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The environmental impact of seepage from gold mine tailings dams near Johannesburg, South Africa

by

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SUMMARY

Gold mining in South Africa resulted in vast volumes of waste material, mainly in the form of tailings material. Poor management of most of the tailings dams resulted in the release of acid mine drainage that in some cases caused soil degradation and water contamination underneath and around these sites.

Although many tailings dams have been partially or completely reclaimed, their contaminated footprints pose a serious threat to the water quality of the underlying aquifers (e.g. dolomitic aquifers). This study investigated the geotechnical, mineralogical and geochemical parameters of eleven selected partially or completely reclaimed sites situated near Johannesburg. The main objective of the field and laboratory experiments was to assess the pathway of contaminant migration resulting from acid mine drainage from tailings materials through the unsaturated zone into the groundwater system.

Comparing extractable contaminant concentrations with a soil standard from literature represents the environmental short-term impact. In contrast, total element concentrations in the soil compared with background values were used to describe the long-term impact or worst-case scenario. Extraction tests have shown that only a minor portion of contaminants (i.e. Co, Ni and Zn) is mobile in acidic soils. This implies that plant growth could be limited because of phytotoxic elements occurring in the topsoils, complicating rehabilitation measures. In addition, the soils often contain anomalous trace element concentrations, providing a pool for future contamination. Buffer minerals will eventually be depleted and the subsequent acidification of the subsoil, could result in the remobilization of contaminants from the subsoil into the groundwater system in the long term.

It is important to understand the parameters, which control the balance between retention and mobility of contaminants in soils. Therefore a risk assessment approach would be required for all tailings dams and reclaimed sites to identify those sites, which need rehabilitation and to define the type and extent of remedial measures. Minimum rehabilitation requirements at reclaimed sites could consist of soil management measures such as liming and the addition of organic material and fertilisers to minimise the contaminant migration from the topsoil into the subsoil and groundwater as well as to provide suitable conditions for vegetation growth and future land use. Removal of remaining tailings and excavation of those portions of the soil, which are excessively contaminated, are necessary. Tailings dams which pose a high risk to the environment would require a well-engineered soil and vegetation cover to limit rainfall infiltration into the impoundment, and thus to reduce the oxidation of sulphide-bearing minerals such as pyrite. Long-term monitoring is an absolute prerequisite to ensure the success of rehabilitation, and therefore the safe use of land and water.

(432 words)

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LIST OF ABBREVIATIONS

Abbreviation	*Full word*
AMD	Acid mine drainage
AVG	Average value
CEC	Cation exchange capacity
CIP	Carbon-in-pulp
DWAF	Department of Water Affairs and Forestry, South Africa
EC	Electrical conductivity (usually expressed in mS/m)
EPA	Environmental Protection Agency, USA
ExC	Extractable concentration
ICP-MS	Iductively coupled plasma mass spectrometry
Igeo	Geochemical load index
M	mol
MAX	Maximum value
MIN	Minimum value
MOB	Mobility
n	Total amount of samples (or population)
n. a.	Information not available
n. d.	Not detectable
P & T approach	Pump and treat approach to decontaminate groundwater
PI	Plasticity index
STDEV	Standard deviation
TC	Threshold concentration
TDS	Total dissolved solids (expressed in mg/l)
TER	Threshold excess ratio
TotC	Total element concentration
U.S.C.S.	United States Classification of Soils
WHO	World Health Organisation
XRD	X-ray diffraction
XRF	X-ray fluorescence spectrometry

Some common elements used in this study

Chemical	*Symbol*	*Chemical*	*Symbol*
Aluminium	Al	Manganese	Mn
Arsenic	As	Molybdenum	Mo
Barium	Ba	Nickel	Ni
Cadmium	Cd	Nitrogen	N
Calcium	Ca	Oxygen	O
Carbon	C	Potassium	K
Chlorine	Cl	Radium	Ra
Chromium	Cr	Sodium	Na
Cobalt	Co	Sulphur	S
Copper	Cu	Tin	Sn
Iron	Fe	Uranium	U
Hydrogen	H	Vanadium	V
Lead	Pb	Zinc	Zn
Magnesium	Mg	Cyanide	CN (radical)

1 INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Acid mine drainage (AMD) is recognised as a global pollution problem. The uncontrolled release of acid mine drainage as a result of poor management of tailings dams (or slimes dams), sand and waste rock dumps, is the single most important impact mining has on the environment (Ferguson & Erickson, 1988). In general, mine residues consist of high volume, low toxicity wastes according to the United States Environmental Protection Agency (EPA, 1985). In 1996 alone, 377 million tons of mine waste was produced, accounting for 81 per cent of the total waste stream in South Africa (Engineering News, 1997).

Gold mining in rocks of the Witwatersrand Supergroup in the Gauteng Province of South Africa has resulted in the construction of hundreds of tailings dams, which cover a total area of about 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 quantities of sulphide minerals (e.g. pyrite), and the tailings are therefore prone to the formation of acid mine drainage. The seepage from these tailings is generally characterised by low pH values, high sulphate loads, as well as elevated concentrations of toxic substances including radionuclides.

Some of the tailings dams south of Johannesburg (Gauteng Province) are being reclaimed and reprocessed in order to extract economically viable concentrations of remaining gold. Once the tailings material has been removed, the polluted soil beneath the footprint of the former tailings dam may seriously affect the development potential of the land. In addition, land affected by reclaimed mine tailings is often situated within highly developed urban areas. Initiatives such as *The Reconstruction and Development Programme* of the South African government initiated in 1994, aim to improve the general living conditions of people from previously disadvantaged communities. Therefore, the availability of land is one of the central themes of this program and the use of reclaimed land for development could provide an alternative source of land closer to centres of employment.

This study is a continuation of a Water Research Commission project, completed in 1988 by the consulting firm Steffen, Robertson & Kirsten, entitled *Research on the Contribution of Mine Dumps to the Mineral Pollution Load in the Vaal Barrage*. This project 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 tonnes of salts into the near surface environment in 1985 alone; the proportion of pollutants eventually transported by surface streams and groundwater 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 in the unsaturated zone determine the type and extent of rehabilitation approach that would be required for safe future land use and the prevention of groundwater contamination. Large-scale pollution of land from tailings dams poses a serious threat to human health and the environment, including the surface and groundwater resources particularly in highly populated areas. Consequently, the protection of water resources and the mitigation of water pollution are becoming an increasingly important issue. Experience in the USA (e.g. under *Superfund*[1]) and Europe has shown that highly polluted areas (e.g. land affected by mine tailings) are often too large to be cleaned up at a reasonable cost with the technology available.

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[1] Responding to public concerns about abandoned hazardous waste sites across the USA, the US Congress passed the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), also known as *Superfund*. Enacted in 1980, Superfund directs the EPA to locate, study, and clean-up the most hazardous sites; to respond to chemical accidents and spills and to pay for clean-up when parties who own or control a site cannot be identified or cannot afford to pay. In 1990 the total amount of the trust fund amounted to $ 15.2 billion. Presently there are more than 37000 identified contaminated sites in the USA with total clean-up costs possibly reaching more than $ 1 trillion over the next 50 years (EPA, 1997b).

In summary, the primary focus of tailings disposal has been on designing a well-engineered impoundment into which the mine slurry could be deposited. Little attention was given to closure requirements and long-term management of the disposal facility, particularly with respect to environmental concerns. Since the reclaimed areas are expected to remain contaminated for an extended period of time, it is essential to understand the potential for contaminant mobilisation in the long-term under changing environmental conditions. While this study focuses on the short and long-term impact of contaminated seepage released from tailings dams of the gold mining industry, other factors such as dam stability, tailings pipeline routes, dust generation and surface run-off are further significant environmental factors that need to be considered.

1.2 RESEARCH OBJECTIVES

Three main research objectives were defined for this project:

1. To identify the nature and extent of contamination in unsaturated and saturated zones underneath reclaimed gold mine tailings dams.
2. To evaluate and define the existing state of knowledge with regard to the long-term environmental impacts of tailings dams on the subsurface.
3. To assess the potentially adverse environmental effects of residual contaminants in the soils underlying tailings dams with respect to future land use of reclaimed sites.

1.3 PREVIOUS WORK

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

- Donaldson conducted studies in 1960 on the geotechnical stability of slimes dams of the gold mining industry (Adamson, 1973). The findings resulted in the publication of a first guideline for slimes dams in 1968, namely the *Code of Practice for the construction of slimes dams and the condition in which they should be left at the time of closure* by the Chamber of Mines.

- Clausen (1969) predicted an annual salt load of 16800 tonnes from mine residue deposits in the Klip River and Suikerbosrand catchments in 1970, decreasing to 6000 tonnes in 1980 and 3000 tonnes 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 dam tops against surface run-off, and the reduction with time of the amount of residual pyrite (much of which had already been 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 mines in the Witwatersrand region and the Free State Province. Acid mine drainage and the leaching of toxic metals such as Co, Cu, Fe, Mn, Ni and Zn resulted in an increase in metal concentrations of three to four orders of magnitude, compared to pristine river systems in South Africa.
- Hahne, Hutson & Du Plessis (1976) conducted a pilot study on the mineralogical, chemical and textural properties of minerals occurring in gold mine dumps. Detailed information about the study was not available.
- Geotechnical investigations regarding 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 water quality of the Vaal catchment area and of the Vaal Barrage. The author found that the contribution of acid mine drainage from sand dumps and slimes dams causes high salt concentrations in the Vaal Barrage water. However, compared to the pollution load originating from underground mine effluents, which are pumped to the surface and discharged into the rivers, pollution from tailings accounts only to 2 per cent of the total load.
- Marsden (1986) analysed the sulphur content in borehole samples from different mine residue deposits at various depths. Rainwater run-off from these deposits can enter the Vaal Barrage system and contribute to the deterioration of water quality.

Seepage from young mine residue deposits contains high levels of pollution. However, the author concluded that mine residue deposits older than 20 years show no significant contribution to the current pollution load.

- De Jesus, Malan, Ellerbeck, Van der Bank & Moolman (1987) conducted an assessment of the ^{226}Ra concentration levels in tailings dams and in environmental waters in the gold/uranium mining areas of the Witwatersrand. The authors concluded that ^{226}Ra concentrations were low in environmental waters as a result of a very low mobility of ^{226}Ra.
- Wagner & Van Niekerk (1987) investigated the quality of effluents originating from gold and uranium tailings dams. The authors found high total dissolved solid values (> 2500 mg/l) associated by elevated concentrations of Ni, Co, Cu and Zn.
- Steffen, Robertson & Kirsten (1988) monitored selected mine residue deposits in the City Deep area (central Johannesburg) which contribute to the pollution load (e.g. salt) of the Vaal Barrage Catchment.
- Funke (1990) investigated the pollution potential of South African gold and uranium mines and found that the potential for the sulphur in mine residue deposits (which is still undergoing oxidation) to cause water pollution is low, particularly when compared with the pollution load derived from mine pumpage and metallurgical plants. The author found that most of the slimes dams in the Witwatersrand area are inactive (i.e. depletion of pyrite oxidation) since more than 20 years.
- Evans (1990) conducted a study on the geochemistry of a reed-bed adjacent to a gold slimes dam and the associated environmental aspects such as the generation of acid mine drainage and heavy metal pollution. The author found that the quality of the water can be related to the oxidation of sulphide minerals (e.g. pyrite) contained in the tailings, resulting in a sulphur-rich seepage and thus, in poor water quality downstream of the mine residue deposits.
- Cogho, Van Niekerk, Pretorius & Hodgson (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 residue deposits has reached a quasi steady-state situation for distances in excess 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, deposits on Beaufort sediments (higher

permeability than Ecca sediments) may show higher quantities of acid mine drainage 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 & Levin (1993) investigated the type and extent of groundwater pollution in the 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 large 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). Water quality determinations and an airborne radiometric method were used to identify anomalous amounts of heavy metals and radionuclides in the vicinity of a tailings dam. The author found that a high concentration of toxic metals (e.g. As, Cd, Ti and V) in the water and high radioactivity (due to a high U content) downstream from the site exceeded permissible limits. High concentrations of toxic metals were also encountered in the stream sediments and soils. However, the mobility of the contaminants in the latter samples is uncertain, because no suitable tests (e.g. extraction or 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 earlier airborne radiometric survey (Coetzee & Szczesniak, 1993). 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 transported sediments. 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, Howie, Otto & Easton (1995) conducted a preliminary situation analysis in order to characterise the impact of Witwatersrand gold mines on catchment water

quality. The authors concluded that mining activities contributed between 30-45 per cent of the total salt load (estimated at 677 000 ton/year in 1995) to the Vaal Barrage catchment, thus having a significant negative impact on agricultural and industrial users.

- Pulles, Heath & Howard (1996) compiled a manual for the assessment and management of gold mining operations on the impact on water quality at three different mines in the Witwatersrand, Carletonville and Klerksdorp areas. They concluded that seepage from various waste deposits such as mine residue deposits was the most significant pollution source of the water. Seepage contributed only about 11 per cent of the overall salt load, but between 75 and 85 per cent of the heavy metal load in waters.
- Rösner (1996) investigated trace and major element contents in samples taken at various depths (< 1 m) from five different gold mine tailings dams in the East Rand area. All samples were taken within the oxidised zone of the tailings dam and significant trace element concentrations of As, Cr, Ni, Pb and Zn were found. However, no correlation between concentration and depth could be established.
- Lloyd (1997) conducted a study on sand dumps and concluded that these have contributed to the salt discharge from gold mine residue deposits in the past, but that their impact has progressively decreased due to rapid pyrite oxidation (which in his view is now complete).
- Blight & Du Preez (1997) investigated sand dumps and found that pollution arises from acid leachate formed by percolation through the more permeable sand dumps and, to some extent, from erosion gullies on the less permeable tailings dams.
- Wates, Strayton & Brown (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 failures such as the Merriespruit disaster in 1994 have led to an intensified public awareness of the safety and environmental hazards associated with mine dumps. These potential hazards are reflected in the promulgation of legislation such as the new National Water Act (1998). A new set of guidelines, *The Code of Practice for Mine Residue Deposits* was also developed under the guidance of the South African Bureau of Standards (South African Bureau of Standards, 1997).

1.4 STUDY AREA

1.4.1 Regional setting within the Vaal River barrage catchment

The study area is located within the Blesbokspruit quaternary sub-catchment system in the East Rand, approximately 50 km south-east of the centre of Johannesburg. This sub-catchment forms part of the Vaal River Barrage catchment and covers a total area of approximately 3600 km^2 (Funke, 1985). The West, Central and East Rand area together (also known as the Witwatersrand), exhibits the highest concentration of domestic and industrial water users in South Africa. In addition, this area plays an important role for agricultural, recreational and natural environment use. It is therefore essential that the water resources within this catchment need to be managed in a sustainable way.

The Vaal River Barrage catchment is not only unique in terms of user requirements, but also with regard to impacts on water quality. It is estimated that approximately five million people (574 people/km^2) live within the catchment and future projections indicate a high growth rate. Whilst the Vaal River Barrage Reservoir relies heavily on return flows from domestic, industrial and agricultural users, its catchment is also characterised by a large number of gold mines (more than 60 of which six are active mines), two active coal mines, 4800 industrial facilities, and 21 waste water reclamation plants. The Department of Water Affairs and Forestry (DWAF, 1996) identified the upper reaches of the Blesbokspruit amongst others, as the stream with the poorest water quality. Furthermore, the Department stated that the gold mines which are situated in a band running south of Johannesburg from Randfontein Estates Gold Mine in the West through Nigel in the east, are probably the largest contributors to diffuse water pollution within the Vaal Barrage catchment. Since a significant number of gold mine tailings dams are located on dolomitic aquifers, groundwater quality has deteriorated to such a degree that the viability of aquifers is currently threatened (Asmal, 1999).

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

Groundwater under pre-mining conditions within the East Rand area had a distinct dolomitic character (Ca-Mg-HCO_3 type) with a conductivity of generally less than 70 mS/m, and rarely between 70-300 mS/m (Walton & Levin, 1993). Currently, the groundwater beneath and close to the tailings dams is dominantly of the Ca-Mg-SO_4-type and is characterised by high loads in total dissolved solids[2], indicating acid mine drainage-related contamination emanating from mining operations (Scott, 1995). It must be stressed that the dolomitic aquifers south of Johannesburg, which underlie large areas of residential, mining and industrial development, will play a major role in future water supply.

1.4.2 Climate

The greater part of South Africa is semi-arid and subject to variable rainfall, droughts, floods, and high evaporation. The mean annual rainfall is only 500 mm, which is 60 per cent of the world average. In addition, this rainfall is poorly distributed relative to areas experiencing economic growth. Only a comparatively narrow region along the eastern and southern coastline is moderately well watered, whereas the greater part of the interior is arid or semi-arid. Given that 65 per cent of the country receives less than 500 mm of rainfall annually (the level regarded as the minimum for successful dryland farming) and 21 per cent receives less than 200 mm, it is anticipated that South Africa will face major shortages in future water supply (Eales, Forster & Du Mhango, 1997).

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[2] The total dissolved solids limit (TDS) for drinking water recommended by the South African Bureau of Standards (1984), expressed in terms of electrical conductivity (EC), is 70 mS/m. Depending on the type of TDS, this is equivalent to a TDS concentration in the range of 350-550 mg/l. The maximum allowable limit in this specification is 300 mS/m, which is equivalent to a TDS concentration of about 2000 mg/l. According to the World Health Organisation (WHO), TDS concentrations of less than 1000 mg/l are generally acceptable (Department of Water Affairs, 1996a). However, it is not so much the TDS value as the concentrations of specific ions that are detrimental to human health, and thus determine the suitability of groundwater for domestic and other uses.

No site-specific climatic data were available but the statistics for the nearest weather station, at the Johannesburg International Airport, were used to describe the climate of the study area. The investigated area falls in the summer rainfall region (mainly between September and April), with the long-term average annual rainfall of 713 mm as shown in Table 1.1a:

TABLE 1.1a - Rainfall (period 1961-1990) and evaporation (A-pan) data for the Johannesburg International Airport and surroundings (Weather Bureau, 1999).

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

The high evaporation rates of the area imply a moisture deficit during the entire year. Table 1.1b represents the average maximum and minimum temperature data for the study area.

TABLE 1.1b - Temperature data (period 1961-1990) for the Johannesburg International Airport and surroundings (Weather Bureau, 1999).

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
MAX average (°C)	25.6	25.1	24.0	21.1	18.9	16.0	16.7	19.4	22.8	23.8	24.2	25.2
MIN average (°C)	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 fieldwork period from April to May 1998.

1.4.3 Location of the study sites

A number of 11 sites were selected for a detailed study. Sites A-K (except H) are situated in the East Rand area, south-east of Johannesburg (Gauteng Province) and are either partially or completely reclaimed. Site H is located near Potchefstroom in the North-West Province and is completely reclaimed. The altitude of the study area is about 1600 m above sea level and falls within the *Highveld Region*. The seven study sites (A-G), where fieldwork was undertaken cover a total area of approximately 400 ha.

The underlying bedrock geology of the sites comprises rocks of the Monte Christo (dolomite) Formation, Transvaal Supergroup (age ± 2600 Ma), sediments of the Dwyka (diamictite and shale) and Vryheid (sandstone and shale) Formations, Karoo Supergroup (age 200-300 Ma) and doleritic intrusions of post-Karoo age. Soils of the study sites are highly weathered and generally characterized by a low organic matter content (< 1 per cent), but a relatively high clay contents averaging 31 per cent and ferricrete horizons of considerable thickness.

The Blesbokspruit flows from the north to the south through the study area and joins the Suikerbosrand River approximately 14 km south of Heidelberg. This river subsequently feeds into the Vaal River. A large wetland system, intersected by a number of road causeways, occurs over a distance of 22 km along the Blesbokspruit east of Springs all the way to Nigel. This wetland has been proclaimed as an international nature conservation site. The wetland modifies the hydrology by attenuating floods and by evapotranspiration loss. It has also been deduced that bed seepage loss occurs (Herold, 1981). A number of gold mine tailings dams are located adjacent to the wetland. Figure 1.1 shows the location of the investigated sites and their underlying geology as well as major drainage systems.

