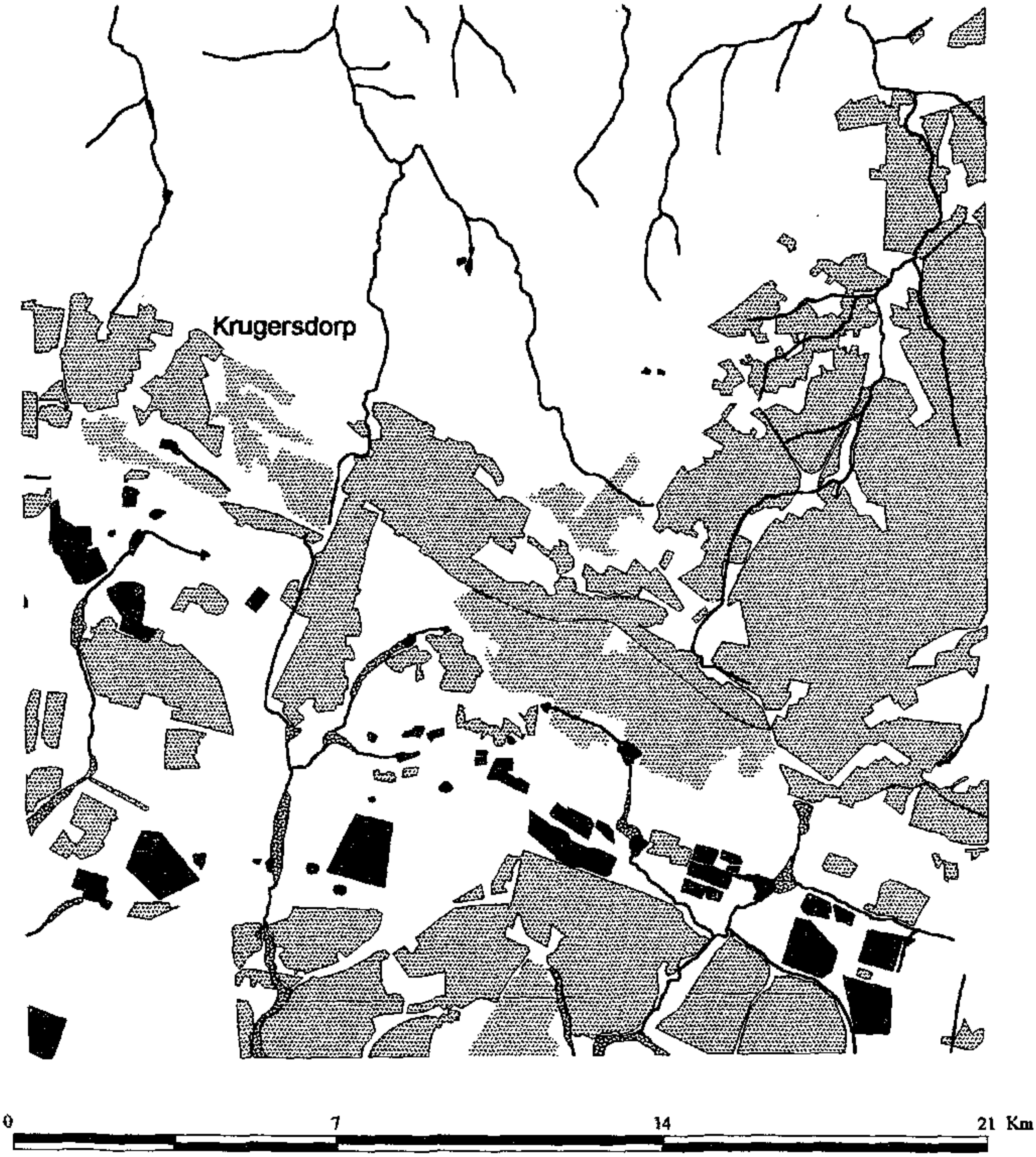
Pulles Howard & De Lange Inc.
October 1998

2627 BA Randfontein



Pulles Howard & De Lange Inc.
October 1998

2627 BB Roodepoort



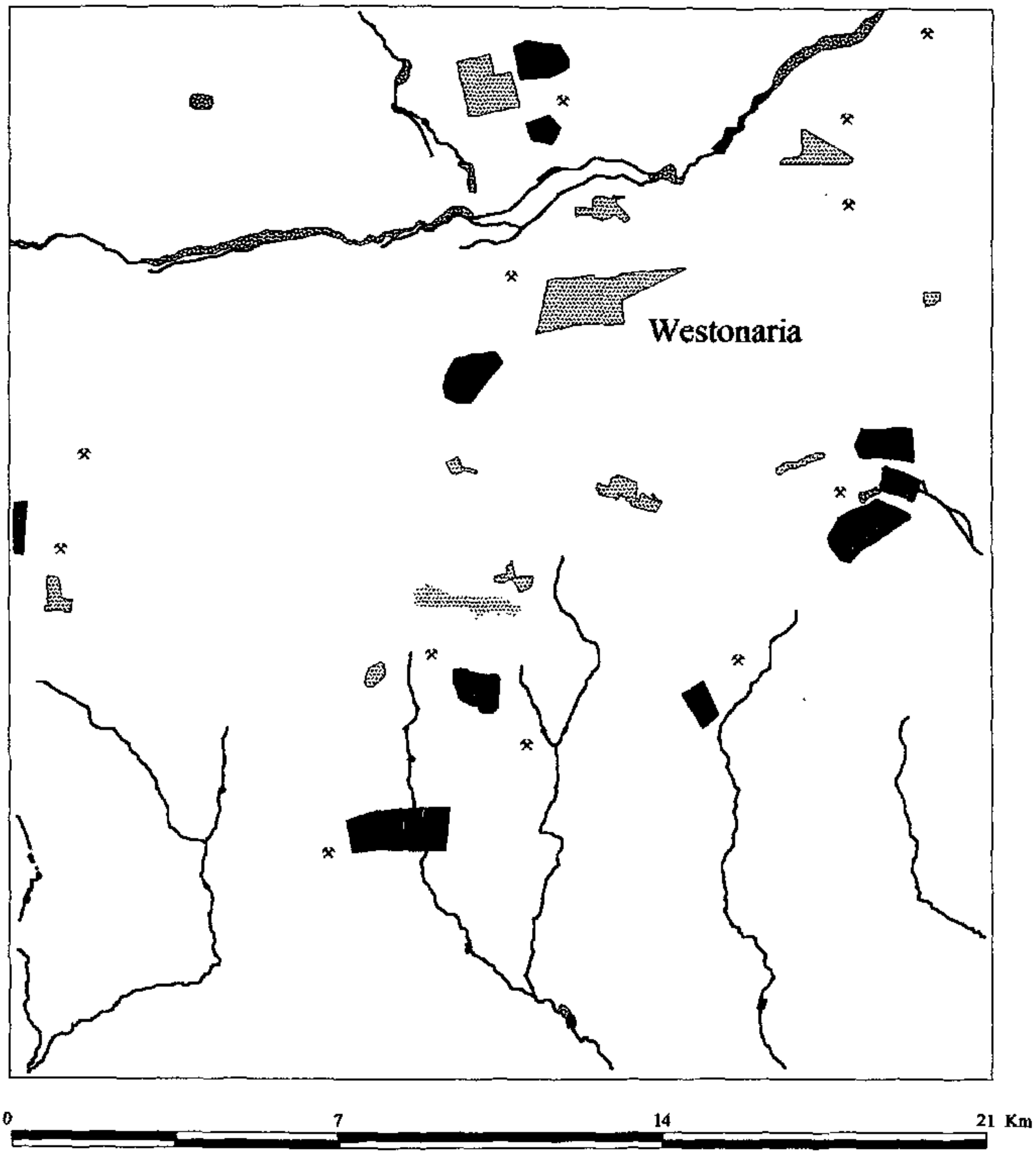
Pulles Howard & De Lange Inc.
October 1998

2627 BB Roodepoort

LEGEND

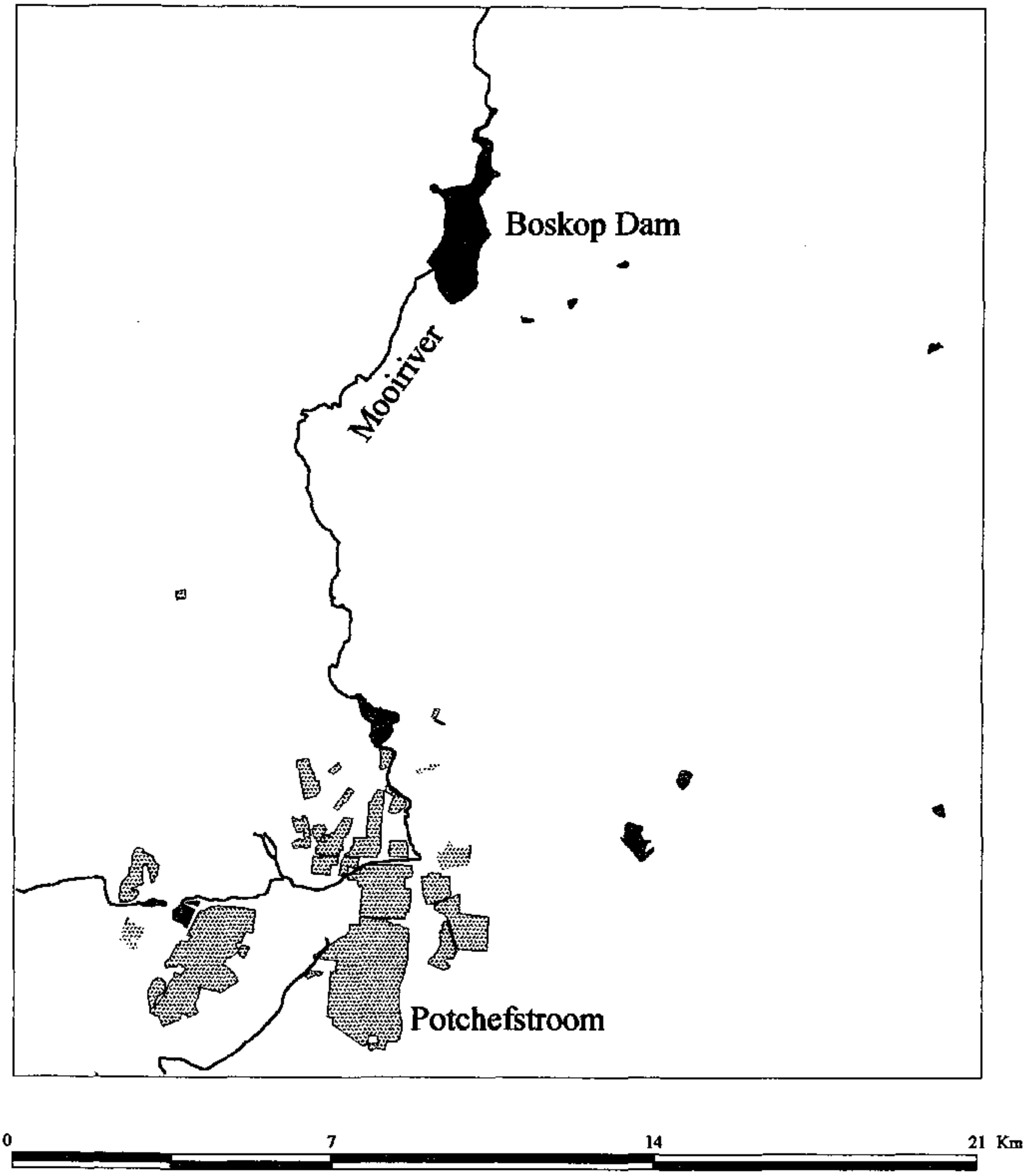
N

- Rivers
- ▨ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



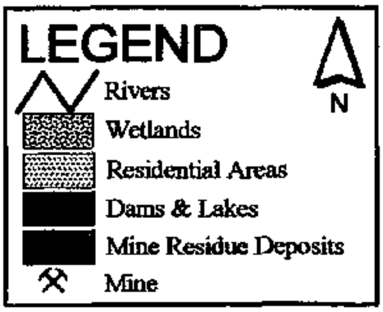
Pulles Howard & De Lange Inc.
October 1998