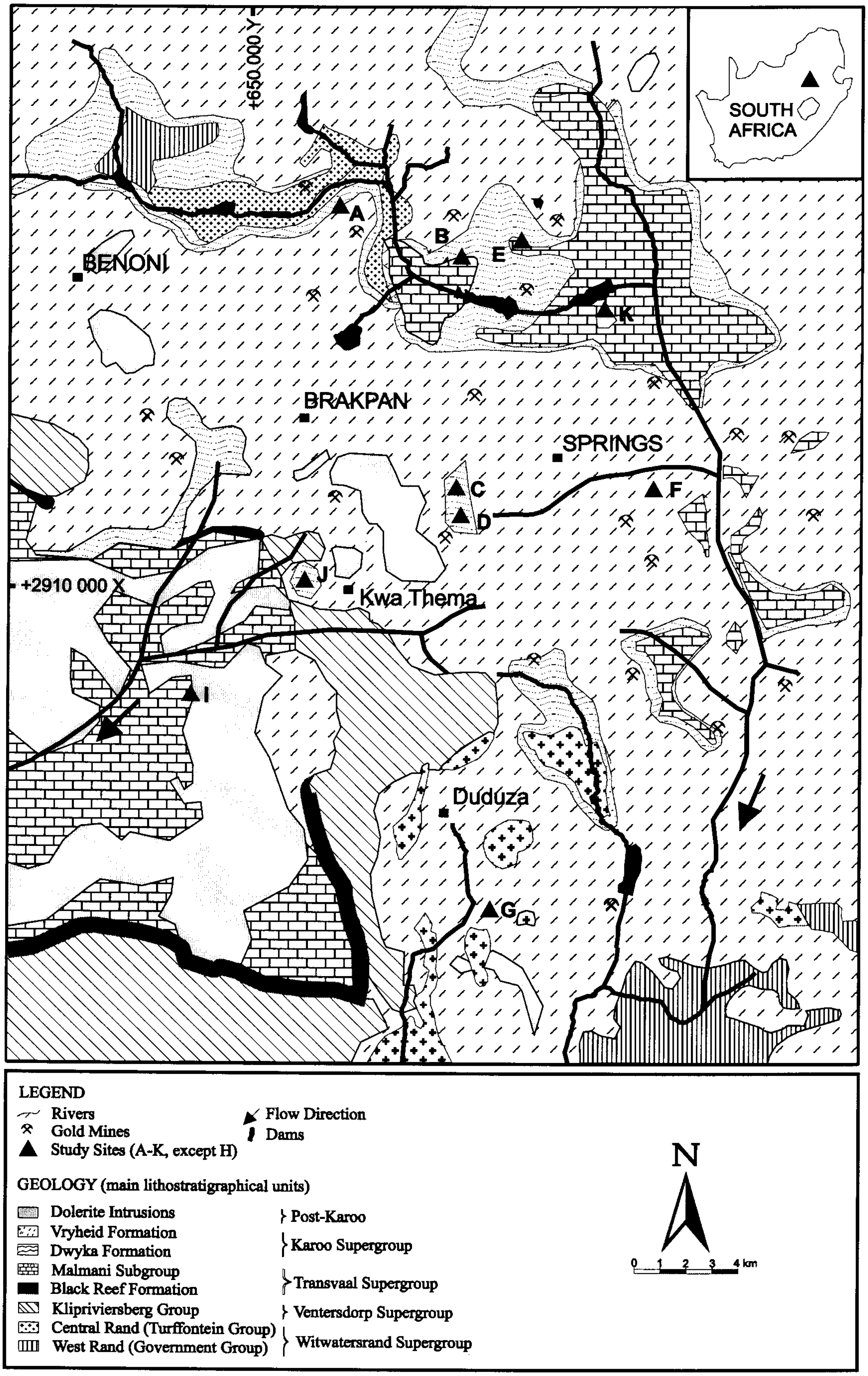

Figure 1.1 - Study area depicting the location of the investigated sites, lithostratigraphical units and major drainage systems (i.e. geological source data from map 2628 *East Rand*, Government Printer of South Africa, 1986).

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2 GEOLOGY, MINERALOGY AND CHEMISTRY OF THE GOLD ORE AND RELATED TAILINGS

2.1 HISTORICAL AND GEOLOGICAL ASPECTS

Gold was discovered in 1886 in the Witwatersrand and this region represents the largest known low-grade gold mineral deposit in the world (Adamson, 1973). The thickness of the Witwatersrand Supergroup reaches 7500 m and occupies an area of thousands of square kilometres in the Gauteng (former Transvaal) and the Free State Provinces. The production from the Witwatersrand Basin, since the first discovery, amounts to about 45 000 tons of gold (Au) and about 150 000 tons of uranium (Robb & Meyer, 1995).

The precious metal occurs in well-defined conglomerate bands (also known as beds, banket or reefs) that are separated by barren sediments consisting mainly of quartzites. Extensive research led to the assumption that the gold together with other heavy minerals including uraninite, was originally deposited in the conglomerates as detrital particles. Subsequently, metamorphic processes resulted in the remobilization of gold particles. Apart from the occurrence in the conglomerates, gold is also contained in banded pyritic quartzites, which fill erosion channels cut in shales, quartzites, and conglomerates underlying the main reef in the Central and East Rand (Liebenberg, 1973). Of special importance for the study area in the East Rand is the Black Reef at the base of the Transvaal Supergroup, where from 1886 until 1962 about 195 000 ounces of Au were recovered, with an average gold content of 15.77 g/ton (Liebenberg, 1973). Table 2.1 presents the generalized lithostratigraphic columnar section for the study area in the East Rand. Dykes and sills consisting mainly of dolerite (post-Karoo), diabase and syenite (both post-Transvaal) intersect the sediments of the Witwatersrand Supergroup. It should be emphasised that the Witwatersrand has been the subject of extensive geological research for more than a century. For detailed geological and mineralogical information reference should be made to the literature available on this topic.

TABLE 2.1 - Generalised lithostratigraphic columnar section for the study area (modified after Kafri, Foster, Detremmerie, Simonis & Wiegmans, 1986 and supplemented with data from the Geological Map 2628 *East Rand*, Government Printer of South Africa, 1986).

Supergroup	Group	Subgroup	Formation	Thickness (m)	Main Lithology
Post-Karoo					Dolerite intrusions
Karoo	ECCA		*Vryheid*		Sandstone and shale
			Dwyka		Diamictite and shale
TRANSVAAL	PRETORIA		*Rayton*	120	Quartzite and shale
			Magaliesberg	300	Quartzite
			Silverton	600	Quartzite and limestone
			Daspoort	80-95	Quartzite
			Strubenkop	105-120	Quartzite and shale
			Hekpoort	340-550	Lava and tuff
			Timeball Hill	270-660	Quartzite and shale
			Rooihoogte	10-150	Quartzite, shale and conglomerate
	CHUNIESPOORT	**Malmani**	*Eccles*	380	Chert rich dolomite
			Lyttleton	150	Chert poor dolomite
			Monte Christo	700	Chert rich dolomite
			Oaktree	200	Chert poor dolomite
			Black Reef	25-30	Quartzite
VENTERSDORP	Not relevant in this study				
WITWATERSRAND	Not relevant in this study				

2.2 MINERALOGY

2.2.1 Macroscopic description of the gold-bearing conglomerate

According to Feather and Koen (1975) the Witwatersrand conglomerate is a greyish, metamorphosed sedimentary rock consisting mainly of quartz (about 80 per cent), cemented by a fine-grained matrix of recrystallized quartz and associated with various phyllosillicates (i.e. a mixture of sericite and chlorite, and sometimes also pyrophyllite and chloritoid). The pebbles vary in composition, size, and colour but consist mainly of vein quartz. Round grains of pyrite, also known as *buckshot pyrite*, are often visible in the matrix, and sometimes are used as indicators for high gold concentrations. The gold is confined to the matrix of the conglomerates and is concentrated predominantly along the bedding planes of the conglomerate beds and on the footwall contact (Liebenberg, 1973).

2.2.2 Mineralogical composition of the gold-bearing conglomerate

The gold-bearing conglomerate mined in the Witwatersrand area contains more than 70 ore minerals (Feather & Koen, 1975), but a typical mineralogical composition is as follows (Liebenberg, 1973):

- Primary and secondary quartz (70-90 per cent);
- Sericite accompanied by variable amounts of pyrophyllite and other minerals such as muscovite, chlorite and chloritoid (10-30 per cent);
- Pyrite, occurring mainly as rounded grains (buckshot pyrite), and also crystals and irregular patches (3-4 per cent);
- Other sulphides such as pyrrothite, chalcopyrite, pentlandite, galena, cobaltite, sphalerite, gersdorffite, linnaeite, and arsenopyrite (1-2 per cent);
- Oval and round grains of primary minerals such as uraninite, monazite, chromite, rutile, garnet, diamond, zircon, xenotime, ilmenite, magnetite, and tourmaline (1-2 per cent). These minerals are associated with alteration products such as hydrated iron oxide (mainly goethite) and leucoxene, and sometimes with secondary minerals such as anatase, and more rarely with calcite.

Lloyd (1981) reported pyrite contents in gold ores in Witwatersrand ranging from 3.2 per cent at Durban-Roodepoort Deep to 1.7 per cent at the East Rand Proprietory Mines (ERPM) in Boksburg. Table 2.2 presents the mineralogical and element composition of conglomerates from the Vaal Reef and the Ventersdorp Contact Reef.

TABLE 2.2 - Mean contents for significant elements and minerals present in the Ventersdorp Contact Reef and Vaal Reef (after von Rahden, 1970).

Element / Mineral	**Unit**	**Ventersdorp Contact Reef**	**Vaal Reef**	
		Venterspost Mine	Hartebeestfontein Mine	Zandpan Mine
Gold	mg/kg	43.8	50.1	39.1
Silver	mg/kg	4.9	7.6	3.3
Uranium Oxide (as U_3O_8)	mg/kg	290	870	930
Quartz	%	88.9	88.3	75.8
Pyrite	%	3.2	6.6	n. a.
Chlorite	%	4.9	0.8	0.9
Muscovite (sericite)	%	3.0	4.4	7.0
Pyrophyllite	%	0.2	0.1	2.5
Zircon	%	0.18	0.08	0.09
Chromite	%	0.15	0.20	0.17
Titanium-bearing minerals (i.e. leucoxene, rutile, altered ilmenite, titaniferous magnetite, titanite)	%	0.11	0.09	0.19

The conglomerates from the different mines are mineralogically very similar, but vary in the relative proportions of minerals comprising them. A detailed discussion on the mineralogy of the Witwatersrand Reefs is provided in Feather & Koen (1975).

2.2.3 Mineralogical composition of gold mine tailings

It can be expected that the mineralogical composition of tailings from the recovery of gold can be derived from the gold ore. In this study, 16 tailings samples have been selected for the determination of mineral content by means of the semi-quantitative X-ray diffraction method (XRD). Table 2.3 presents the result of these analyses.

TABLE 2.3 - Mineral distribution in gold mine tailings at three different sites (n=16).

Sample 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	

Quartz (SiO_2) is the dominant mineral phase in tailings material ranging from 70-93 per cent, averaging 78 per cent. These results correspond to the geochemical ore and tailings composition. The latter is listed in Table 2.6a. The high weathering resistance of quartz results in its relative enrichment compared to readily weathered minerals. The sulphide mineral oxidation results in the formation of secondary minerals such as gypsum ($CaSO_4 \cdot 2\ H_2O$, Figure E.12) and jarosite ($KFe_3(SO_4)(OH)_6$). Gypsum and other secondary minerals 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 due to evaporation of solutions supersaturated with respect to Ca^{2+} and SO_4^{2-}, resulting in the precipitation of gypsum. The fact that no pyrite was found can be explained by the shallow sampling depth within the oxidised zone, resulting in the depletion of pyrite after years of oxygen exposure. In addition, primary mineral phases occurring within the tailings are muscovite [$KAl_2(AlSi_3)O_{10}(OH)_2$], clinochlor [$Mg_5Al_2Si_3O_{10}(OH)_8$] and pyrophyllite [$Al_4[Si_8O_{20}](OH)_4$]. De Jesus et al. (1987)

reported high contents of phyrophyllite (max. 16 per cent) and sericite (max. 2 per cent) as well as quartz contents of 80-90 per cent in tailings material. Pyrophyllite and muscovite show similar physical properties to kaolinite: low expanding capabilities when hydrated (swelling and shrinking, with changes in moisture content), and a low cation exchange capacity.

It is important to note that these mineral phases in tailings impoundments control the pore water chemistry, thus affecting the chemical composition of acid mine drainage.

2.3 CHEMISTRY

2.3.1 Chemical composition of the gold-bearing conglomerate

Table 2.4 provides the major element composition of conglomerates from two different gold mines of the Central Rand, where more than 40 per cent of the gold from the Witwatersrand Basin were recovered.

TABLE 2.4 - Major element composition of conglomerates from the Central Rand (after Liebenberg, 1973).

Major Element (%)	**Witwatersrand Deep Mine**	**Durban Roodepoort Deep Mine**
SiO_2	88.76	85.60
Al_2O_3	6.91	3.50
Fe_2O_3	2.65	8.60
FeO	n. d.	n. d.
CaO	traces	traces
MgO	0.70	n. d.
K_2O	n. d.	n. d.
MnO	n. d.	n. d.
FeS_2	2.75	2.15
TiO_2	n. d.	n. d.
P_2O_5	n. d.	0.10
CO_2	n. d.	n. d.
H_2O	n. d.	n. d.
TOTAL	99.77	99.95

Gold has been also recovered in the East Rand area where the Black Reef Formation occurs at the base of the Transvaal Supergroup (Table 2.1), particularly where it is in close proximity to the underlying gold-bearing Witwatersrand beds (Liebenberg, 1973). In this context, Barton & Hallbauer (1996) reported average trace metal concentrations for pyrite grains of the Black Reef Formation of the Transvaal Supergroup and a summary is listed in Table 2.5.

TABLE 2.5 - Average of maximum trace elements contents in pyrite of the Black Reef Formation, Transvaal Supergroup (after Barton & Hallbauer, 1996).

Trace element (mg/kg)	**Concentration**
As	1394
Co	1006
Cu	346
Cr	33
Ni	1930
Mn	16
Sr	3
Ti	98
Pb	844
Zn	90

High trace element concentrations of As, Co, Cu, Cr, Ni, Pb and Zn in pyrite generally correspond to high concentrations in the related tailings, which are discussed in the following paragraph.

2.3.2 Chemical composition of gold mine tailings

Table 2.6a presents the concentrations of major elements in tailings samples, collected from five different deposits in the East Rand area.

TABLE 2.6a - Average major element concentrations of five different gold mine tailings dams in the East Rand area (Rösner, 1996, n=36).

Major element (%)	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
SiO_2	80.44	84.14	82.33	83.44	77.63
TiO_2	0.49	0.48	0.47	0.27	0.60
Al_2O_3	8.24	6.33	8.05	5.68	9.77
Fe_2O_3	3.66	3.23	3.65	3.66	3.60
MnO	0.02	0.02	0.01	0.01	0.01
MgO	0.94	0.77	0.6	0.29	0.60
CaO	0.28	0.55	0.12	0.43	0.20
Na_2O	0.15	0.21	0.19	0.17	0.22
K_2O	1.91	1.34	1.95	1.1	2.70
P_2O_5	0.03	0.04	0.04	0.03	0.03
(SO_3)	0.1	0.12	0.02	0.08	0.06
(Cl)	0.02	0.04	0.03	0.03	0.03
(F)	0.02	0.01	0.01	0.01	0.01
LOI	3.46	2.36	2.32	4.31	4.24
TOTAL	99.76	99.64	99.79	99.51	99.70

The main parameters causing variation in major element contents are the following:

- Changing ore body geochemistry;
- Weathering process in the mine tailings.

According to the chemical composition of the tailings material, the high SiO_2 values correspond to the high quartz content in the gold ore (Table 2.4). Carbonate occurs as traces in the Witwatersrand gold ore, but lime is added during the gold recovery process, resulting in an alkaline slurry and, thus in elevated carbonates contents in the tailings. However, these contents in the tailings are too low to provide sufficient acid neutralisation capacity to prevent the generation of the acid mine drainage.

The loss of ignition (LOI) as shown in Table 2.6a usually reflects the total content of organic matter and volatile elements such as CO_2, H_2O, C, Cl, F, S and CN (cyanide). It is most unlikely that tailings contain any significant concentrations of organic material as the content of kerogen is generally low in the gold ore. Cyanide is used amongst others during the gold recovery process to dissolve the gold and this process is described in more detail in the next paragraph. However, CN is unstable and decomposes rapidly if exposed to sunlight and the atmosphere (Adamson, 1973).

It can be argued that the pyrite (FeS_2) content of the analysed tailings samples is lower than in the ore (parent rock) or unweathered tailings, because all samples were taken within the oxidised zone (2-3 m depth) of the deposit. In this zone pyrite reacts in the presence of oxygen and moisture resulting in high sulphate loads and a low pH in the tailings pore water, known as acid mine drainage. For example, Blight & Du Preez (1997) investigated the total sulphur content, paste conductivity (measured in the field) and the paste pH beneath the surfaces of slopes and the top surface of a decommissioned tailings dam in the Gauteng Province. Samples were taken at intervals of 0.5 m to a maximum depth of 5 m. A total sulphur content of approximately 0.1 per cent within the first metre below the surface indicates that the tailings have almost fully oxidised whereas sulphur contents at depths greater than 1 m increase to approximately 1.5 per cent. The pH profile indicates values from 3-7 within the first 0.5 m below surface and constantly low pH values (below 4) at depths from 0.5-5 m. The paste conductivity profile corresponds to the pH and sulphur content profile with low conductivities (below 100 mS/m) within the first metre of the deposit and maximum values of 1000 mS/m at depths greater than 1 m. Blight & Du Preez (1997) concluded that the salt and sulphur-rich tailings in the impoundment are separated from the atmosphere by a 1-1.5 m thick outer layer of oxidised, leached, relatively innocuous material.

Table 2.6b presents the concentrations of some of the trace elements, contained in samples from five different gold mine tailings dams in the East Rand area.

TABLE 2.6b - Average trace element concentrations of five different gold mine tailings dams in the East Rand area (Rösner, 1996; n=36).

Trace element (mg/kg)	Site 1	Site 2	Site 3	Site 4	Site 5
As	109.0	82.7	103.5	112.5	123.4
Co	13.1	4.8	4.0	18.6	20.5
Cu	27.0	14.0	17.5	22.7	25.1
Cr	462.4	395.8	347.3	445.5	553.1
Ni	71.6	54.5	33.6	73.1	88.4
Pb	46.4	20.8	36.3	125.0	23.1
Zn	45.4	27.8	17.6	94.4	21.4
Th	< 3.0	< 3.0	< 3.0	3.5	4.0
U	17.9	9.7	9.5	46.4	13.7

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

- Fluctuations in the pyrite content of the mined ore;
- Dilution effect by the matrix;
- Metallurgical separation during the gold recovery process;
- Oxidation within the surface layer and migration into deeper zones of the impoundment.

The correlation coefficients of all measured elements (major and trace elements) were calculated and are presented in Table B-7 (Appendix B).

These correlation coefficients could be explained on a mineralogical basis. The phyllosilicate muscovite ($K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$) accounts for the correlation coefficients between the K_2O-SiO_2-Al_2O_3 components, as indicated by the structural formula. Secondary sulphides (including galena, PbS), consisting predominantly of pyrrothite, chalcopyrite, pentlandite and sphalerite (ZnS) often accompany the gold in the uraninite (Liebenberg, 1973). Niccolite (NiAs) and cobaltite (CoFeAsS) are rare minerals in Witwatersrand-type ores, but are closely related when they are present (Feather & Koen, 1975). However, both Co and Ni can be camouflaged by Fe in pyrite.

Subsequently, the mobility of various trace elements in 13 tailings samples was investigated. The extractable concentrations and the relevant threshold value for soils are presented in Table 5.1. In summary, high concentrations of sulphur (S) in the leachate are caused by the oxidation of sulphide minerals such as pyrite. Furthermore, Co, Cr, Cu, Ni, Pb and Zn exceed in the bulk of the leachate samples the soil standard used in this study.

2.4 GOLD RECOVERY

The recovery of gold in South Africa is achieved by a number of mechanical and metallurgical processes (Adamson, 1973). The first step in the recovery is sorting to reduce the mass of ore milled by eliminating dilution with waste rock from run-of-mine feed. The waste rock is either deposited, or sold as construction material. The second step is crushing and milling to reduce the grain size of the ore to a size less than 0.1 mm. The fine-milled material is suspended in water and passed through a hydrocyclone in order to separate over-size material for recycling to the mill. In the next metallurgical step gold is recovered partly by gravity concentration (for coarse gold) and partly by cyanidation (for fine gold), where mine water from tailings ponds is used to augment the water in the milling circuit.

2.4.1 Metallurgical process

Various processes (not necessarily listed in the proper sequence) achieve the metallurgical recovery of gold:

- Gravity concentration;
- Thickening;
- Cyanidation;
- Filtration;
- Precipitation and smelting;
- Carbon-in-pulp (CIP) process.