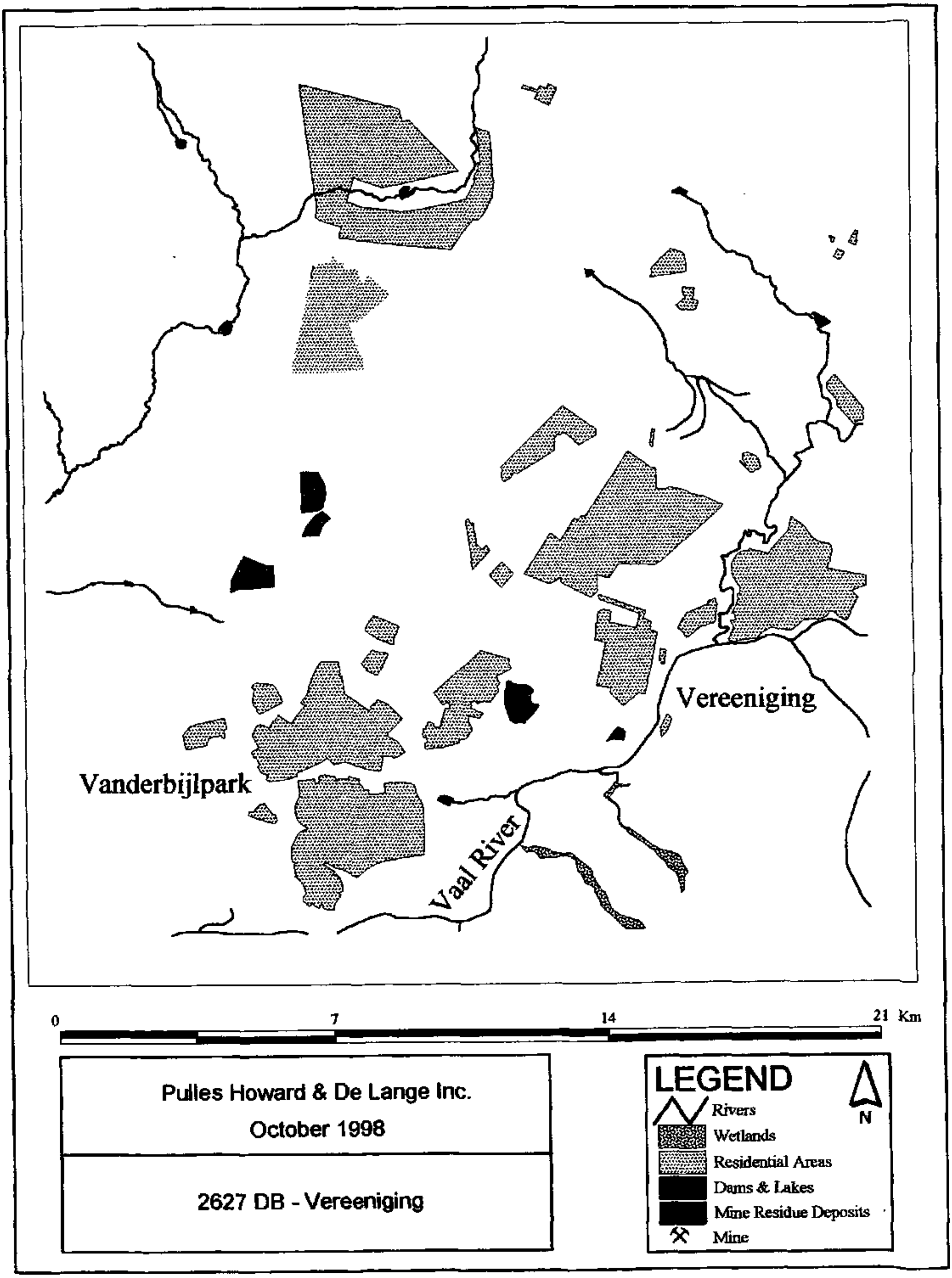
2627 BC Westonaria



Pulles Howard & De Lange Inc.
October 1998

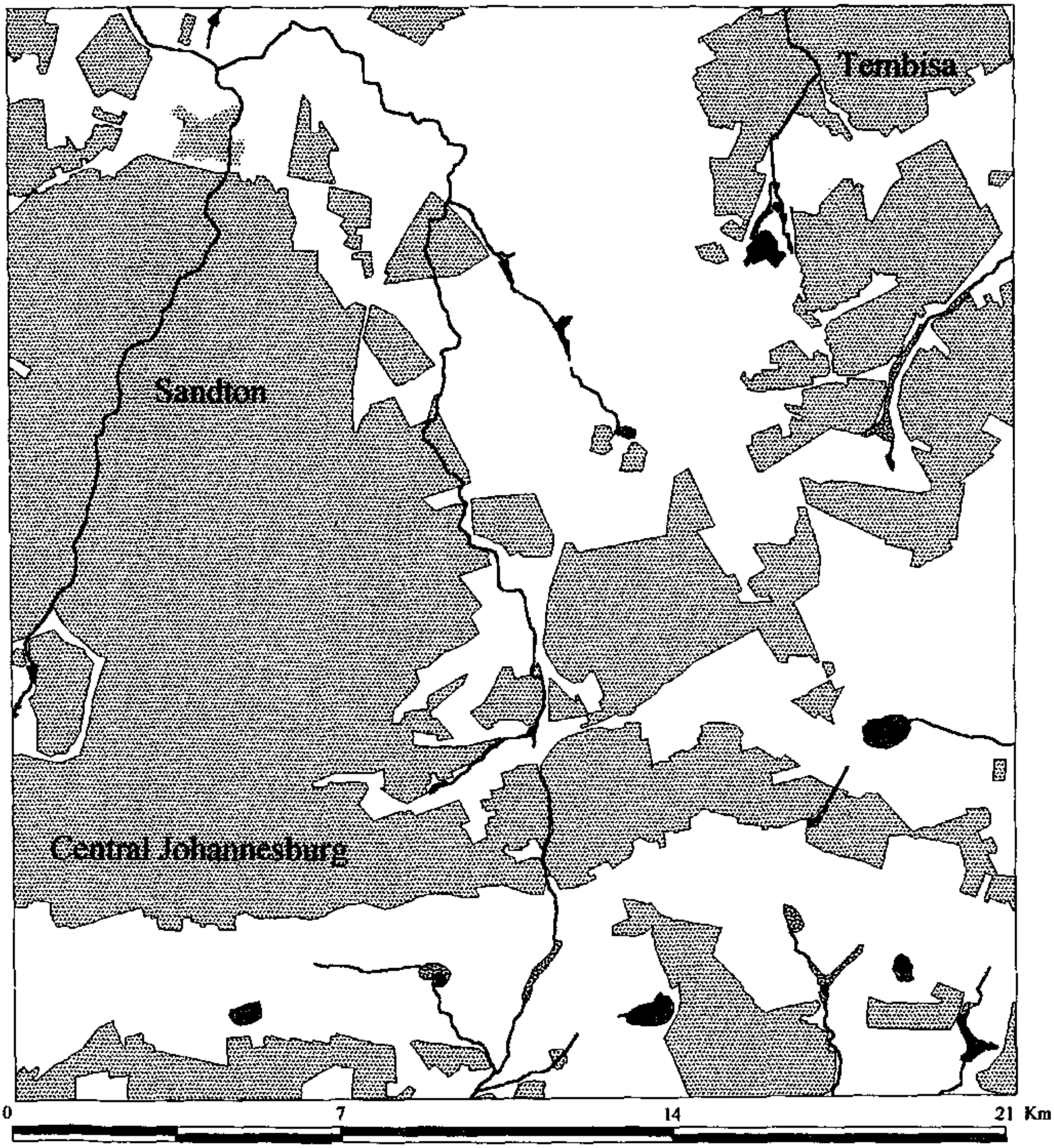
2627 CA Potchefstroom





Pulles Howard & De Lange Inc.
October 1998

2627 DB - Vereeniging



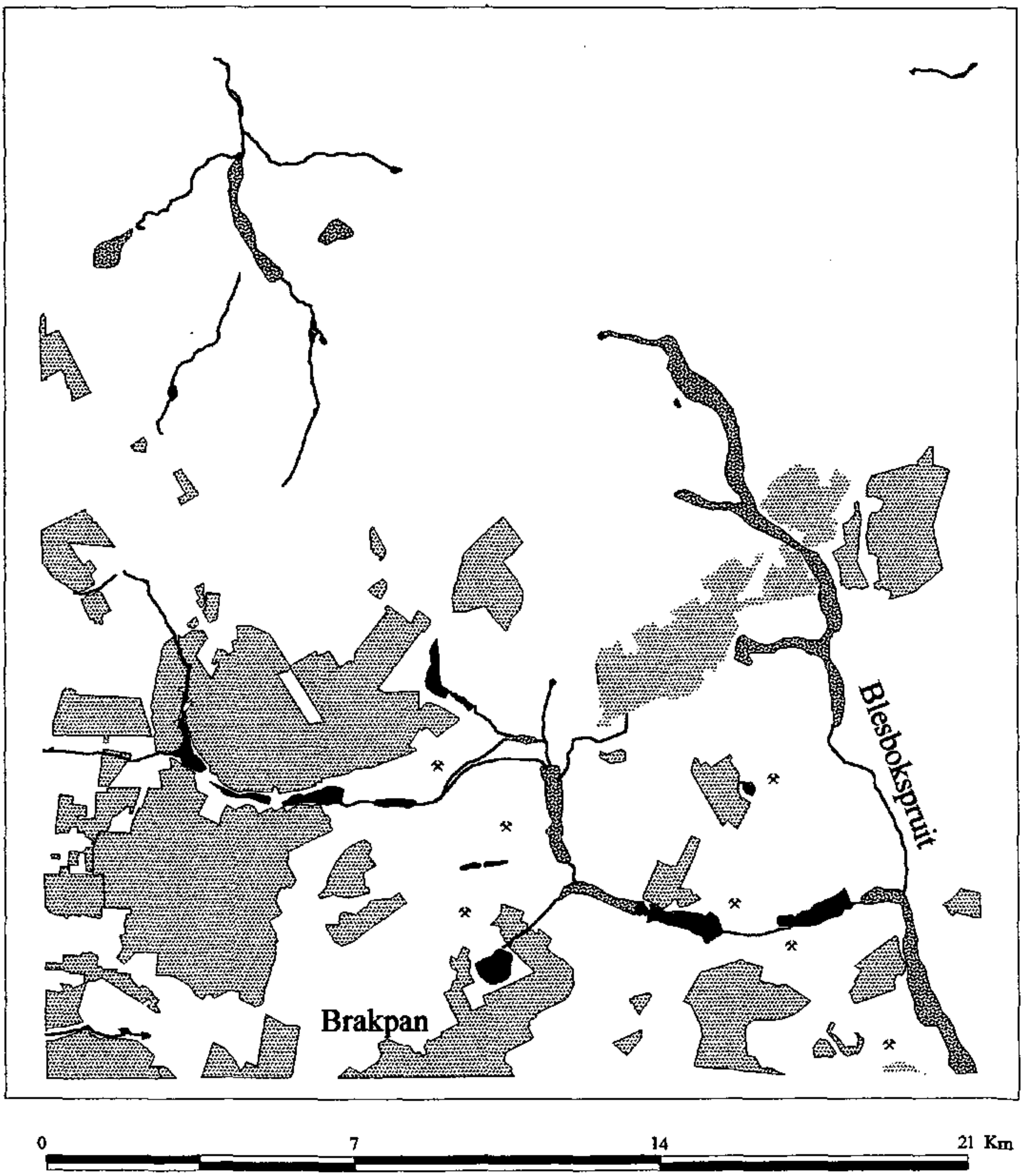
Pulles Howard & De Lange Inc.
October 1998

2628 AA Johannesburg

LEGEND

N

- Rivers
- ▨ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



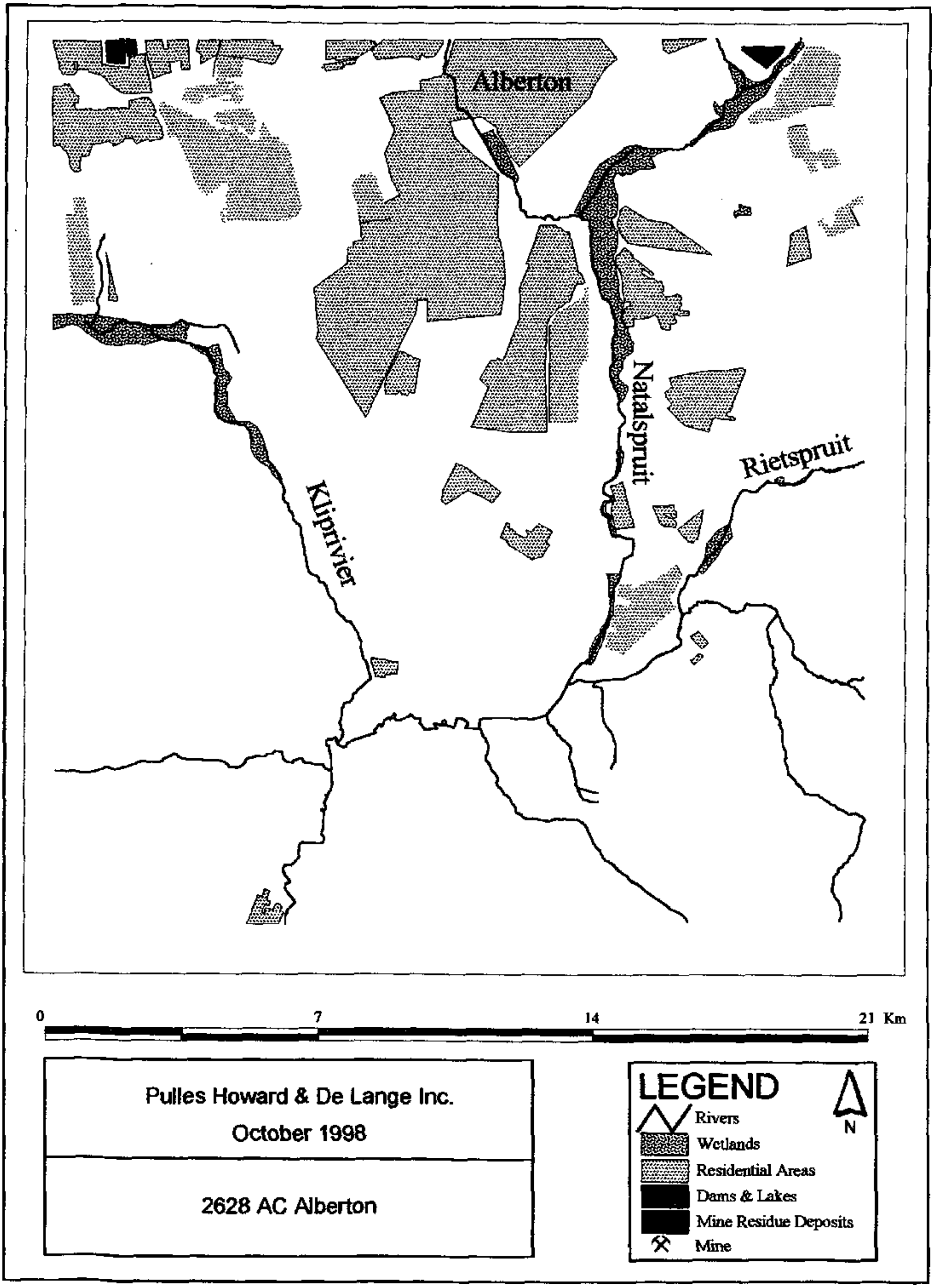
Pulles Howard & De Lange Inc.
October 1998