During the first process, the coarse and dense particles recovered at the bottom outlet of the hydrocyclone are gravity concentrated to separate coarse gold and pyrite from the remaining ore material. Thereafter, the concentrates gold and pyrite are refined by amalgamation with mercury (Hg) or by treatment with a strong cyanide solution. These days coarse gold is recovered by means of corduroy tables – the amalgam method has not been used for the last 20-30 years.

The fine material from the top outlet of the hydrocyclone, or overflow, has to be thickened by adding lime and organic compounds as flocculants (Funke, 1990). The amount of lime added to the slime (or slurry) ranges from 0.75 to 1.5 kg/t to maintain an alkalinity between 0.010 and 0.25 per cent CaO (Adamson, 1973). Subsequently, the thickened slime is pumped to the cyanidation tanks, where approximately 0.15 kg NaCN/t (or KCN) is added to dissolve the gold (Funke, 1990). In addition, compressed air is passed through the slurry to provide oxygen, which is required for the dissolution reaction:

$$4\,Au + 8\,NaCN + O_2 + 2\,H_2O \rightarrow 4\,NaAu(CN)_2 + 4\,NaOH \qquad [2.1]$$

Cyanide is consumed during agitation by the decomposition products of pyrite and the presence of CO_2 contained in the compressed air. The total air-agitation for the maximum dissolution of gold varies from 15 to 45 hours, depending on (after Funke, 1990):

- Grain size of the free gold particles;
- Degree of pyrite encasement;
- Consistency of slime grading.

Filters currently achieve separation of the gold-cyanide solution from slime. As a result of lime added to the cyanide solution, $CaCO_3$ precipitates due to the reaction with CO_2 in the interstices of the filter cloth, leading to a gradual reduction of the filtration rate (Adamson, 1973). The precipitation of gold from the filtered cyanide solution is achieved by the reaction with zinc dust and the addition of small quantities of lead nitrate, which is not shown in the reaction below. The chemical reaction of the precipitation of gold from the cyanide solution can be expressed by the reaction:

$$Zn + 2\,NaAu(CN)_2 \rightarrow Na_2Zn(CN)_4 + 2\,Au \qquad [2.2]$$

The zinc-lead gold precipitate is subsequently removed from the solution by filter presses. The precipitation product or cake in the filters is passed to an acid vat where sulphuric acid is added to dissolve excess zinc and other soluble constituents. After dewatering, the slime is roasted by calcining at approximately 600° C and is then smelted in electrode arc furnaces between 1200 and 1300° C for a period of about two hours. Finally, the recovered gold is transported in bars to the refinery plant.

The carbon-in-pulp process is applied to recover gold directly from the cyanide leached slime by adsorption onto granular activated carbon. The gold-loaded carbon is separated from the slimes by screening and is then eluted with hot NaCN under pressure to achieve a gold-containing solution. The gold can be recovered by either direct electro-winning cells or by zinc precipitation and subsequent smelting. Due to the smaller volumes used by this approach, financial savings are considerable (Funke, 1990).

Large quantities of sulphuric acid are required for the extraction of uranium from gold plant residues. Pyrite is recovered from some ore as a by-product to produce sulphuric acid. For this process, copper sulphate ($CuSO_4$) is essential for the successful froth flotation of pyrite by means of a collector (xanthate) and a phosphate containing frother (Aerofloat 25) according to Adamson (1973). In such cases the pyrite content in the tailings will be reduced, whereas the Cu and phosphates contents will be increased. In contrast to the recovery of gold by cyanide, complete dissolution of uranium is achieved by oxidizing agents such as MnO_2 (until about 1970) or ferric sulphate (since about 1970), the latter being produced by bacterial oxidation of ferrous sulphate. The MnO_2 would cause an increase of $MnSO_4$ in the tailings.

In summary, a variety of substances such as Hg, Ca, Cu, Zn, Pb, Mn, phosphate and NaCN are introduced during the gold and uranium recovery process, so that the tailings contain higher values of these substances than the original ore.

2.5 MANAGEMENT AND RECLAMATION OF TAILINGS DAMS IN SOUTH AFRICA

2.5.1 Introduction

In most cases the basic requirements of a tailings facility are to store the tailings in such a way that the impoundment structure remains stable, has little impact on local residents and the environment, and the tailings dam can be rehabilitated once the mine is closed. The main short and long-term impacts associated with tailings storage are:

1. Soil and water pollution (including groundwater);
2. Dam safety and stability;
3. Air pollution by dust;
4. Visual or aesthetic impact;
5. Reclamation and rehabilitation.

It should be noted that already in the in the early days of gold recovery in the Witwatersrand, a variety of methods existed for the construction of slimes dams or tailings dams, particularly with respect to slope angles, width of dam walls, rate of deposition and final height. Since the 1960s practically all new dams have been constructed in accordance with recommendations of G.W. Donaldson (outlined in Adamson, 1973), who conducted studies on the geotechnical stability of slimes dams. In 1968, the Chamber of Mines published *The Code of Practice for the construction of slimes dams and the condition in which they should be left at the time of closure*, mainly based on the findings of Donaldson.

As a result of the Merriespruit disaster in February 1994, where a tailings dam collapsed, killing and injuring residents nearby a suburb of Virginia (Free State Province), the Department of Minerals and Energy took an initiative to improve existing guidelines for the construction, operation and rehabilitation and thus, appropriate environmental management, of mine residue deposits. Thus, a new *Code of Practice for Mine Residue Deposits* has been developed in collaboration with the South African Bureau of Standards (1997) and various specialists of the mining industry and consulting firms. The Code is not restricted to the safety and stability of mine residue deposits but also includes environmental aspects such as:

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

This Code provides mining companies with guidance to ensure good practice in the various stages of the life cycle of tailings dams. In addition, current legislation requires from all mining companies to publish regular *Environmental Management Programme Reports* on all mining operations potentially affecting the environment during the life time of a mine, including tailings dams. The construction, operation, decommissioning and reclamation of tailings dams in the view of legal aspects is extensively discussed in Cogho et al. (1992), Fuggle & Rabie (1992), Richter (1993), and Wates et al. (1997).

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 three categories:

- Waste rock dumps consisting of coarse-grained low-grade or barren country rock, the processing of which for the recovery of gold is not economically viable (Daniel, 1993). Rock dump material is usable as construction material for infrastructure such as roads.
- Sand dumps were mechanically deposited in a wet state, reaching heights of up to 100 m above ground surface. 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 rapid generation of acid mine drainage. 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).

- Tailings dams (also termed slimes dams) are characterised as hydraulically constructed ring dyke impoundments. The particle size of tailings material is mainly < 75 μm. Hence, the oxidation of sulphide minerals (e.g. pyrite) is confined to a depth of a few metres below the surface of the impoundment. The solid to water ratio in the wet tailings varies from 1:1 for gold tailings up to 1:4.5 in tailings 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.

2.5.2 Construction

As stated above, since the 1960s, all mine residues from the gold, uranium and pyrite extraction process have been deposited hydraulically (water/solid ration ≥ 1) by using ring dyke impoundment systems. In these ring dyke impoundments (Figure 2.1), the tailings slurry is pumped to the inner dam wall during the daytime (so-called day-paddocks or outer paddocks), contained by a freeboard of about 1 m.

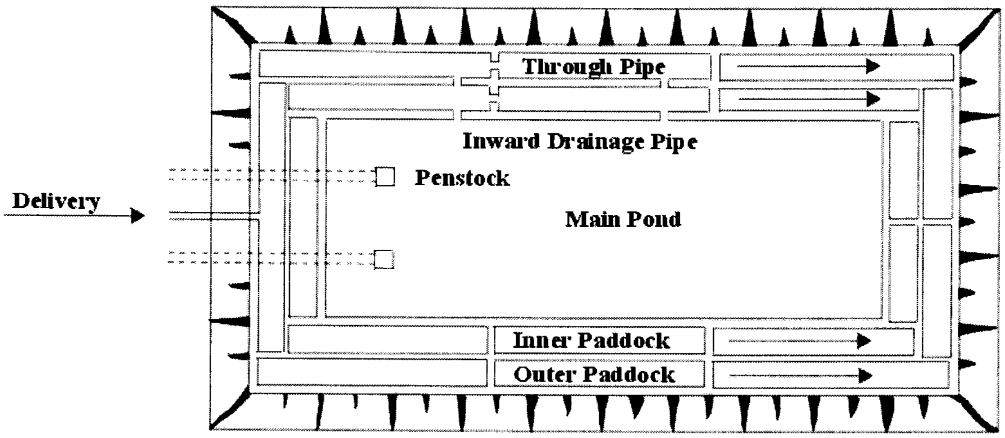


FIG. 2.1 - Typical layout of a tailings dam (after Adamson, 1973).

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 (or inner paddocks), where sedimentation of the fine tailings material takes place. 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/year, 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 1450 kg/m^3 and a cycle time in the day-paddocks of approximately two weeks (allowing for the desiccation, compaction and cracking of the slime to reduce the ratio between horizontal and vertical permeability).

A further approach is the cycloned deposition method (e.g. applied at study site I), which involves the separation of the coarser tailings material prior to the deposition, whereby the tailings are sprayed with a canon at high pressure into the pond of the impoundment. This type of deposition results in a zone of coarse solids relatively free of excess solution and a pool of solution including fine solids, which may not drain readily and, therefore, consolidate. Daniel (1993) reports that such cycloned operations require detailed planning and management if the system is to work properly and is extensively discussed in his textbook.

2.5.3 Operation and decommissioning

This study has shown that there is a total number of 272 gold mine tailings dams covering an area of about 181 km^2 in South Africa, of which most were decommissioned about 30 to 50 years ago (Funke, 1990). For comparison, according to the international study *Tailings Dam Incidents: 1980-1996*, it is assumed that there are a total of approximately 300 tailings dams in Canada, 400 in Australia and 500 in Zimbabwe (Mining Journal Research Services, 1996).

The tailings dam or pond remains almost saturated during the operational phase, as well as for some time after closure. This is mainly due to the particle size distribution (fine sand and coarse to medium silt) of gold mine tailings, which allows water retention by capillary forces. After the slurry deposition has been completed, the phreatic (line of zero pore water pressure) surface slowly subsides at a rate which depends on the conditions of the seepage collection system and the size of the impoundment. Reported subsidence of the phreatic surface is generally about 0.3 m/year (Blight & Du Preez, 1997).

Figure 2.2 shows the position of the phreatic surface within the dam wall during operation and after decommissioning (closure). It is important to note that the majority of tailings dams in South Africa were constructed without seepage collection systems.

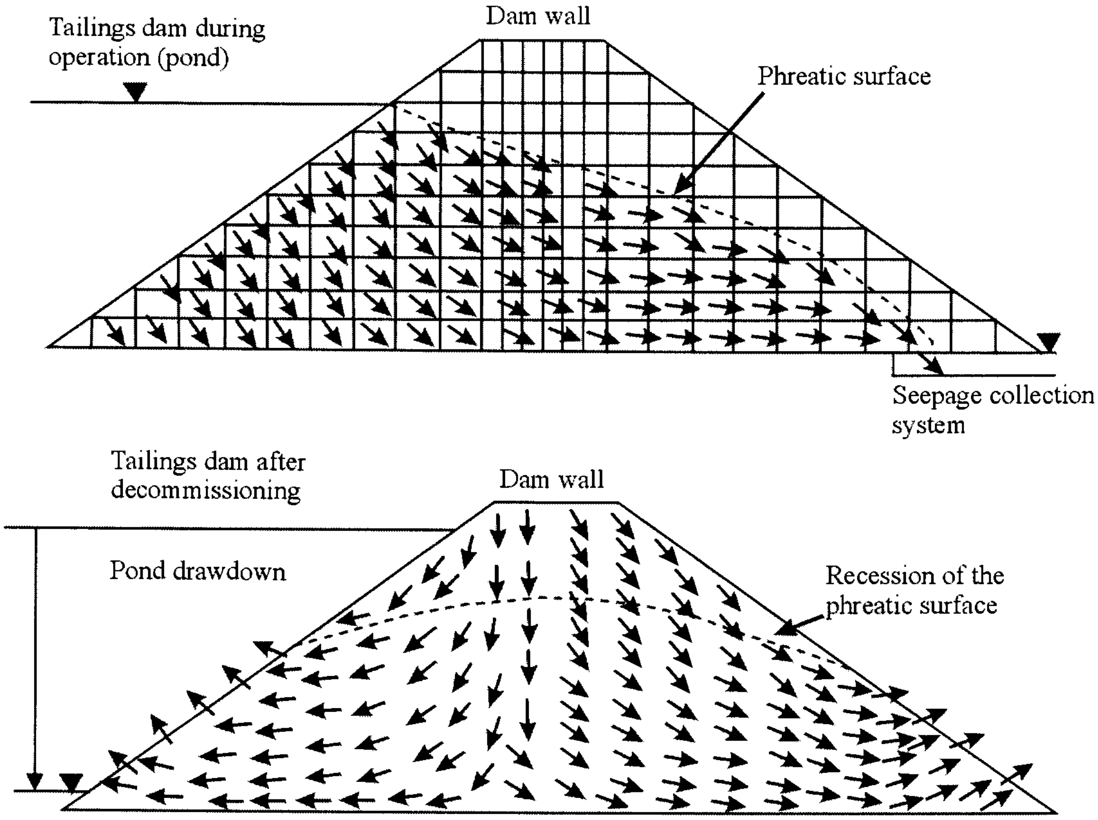


FIG. 2.2 - Position of the phreatic surface in a tailings dam during operation and after closure.

In hydraulically constructed tailings dams, the *anisotropy coefficient* or the ratio between horizontal and vertical permeability, is higher than in mechanically deposited and compacted dams, because the layered structure of hydraulically constructed tailings dams is enhanced due to compaction. The anisotropy coefficient is usually between 5 to 10, but can reach values of more than 200 in case of poor construction (Williams & Abadjiev, 1997). Various factors influence the anisotropy coefficient (after Fell et al., 1992):

- Height of pond water table;
- Beach grain size segregation;
- Foundation permeability;
- Decreasing tailings permeability with depth as a result of compaction;
- Underdrainage systems.

A high anisotropy coefficient of most of the tailings dams results in a high phreatic surface, which frequently leads to failure of the horizontal drain systems and seepage at the slope surface. In turn, the seepage at the slope surface causes erosion and results in a considerable risk increase regarding dam failure and contamination by acid mine drainage and associated contaminants.

Some tailings dams contain built-in horizontal drainage systems, which are ineffective, because the elevated phreatic surface cannot be effectively lowered. Common practices 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 is given in Williams & Abadjiev (1997).

2.5.3.1 Seepage and the development of a groundwater mound

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 during the construction phase of the tailings dam. Authors such as Van den Berg (1995); Rust, Van den Berg & Jacobsz (1995) and Wagener, Van den Berg & Jacobsz (1997) have described various approaches dealing with 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 dam wall;
- Through the foundation materials.

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

- Hydrogeological conditions of the impoundment foundation;
- Hydraulic conductivity of the tailings material;
- Hydraulic conductivity of the foundation;
- Geometry of the impoundment and dam wall;
- The design, construction and operation of the impoundment.

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

The concept of different zones of saturation has been utilised at tailings ponds to prevent seepage from reaching the water table. Seepage initially moves as an advancing wetting front downward under a hydraulic gradient. As Figure 2.3 illustrates, various saturation or moisture zones were identified (Ward & Robinson, 1990):

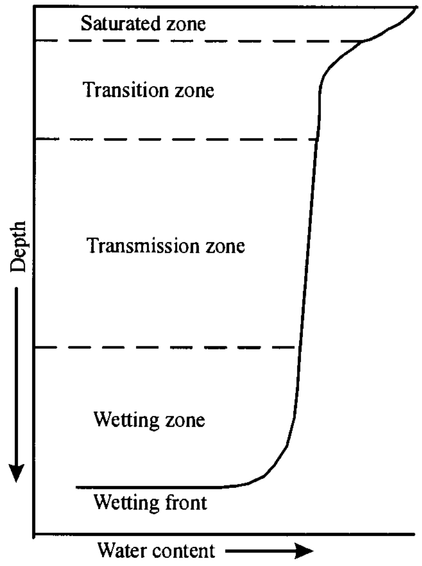


FIG. 2.3 - Saturation zones during ponded water infiltration (after Ward & Robinson, 1990).

The volume of seepage reaching the water table is less than that escaping from the impoundment, because some seepage is retained in the unsaturated zone.

However, this storage capacity within the unsaturated zone can only be used once, unless the adsorbed moisture is removed by evaporation and/or evapotranspiration. This will not normally occur underneath such an impoundment. It is more likely that the subsequent wetting fronts that arise from continued release of seepage or rainfall recharge will tend to displace rather than bypass the previously adsorbed seepage (Horton & Hawkins, 1965). However, the more continuous release of seepage allows dilution in the underlying aquifer. It should be emphasised that acidic seepage (i.e. AMD) may also remobilize contaminants which have been precipitated due to neutralisation of the initial seepage wetting front (Klippel & Hagarman, 1983).

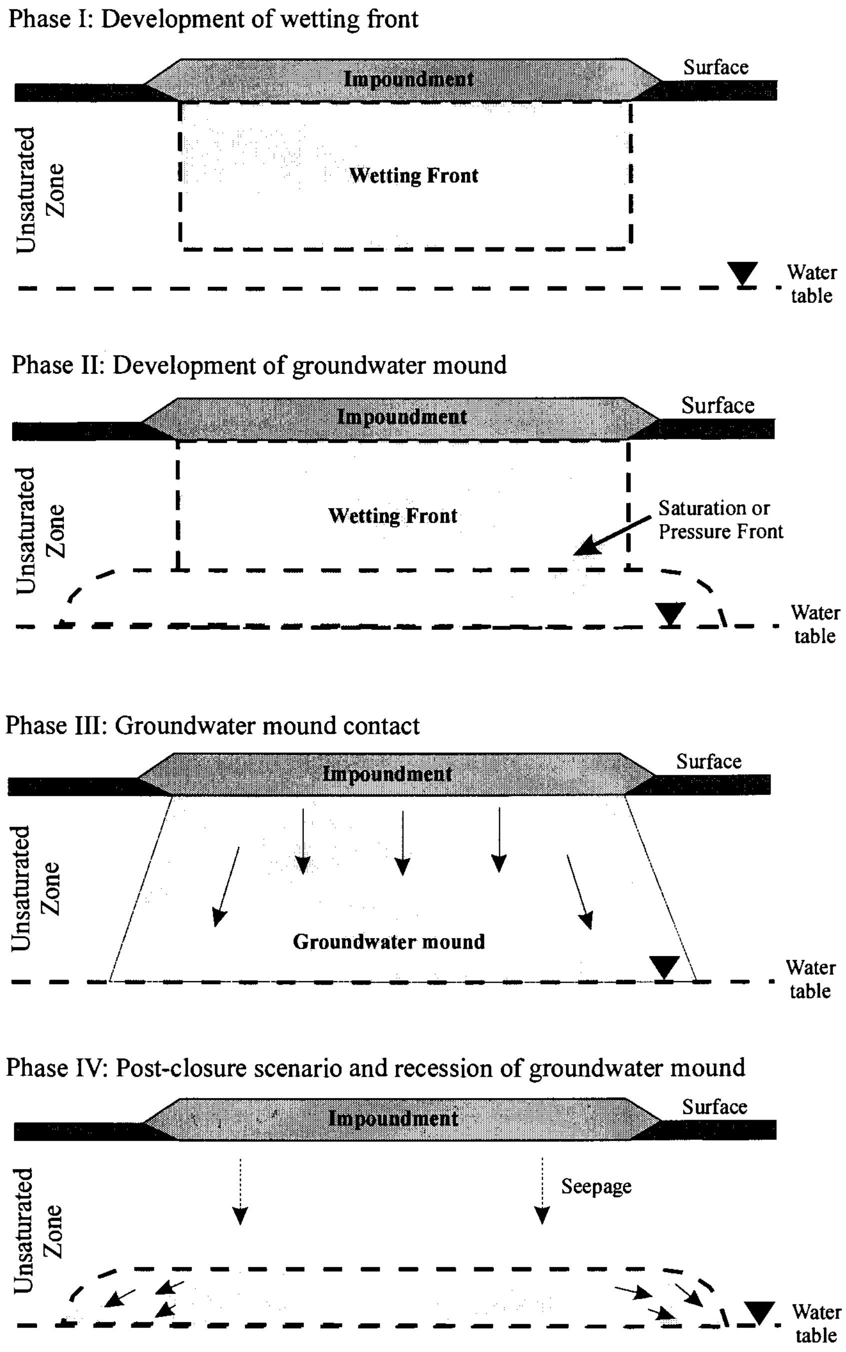
As a result, the moisture retention has to be taken into account during the design, construction, operation and decommissioning of tailings dams, when rainfall recharge is low (Martin & Koerner, 1984a). This is for example the case in the study area near

Johannesburg. A further problem is the development of a contaminated groundwater mound underneath an impoundment.