2628 AB Benoni

LEGEND

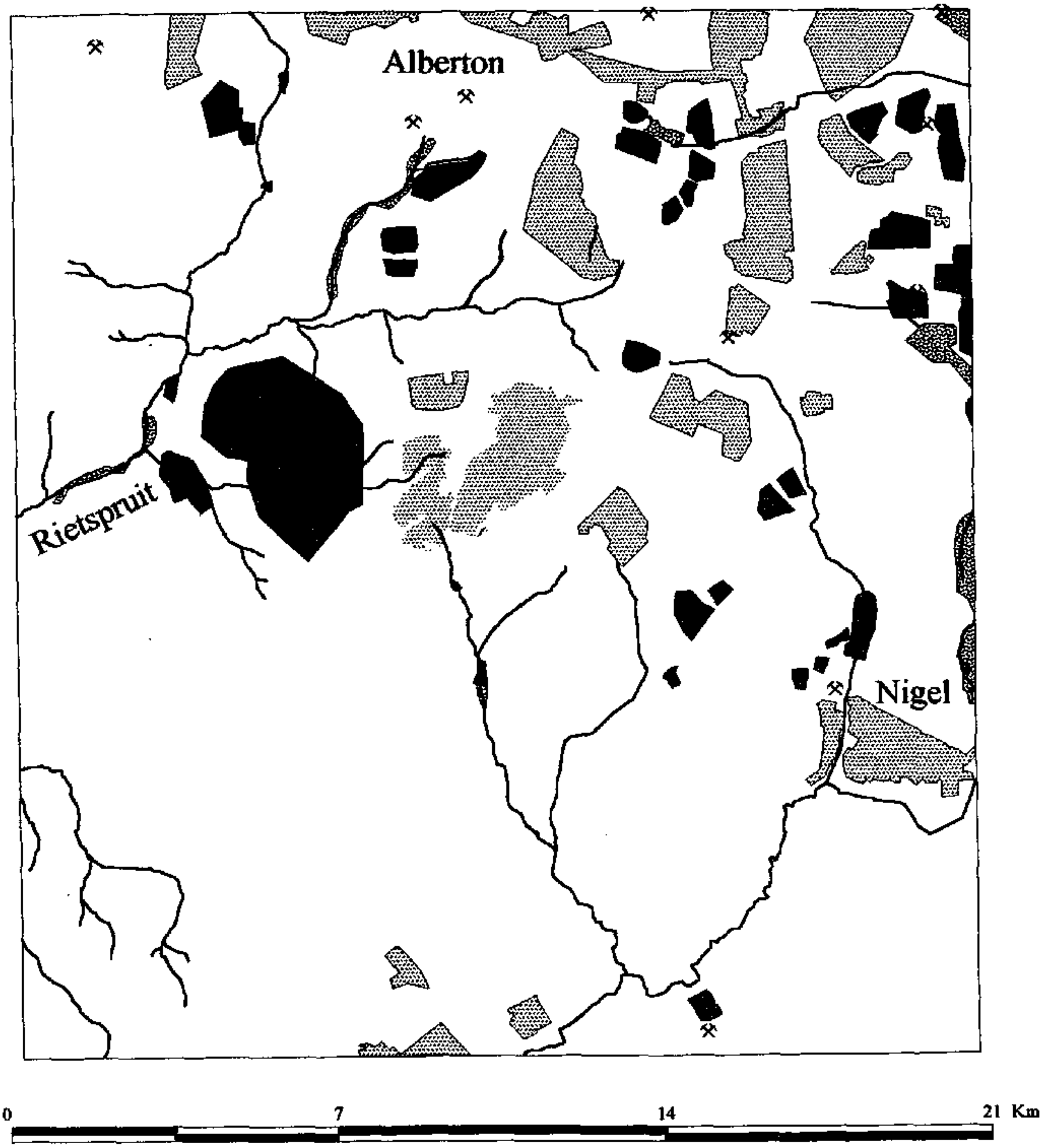
N

- ∧∧ Rivers
- ▨ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



Pulles Howard & De Lange Inc.
October 1998

2628 AC Alberton



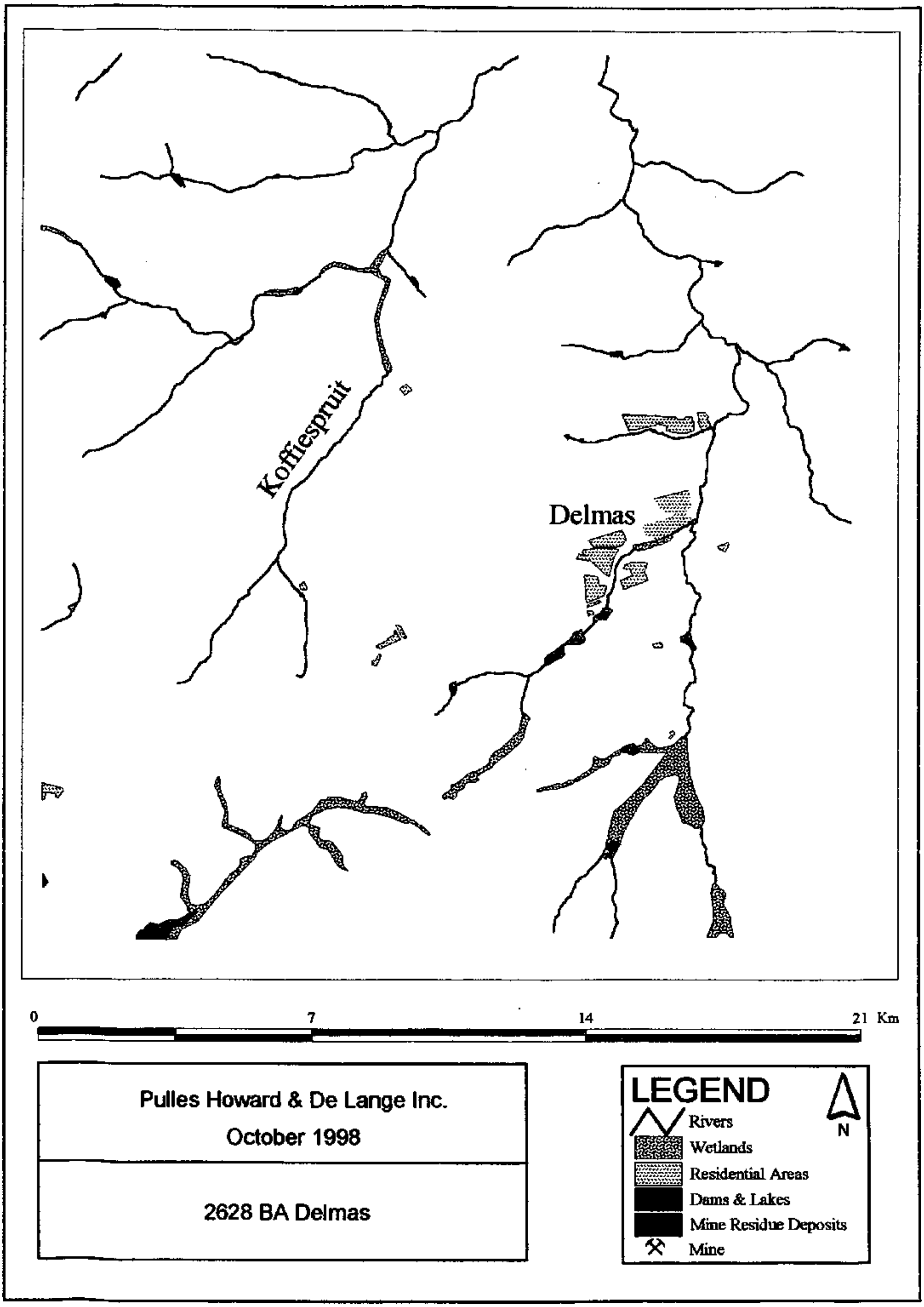
Pulles Howard & De Lange Inc.
October 1998