The development of a groundwater mound as a result of such wetting zones is a typical phenomenon in connection with the disposal of tailings slurry (solid-water ratio 1:1 to 1:4.5). When seepage rates change, unsteady or transient phases exist as the distribution of moisture and pressure within the unsaturated zone adjust to the new hydraulical loading (Martin & Koerner, 1984b). Increasing seepage rates will cause a wetting front to move from the pond towards the saturated zone (i.e. water table), leading to the formation of a groundwater mound (Figure 2.4).

The groundwater mound may eventually come into contact with the base (Phase III) of the pond or impoundment if the groundwater table is shallow or the permeability of the underlying aquifer is low. However, this might only occur after an extended period of time, because a considerable quantity of seepage is required to saturate the soil when the soil has a low initial moisture content or when the water table is deep. If the rate of seepage is limited, or the lifetime of the impoundment is short, then Phase III might never fully develop.

Therefore, it is necessary to investigate the first two transitional phases that precede development of continued saturation by seepage. In Phase I, a wetting front advances from the impoundment towards the water table. This front may be saturated or unsaturated, depending on whether the impoundment is lined or unprotected (no seepage control measures), and also whether air is freely displaced by the seepage. In Phase II, the positive pressure mound forms and rises. If the initial wetting front was saturated, this occurs rapidly, as a pressure wave moves up from the water table and changes the pressure conditions from positive to negative (suction). In contrast, if the initial wetting front was unsaturated, a further delay of Phase III occurs as continued seepage is diverted to form the rising groundwater mound. A post-closure scenario with decrease in seepage escape from the impoundment will result in desaturation and the recession of the groundwater mound as shown in Phase IV (Martin & Koerner, 1984b).


Phase I: Development of wetting front

Phase II: Development of groundwater mound

Phase III: Groundwater mound contact

Phase IV: Post-closure scenario and recession of groundwater mound

FIG. 2.4 - Development of groundwater mound underneath an impoundment (after Martin & Koerner, 1984b).

2.5.3.2 Seepage control measures

Typical pollution control measures at tailings dams are:

- Toe dams;
- Penstock systems;
- Drain or seepage collection systems.

Toe dams 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 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 (Steffen, Robertson & Kirsten, 1988).

In the past, so-called paddocks were used at reclaimed sites in South Africa to prevent surface run-off from entering streams, dams and other reservoirs. Paddocks consist of low slurry dam walls (approximately 1-2 m height), which are build in squares of a few metres diameter in order to capture rainwater on site to prevent surface-run-off. However, the use of paddocks increases the infiltration rate into the subsurface and, therefore enhances the dispersion of contamination in soils and groundwater underneath the site.

2.5.4 Reclamation

In the 1970s, various mining companies started to reclaim tailings. The recovered tailings material is reprocessed to extract gold, which may be present in economically viable quantities (currently 0.4 g Au/ton according to Creamer, 1998). A common reclamation approach is jetting the tailings dam with high pressure water, thereby liquefying the slime. The slime then drains to the pump station, from where it is pumped to the processing plant.

Approximately 70 tailings dams have been reclaimed in the Gauteng Province, resulting in nearly 13 km^2 of land becoming available for potential development (Rösner, Boer, Reyneke, Aucamp & Vermaak, 1998). Most of the reprocessed tailings material has been disposed onto large dams close to Brakpan in the East Rand.

The author found that for the majority of the investigated sites the tailings material was incompletely reclaimed and significant quantities of residual tailings remained on the sites. Such sites or areas are often devoid of any vegetation or show only a poor vegetation cover and are also known as *abandoned mined lands* (Sutton & Dick, 1984).

Owing to the inadequate vegetation cover on these abandoned mine lands, the combined effects of acid mine drainage and excessive erosion often occur, causing major environmental problems. The EPA (1976) reported that the erosion rate is approximately 100 times higher for such abandoned mined lands compared to similarly located forest lands.

2.5.5 Land use after reclamation

The need for development of low-cost housing in highly urbanised areas such as near Johannesburg 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, in order to enable a safe future land use.

2.6 HYDROGEOCHEMICAL PROCESSES DURING THE WEATHERING PROCESS OF TAILINGS

Acid mine drainage is the main environmental effect of mining operations where a sulphide-bearing ore is processed. Acid mine drainage is characterised by low pH and often contains high concentrations of dissolved heavy metals and salts which exceed drinking water standards up to a toxic level. In addition, the gold-bearing conglomerates of the Witwatersrand Basin contain radioactive minerals such as uraninite (Adamson, 1973), resulting in elevated concentrations of uranium and its daughter products in the tailings (De Jesus et al., 1987).

The first studies dealing with acid mine drainage processes were conducted in the early 1980s at Elliot Lake in Canada (Cherry, Blackport, Dubrosvsky, Gilham, Lim, Morin, Murray, Reardon & Smith, 1980; Blair, Cherry, Lim & Vivyurka, 1980; Morin, 1983; Blowes, 1983; Dubrosvsky, Cherry, Reardon & Vivyurka, 1984a; Dubrosvsky, Morin, Cherry & Smyth, 1984b; Dubrosvsky, 1986; Morin, Cherry, Dave, Lim & Vivyurka, 1988a and Morin, Cherry, Nand, Lim & Vivyurka 1988b). Since then many researchers world-wide have focussed on the processes and environmental impacts related to acid mine drainage and associated contaminants.

The processes that generate acid mine drainage are natural, but they are enhanced by mining operations and can produce large quantities of contaminated seepage. Acid mine drainage originates from the rapid oxidation of sulphide minerals such as pyrite and 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 and the residues of mining operations, known as tailings. Although the knowledge about the acid generating process is limited, several influencing parameters are known to control the production of acid mine drainage 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 and geochemical 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, and the metallurgical processing.

2.6.1 Sulphide oxidation and acid generation processes

The release and migration of potentially toxic heavy metals and radionuclides strongly depend on the acidification process of tailings and soils. The low pH results from the oxidation of sulphide minerals in the unsaturated zone of the tailings dams.

Ferguson & Erickson (1988) classify and describe the factors controlling acid mine drainage 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.

2.6.1.1 Primary factors

The primary factors comprise the availability of sulphide minerals such as pyrite, oxygen, water, 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:

$$FeS_2(s) + 7/2\ O_2 + H_2O \Rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \qquad [2.3]$$

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+} by:

$$Fe^{2+} + \frac{1}{4}\ O_2 + H^+ \Rightarrow Fe^{3+} + \frac{1}{2}\ H_2O \qquad [2.4]$$

The Fe^{3+} resulting from Reaction 2.4 may react to further oxidise pyrite:

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \Rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \qquad [2.5]$$

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

$$Fe^{3+} + 3\ H_2O \Leftrightarrow Fe(OH)_3 + 3\ H^+ \qquad [2.6]$$

The sequence of reactions above 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 [$Fe_{10}O_{15} \cdot 9\ H_2O$], 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 colloidal Fe and Mn co-precipitates can adsorb significant amounts of heavy metals such as Co, Cr, Cu, Mn, Ni, Mo, V and Zn (Alloway, 1995). Furthermore, these relatively slow reactions comprise the initial stage in the three-stage acid mine drainage production process described by Kleinmann, Crerar & Pacelli (1981):

Stage 1: pH around the tailings particles is moderately acidic (pH > 4.5).
Stage 2: pH declines and the rate of Fe hydrolysis 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.

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.

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 acid mine drainage process only occurs when the micro-organisms become established, which requires a certain biogeochemical 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 of *Thiobacilli* (Kölling, 1990).

The bacteria mentioned above can attack most sulphide minerals under suitable conditions (Duncan & Bruynesteyn, 1971 and Lundgren, Vestal & Tabita, 1972) and increase the oxidation rate up to several orders of magnitude (Singer & Stumm, 1970; Silver, 1987 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 acid mine drainage, 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, Smith & Shumate (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) 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 Silver (1987):

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

Sulphide minerals often contain significant concentrations of various toxic heavy metals (Table 2.5), which have initially been used to establish genetic relationships among different ore types (Vaughan & Craig, 1978) and as an indicator to trace pollution caused by acid mine drainage.

2.6.1.2 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 formed acids (also known as *liming* if added to acid soils to increase the soil pH). The reaction, where acid produced by the oxidation of pyrite is neutralised by calcite can be expressed as (after Williams, Rose, Parizek & Waters, 1982):

$$FeS_2(s) + 2\ CaCO_3(s) + 15/4\ O_2(g) + 3/2\ H_2O \Rightarrow \qquad [2.7]$$
$$Fe(OH)_3(s) + 2\ SO_4^{2-} + 2\ Ca^{2+} + 2\ CO_2(g)$$

As a result of Reactions 2.3 to 2.6 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).

According to Reaction 2.7 two mols of $CaCO_3$ equivalent to 200 g are required to neutralise one mole of pyrite or 64 g of S. However, this reaction assumes that gaseous carbon dioxide (CO_2) will entirely exsolve, and may underestimate the fact that some CO_2 will dissolve and contribute to the acid potential of the solution. As a result, Cravotta, Brady, Smith & Beam (1990) modified the reaction to demonstrate the maximum acid potential:

$$FeS_2(s) + 4\ CaCO_3(s) + 15/4\ O_2(g) + 7/2\ H_2O \Rightarrow Fe(OH)_3(s) + 2\ SO_4^{2-} + 4\ Ca^{2+} + 4\ HCO_3^- \qquad [2.8]$$

In this reaction, four moles of $CaCO_3$ are required to neutralise the acids produced by the oxidation of one mole of pyrite. On average, the Witwatersrand gold-bearing quartz conglomerates contain 30-50 kg pyrite per ton (Hallbauer, 1986). Consequently, about 134 kg of lime ($CaCO_3$) is required to neutralise 40 kg of pyrite, containing about 21 kg of S in one ton of the mined ore.

The rapid equilibrium controlled dissolution of carbonate minerals (Reactions 2.7 and 2.8) results in a decrease of the acid potential, which is controlled by four key parameters:

1. Partial pressure of CO_2;
2. Temperature;
3. Mineral type;
4. Concentration of dissolved constituents.

The reaction rate of the interaction between sulphide and carbonate minerals determines the seepage water quality and consequently the soil quality, which can range from high pH and low sulphate concentrations in carbonate dominated materials to low pH (pH ≈ 2-3) and high sulphate concentrations (> 1000 mg/l) in a carbonate-deficient environment (Caruccio, 1968).

Other secondary factors comprise the weathering of oxidation products by further reactions. This includes ion exchange onto clay minerals, the precipitation of gypsum

($CaSO_4 \cdot 2 H_2O$, Figure E.12), and the acid-induced dissolution of other minerals. Ferguson & Erickson (1988) found that these reactions change the quality of seepage, often by adding various other elements (e.g. Al, Mn, Cu, Pb, Zn) and replacing Fe with Ca and Mg contained in carbonates.

2.6.1.3 Tertiary factors

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

Coarse-grained material is typically found in sand dumps 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 waste rock dumps, oxygen transport is supported by wind speed, changes in barometric pressure and internal dump heating originating from the exo-thermal oxidation reaction.

Another aspect is the physical weathering tendency 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, Cherry & Reardon, 1988 and Mills, 1993), Europe (e.g. Ferguson & Erickson, 1988; Mende & Mocker, 1995) and South Africa (e.g. Förstner & Wittmann, 1976 and 1981; Steffen, Robertson & Kirsten, 1988; Funke, 1990 and Cogho et al., 1992) has clearly shown that, even decades after decommissioning of mining operations, significant loads of salts, heavy metals and in some cases radionuclides are released from such deposits, unless appropriate pollution control and rehabilitation measures (e.g. cover and/or drainage systems) have been taken place.

A further tertiary factor is the pore water flow throughout the tailings dam. Significant acid generation within the saturated zone may not occur because of a limited oxygen flux (Ferguson & Erickson, 1988). However, a fluctuating phreatic surface level within the tailings dam, which is particularly common in operating tailings dams and may occur even after decommissioning 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 waste 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).

2.6.1.4 Subsurface and 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 tailings dam.

Ferguson & Erickson (1988) reported that the dissolved oxygen content and pH of the water may decrease downstream from tailings dams as a result of dilution effects and the presence of acid neutralising minerals in the riverbed. Further reactions with carbonates rise the pH in the water to 7-8. While most of the metals will precipitate under these pH conditions, salts such as calcium sulphate ($PbSO_4$, $RaSO_4$ and $BaSO_4$ are virtually insoluble) remain dissolved in the aqueous phase.

2.6.1.5 Further geochemical aspects

The phase diagram in Figure 2.5a illustrates the Eh and pH stability fields for some common aquatic environments. Figure 2.5b shows the stability relationships between iron oxides, sulphides and carbonates in the aqueous phase under variable Eh and pH conditions (after Garrels & Christ, 1965).

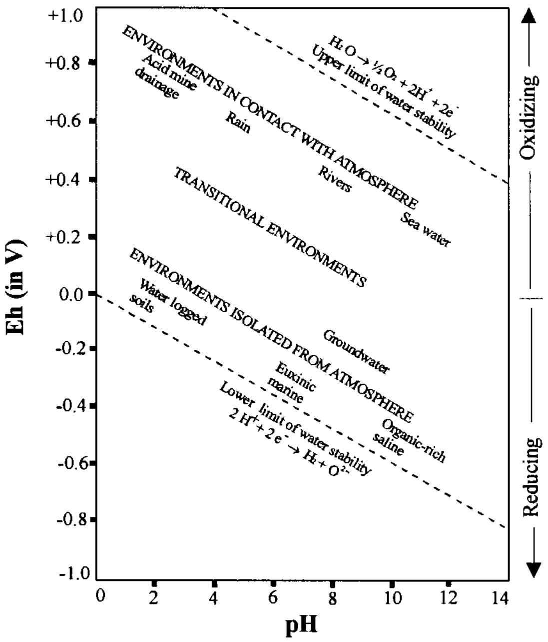


FIG. 2.5a

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

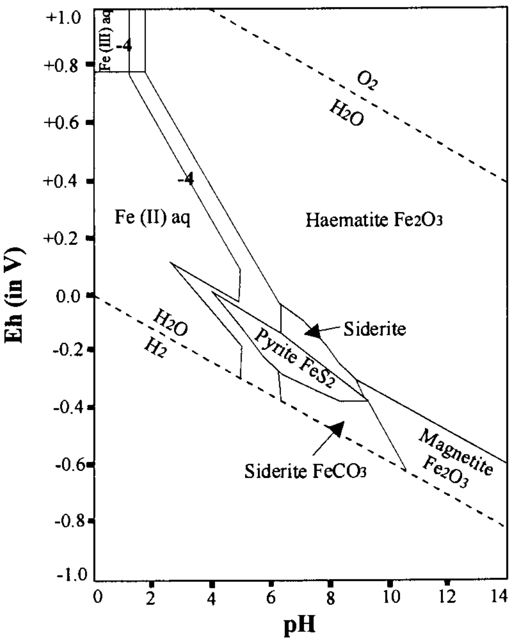


FIG. 2.5b

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).

In the view of Figure 2.5b, above four different types of reactions can be derived:

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

$$2\ Fe^{3+}(aq) + 3\ H_2O(l) \Rightarrow Fe_2O_3(s) + 6\ H^+ \qquad [2.9]$$

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

$$Fe^{2+}(aq) \Rightarrow Fe^{3+}(aq) + e^- \qquad [2.10]$$

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

$$2Fe^{2+}(aq) + 3H_2O(l) \Rightarrow Fe_2O_3(s) + 6H^+(aq) + 2e^- \qquad [2.11]$$

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:

$$Fe^{2+}(aq) + CO_2(g) + H_2O(l) \Rightarrow FeCO_3(s) + 2H^+(aq) \qquad [2.12]$$

Iron is stable as Fe^{2+} and Fe^{3+} under acidic conditions, 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 conditions. 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 Figure 2.5b that relatively small shifts in Eh or pH can have a major effect on the solubility of Fe. Thus, when pyrite is exposed to oxygenated water, Fe will be readily dissolved. This fact is of major importance to the formation of acid mine drainage from tailings.

It can be concluded that solubility and mobility of trace elements are controlled by four main influence parameters, according to Förstner & Kersten (1988):

- Decrease in pH - acidity poses problems in all aspects of metal mobilisation 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). In South Africas mining areas, acid mine drainage 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. It can expected that changes from reducing to oxidising conditions, which involve oxidation of sulphides and subsequently a shift to more acid conditions, will increase the mobility of typical chalcophilic[3] elements such as Cu, Pb and Zn.
- Increased occurrence of natural and synthetic complexing agents - can form soluble metal complexes with trace elements that would usually be adsorbed to solid matter.

The predominance of simple mineral solution equilibria explains the concentrations of major elements in the surface environment, but the hydrogeochemical properties of many trace elements are more complex and are also determined by other factors such as co-precipitation, sorption effects and interaction with organic matter.

2.7 OCCURRENCE OF TRACE ELEMENTS IN SOIL AND ITS TOXICITY

2.7.1 Occurrence of trace elements in soil

Climatic and soil factors influence the speciation and mobility gradient of trace elements such as heavy metals in soils, and therefore control their bio-availability (Kabata-Pendias, 1984). However, total trace element concentrations in a soil are a poor reflection of trace element bio-availability (Pierzynski, Sims & Vance, 1994) where the bio-available fraction refers only to a certain portion of the total trace element concentration. Trace elements occur in different adsorbing phases in soils and these phases can be investigated by performing special leaching tests such as sequential extraction tests. The following adsorbing phases are distinguished for trace elements, i.e. Cd, Cu, Cr, Ni, Pb, and Zn (after Kabata-Pendias, 1994) and an example is illustrated in Figure 2.6:

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[3] Chalcophilic elements are elements with a strong affinity for sulphur, characterised by sulphide ore minerals such as pyrite. Examples are: As, Fe, Cd, Cu, S, Se, Pb, Zn (Whitten & Brooks, 1972).

- Easily soluble phase and exchangeable phase (e.g. soluble in NH_4NO_3 according to Umweltbundesamt, 1996);
- Bound to organic matter and to colloidal oxides of Fe and Mn (e.g. soluble in HCl according to Umweltbundesamt, 1996);
- Residual fraction or bound to silicates (only soluble in hot HNO_3 conc. or other very strong acids, according to Förstner, 1989).

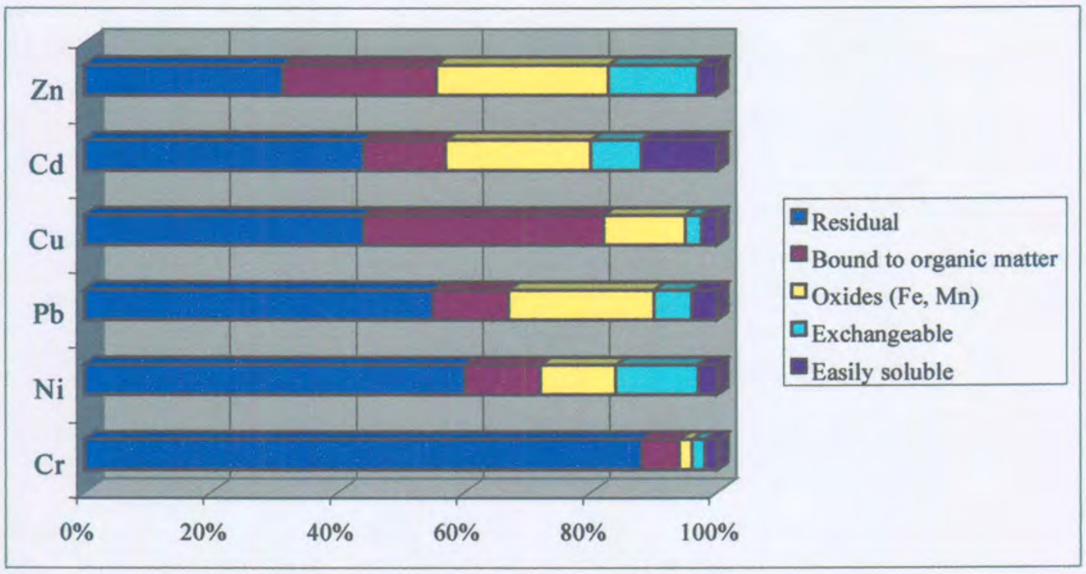

FIG. 2.6 - Speciation of trace elements in a podzolic loamy sand soil (in percentage of the total content), after Kabata-Pendias (1994).

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 potential bio-availability of a trace element.