2628 AD Springs

LEGEND

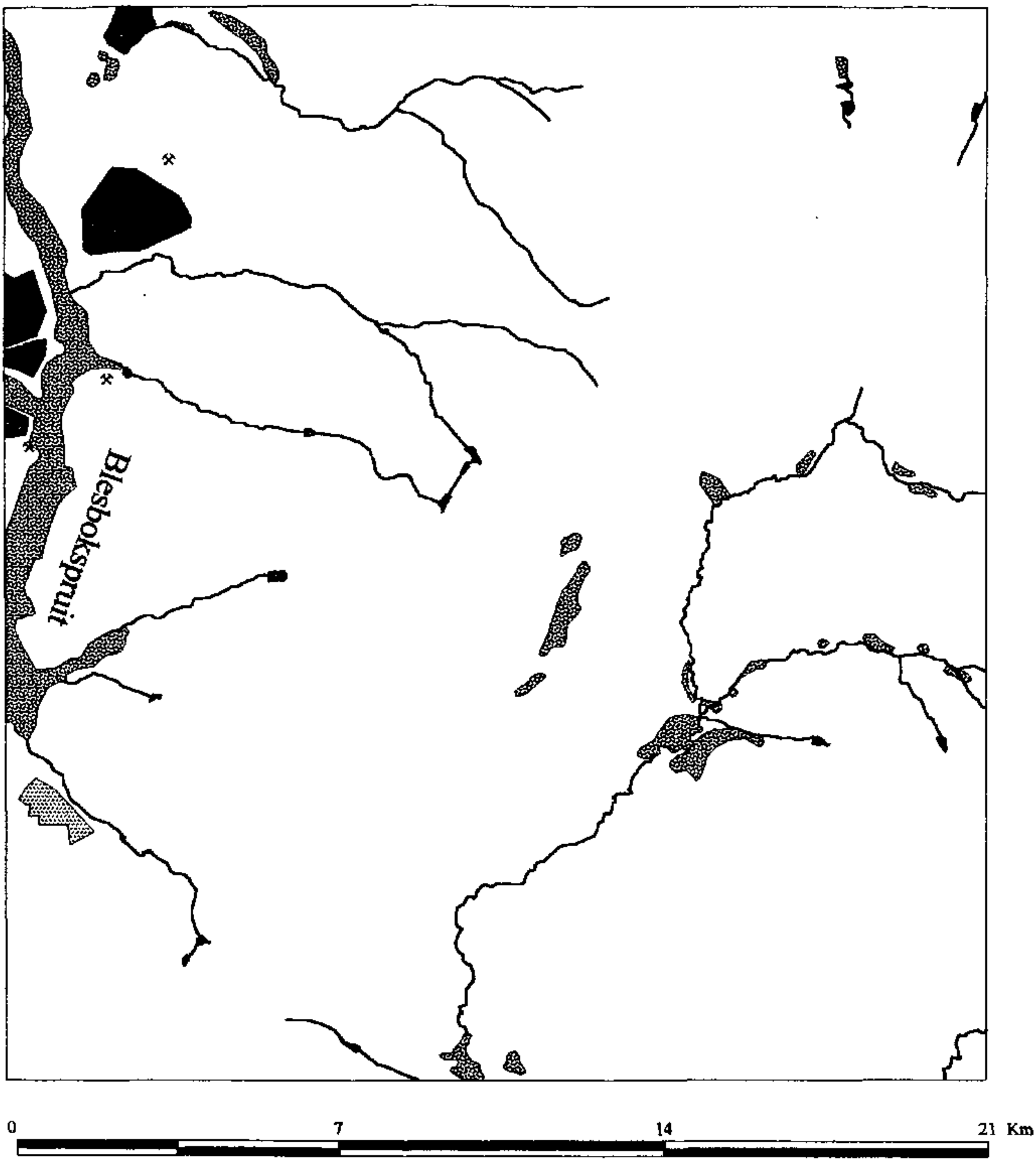
N

- Rivers
- ▨ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



Pulles Howard & De Lange Inc.
October 1998

2628 BA Delmas



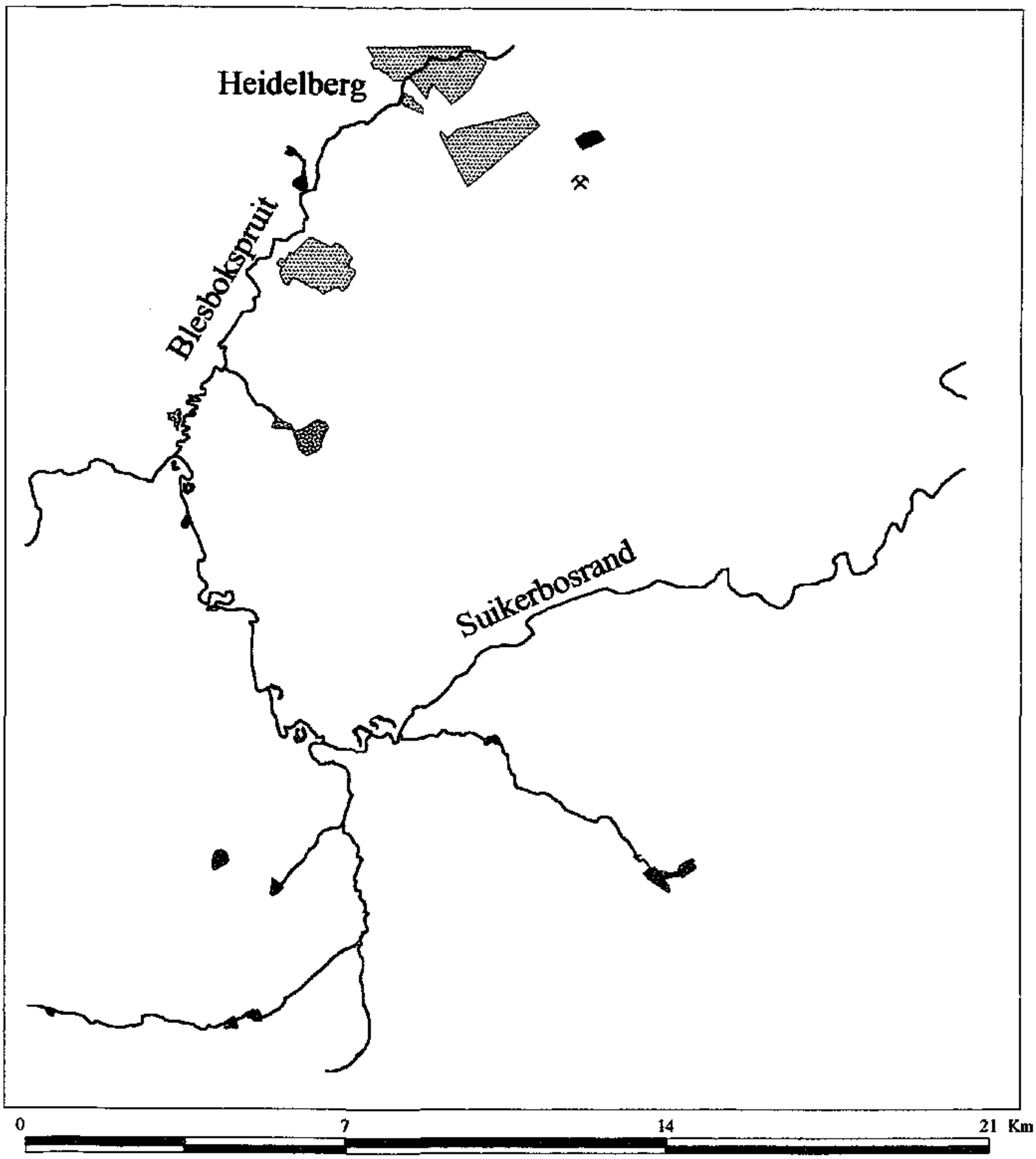
Pulles Howard & De Lange Inc.
October 1998

2628 BC Endicott

LEGEND

N

Rivers
▨ Wetlands
▨ Residential Areas
■ Dams & Lakes
■ Mine Residue Deposits
⚒ Mine



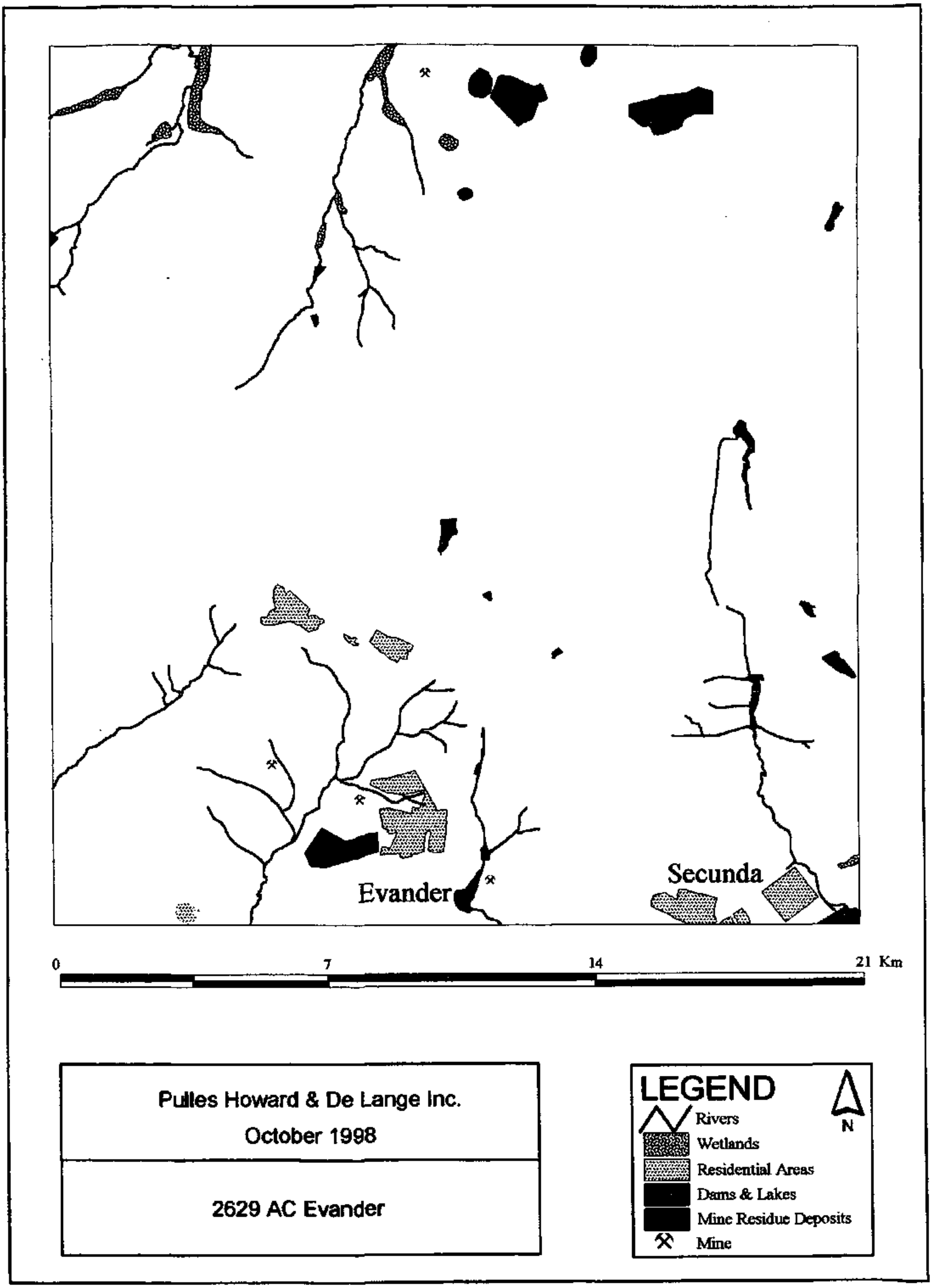
Pulles Howard & De Lange Inc.
October 1998

2628 CB Heidelberg

LEGEND

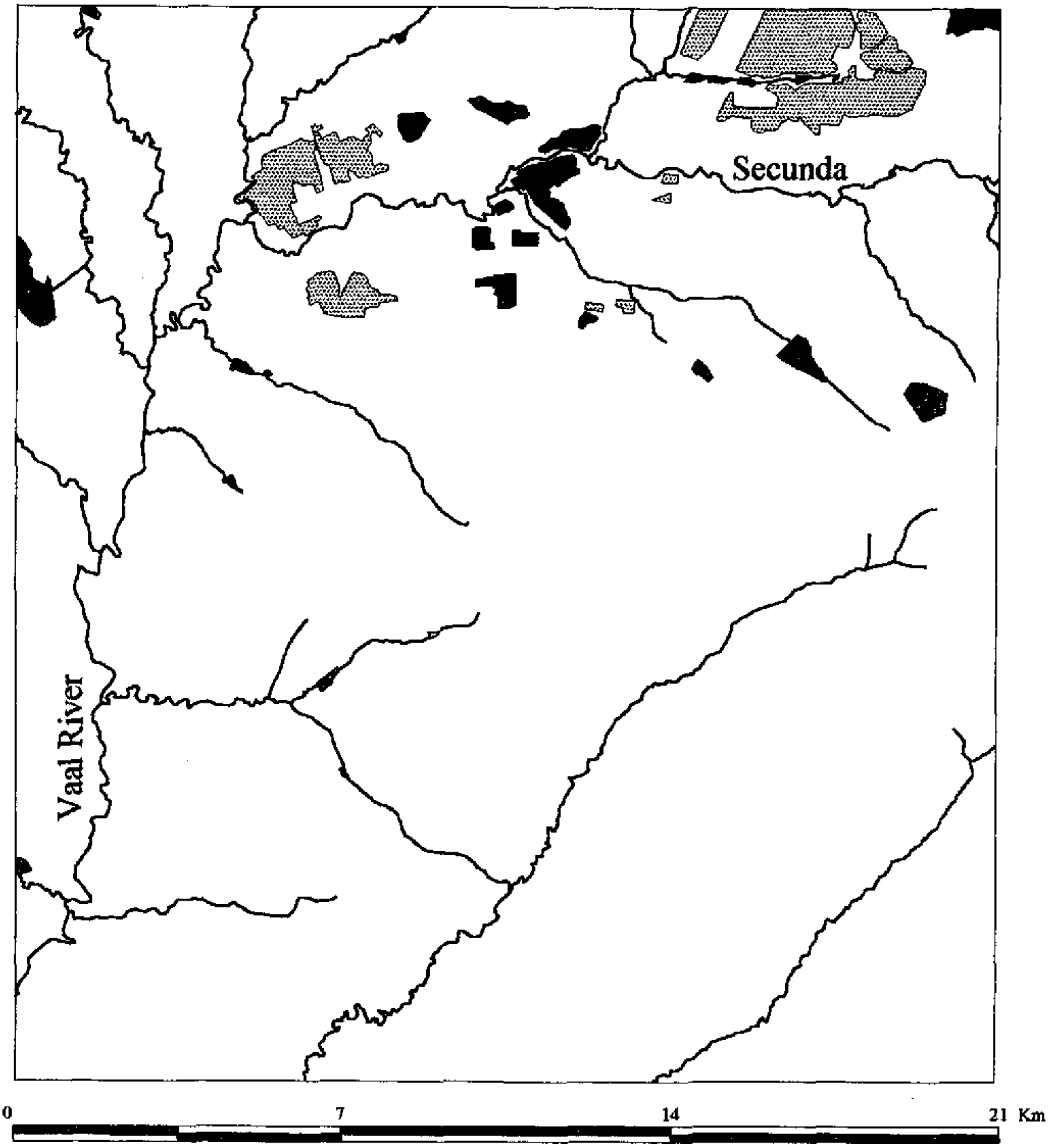
N

⋀	Rivers
▩	Wetlands
▨	Residential Areas
■	Dams & Lakes
■	Mine Residue Deposits
⚒	Mine