The actual mobility of contaminants is also determined by the pH, redox conditions and the presence of other ions, dissolved organic matter and clays. In the unsaturated and saturated zones, the most important sorption and/or exchange process is reflected by adsorption of ions on mineral surfaces (Lloyd & Heathcote, 1985) and organic material surfaces. Sorption and exchange processes are limited by the sorption or exchange capacity of the solid phase. Solids such as clay minerals (e.g. kaolinite), organic matter and oxides/hydroxides (e.g. ferricrete) have a certain exchange capacity for cations and anions. However, the cation exchange capacity of kaolinite is very low if compared to other clay minerals such as montmorillonite or vermiculite (Table 3.5).

For example, the soil organic matter content can account for 20-70 per cent of the cation exchange capacity of soils (Pierzynski et al., 1994). However, it must be stressed that the highly weathered soils of the study area generally contain negligible contents of organic matter compared to soils of humid regions, and, thus, have generally a low contaminant retention capacity[4]. The organic matter content depends on various factors such as soil type and structure, water holding capacity, nutrient availability and soil pH.

Alternatively for the estimation of bio-availability, a transfer coefficient is available, referring to the contaminant (mostly metals) concentration in the plant relative to the total concentration in the soil. It should be noted that chemical plant analysis was not conducted in this study as a result of a very poor vegetation cover for most of the sites. Alloway & Ayres (1996) presented generalised transfer coefficients for the soil-plant system, which are listed in Table 2.7.

TABLE 2.7 - Transfer coefficients of metals in the soil-plant system (after Alloway & Ayres, 1996).

Element	**Transfer Coefficient**
As	0.01-0.1
Cd	1-10
Co	0.01-0.1
Cr	0.01-0.1
Cu	0.01-0.1
Hg	0.1-1
Ni	0.1-1
Pb	0.01-0.1
Se	0.1-10
Zn	1-10

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[4] The typical range of organic matter in agricultural soils varies generally between 1.5-4 per cent (dry weight), where about 58 per cent of the organic matter is accounted for organic carbon (Scheffer-Schachtschabel, 1984).

The transfer coefficients are based on root uptake of metals, but it should be realised that plants can accumulate relatively large amounts of metals by foliar adsorption of atmospheric deposition on plant leaves. In addition, soil pH, organic matter content and plant genotype can have significant effects on metal uptake. From Table 2.7 it is evident that Cd, Se and Zn have the highest transfer coefficients (maximum accumulation by a factor of 10), which is a reflection of their relatively poor sorption in the soil. In contrast, metals such as Cu, Co, Cr and Pb have low coefficients because they are usually strongly bound to soil colloids (Alloway & Ayres, 1996).

2.7.2 Toxicity

Substances are defined as toxicants if they show harmful effects to living organisms (Moore & Ramamoorthy, 1984 and Morel & Hering, 1993). Environmental data in relation to hazards for man, animals and plants should be interpreted in terms of bio-availability, i.e. an indication of how easily contaminants could become incorporated into living organisms via various pathways such as air, water and solids.

There are two primary reasons for concern about elevated concentrations of trace elements in soils and the aquatic system. Firstly, increased human and animal exposure to the contaminants can occur through food chain transfer, ingestion of wind-blown dust, or direct ingestion of affected soil or water. A study in the USA has shown that persons living downwind of an old smelter site could consume at least 50 per cent more Pb and Cd by eating some of their home-produced food items than by eating comparable items, purchased in a control area (Laegerwerff & Brower, 1974).

The second reason for concern relates to the phytotoxic potential of certain trace elements, which can limit biomass production. This inhibition of plant growth can have direct negative effects, such as the limitation of crop yields. A poor vegetation cover due to phytotoxic effects of trace elements results in a higher erosion rate by wind and water, which further disperses the contaminants and increases the probability of human exposure via wind-blown dusts (Pierzynski et al., 1994). In addition, poorly vegetated soils in fairly flat areas are generally characterised by increased rainfall recharge, resulting in groundwater pollution and leaching of nutrients, thus a reduction of soil fertility. Acid soil conditions such as those within the study area would allow only acid-tolerant plants to survive. A list with seeds and plants usable for revegetation is provided in Adamson (1973).

The most phytotoxic metals for both plants and several micro-organisms are Hg, Cu, Ni, Pb, Co, Cd, and possibly Ag, Be and Sn (Kabata-Pendias, 1994), but it depends on soil parameters such as soil pH, the plant species and growing conditions.

2.7.3 Environmental quality standards

Soil and groundwater protection is an international concern. Particularly in South Africa where the predicted shortage of surface water resources to meet future demands and the growing costs of developing these resources suggest that groundwater resources could contribute to the national water supply more significantly, either in association with surface water resources or as a sole source. Due to the irreversible deterioration of soils by persistent contaminants and physical erosion, policymakers and scientists in many countries are beginning to realise that the soil environment in particular is a limited resource. Therefore a number of countries and international institutions have developed policies to protect their soils generically, or dependent on land use.

Until recently a classification system for contamination was used for soils which comprised three indicative values: (A) the normal reference value; (B) the test value to determine the need for further investigations; and (C) the intervention value above which the soil definitely would require clean-up. This system has been superseded by a health risk-based protocol, namely the *Environmental Quality Standards for Soil and Water* or *Dutch List* (Netherlands Ministry of Housing, Physical Planning and Environment, 1997). The *Dutch List* is accepted throughout the European Union. These standards are based on ecological functions and comprise *target* and *intervention values* for soils and are summarised in Table 2.8. All limits are valid for a standard soil, consisting of 25 per cent clay and 10 per cent humus. The target value is the maximum permissible content of selected metals (total concentration) in soils with no risk for humans, plants, animals and ecological systems. Concentrations above the target value would require further site investigations, whereas the intervention value implies a significant risk and if exceeded, would require remedial measures (Alloway & Ayres, 1996).

TABLE 2.8 - Soil quality standards according to the Dutch List (Netherlands Ministry of Housing, Physical Planning and Environment, 1997).

Soil quality standards	**As**	**Co**	**Cr**	**Cu**	**Mo**	**Ni**	**Pb**	**Zn**
Target value (mg/kg)	29	20	100	36	10	35	85	140
Intervention value (mg/kg)	55	240	380	380	200	210	530	720

The type and extent of remediation is dependent not only on the toxic properties of the contaminant itself, but also on the proposed land use and potential groundwater vulnerability. As a consequence only the findings of an overall site assessment would identify an appropriate remediation strategy. It is important to emphasise that currently no standardised soil quality goals are available in South Africa.

A comparison of averaged soil background concentrations of the study area with the Dutch List revealed that Cr, Mo and Ni exceed the target value, indicating highly mineralised soils rather than pollution. If the Dutch List is compared with the 75th percentile value of trace element concentrations in soils of the study sites (i.e. sites A-G, Table 5.2) it was found that all trace element contents were below the intervention value, but As (sites A and G), Co (all sites except site A), Cr (all sites), Cu (all sites), Ni (all sites) are higher than the target value. In addition, if the Dutch List is compared with maximum trace element concentrations in soils of the study area, the metals As (sites A, D, F and G), Co (site D), Cr (sites A, B, C and E), Ni (sites B, C, and F) exceed the intervention value.

There are further quality standards available for soils, e.g. for the UK from the Department of the Environment Interdepartmental Committee for the Reclamation of Contaminated Land (Young, Pollard & Crowcroft, 1998), which published a list of trigger concentrations for contaminants. These standards are more pragmatic and based mainly on the risk to human health. A similar system has also been developed by the Canadian Council of Ministers of the Environment in 1991 with *The National Classification List for Contaminated Soils*, providing maximum contaminant levels for pristine (background values), agricultural, residential and industrial land.

In this context, Table C.1 (Appendix C) provides basic geochemical properties of elements of concern and is also supplemented with target water quality standards for drinking (domestic use) and irrigation (agricultural use) water, applied in South Africa by the DWAF. In case a South African water quality standard deviates from international standards, a further drinking water standard of the European Union (guideline EU 98/83/EG) is also given.

3 METHODS OF INVESTIGATION

3.1 SCOPE OF WORK

A literature study, which included a request for data from various mining companies, was undertaken in order to describe the contamination status at selected sites and assess various attenuation and migration mechanisms of contaminants from gold mining tailings and affected soils. All relevant information was entered into a database-linked geographic information system, which allows the evaluation and display of important features such as the spatial distribution of tailings dams, reclaimed sites, surface water systems, and residential and industrial areas. The map based on such a geographic information system, contains information gathered from topographical and geological maps and technical drawings provided by mining companies and a satellite image of the Johannesburg area (Figure E.13, Appendix E). Based on this information, a selection of appropriate sites was carried out. A total of eleven sites was identified as being suitable for the purposes of this study. Sampling was conducted at seven of the eleven sites in order to close gaps in the database. All the investigated sites were either partially or completely reclaimed for the recovery of gold, and are situated above Karoo or dolomitic aquifer systems. Therefore, the selected sites represent the most typical environmental conditions for tailings disposal sites in South Africa.

Furthermore, all sites are within one km of either residential areas or areas of agricultural land use. Most of the mine residue deposits have been present in the area for decades. The study area is situated in the Gauteng Province and stretches from Brakpan in the north to Springs in the south, with the exception of one site, being 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. Soil profiling to depths of 2.40 m was conducted and 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 from the 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 the study sites. This index comprises different contamination classes and thus, various risk levels for groundwater resources and land development.

3.2 FIELD SURVEY AND SITE INFORMATION

A total of 22 test pits (three per site, except at site F where four test pits were investigated) were excavated by means of a Schaeff backactor on a Mercedes Unimog truck (Figure E.8, Appendix E). The test pits were excavated 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 were taken at various depths: topsoil (< 30 cm depth) to water table or maximum test pit depth. Pedological conditions were described using the protocol of the Soil Classification Working Group (1991) and Jennings, Brink & Williams (1973). Soil profiles are presented in Appendix A.

Each site has been described according to site characteristics (e.g. area, geology, vegetation, reclamation status), geotechnical parameters, hydrogeological 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, ortho-photographs and a satellite image of the Johannesburg area.

Table 3.1 presents a summary of the selected tailings dam sites with important features such as geology, area and status of reclamation and rehabilitation.

TABLE 3.1 - Summary of site information for the investigated sites. Note that the period of deposition is unknown except study site I: 1977–1984.

Site	Type	Lithological units	Area ha	Reclamation status %	Period of reclamation	Environ. monitoring	Rehab. Measures
A	Slime	Vryheid F. Dwyka F.	50	50	Until 1996	n. a.	Paddocked
B	Slime	Dwyka F. Oaktree F.	47	90	Late 1980s	None	Paddocked
C	Slime	Dwyka F.	28	100	1977 – mid 1980s	None	All slime removed
D	Slime	Dwyka F.	71	100	1977 – mid 1980s	None	All slime removed
E	Slime	Dwyka F. Oaktree F.	70	90	Early 1990s	Surface water	Outstanding
F	Slime	Vryheid F. Dwyka F.	120	95	Late 1980s – early 1990s	None	Slime removal ongoing
G	Slime	Vryheid F.	13	95	1994 – 1995	None	Partly paddocked
H	Slime	Oaktree F.	4	100	1940s	Surface and groundwater	n. a.
I	Slime	Post-Karoo dolerites, Monte Christo / Oaktree F.	1400	30	1996	Surface and groundwater	Partly paddocked
J	Slime	Dwyka F.	117	85	1985 – present	Surface water	Partly paddocked
K	Slime	Karoo S., Malmani SG	111	15	Started in 1997	Surface and groundwater	n. a.

Note: Lithostratigraphical units are shown in Table 2.1. Reclamation status refers to the percentage volume of tailings removed. Abbreviations: F = Formation and SG = Subgroup and S = Supergroup.

Data are generally lacking for the period of deposition due to changing ownership of the sites.

3.3 SAMPLING AND LABORATORY TESTING

Soil samples were analysed for various chemical constituents in order to determine the degree of contamination. The following elements were measured in the fine grain size fraction: Fe_2O_3 (total), MnO, As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Rb, Th, U, V, Zn and Zr. The grain size fraction $< 75\ \mu m$ was chosen for total element analyses, since the majority of trace elements is concentrated in the clay-silt particle size range (Förstner & Kersten, 1988; Förstner, 1989; Labuschagne, Holdsworth & Stone, 1993). Geochemical element analyses of the solid phase were conducted using the simultaneous X-ray fluorescence spectrometry (XRF) technique. Trace and major element analyses on gold mine tailings were obtained from Rösner (1996), who selected five different tailings dams in the East Rand for sampling at various depths. Additionally, information on the geochemistry of tailings was supplemented with data from Adamson (1973) and Blight & Du Preez (1997). Soil extraction tests were conducted on a limited number of samples, generally characterised by high pollution loads. Subsequently, leachate samples were measured by means of inductively coupled plasma mass spectrometry (ICP-MS) with the exception of U, which was measured spectrophotometrically (as U_3O_8) after solvent extraction. Mineralogical analyses were carried out on a limited number of tailings samples by means of X-ray diffraction (XRD) and additional data for soils affected by gold mine tailings were provided by Joubert (1998).

Standard foundation tests were conducted on a large number of soil samples to determine the general geotechnical properties such as hydraulic conductivity and size of the clay fraction.

Standard quality control was applied during analytical testing (e.g. standards and blank samples, double-measurements). The accuracy or correctness of data obtained from other sources (e.g. mining companies) was estimated using the electro-neutrality (EN) equation, which is based on the percentage difference defined as follows (American Public Health Association, 1995):

$$EN(\%) = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \cdot 100 \qquad [3.1]$$

where cations and anions refer to equivalent concentrations. The sum (expressed as milliequivalents per litre) of positive and negative charges in water must balance and are calculated from the cations Na^+, K^+, Mg^{2+} and Ca^{2+}, and the anions Cl^-, HCO_3^-, SO_4^{2-} and NO_3^-. Results with deviations larger than 5 per cent would require an examination of sampling and analytical procedures (which is not possible for data obtained from other sources) and should be considered with caution.

Geochemical background values typical of pristine topsoils, overlying rocks of the Vryheid Formation (i.e. sandstone and shale) and Malmani Subgroup (i.e. dolomites) were obtained from Aucamp (1997) and Elsenbroek & Szczesniak (1997).

The various analytical tests conducted in this study are summarised in Table 3.2 and the methods are discussed in detail in the next paragraphs.

TABLE 3.2 - Summary of analytical tests applied in this study.

Number of samples	Tailings	Soil	Method	Testing facility
Total element analyses	36	81	X-ray fluorescence spectrometry (XRF)	University of Pretoria Council for Geoscience
Mineralogical composition	16	-	X-ray diffraction (XRD)	Council for Geoscience
Soil extraction tests	13	16	NH_4NO_3 / Inductively coupled plasma mass spectrometry (ICP-MS)	Council for Geoscience / Anglo American Research Laboratories
Soil paste pH	-	58	American Society for Testing Materials (1990)	Council for Geoscience
Geotechnical properties	-	59	Standard foundation tests	Council for Geoscience

3.3.1 X-ray fluorescence spectrometry (XRF)

The fine grain size fraction of 81 soil samples from the investigated sites were analysed using a Philips PW 1606 simultaneous XRF at the Council for Geoscience in Pretoria. Tailings samples were analysed by Rösner (1996) using the ARL 8420 wavelength dispersive XRF of the University of Pretoria. In addition, the trace elements As and Sn were determined at the University of Erlangen-Nürnberg (Germany) using the Philips PW 2400 XRF.

Samples were dried and roasted at 950°C to determine loss on ignition (LOI). Major element analyses were conducted on fused beads according to the description of Bennet & Oliver (1992), using 1 g of a pre-roasted sample and 6 g of a lithium-tetraborate flux mixed in a crucible (i.e. 5 per cent Au, 95 per cent Pt) and fused at 1050°C in a muffle furnace with occasional swirling. The glass disk is poured into a preheated Pt/Au mould and then bottom surface analysed. Trace elements were analysed on pressure powder pellets using a saturated Movial solution as binder. The spectrometer was calibrated with certified reference materials. A parameter program was used for matrix correction of major elements and Ba, Cl, Co, Cr, Sc, S and V.

Standard deviation and detection limits for major and trace elements are listed in the Tables 3.3a and 3.3b:

TABLE 3.3a - Detection limits and standard deviations for major elements using XRF technique (after Bennett & Oliver, 1992).

Major Element	Standard deviation	Detection limits %
SiO_2	0.4	0.02
TiO_2	0.03	0.0032
Al_2O_3	0.3	0.01
Fe_2O_3	0.3	0.0097
MnO	0.0065	0.0013
MgO	0.1	0.0118
CaO	0.07	0.01
Na_2O	0.11	0.0265
K_2O	0.06	0.005
P_2O_5	0.08	0.01
Cr_2O_3	0.0053	0.0006
NiO	0.01	0.0013
V_2O_5	0.0018	0.0008
ZrO_2	0.005	0.0009
CuO	0.0037	0.0003

TABLE 3.3b - Detection limits and standard deviations for trace elements using XRF technique (after Bennett & Oliver, 1992).

Trace Elements	Standard deviation	Detection limits mg/kg
As	n. a.	10
Ba	50	50
Cl	100	11
Cu	3	2
Cr	40	15
Ga	2	2
Mo	1	1
Nb	3	2
Ni	6	3
Pb	3	3
Rb	5	3
S (in %)	0.02	0.01
Sc	5	1
Sn	n. a.	2
Sr	4	3
Th	6	5
U	6	3
V	10	1
Y	3	3
Zn	5	4
Zr	6	10

3.3.2 Soil extraction tests and inductively coupled plasma mass spectrometry

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 (i.e. 1 M NH_4NO_3) were used to estimate the mobility of trace elements in the fine fractions (particle size < 75 μm) of soils.

The NH_4NO_3 soil extraction method is an accepted method in the Federal Environmental Agency of Germany for conducting hazard assessments (Umweltbundesamt, 1996), and is likely to become an internationally recognised soil leaching method for environmental studies. Schloemann (1994) and Utermann, Gäbler, Hindel, Kues, Mederer & Pluquet (1998) described the method in detail, where 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. The results of the soil extraction methods using salt solutions such as NH_4NO_3 can be correlated with the amount of ions held on charged soil surfaces (e.g. clays and organic material, oxides) and with 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, Turian & Schweikle (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 extractable elements in soils are listed in Table 3.12.

Steffen, Robertson and Kirsten (1988) reported that extraction tests are not necessarily representative of the quantities of trace elements that will be leached out of the deposits in a single rain storm, but only of the quantities which are potentially available.

3.3.2.1 Method for the soil extraction test

The NH_4NO_3 (1 Molar) extraction method according to Schloemann (1994) was applied and is described in the following:

1. Sieve the air-dried soil sample through a 75 µm nylon or stainless steel sieve and discard the coarse fraction.
2. Weigh out 20 g air-dried sieved soil into an acid cleaned 250 ml Erlenmeyer flasks.
3. Ad 50 ml NH_4NO_3 (1 mol/l NH_4NO_3) solution to the soil sample.
4. Closed Erlenmeyer flasks containing the soil and salt solution were shaken for 2 hours at 20 °C on a horizontal shaking table.
5. Filtrate supernatant solution through a 150 mm diameter Whatmann no. 40 ash-less filter paper into acid-cleaned 100 ml polyethylene bottles.
6. Stabilise the extract by adding 0.5 ml conc. HNO_3 (i.e. 65 per cent).
7. Determine trace elements except U by means of the ICP-MS. Uranium is determined spectrophotometrically as U_3O_8 after solvent extraction.

3.3.2.2 Inductively coupled plasma mass spectrometry (ICP-MS)

Leachate samples from extraction tests and seepage samples collected from shallow groundwater were analysed for trace elements using a FISON simultaneous ICP-MS at Anglo American Research Laboratories in Johannesburg.

The samples were poured in pre-cleaned polyethylen bottles, instantly acidified (i.e. diluted HNO_3) to prevent precipitation, and stored in a refrigerator. All samples were submitted to the laboratory within 24 h for analysis. The detection limits for the ICP-MS are listed in Table 3.4:

TABLE 3.4 - Detection limits for ICP-MS
(after Heinrichs & Herrmann, 1990).

Element	**Detection limit** µg/l
Fe	0.8
Mn	0.05
Al	0.2
As	0.5
Ca	5.0
Co	0.02
Cr	0.03
Cu	0.03
Na	0.05
Ni	0.03
Pb	0.03
Sn	0.04
Th	0.03
U	0.03*
V	0.04
Zn	0.09

Note: *U was measured spectrophotometrically (as U_3O_8) after solvent extraction.

3.3.3 X-ray diffraction (XRD)

The mineralogical composition of sixteen tailings samples was analysed using a Siemens D 5000 XRD at the Council for Geoscience in Pretoria. Results are semi-quantitative to ± 20 per cent or better, depending on the crystallinity of the mineral present and the sample preparation method. Detection limit for a mineral is 1-3 per cent depending on background noise and peak resolution of the diffractogram pattern, as well as sample preparation. The XRD is run with a secondary monochromator[5] and a copper X-ray tube ($\lambda = 1.54$ Å), which is appropriate for general sedimentological studies. Data evaluation was supported by using the software package *Diffrax Plus*.