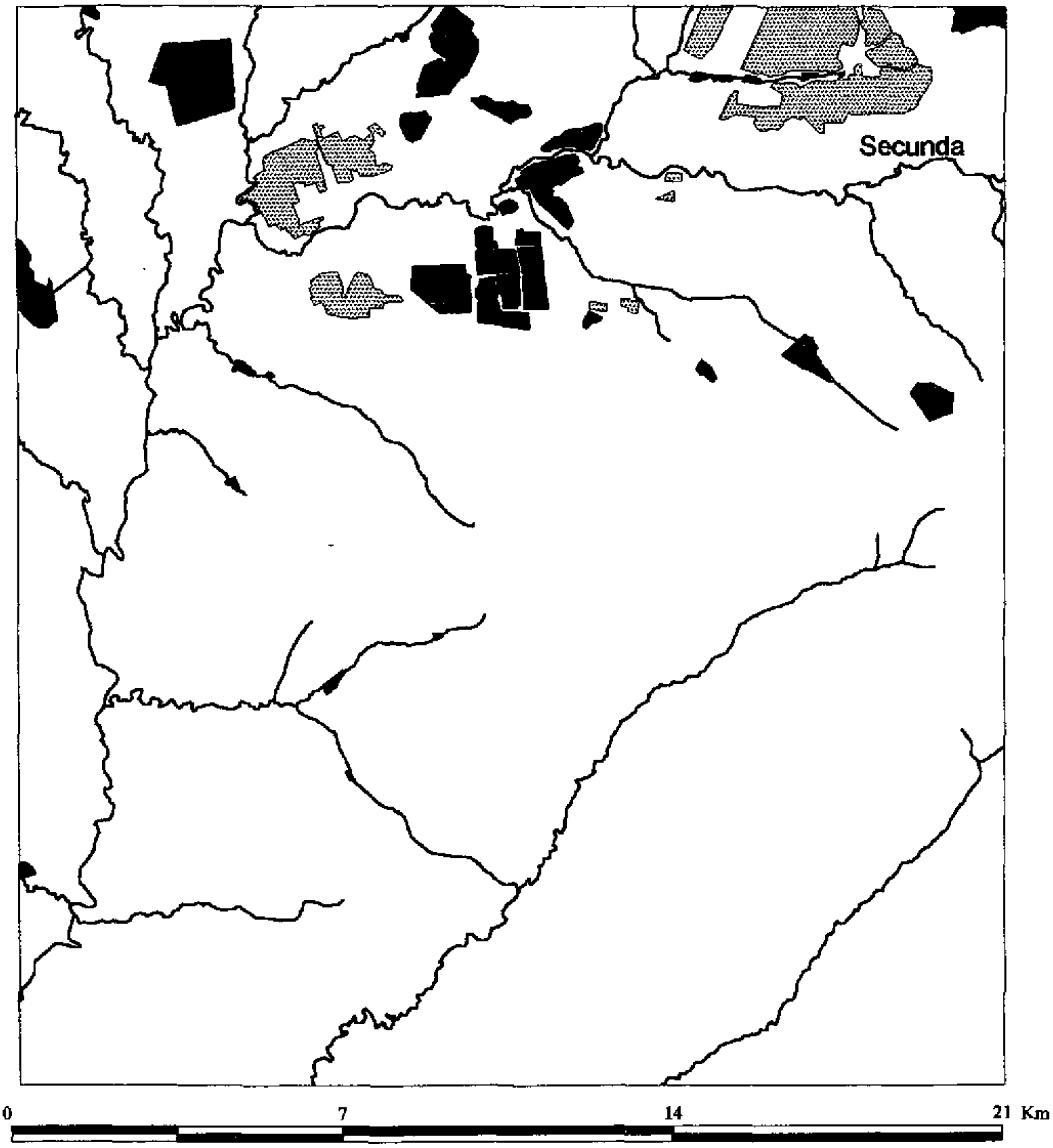
Pulles Howard & De Lange Inc.
October 1998

2629 AC Evander



Pulles Howard & De Lange Inc.
October 1998

2629 CA Secunda



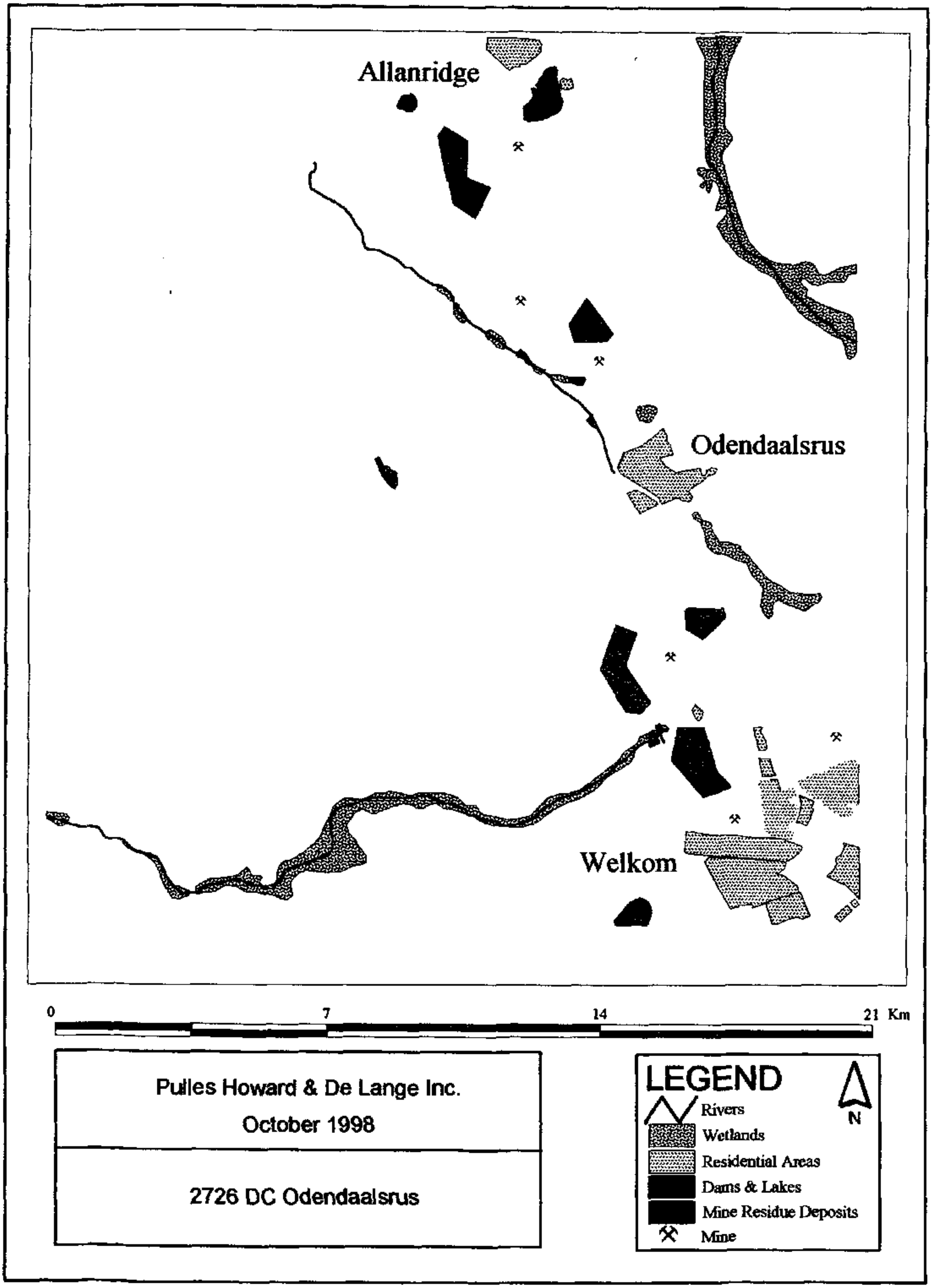
Pulles Howard & De Lange Inc.
October 1998

2629 CA Secunda

LEGEND

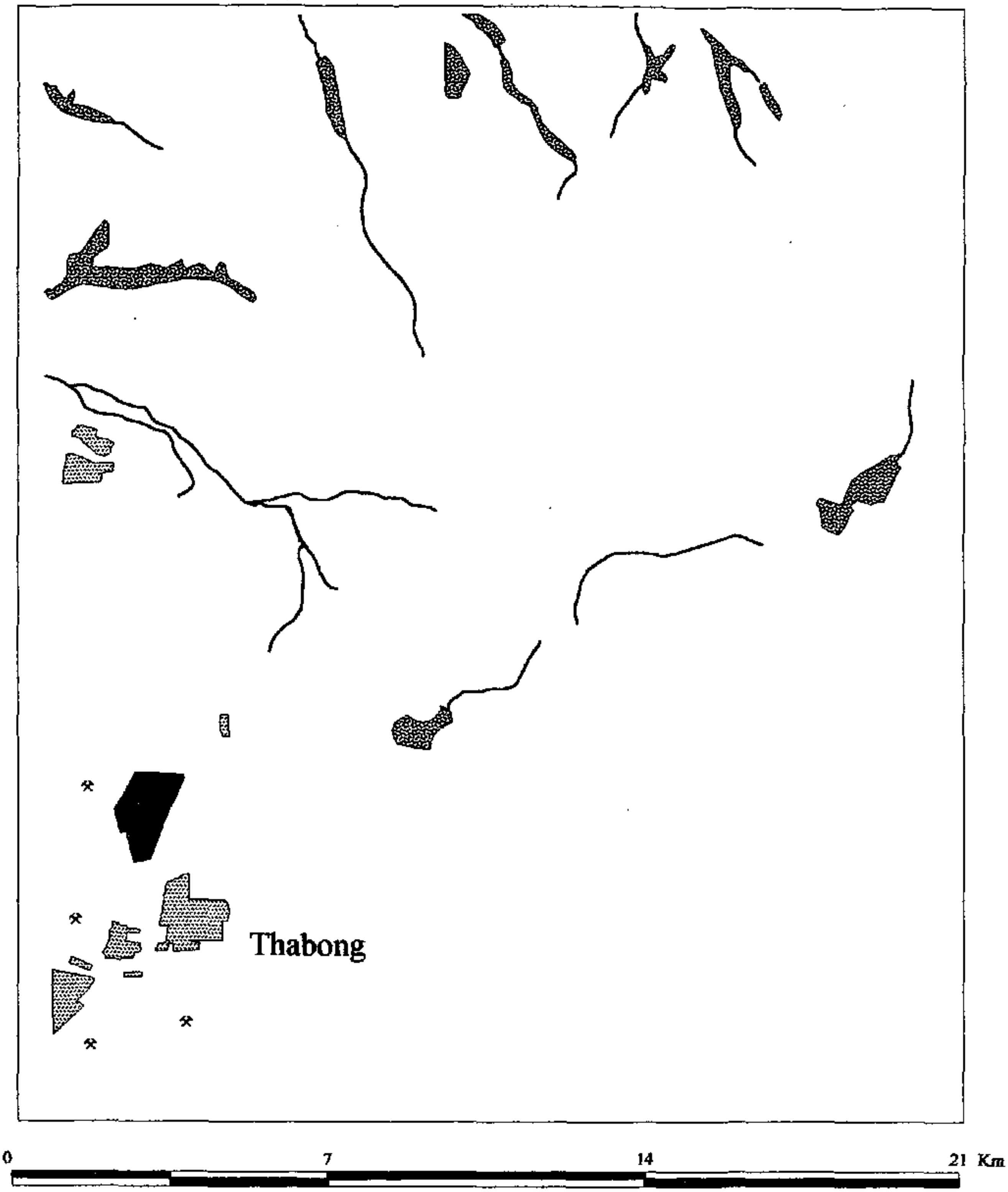
N

- ⋀⋁ Rivers
- ▩ Wetlands
- ▨ Residential Areas
- ■ Dams & Lakes
- ■ Mine Residue Deposits
- ⚒ Mine



Pulles Howard & De Lange Inc.
October 1998

2726 DC Odendaalsrus



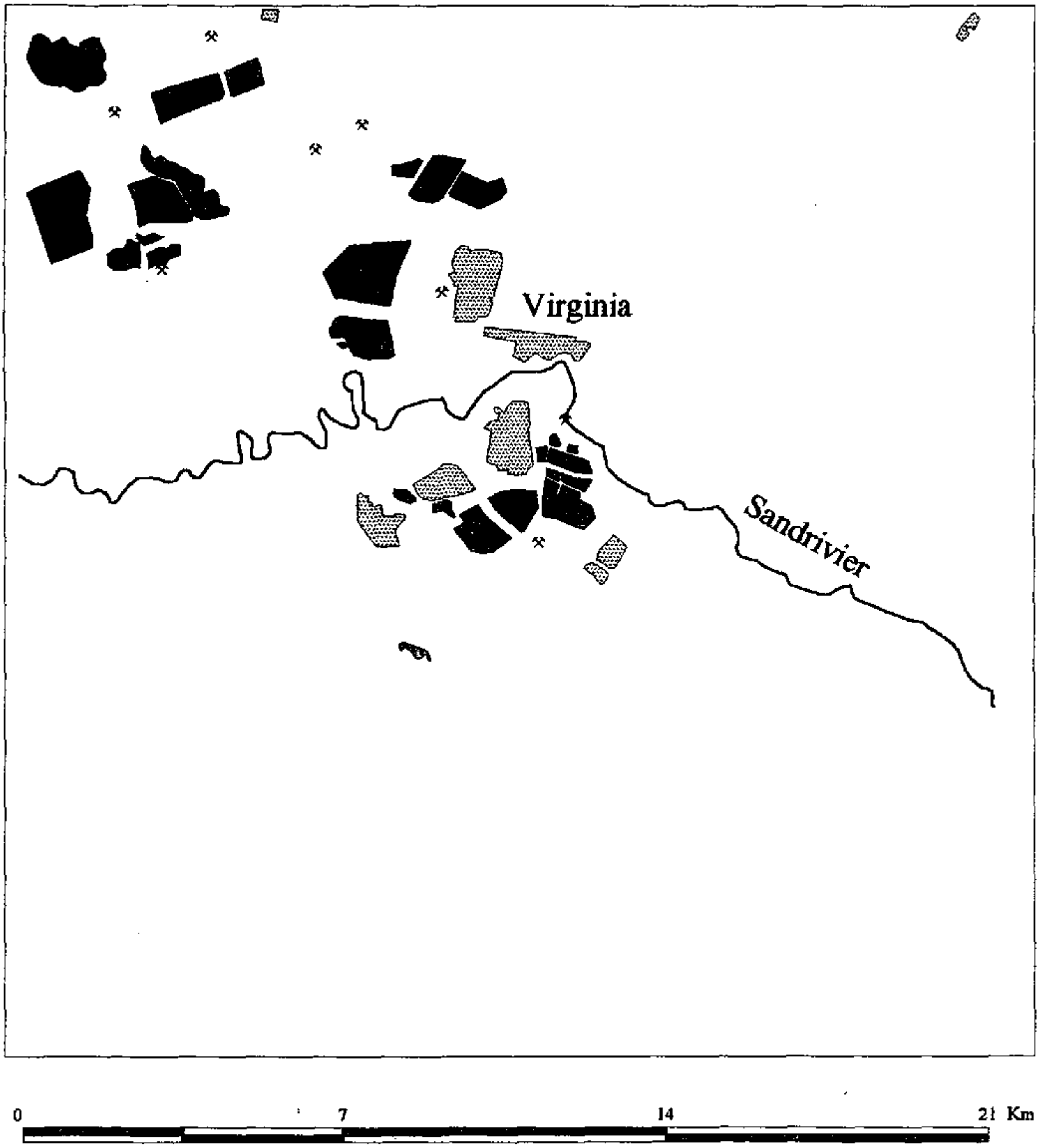
Pulles Howard & De Lange Inc.
October 1998

2726 DD Riebeeckstad

LEGEND

N

Rivers
▨ Wetlands
▨ Residential Areas
■ Dams & Lakes
■ Mine Residue Deposits
⚒ Mine



Pulles Howard & De Lange Inc.
October 1998

2826 BB Virginia

APPENDIX F

Photographs of the Case Study Sites

Figure 1: Case study site A. 50 % reclaimed

Figure 2: Case study site B. 90 % reclaimed. Paddocks were established to prevent storm water run-off.

Figure 3: Case study site B. One of the test pits, maximum depth 2.5 m.

Figure 4: Case study site D. Completely reclaimed. Grass cover is poorly developed.

Figure 5: Case study site E. 90 % reclaimed. Paddocks were established to prevent storm water run-off.

Figure 6: Case study site F. 95 % reclaimed. Grass cover is poorly developed

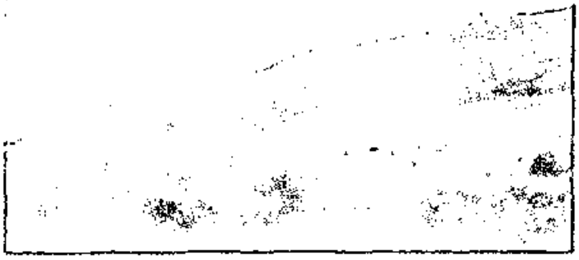


Figure 7: Case study site I. Rehabilitation of the slope wall to prevent wind erosion.

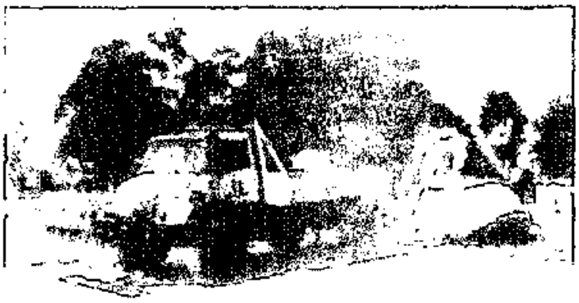


Figure 8: Schaeff backactor in action at one of the investigated sites.

Figure 9: Seepage sampling next to an operating tailings dam site

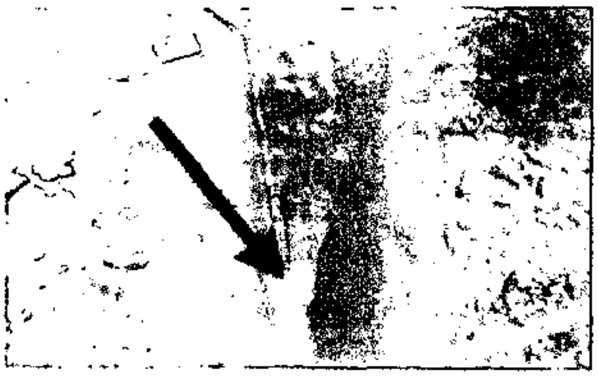


Figure 10: Perched groundwater table in test pit D/2.

Figure 11: Ferricrete block.

Figure 12: Precipitation of secondary minerals such as gypsum. Photograph taken at site G.

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Web: http://www.wrc.org.za