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[5] The use of a secondary monochromator would reduce the fluorescence of a high Fe content with Cu radiation, decreasing the background noise, and thereby limiting the interference with mineral identification and percentage estimation.

For the purpose of this study, about 1-3 g of representative sample material was milled under alcohol to about 5-10 µm (talcum powder size) using a mortar and pestle. Subsequently, the sample was mounted in a sample holder in such a way to minimise preferred orientation for XRD analysis.

3.4 GEOTECHNICAL PROPERTIES

Standard foundation tests were conducted to characterise basic geotechnical parameters such as:

- Distribution of soil types across the investigated sites;
- Grain size distribution;
- Atterberg limits (i.e. soil plasticity);
- Hydraulic conductivity (i.e. derived from geotechnical parameters).

3.4.1 Estimation of hydrogeological conditions from geotechnical data

The amount of water that can be stored in a certain volume of soil and the rate of water movement (flux) through that soil, depend on various parameters such as soil texture (i.e. particle size distribution), soil structure (i.e. aggregation of soil particles), density and shape of grains and the presence of preferential flow paths. Water may occupy both interstructural and textural voids (between the particles). At high moisture contents, water-flow through the voids may be the dominant transport process, but becomes rapidly less important as the soil moisture decreases and matrix flow dominates. Generally, the coarser and/or better sorted the solid particles, the larger the intervening voids and the easier it will be for draining water to pass through. As a result, sandy soils tend to be freely draining and permeable, while clayey soils are both slower to absorb and to drain water.

Clay minerals (or grains < 0.002 mm) are the most important particle size fraction in determining the physical and chemical properties of soil. The silt and sand fractions mainly comprise quartz and other primary minerals that have undergone little chemical alteration while the clay material, in contrast, results from chemical weathering, forming secondary minerals with a great variety of properties (Wild, 1988 and White, 1989).

One difference is that the clay minerals often consist of plate-like sheets and have a much larger specific surface than other particle types such as silt and sand. Most clays have negatively charged surfaces and are balanced externally by cations which are not part of the clay structure and which can be replaced or exchanged by other cations. The latter process is known as *cation exchange capacity* (CEC) and plays a major role in contaminant attenuation processes. Some clay minerals (e.g. montmorillonite) have only weak bonds between the adjacent sheets, and the internal surfaces may also be available for taking part in reactions such as the retention and release of nutrients, salts and contaminants (Rose, 1966). Moisture can enter between these sheets, causing them to shrink or to swell. Many clayey soils swell under moist conditions and shrink and desiccate under dry conditions, which could influence the porosity and other hydraulic properties of the soil. Typical properties of common clay minerals are shown in Table 3.5.

TABLE 3.5 - Typical values of some properties of common clay minerals (White, 1989 and Holtz & 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 (m^2/kg)	15	80	80	800	n. a.
CEC ($cmol_{(+)}/kg$ soil)	3 - 20	10 - 40	n. a.	80 - 120	100 – 150
Plasticity	Low	Medium	Medium	High	Medium
Swelling/ Shrinking	Low	Medium	Low	High	n. a.

Note: CEC means cation exchange capacity, (+) refers to cations. 1 $cmol_{(+)}/kg$ equals 1 meq/100 g soil.

Table 3.6 summarises the clay contents of the investigated study sites, which were determined by geotechnical testing.

TABLE 3.6 - Clay contents in soil samples of the study sites (n=59).

Site	**MIN** %	**MAX** %	**AVG** %	**Number of samples (n)**
A	7.5	15.8	10.9	8
B	29.8	63.7	40.2	8
C	19.5	48.7	34.7	9
D	14.4	51.4	33.3	9
E	33.3	46.6	38.6	7
F	13.7	44.2	31.9	12
G	14.1	31.5	22.5	6
All sites	7.5	63.7	30.7	59

The clay contents of the investigated soils show a varying spatial distribution as a result of different soil types, parent rock material and weathering conditions, characterised by seasonal changes. In addition, Table 3.7 shows a list with the percentage portion of the clay content in the soils of the study sites. Nearly 50 per cent of all soil samples contain more than 30 per cent clay. No relationship was found between clay content and sample depth, nor between clay content and element concentrations.

TABLE 3.7 - Classification of clay contents according to the percentage portion in soil samples of the study sites.

Clay amount	**> 10** %	**> 10–20** %	**> 20–30** %	**> 30–40** %	**> 40– 50** %	**> 50–60** %	**> 60** %
Number of samples	3	12	11	18	11	3	1
Percentage of samples	5.1	20.3	18.6	30.6	18.6	5.1	1.7

Geotechnical data allowed the estimation of hydraulic conductivities in 23 soil samples, which are listed Table 3.8 (approach after Mathewson, 1981 and Tavenas, Jean, Leblond & Leroueil, 1983). The methodology for these approaches is discussed in paragraph 3.5.3.

TABLE 3.8 - Estimated hydraulic conductivties of soils from the study sites (n=23) according to the methods of Mathewson (1981) and Tavenas et al. (1983).

Site	**MIN** m/s	**MAX** m/s	**Number of samples (n)**
A	1×10^{-9}	1×10^{-9}	3
B	1×10^{-10}	1×10^{-10}	2
C	1×10^{-11}	9.5×10^{-8}	4
D	7.5×10^{-10}	7×10^{-9}	4
E	8×10^{-10}	9×10^{-9}	4
F	6×10^{-10}	6×10^{-9}	4
G	1×10^{-9}	1×10^{-9}	2
All sites	1×10^{-11}	9.5×10^{-8}	23

Estimated hydraulic conductivities range from impermeable (i.e. 1×10^{-11} m/s) to a very low hydraulic conductivity (i.e. 9.5×10^{-8} m/s), which is typical for soils having a high clay content. Since more than half of all investigated soil samples showed a clay content > 30 per cent, the unsaturated zone can be regarded as nearly impermeable. However, high salinity in groundwater samples and the lack of correlation between contaminant concentrations and clay contents in soils (Table B.9, Appendix B) collected on and around the investigated sites indicate the presence of alternative flow mechanisms that bypass the soil matrix, known as preferential flow. Such conditions would result in high hydraulic conductivities and an insufficient contact time between the aqueous and solid phase (soil matrix) to adsorb contaminants.

3.4.2 Soil types and properties

The reclaimed sites are underlain by various soil types, which were described in the field according to the protocol of the *Soil Classification System for South Africa* (Soil Classification Working Group, 1991). The classification comprises the following instructions amongst others:

- Identify major horizons within the soil profile;

- The horizon needs to be within the first 1.5 m of the soil profile. In this study soils were described up to the bottom of the test pit (max. 2.40 m depth).
- Use the key in the soil classification protocol to identify the soil type.

Each soil type is distinguished by a name such as *Shortlands* and differs from other soil types on the basis of certain pedological criteria. It is important to note that the different horizons have not been formed separately, but as a result of a combination of processes acting on the entire soil profile. Thus, horizons of the same soil type can vary considerably in terms of different physical characteristics such as clay content and hydraulic conductivity. Each soil is therefore described according to general geotechnical properties by means of field testing methods, which are outlined below (Jennings et al., 1973):

- Moisture;
- Colour;
- Consistency;
- Structure;
- Soil type;
- Origin.

It is important to note that soils of the study area are generally characterised by low organic matter contents as a result of poor vegetation and extensive weathering. The following soil types were encountered at the investigated sites and are summarised in Table 3.9:

TABLE 3.9 - Soil types occurring at the investigated sites.

Soil type	**Description**	**Occurrence at the study sites**
Arcadia	Vertic A horizon	Site I
Avalon	Orthic A horizon, a yellow-brown apedal B horizon and a soft plinthic B horizon	Test pits A/2, A/3, C/1, G/1, G/2, G3
Glencoe	Orthic A horizon, a yellow brown apedal B horizon and a hard plinthic B horizon	Test pit A/1
Katspruit	Orthic A horizon above a water table (G horizon)	Test pit E/1
Rensburg	Vertic A horizon above a water table (G horizon)	Test pits E/2, E/3

TABLE 3-9 continued.

Shortlands	Orthic A horizon above a red structured B horizon.	Test pits B/1, B/2, C/2, D/1, F/1, F/2, F/3
Willowbrook	Melanic A horizon above a water table (G horizon)	Test pits B/3, C/3, D/2, D/3

According to the Soil Classification System of South Africa, an orthic A horizon is a surface horizon without significant organic matter or clay content. A melanic A horizon is a dark coloured soil unit with strongly developed structure without slickensides, while a vertic A horizon is a soil unit with strongly developed structure with slickensides (only in combination with smectites). 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 is diagnostically red when wet with strongly developed soil structure. A soft plinthic B horizon has undergone localised 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 (Soil Classification Working Group, 1991). The most common soil types encountered at the study sites are *Shortlands* and *Avalon*.

The Shortlands soil type usually forms under warm temperate and subtropical climatic conditions. The parent rock of this soil type is generally characterised by a high Fe and basic mineral content, resulting in the accumulation of Fe, Si and Al (termed *fersialization*) in the overlying soil. The high Fe content causes the typical red colour of this soil type (Figure E.2, Appendix E). Kaolinite is the most likely clay mineral occurring in this soil type.

The Avalon soil type form is characterised by the accumulation of sesquioxides (e.g. haematite occurring in ferricretes, Figure E.11) as a result of the removal of silica and bases by fersialization (Driessen & Dudal, 1991), i.e. relative accumulation of Fe and Al in the soil. Thus, sufficient Fe must be present, originating from the parent material or introduced by seepage (e.g. acid mine drainage). The soil typically has a pH ranging from 5 to 8 and high hydraulic conductivity. A short dry period is an important prerequisite for the formation of this soil type. The change from wet (i.e. summer) to dry (i.e. winter) climatic conditions results in the segregation of Fe and Mn concretions (e.g. ferricrete).

Furthermore, although soils in the study area show clay contents up to 60 per cent (nearly 50 per cent of all soil samples contain more than 30 per cent clay) contaminant retention is reasonably low as a result of potential preferential flow (also known as *macro-pore flow*) conditions throughout the unsaturated zone. Preferential flow is caused by large pores represented by structural cracks, fissures or paths of plant-root systems (Ward & Robinson, 1990). Cracks or fissures can be a result of alternate swelling and shrinking of expanding clays as well as cracking in the subsoil. Cracking at varying depths (up to 2 m) was observed in test pits of study site E and could be caused due to high salt loads in the soil and the alleviation of the former load, i.e. the reverse process of consolidation. In addition, preferential flow paths might be also associated with relatively impermeable ferricrete layers overlying less impermeable soil and enforcing lateral instead of vertical flow. Notably is that the dry density of the soils within the study area is higher if compared to natural soils, indicating consolidation and compaction.

Joubert (1998) investigated clay types at study site F by means of X-ray diffraction and confirmed the dominance of kaolinite $Al_2[(OH)_4/Si_2O_5]$ in all samples (n=10). Kaolinite is typically formed in highly weathered soils such as those occurring in the study area and is often associated with sesquioxides (Brink, 1985). In addition, minor amounts of the clay mineral palygorskite $(Mg,Al)_2Si_4O_{10}(OH) \cdot 4\ H_2O$ were found.

3.5 DATA EVALUATION

3.5.1 Correlation coefficients

Correlation coefficients were calculated for elements occurring in tailings and soils using the Pearson approach, in order to identify trends between two variables (bivariate). A trend is a change of the property x corresponding to a change of property *y*. The goodness of the trend can be estimated from the product moment correlation coefficient, *r*.

The coefficient ranges from + 1 to –1, where these extremes denote a perfect linear relationship between *x* and *y*; which may be direct or indirect, respectively, i.e. on a rectangular *x, y* coordinate system, where all points are located strictly on an ascending ($r = +1$) or descending ($r = -1$) straight line. If *r* deviates from + 1, the linear relationship becomes progressively blurred. A trend of increasing *x* associated with increasing *y*, is termed positive. If r is negative, there the correlation is negative. The value $r = 0$ indicates that there is no trend at all. In this case the plotted points are distributed randomly in the coordinate system (Marsal, 1987).

The correlation coefficient *r* can be expressed as:

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{\left[n\Sigma x^2 - (\Sigma x)^2\right]\left[n\Sigma y^2 - (\Sigma y^2)\right]}} \qquad [3.2]$$

3.5.2 Geochemical background values

Many soils, surface and groundwaters contain natural concentrations of chemical constituents that exceed soil quality or drinking water standards (Thornton, 1983; Runnels, Sheperd & Angino, 1992). To determine the extent of contamination by toxic elements in a soil or aquatic system, it is necessary to define this natural level (or pre-civilisation value) in a comparable pristine area, and then to subtract it from present values, thereby deriving the total accumulation by anthropogenic impacts (Förstner, 1983). A common approach (Turekian & Wedepohl, 1961; Banks, Reiman, Royset, Skarphagen & Saether, 1995 and Lahermo, Mannio & Taravainen, 1995) is to sample river sediments upstream (similar geology) of the contamination source, where the water quality is presumably unaffected, and to compare the sediment concentrations with samples collected directly downstream of the contamination source. However, especially in highly populated and industrialised areas, it is difficult to identify a sampling point in a river or aquifer where the sediment quality seems to be unaffected by human activities.

In this study, test pits from the reclaimed sites were excavated in soils or alluvial sediments derived mostly from sandstone and shales of the Vryheid Formation, diamictite and shales of the Dwyka Formation, or dolomites of the Malmani Subgroup. The trace element concentrations of the soils retrieved from the investigated sites were compared to average trace element concentrations from topsoils overlying identical bedrock conditions, having the same grain size (< 75 µm). The method to calculate an accumulation factor (i.e. geochemical load index) is discussed in the paragraph 3.5.5. Background concentrations for topsoils of the Malmani Subgroup were obtained from Elsenbroek & Szczesniak (1997) and of the Vryheid Formation from Aucamp (1997). Table 3.10 summarises the average background values for the Vryheid Formation and Malmani Subgroup.

TABLE 3.10 - Average background values and their standard deviations in topsoils obtained from the Vryheid Formation, Karoo Supergroup (n= 21) and Malmani Subgroup, Transvaal Supergroup (n= 4248, particle size <75 µm). Vryheid Formation data from Aucamp (1997) and Malmani Subgroup data from Elsenbroek & Szczesniak (1997).

Parameter	**Vryheid Formation** mg/kg	**Standard deviation**	**Malmani Subgroup** mg/kg	**Standard deviation**
As	22	4	18	17
Co	14	3	15	40
Cr	130	32	268	958
Cu	35	7	31	81
Fe_2O_3 (in %)	4.4	1.1	6.11	3.1
MnO (in %)	0.08	0.03	0.7	0.7
Mo	23	5	13	8
Ni	45	10	57	107
Pb	15	8	5	25
Th	13	3	18	5
U	n.d.	-	n.d.	-
Zn	103	55	50	79

3.5.3 Estimation of hydraulic conductivities in soils

Saturated hydraulic conductivities in soil samples were estimated according to the methods of Tavenas et al. (1983) or by means of comparison to the permeability, after

Mathewson, (1981). Figure 3.1 shows the procedure after Tavenas et al. (1983) to estimate saturated hydraulic conductivity in a fine-grained soil:

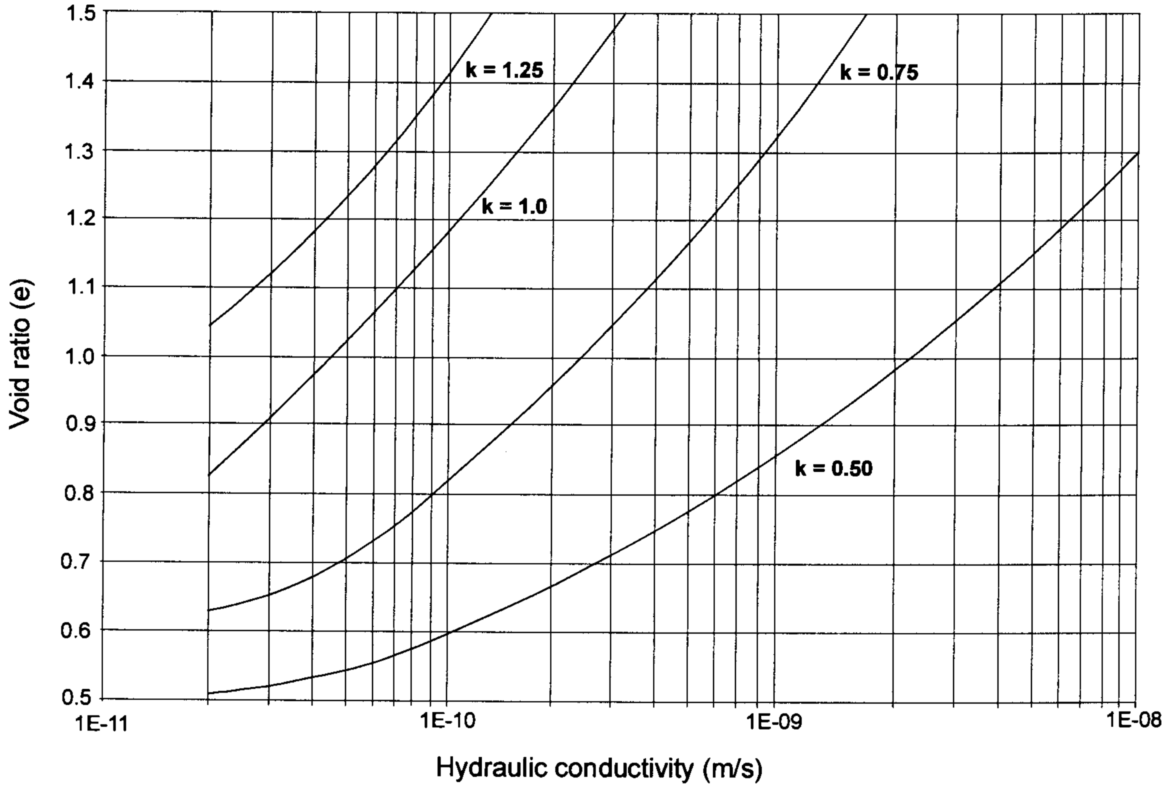

FIG. 3.1 - Estimation of saturated hydraulic conductivity (m/s) in a fine-grained soil (after Tavenas et al., 1983).

Tavenas et al. (1983) established a relationship between saturated hydraulic conductivity and the void ratio, clay fraction and plasticity index (PI) values. The soil properties are plotted on Figure 3.1 and the saturated hydraulic conductivity can be then obtained. The k value represents the sum of clay fraction and the plasticity index (example: a soil with a clay content of 45 % and a PI of 10 would have a k value of 0.45 + 0.1 = 0.55). The latter is one parameter of the Atterberg limits. Table 3.11 presents the US soil classes (U.S.C.S.) and associated hydraulic conductivities, published by Mathewson (1981).

TABLE 3.11 - Estimated hydraulic conductivity value from soil type (after Mathewson, 1981).

Soil type		U.S.C.S symbol	Soil description	Hydraulic conductivity m/s
COARSE-GRAINED SOIL (< 50 % of material pass 0.075 mm)	Gravel	GP	Poorly-graded gravel, little fines	$10^{-5} - 10^{-2}$
		GW	Well-graded gravel, little fines	$10^{-4} - 10^{-2}$
		GM	Silty gravel, gravel-silt-sand mixture	$10^{-8} - 10^{-5}$
		GC	Clayey gravel, gravel- sand-clay mixture	$10^{-9} - 10^{-6}$
	Sand	SP	Poorly-graded sand, little fines	$10^{-6} - 10^{-3}$
		SW	Well-graded sand, gravelly sand, little fines	$10^{-7} - 10^{-3}$
		SM	Silty sand, sand-silt mixture	$10^{-8} - 10^{-6}$
		SC	Clayey sand, sand-clay mixture	$10^{-9} - 10^{-7}$
FINE-GRAINED SOIL (> 50 % of material pass 0.075 mm)	Silt	ML	Inorganic silt and very fine sand, silty or clayey fine sand, clayey silt with slight plasticity	$10^{-9} - 10^{-6}$
		MH	Inorganic silt, micaceous or diatomaceous fine sandy or silty soil, elastic silt	$10^{-9} - 10^{-7}$
	Clay	CL	Inorganic clay with low-medium plasticity, gravelly or sandy clay, lean clay	$10^{-10} - 10^{-8}$
		CH	Inorganic clay with high plasticity, fat clay	$10^{-11} - 10^{-9}$

3.5.4 Short-term impact

The short-term or current contamination impact was investigated using the trace element mobility coefficient (MOB) and threshold excess ratio (TER), which can be expressed as:

$$TER = \frac{ExC}{TC}, \qquad [3.3]$$

where TER is the threshold excess ratio for an element, ExC is the NH_4NO_3 extractable concentration and TC is a given set soil threshold value or soil quality standard, after Prüeß et al. (1991). A concentration that is exceeding the soil threshold value can limit the functioning of the soil. Table 3.12 indicates which of the soil functions are most threatened by a certain contaminant in order to assist in the decision on appropriate counter measures.

TABLE 3.12 - Recommended maximum NH_4NO_3 extractable threshold concentration in soils (after Prüeß et al., 1991).

Element	**Threshold concen.** mg/l	**Soil functions and ranking of concerns**				
		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
As	0.1	PC	X	C	X	C
Co	0.5	X	C	C	X	X
Cr	0.1	X	X	X	PC	C
Cu	2	X	C	C	PC	C
Mo	1	X	PC	C	X	X
Ni	1	X	X	C	X	X
Pb	2	PC	C	X	C	C
V	0.1	C	C	INV	X	X
Zn	10	X	X	C	X	X
U	0.04	X	X	X	X	INV

Note: Abbreviations for the ranking of concern if the threshold concentrations are not greatly (e.g. several times) exceeded: PC = primary concern, C = concern, INV = further investigations needed to assess risk. Limited soil functioning only if the threshold concentrations are greatly exceeded: X.

In addition, the mobility of trace elements was derived by comparing the extractable ratio of an element to the total concentration:

$$MOB(in\%) = \frac{ExC}{TotC}, \qquad [3.4]$$

where MOB represents the percentage mobility of an element, ExC is the NH_4NO_3 extractable fraction and TotC is the total trace element concentration measured in soil samples. The MOB coefficient gives an indication of the contaminant concentration, which could be remobilised and is thus potentially bio-available.

In this study, TER and MOB were only applied experimentally to samples of the site F, and were then extrapolated to the other samples from the remaining sites A-G. Site F generally showed the highest pollution potential of all investigated sites with respect to uranium.

3.5.5 Long-term impact

The potential future impact of contamination (worst-case scenario) was assessed by using the geochemical load index (I_{geo}), introduced by Müller (1979).

$$Igeo = \log_2 \frac{Cn}{Bn \cdot 1.5}, \qquad [3.5]$$

where C_n is the measured concentration of the element n in the soil/sediment and B_n is the average geochemical background value obtained from literature. The safety factor 1.5 is used to compensate for variation in the background data. The hazard rating comprises six different contamination classes (i.e. I-VI), which are shown in Table 3.13:

TABLE 3.13 - Classification of contamination by using the geochemical load index (after Müller, 1979).

Geochemical Load Index (I_{geo})	Contamination class	Level of contamination
> 0-1	I	Non-polluted to moderately contaminated
> 1-2	II	Moderately contaminated
> 2-3	III	Moderately to highly contaminated
> 3-4	IV	Highly contaminated
> 4-5	V	High to excessively contaminated
> 5	VI	Excessively contaminated

The application of this index reflects a worst-case scenario, assuming that the total concentration of contaminants contained in the solid phase can be remobilized and hence, is potentially bio-available. The geochemical load index is also intended to represent the long-term capacity of the soil to retain contaminants. If the geochemical load index is exceeded (i.e. greater than 1 or beginning with contamination class II), it can be assumed that further damage to the environment is occurring and the general quality of the environment is deteriorating. However, it is important to note that such an excess does not necessarily mean that damage has to occur right now. It is a calculation that damage, however defined, will occur at some time, possibly now, possibly later, if the introduction of contamination into the soil system is not reduced.

The index was 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, 1974 and Förstner, 1982), and also recently in the geochemical mapping program of topsoils in the city of Berlin and in the Czech Republic, conducted by the German Federal Environmental Agency (Birke, 1998).

4 CASE STUDIES

4.1 CASE STUDY A

4.1.1 Site location and drainage

Site A is situated approximately 1 km east of the suburbs of Benoni and covers an area of approximately 50 ha (Figure 1.1). 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. Test pit locations are shown in Figure D.1[6].

4.1.2 Reclamation and rehabilitation status

Approximately 50 per cent of the tailings material has been removed. No vegetation has been established on site except a poor grass cover and some trees on top of the toe wall (Figure E.1). The oxidised zone in the remaining toe wall is clearly visible and reaches up to a depth of approximately 5 m. Paddocks were constructed to prevent storm water surface run-off from the site.

4.1.3 Geological conditions

Site A is underlain by sedimentary rocks of the Vryheid Formation (sandstone and shale), in the southern part of the site. The Dwyka Formation (diamictite and shale) underlies the northern portion of the site.

4.1.4 Soils

The soils of the site A are mainly represented by the Avalon (test pits A/2 and A/3) and Glencoe (test pit A/1) soil type. No perched water table was encountered during the excavation of the test pits. Table 4.1 presents a summary of soil parameters of site A.

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[6] The Figures are contained in the relevant Appendixes (e.g. D and E).

TABLE 4.1 - Summary of soil parameters for study site A.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Colluvium	8.5-15.8	2.89-6.90	1752.9-1816.1	2.72	0.50-0.55	1 x 10^{-9}	ML, SC, GM	3.1-6.5
Nodular ferricrete	11.31	5.11	-	-	-	-	SC	6.9
Hardpan Ferricrete	7.5-12.10	5.94-8.90	1551.43	2.81	0.81	1 x 10^{-9}	ML, SC	4.4-6.9

Note: U.S.C.S. symbols are explained in Table 3.11.

Vertical preferential flow occurs in the clayey sand, colluvial topsoil unit (0.20-0.55 m thickness) which is characterised by cracks. The yellow-brown coloration along the cracks indicates the movement of overlying tailings within these structures. Lateral preferential flow may occur at depths 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 A/1 at 0.60 m depth. The hardpan ferricrete unit shows zones of moist, brown, loose clayey sand within the matrix of very densely cemented clayey sand, through which preferential flow might occur. The ferricrete units in the profile might cause a perched water table during the wet season.

4.1.5 Assessment of contamination

4.1.5.1 Trace element concentration in soil

Soil pH conditions are favourable for metal leaching, with the lowest pH of 3.1. All test pits show a significant positive trend for Fe with depth, where the concentration progressively increases from 3.5 per cent in the topsoil up to 18 per cent at 1.0 m depth. The average concentration of Fe is significantly higher than the average background value of 4.4 per cent. This indicates the release of Fe during the pyrite oxidation process and its downward migration through the subsoil.

Chromium generally accumulates in subsoil and exceeds the average background value of 130 mg/kg (i.e. Vryheid Formation) in all samples. However, the bulk of the Cr seems to be associated with Fe_2O_3, reflected in a very good positive correlation ($r = 0.83$). Arsenic in contrast accumulates in the topsoil to concentrations which exceed considerably (5-fold) the average background value of 22 mg/kg (i.e. Vryheid Formation). The high concentrations of As found in the topsoils and the negative correlation with depth strongly suggest the leaching of As from reclaimed tailings into the topsoil, whereupon As seems to be immediately immobilised on solid surfaces such clay minerals or the formation of iron arsenates. The low remobilization and thus mobility of As has been confirmed by extraction tests. In two samples, measured U concentrations of 12 and 7 mg/kg are very low compared to site F, but still above the average background value. A list of geochemical soil data is provided in Table B.1 (Appendix B).

4.1.5.2 Short-term impact

The application of the extrapolated extractable fraction resulted in no excess of the threshold value in case of As, whereas Co, Ni and Zn exceed the threshold in all samples, resulting in a limited soil function. Chromium, Cu, Pb and Zn showed excess 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 excess of Ni can be explained by a high mobility (MOB of 51 per cent). In contrast, Zn reaches only a maximum of 3-fold excess.

4.1.5.3 Long-term impact

Soil samples of the test pits A/1, A/2 and A/3 show moderate contamination (class II) for As, Fe, Cr, Cu and Pb using the geochemical load index. Only U occurs in concentrations which are classified as moderately to highly contaminated (class III) due to a average background value of 1 mg/kg.

4.1.6 Discussions and conclusions

The low clay content in connection with a generally low organic matter and the presence of preferential flow paths might cause ongoing groundwater contamination. In addition, the most common clay mineral is likely to be kaolinite, characterised by its very low cation exchange capacity. Dry density values (i.e. colluvium) are very high compared to natural soils and only very few plant would grow satisfactorily under such conditions.

The fact that nearly half of the tailings material still remains on site, which provides a source for continuing pyrite oxidation, gives rise to concern. Furthermore, paddocks, which are situated on the reclaimed portion of the site are inappropriate as they increase rainfall infiltration and, thus enhance contaminant migration. Nickel mobility is very high in the soil and could complicate efforts to establish a self-sustaining vegetation cover as the soil function is limited.

In this condition, the soil is not fit for revegetation. It is recommended to remove the paddocks and to cover the remaining tailings material by an impermeable layer. Such a soil cover would prevent the dispersion of fine tailings material by wind and would minimise rainfall infiltration into the tailings and, thus the generation of acid mine drainage. In addition, lime should be added to the topsoil to neutralise acids. The introduction of fertilisers would improve growth conditions on the reclaimed portion of the site. In addition, lime would also enhance the attenuation capacity of the soil.

4.2 CASE STUDY B

4.2.1 Site location and drainage

Site B is situated to the south-east of Springs in close proximity to a residential area on its eastern border (Figure 1.1). The site covers an area 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. The location of the test pits is shown in Figure D.2.

4.2.2 Reclamation and rehabilitation status

About 90 per cent of the tailings material has been removed (Figure E.2). The remaining tailings will be reclaimed by the year 2003. The site shows vegetation, consisting of a poor developed grass cover and some trees. Paddocks were constructed to prevent storm water surface run-off.

4.2.3 Geological conditions

The southern section of site B is located on dolomites of the Oaktree Formation, Malmani Subgroup, whereas the northern part is situated on Dwyka Formation (diamictite and shale).

4.2.4 Soils

The soils of site B are represented by the Shortlands (test pits B/1 and B/2) and Willowbrook (test pit B/3) soil type. The photographed soil profile is presented in Figure E.3. The soil parameters of study site B are summarised in Table 4.2:

TABLE 4.2 - Summary of soil parameters for study site B.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Colluvium	29.80-63.66	11.28-19.63	1619.22-1695.54	2.45-2.48	0.46-0.51	1 x 10^{-10}	CL, MH	3.53-6.63
Nodular ferricrete	19.02-50.24	8.21-25.67	-	-	-	-	SC, MH	5.7-6.7

Note: U.S.C.S. symbols are explained in Table 3.13.

The open-structured nature of the topsoil unit may facilitate preferential vertical infiltration, although the abundance of gypsum crystallisation could close up 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 profiles suggest the presence of either a seasonal perched water table or very high moisture saturation.

4.2.5 Assessment of contamination

4.2.5.1 Trace element concentration in soil

Iron shows in all test pits a positive correlation with depth of the profile (maximum depth 2.10 m). Total concentrations of Fe exceed in nearly all samples the relevant average background value of 6.1 mg/kg, suggesting the release of Fe during pyrite oxidation. Chromium is likely to bound onto Fe-oxides reflected in a significant positive correlation with Fe_2O_3 ($r = 0.83$).

Arsenic, Ni (except in test pit B/3) and Zn, in contrast, tend to accumulate in the upper soil unit and exceed in a number of samples the average background value. It is suggested that these elements have migrated from the tailings into the topsoil, where they became readily immobilised. A further downward migration of Ni and Zn is likely since low pH conditions enhance leaching. A list of geochemical soil data is provided in Table B.1.

4.2.5.2 Short-term impact

The application of the extrapolated extractable fraction would result in a high threshold excess ratio for Co (38-fold), Ni (88-fold) and Zn (53-fold). No significant excess, in contrast, was found for Cr, Pb and Fe.

4.2.5.3 Long-term impact

Site B is moderately contaminated (class II) by Ba, Cu and Ni, moderately to highly contaminated by Co and highly contaminated by Pb using the geochemical load index.

4.2.6 Discussions and conclusions

The high clay content can support contaminant attenuation mechanisms within the soil matrix. However, kaolinite is most likely the dominating clay type, having a low cation exchange capacity. In addition, paddocks are inappropriate as they increase rainfall infiltration and thus, enhance contaminant migration. High mobility of Ni and Zn in soils could complicate efforts to establish a self-sustaining vegetation cover, as these trace elements are known to be phytotoxic.

In this condition, the soil is not fit for revegetation. It is recommended to remove the paddocks and remaining (or residual) tailings material from the surface and to add lime to those portions of the topsoil, delineated as acid soils. Further soil management measures like the addition of fertilisers would improve growth conditions. In addition, lime would also enhance the attenuation capacity of the soil.

4.3 CASE STUDY C

4.3.1 Site location and drainage

The site covers an area of approximately 28 ha and is located to the south-east of Springs (Figure 1.1) 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. The general surface drainage direction is in southerly direction towards a canal and dam. The location of the test pits is shown in Figure D.3.

4.3.2 Reclamation and rehabilitation status

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

4.3.3 Geological conditions

Site C is mostly is covered by alluvial sediments deposited by a tributary of a perennial stream. Sedimentary rocks of the Dwyka Formation (diamictite and shale) underlie the alluvium.

4.3.4 Soils

Site C is covered by the following soil types: Colluvium of the Avalon (test pit C/1) type and alluvium of the Shortlands (test pit C/2) and Willowbrook (test pit C/3) types. Table 4.3 summarises the soil parameters for study site C.

TABLE 4.3 - Summary of soil parameters for study site C.

	Field test results							
	Geotechnical parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. Soil group	
Upper alluvium (< 0.60 m)	24.58-38.41	11.95-23.52	1700.96	2.40	0.41	1 x 10^{-10}- 1 x 10^{-11}	CI	3.5-6.1
Deeper alluvium (> 0.60 m)	19.51-48.66	13.46-28.47	1738.90	2.57	0.64	1 x 10^{-9}	CH	7.4-7.7
Ferruginous colluvium	28.90-46.78	14.06-14.26	1520.08-1602.09	2.61-2.80	0.63-0.84	8 x 10^{-8}- 9.5-10^{-6}	CI	3.8-5.0

Note: U.S.C.S. symbols are explained in Table 3.11.

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

4.3.5 Assessment of contamination

4.3.5.1 Trace element concentration in soil

Iron and Cr accumulate in the subsoil and exceed the average background value considerably. Almost neutral pH values were measured at the bottom of the test pits (about 2.40 m depth), indicating the effect of buffering minerals such as carbonates and/or fluctuations in a shallow groundwater table causing dilution effects. The neutral pH conditions at greater depths would result in metal precipitation, and thus immobilisation.

A shallow water table was encountered in test pit C/2 (Figure E.10) and a chemical analysis was conducted to assess the impact of the seepage on groundwater quality. The results are presented in Table 4.4a and 4.4b:

TABLE 4.4a - Chemical analyses of seepage water from test pit C/2 depicting macro-chemistry and other main parameters.

C/2	pH	EC	TDS	Ca	Mg	Na	K	Cl	NO$_3$	HCO$_3$	SO$_4$
		mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	6.3	309	2214	219	147	262	5.37	336	<0.1	348	1006

Note: Accuracy of the analysis, which is outlined in paragraph 3.3: Δ -2.22 per cent (high accuracy).

The pH conditions in the seepage sample correspond to the soil pH. Total dissolved solids (TDS) are relatively high and mainly caused by high salt concentrations such as SO$_4^{2-}$ and Cl$^-$. Table 4.4b represents metal and cyanide concentrations determined in the seepage sample.

TABLE 4.4b - Chemical analyses of seepage water from test pit C/2 showing metal and CN concentrations.

C/2	As	Cu	CN	Fe	Mn	Ni	Pb	Zn
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	<0.1	<0.01	<0.2	3.2	0.76	0.13	<0.01	0.05

Arsenic, CN, Cu and Pb concentrations are below the detection limit, therefore, there is tendency that these elements are retained from the soil. Additionally, the cyanide ion (CN$^-$) decomposes in aqueous solutions to cyanate (OCN$^-$), which is not stable and further disintegrates to CO$_2$ and NH$_3$ (Mortimer, 1987). The extraction test has shown that As, Cu and Pb have very low mobilities even under acidic conditions. The concentrations of Fe, Mn, Ni and Zn are low compared to seepage samples of the sites G and F. High alkalinity values in seepage reflect the acid neutralisation capacity of the subsoil by carbonate containing minerals. A list of geochemical soil data is provided in Table B.1.

4.3.5.2 Short-term impact

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

4.3.5.3 Long-term impact

Site C is moderately contaminated (class II) by Cu, Fe, Ni, Mn, V and Zn while the site is highly (class IV) contaminated by Co using the geochemical load index.

4.3.6 Discussions and conclusions

The relatively high clay content may support contaminant attenuation mechanisms within the soil matrix. However, kaolinite is most likely the dominating clay type, having a low cation exchange capacity. The mobility of the phytotoxic elements Co, Cr and Ni is considerable and could endanger the present vegetation cover in the long-term.

Soil management measures like the addition of lime and fertilisers are currently not required since a vegetation cover has developed on site, but might be necessary in the future. Vadose zone monitoring (pH, redox conditions and trace element concentrations in seepage by using lysimeters) is advised, as the future contamination potential (worst-case scenario) of the soil is high.

4.4 CASE STUDY D

4.4.1 Site location and drainage

Site D is situated adjacent to a highway and in close proximity to a large township (Figure 1.1). It covers an area of approximately 71 ha and is located at an altitude of ± 1610 m above sea level. Surface run-off may occur towards a canal in northern direction. The location of the test pits is shown in Figure D.4.

4.4.2 Reclamation and rehabilitation status

Site D has been completely reclaimed and poor grass vegetation covers the entire area (Figure E.4). No rehabilitation measures were undertaken.

4.4.3 Geological conditions

Site D is mostly underlain by sedimentary rocks of the Dwyka Formation (diamictite and shale).

4.4.4 Soils

The soils of the site D are represented by the following soil types: Colluvium of the Willowbrook (test pits D/2 and D/3) and Shortlands (test pit D/1) types. Table 4.5 presents a summary of soil parameters of site D:

TABLE 4.5 - Summary of soil parameters for study site D.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Colluvium	14.37-42.23	6.09-14.55	1566.60-1684.51	2.61-2.64	0.55-0.69	9×10^{-9}	CL, SC	3.5-6.8
Ferruginous colluvium	20.93-51.44	9.36-30.32	1553.81-1644.29	2.68-2.69	0.64-0.72	7.5×10^{-10}	CL, SC	6.3-6..8

Note: U.S.C.S. symbols are explained in Table 3.11.

The soils exhibit an open soil structure to a maximum depth of 1.40 m. This structure might facilitate preferential vertical infiltration, although the abundance of gypsum crystallisation could close up the pores and, thus reducing 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 Fe-oxides that may close pores to reduce vertical permeability.

Lateral preferential flow may also occur at 1.40 m at test pit D/3 on the boundary between the ferruginous colluvium and the residual shale. Cracking occurs from 0.80-2.30 m and might allow vertical preferential flow. A hard pan ferricrete unit occurs at 1.60 m in test pit D/1 and lateral preferential flow may be induced on this layer.

4.4.5 Assessment of contamination

4.4.5.1 Trace element concentration in soil

Iron shows low concentrations in the topsoils (3.4-8.9 per cent), but an accumulation in the subsoil (6.8-12.0 per cent). Test pit C/3 shows generally much lower Fe and As concentrations than in the two other test pits. The pH value in all topsoil samples varies from 3.5-3.8, thus indicating favourable leaching conditions for metals. A list of geochemical soil data is provided in Table B.1.

4.4.5.2 Short-term impact

Extrapolated extractable concentrations for Co would result in threshold excess of 28 to 53-fold and 24 to 72-fold for Ni, respectively. In contrast, Cr and Cu exceed the threshold concentration only by a factor of 6 to 10 and 2 to 4, respectively. Extractable concentrations of Zn and Pb are negligible.

4.4.5.3 Long-term impact

Site D is moderately contaminated (class II) by As, Cr, Fe while the site is moderately to highly contaminated (class III) by Ni and Pb. The site is highly contaminated (class IV) by Co, U and V using the geochemical load index.

4.4.6 Discussions and conclusions

The relatively high clay content may support contaminant attenuation mechanisms within the soil matrix. However, kaolinite is most likely the dominating clay type, having low expanding capabilities and thus, a low cation exchange capacity. A high mobility of the phytotoxic elements Co and Ni could endanger the present vegetation cover in the long-term.

Liming is not recommended as the primary pollution source was removed and a grass cover has developed on site, but might be necessary in the future. However, vadose zone monitoring is advised as the future contamination potential (worst-case scenario) of the soil is high.

4.5 CASE STUDY E

4.5.1 Site location and drainage

Site E is situated approximately 1 km to the north of the outskirts of Springs (Figure 1.1) 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 of approximately 70 ha and occurs at an altitude of ±1585 m above sea level. Surface drainage occurs towards a drainage canal in a southerly direction. This canal feeds a dam further downstream. The location of the test pits is shown in Figure D.5.

4.5.2 Reclamation and rehabilitation status

The site has been almost completely reclaimed, with about 90 per cent of the tailings being removed. The site shows a poor grass cover and paddocks systems were established to prevent storm water surface run-off from the site (Figure E.5).

4.5.3 Geological conditions

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 Formation (diamictite and shale) and by dolomitic rock (low chert content) of the Oaktree Formation in the southern portion of the site. A dolerite sill occurs in the central portion of the site.

4.5.4 Soils

The soils of site E are represented by the following soil types: Alluvium of the Rensburg (test pit E/2 and E/3) type and colluvium of the Katspruit (test pit E/1) type. A summary of the soil parameters is presented in Table 4.6.

TABLE 4.6 - Summary of soil parameters for study site E.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Alluvium	35.02-46.55	22.27-38.38	1484.87-1535.06	2.68	0.75-0.80	9×10^{-9}-8×10^{-10}	CH, CL	5.1-8.3
Colluvium	33.29-40.06	21.28-23.05	1535.78-1775.29	2.55-2.70	0.44-0.76	1×10^{-10}-9.5×10^{-9}	CL	6.7–7.0

Note: U.S.C.S. symbols are explained in Table 3.11.

In the clayey alluvial soils of test pits E/2 and E/3, cracking occurs between 0.60 m and a maximum of 1.50 m and these features may be preferential vertical flow paths. Both test pits refused on an alluvial boulder layer (at 1.50 m in test pit E/2 and 1.30 m in E/3). A perched water table occurs 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.

4.5.5 Assessment of contamination

4.5.5.1 Trace element concentration in soil

Iron, Cr and V show increasing concentrations with depth, thus indicating the downward migration through the subsoil, whereas Pb and Zn tend to accumulate in the topsoil. A list of geochemical soil data is provided in Table B.1.

4.5.5.2 Short-term impact

No information on extractable metal concentrations of the soil is available. Leaching tests, conducted by the mining company, indicated high SO_4^{2-} concentrations even after the fourth extraction, exceeding the recommended maximum concentration of 600 mg/l (South African Bureau of Standards, 1984). The high SO_4^{2-} concentrations in the topsoil are a result of pyrite oxidation and the subsequent leaching from the reclaimed tailings. However, pH conditions in the top and subsoil are fairly neutral and would not allow significant contaminant mobilisation.

4.5.5.3 Long-term impact

Site E is moderately contaminated (class II) by Fe, Co, Pb and V, while the site is moderately to highly contaminated (class III) by Pb and V using the geochemical load index. Seepage is characterised by high SO_4^{2-} concentrations as a result of pyrite oxidation. A dolomitic aquifer system, which is in particular vulnerable to pollution (high flow velocities along fissures, fractures and cracks), underlies the southern portion of this site.

4.5.6 Discussions and conclusions

The relatively high clay content may support contaminant attenuation mechanisms within the soil matrix. However, kaolinite is most likely the dominating clay type, having low expanding capabilities and thus, a low cation exchange capacity. In addition, the site is partially situated on dolomite.

However, the remaining tailings should be removed and vadose zone monitoring is advised as the future contamination potential (worst-case scenario) of the soil is moderately to high. In addition, extraction tests for metals should be conducted. Liming is not required since the soil pH conditions are in a normal range.

4.6 CASE STUDY F

4.6.1 Site location and drainage

Site F is situated approximately 1 km south of the outskirts of Springs (Figure 1.1) 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 of approximately 120 ha. The site is located at an altitude of ±1585 m above sea level. Surface drainage is towards a perennial stream in the east. The location of the test pits is shown in Figure D.6.

4.6.2 Reclamation and rehabilitation status

Both sites have been reclaimed, but small volumes of tailings material still remain on site and indicate the footprint of the former deposit. Some poor vegetation has been developed on site. The mining company is currently in the process of removing these residual tailings (Figure E.6).

4.6.3 Geological conditions

The larger portion of the site is underlain by rocks of the Vryheid Formation (sandstone and shale); whereas the remainder in the south-eastern section is underlain by sedimentary rocks of the Dwyka Formation (diamictite and shale).

4.6.4 Soils and groundwater

The soils of site F are represented by the Shortlands soil type. Table 4.7 presents a summary of soil parameters:

TABLE 4.7 - Summary of soil parameters for study site F.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Colluvium	13.70-44.22	6.64-14.33	1661.44-1711.02	2.51-2.78	0.47-0.67	6 x 10^{-9} to 1 x 10^{-10}	CL	3.7-6.7
Nodular ferricrete	19.72-39.56	6.21-15.89	1739.57	2.72	0.56	6 x 10^{-10}	CL	4.7

Note: U.S.C.S. symbols are explained in Table 3.11.

This study site is characterised by an average clay content of about 32 per cent, thus providing potential contaminant attenuation within the soil matrix. However, Joubert (1998) conducted mineralogical analyses using X-ray diffraction on soil samples (n=28) and found that kaolinite is the dominating clay type, which has a low cation exchange capacity. Furthermore, Fe oxide was detected in all samples, mostly as ferricrete. Such ferricrete layers can adsorb significant amounts of metals.

The soils are open structured between a minimum depth 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 presence of gypsum (observed at various depths) 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. No perched water tables were encountered but the basal nodular ferricrete unit present in most of the test pits is indicative of seasonal high moisture contents or a perched aquifer at the base of the profiles.

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. The water table was determined at approximately 11 m below surface. No groundwater quality data were available.

4.6.5 Assessment of contamination

4.6.5.1 Trace element concentration in soil and groundwater

The site shows relatively low concentrations of Mn, Co, Pb, Zn compared to the average background value for the Vryheid Formation. However Fe shows higher concentrations than the averaged background, indicating the potential release of Fe during the pyrite oxidation process. Test pit F/1 shows the highest concentrations of As, Cu, Ni, U and Zn at a depth of about 70 cm, which is characterised as a sandy clay with abundant gypsum crystals.

Arsenic and Ni show 8-fold higher concentrations than the averaged background, however their mobility is very low. Very high concentrations of U were found in six of sixteen samples. Of those, three samples showed concentrations greater than 700 mg/kg, two of them collected from the topsoil. It is likely that the high U concentrations (which are in the range of gold/uranium ore, Table 2.2) in the soil emanate from the deposition of radioactive material generated prior to the tailings disposal by a uranium processing plant (according to staff information of the former site operator).

Measured groundwater quality on site is presented in Table 4.8:

TABLE 4.8 - Groundwater quality at site F, measured in January, April and August 1996. Data obtained from mining company. Recommended maximum limit (RML) according to Aucamp & Vivier (1987).

Sampling date (mg/l)	**pH**	**TDS**	**Alk**	**Ca**	**Mg**	**Na**	**K**	**Cl**	**SO_4**	**NO_3**	**CN**
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

Note: n. a. means information not available. Accuracy of the analysis, which is outlined in paragraph 3.3: January 1996: $\Delta = 14.6$ per cent; April 1996: $\Delta = -5.0$ per cent and August: $\Delta = -28.4$ per cent.

These results indicate that groundwater underneath the reclaimed site shows a poor quality and does not conform with specified drinking water limits of South African Bureau of Standards (1984) with regard to Ca^{2+}, Mg^{2+}, SO_4^{2-} and NO_3^-. The groundwater shows a predominant Mg-Ca-SO_4 character, which becomes more pronounced with increasing values for total dissolved solids (TDS). The pH is fairly neutral, although high concentrations of total dissolved solids occurred in January 1996 indicating the acid neutralisation capacity of the groundwater (most likely of dolomitic nature) in this particular area. Lower concentrations of total dissolved solids and earth alkali metals in April 1996, in contrast, can be explained with dilution effects as a result of rainfall recharge to the aquifer. No information regarding heavy metals in the groundwater was available. A list of geochemical soil data is provided in Table B.1.

4.6.5.2 Short-term impact

The extractable concentrations of trace elements of all soil samples were determined and extrapolated to the other sites A-G. The calculation of threshold excess revealed that Co, Ni and U exceed significantly the threshold concentration. Co reaches an excess of up to 40, Ni of 72.5 and U of 118.75. The latter due to a very high mobility of 6.4 per cent at pH values between 3-4. Low threshold excess was found for Cu, Pb and Zn due to relatively low total concentrations. However, the mobility as shown in the extraction tests is fairly high for these elements.

The soil pH indicates an pH increase with depths from 4.4 to 6.3 and 4.5 to 5.2, respectively in two test pits, whereas the two other test pits showed lower pH values even at greater depths (maximum depth 2.4 m). The fluctuating soil pH conditions might be a result of the spatial variation of buffer minerals within the soil or a localised perched water table.

4.6.5.3 Long-term impact

Site F is moderately contaminated (class II) by Mn, Co and Th while the site is moderately to highly contaminated (class III) by As and Ni, although As seems to have a very low mobility. In addition, U excessively contaminates (class VI) the site. Important to note is that U showed a high mobility, thus becoming easily bio-available to organisms and plants. Groundwater in general is of poor quality, mainly reflected by high total dissolved solid values.

4.6.6 Discussions and conclusions

The mining company is currently in the process of removing residual tailings. However, high mobility of Co and Ni could complicate efforts to establish a self-sustaining vegetation cover, as these metals are known to be phytotoxic. The topsoil shows favourable leaching conditions and soil management measures such as liming would be required to neutralise acids and to improve growth conditions. Lime would also enhance the attenuation capacity of the soil.

Uranium concentrations are unacceptably high and a detailed risk-based site investigation would be necessary to assess the radiological impact on groundwater and plants, and subsequently, the degree of site rehabilitation required. In addition, vadose zone and groundwater monitoring is advised as the future contamination potential (worst-case scenario) of the soil is very high and groundwater underneath the reclaimed site is of poor quality.

4.7 CASE STUDY G

4.7.1 Site location and drainage

The site situated approximately 4 km north-east of the outskirts of Nigel (Figure 1.1). The site covers an area 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 take place in immediate vicinity of the site. The location of the test pits is shown in Figure D.7.

4.7.2 Reclamation and rehabilitation status

The reclamation of tailings dam site G has been completed, except some waste rock material at the south-eastern border. However small volumes of residual tailings material indicate the presence of the former deposit. Vegetation is poorly developed and consists of isolated trees and grass.

4.7.3 Geology

The reclaimed site G is underlain by sedimentary rocks of the Vryheid Formation (sandstone and shale).

4.7.4 Soils

The soils of the site G are represented by the Avalon soil type. Table 4.9 summarises the soil parameters for site G:

TABLE 4.9 - Summary of soil parameters for study site G.

	Field test results							
	Geotechnical parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Colluvium	14.10-24.69	5.78-8.27	1786.21	2.64	0.48	1 x 10^{-9}	SC	4.0-4.8

Table 4.9 continued.

Nodular ferricrete	22.63-31.45	7.60-9.48	1782.53	2.68	0.50	1 x 10^{-9}	SC, CL	6.3-6.9

Note: U.S.C.S. symbols are explained in Table 3.11.

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 between 0.95-1.30 m in all test pits, which could indicate the presence of preferential flow paths.

4.7.5 Assessment of contamination

4.7.5.1 Trace element concentration in soil

Most of the elements show no geochemical pattern except As, having the highest concentrations in the topsoil. Cobalt, Cu and Th exceed the average background value. Chromium, Pb, V and Zn, in contrast show lower concentrations than the average background. A list of geochemical soil data is provided in Table B.1.

4.7.5.2 Short-term impact

Low soil pH values (4.0-4.8) indicate favourable leaching conditions for metals, which is also reflected in one chemical analysis on seepage water from test pit G/2. The results of the chemical analysis are shown in Tables 4.10a and 4.10b.

TABLE 4.10a - Chemical analyses showing macro-chemistry and other parameters of seepage water in test pit G/2.

G/2	**pH**	**EC** mS/m	**TDS** mg/l	**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
	4.9	670	6802	525	257	227	154	207	<0.1	8	4760

Note: Accuracy of the analysis, which is outlined in paragraph 3.3: Δ = -26.4 per cent (high inaccuracy).

TABLE 4.10b - Chemical analyses showing various metal and CN concentrations of seepage water from test pit G/2.

G/2	**As** mg/l	**Cu** mg/l	**CN** mg/l	**Fe** mg/l	**Mn** mg/l	**Ni** mg/l	**Pb** mg/l	**Zn** mg/l
	0.12	0.1	<0.2	431	359	4.4	0.03	0.3

It is apparent that high total dissolved solid values and elevated metal concentrations are caused by leaching from tailings.

4.7.5.3 Long-term impact

Site G is moderately contaminated (class II) by Co using the geochemical load index.

4.7.6 Discussions and conclusions

Soil management measures are not required as the tailings were removed and a grass cover has developed.

The following site information (study sites H-K) was obtained from a literature survey and supplemented with data from mining companies. Only limited extraction test or geochemical soil data were available, thus final conclusions are premature. However, for some of these sites radiological and groundwater data became available and supplemented the following site assessments. The structure of the following paragraphs varies depending on the availability of site-specific data. Those data, which are not referenced, were provided by mining companies and are confidential.

4.8 CASE STUDY H

4.8.1 Site location and drainage

The site is located in the North-West Province, west of Potchefstroom and is isolated from industrial or residential development. The reclaimed investigated site covers an area of approximately 4 ha. The altitude varies between 1373-1560 m above sea level. Predominant drainage mechanism of the site is sheet-wash in southerly direction. The drainage has resulted in portions of a floodplain being covered by fine slimes material originating from the tailings dams. In addition, the residual tailings are heavily eroded and fine material has spread onto farmland in the direction of prevailing wind. The quantity of residual tailings material is estimated at 2 million tons for the entire site (Aucamp, 1997). The position of the auger holes is shown in Figure D.8.

4.8.2 Reclamation and rehabilitation status

The site is not completely reclaimed and significant quantities of residual tailings material remain on site. Three other tailings dams and a waste rock dump are situated within a radius of one km of the investigated site. Vegetation on site comprises poorly developed grassveld and small shrubs. Exotic trees (including *Eucalyptus*) occur around the old mine operations and on top of the disposed material (Aucamp, 1997). The Department of Minerals and Energy currently is developing a rehabilitation plan for the site.

4.8.3 Geology

The entire area is underlain by dolomite (low chert content) of the Oaktree Formation (Aucamp, 1997).

4.8.4 Soil

Three different dolomite residuum soil and rock units were identified. A chert-rich residual dolomite occurring in auger holes H/1 and H/2, a shale horizon occurring in auger hole H/1 and a ferricrete-rich and chert-poor soil horizon in auger holes H/2 and H/3. A geotechnical description of the soil is not possible since these data are not available. However, soil profiling in three auger holes revealed three general soil and rock units, consisting of a chert-rich topsoil, underlain by a sandy clay with a shale horizon and a ferricrete and chert-poor horizon (Aucamp, 1997).

The sandy topsoil, which is mixed with varying amounts of tailings would allow a rapid recharge. This would be enhanced by chert gravel, found in auger hole H/1 up to a depth of approximately 1.50 m. The clayey sand (in auger holes H/2 and H/3) at the interface to the overlying soil is, in contrast, relatively impermeable, enhancing lateral preferential flow. Additionally, lateral preferential flow may occur at the boundary between the sandy clay and nodular ferricrete units (Aucamp, 1997).

4.8.5 Assessment of contamination

4.8.5.1 Radioactive contamination in tailings, soils and sediments

A survey was conducted in the mid 1990s by the Council for Nuclear Safety on the entire site, which covers approximately 43 ha, to assess risks associated with dispersing radioactive material contained in the fine tailings. The results clearly indicate elevated levels of contamination on the mine site, adjoining farmland and in stream sediments significantly above background values. Background values for pristine or uncontaminated soils in the Highveld region vary from 15-75 Bq/kg (or 1.2-5.9 mg/kg) of ^{238}U. Each of its radioactive decay products including ^{226}Ra and

^{232}Th, show a similar range. ^{40}K is a widely distributed naturally occurring radionuclide usually found at levels of a few hundred Bg/kg in soils (Council for Nuclear Safety, 1996). Table 4.11 lists the results for different radionuclides:

Table 4.11 - Solid samples collected in November 1995 around study site H. Samples 1, 3, 5 and 6 were taken from material that has been eroded from the tailings dams.

Sample No.	^{40}**K** Bq/kg	^{226}**Ra** Bq/kg	^{232}**Th** Bq/kg	^{238}**U** Bq/kg	**Sampling medium**
1	770	285	60	200	Fines accumulated in erosion channels
3	590	740	45	1300	Fines in water collected in sump
5	935	1360	100	<400	Sediment on nearby farm land
6	830	200	45	<400	Fines accumulated in erosion channels
7	200	220	100	7100	Sample taken within the vicinity of the site
10	440	145	30	<400	Average tailings sample
11	260	20	20	<100	Background sample taken some distance away on a ploughed field

The contamination depth in soils varies within the topsoil and the deposits (eroded tailings dam material) were particularly thick in the streambed. The Council for Nuclear Safety (1996) concluded that although soils on the nearby farmland and stream sediments are contaminated with radionuclides, the level of activity is relatively low and does not cause an immediate radiation hazard. However, in the long-term the material may disperse and accumulate in certain areas (such as areas situated in the prevailing wind direction) and could cause an unacceptable long-term risk. Further investigations including water analyses are ongoing until a final rehabilitation plan is in place.

4.8.5.2 Groundwater

Two sets of groundwater measurements from one borehole on site are available and are presented in Table 4.12.

Table 4.12 - Groundwater chemistry of the site H (Aucamp, 1997).

Sampling 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	62.3	66.8	30.3	527	310

Note: Accuracy of the analysis, which is outlined in paragraph 3.3: June 1998: Δ = 0.1 per cent (very high accuracy) and July 1998: Δ = -4.1 per cent (high accuracy).

High concentrations of SO_4^{2-} indicate the impact of acid mine drainage on groundwater quality. High concentrations of Ca^{2+} and Mg^+ are a result of the dissolution of dolomitic rock causing neutral pH conditions.

4.8.5.3 Short-term impact

Extraction tests, using the 2 mm particle size fraction, were conducted to assess the current contamination impact. Extractable concentrations of Ni, Zn and Cd in the soil increase where nodular ferricrete is more distinctly developed in the soil. The extractable 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 excess of almost 10. Copper, Ni and Zn pose a hazard in both the ferricrete-poor soil and the ferricrete. Mercury does not pose a hazard, because the mobile portion in soils is very low (Aucamp, 1997).

No hazard rating could be established for this site. However, high concentrations of SO_4^{2-} in groundwater indicate the migration of acid mine drainage into the aquifer. Residual tailings material on the surface would provide a long-term source for further pyrite oxidation and contaminant remobilization.

4.8.6 Discussions and conclusions

The dispersion of tailings material and subsequent accumulation on farmland and in stream sediments as a result of wind erosion, is a concern in terms of agricultural land use. In addition, a variety of trace elements such as Co, Cu, Ni and Zn are extractable and could complicate efforts to establish a self-sustaining vegetation cover on site.

The high levels of trace elements and radionuclides would require a detailed risk-based site investigation (site is here considered as the entire area of approximately 43 ha) as the long-term risks for the groundwater and surface exposure routes (plants, animals, humans and environment) are currently unknown. In addition, vadose zone (pH, redox conditions and trace element concentrations in seepage by using lysimeters) and groundwater monitoring is advised as the future contamination potential (worst-case scenario) of the site seems to be very high and groundwater underneath the reclaimed site shows a poor quality.

The residual tailings material should be covered using an impermeable cover to prevent further wind dispersion of fine tailings and to reduce seepage and, thus minimising acid mine drainage. Soil management measures would be required to neutralise acids and improve growth conditions.

4.9 CASE STUDY I

4.9.1 Site location and drainage

The site is located adjacent to the R23 (Old Heidelberg Road) between Brakpan and Heidelberg (Figure 1.1). A township is situated less than 2 km east of the tailings dam and farming is taking place in the immediate surroundings of the deposit. A perennial stream flows through a wetland system in a north-westerly direction at a distance of less than one km from the western boundary of the site. The area slopes gently in a westerly direction towards the wetland system. Surface run-off is controlled and limited by a drainage collection system surrounding the tailings dam.

4.9.2 Reclamation and rehabilitation status

The tailings dam comprises a southern compartment, which is currently reclaimed and retreated, and a northern compartment (active dam) where gold mine tailings are currently disposed at a rate of approximately 950000 tons/day, using the cycloned deposition approach. Disposal activities commenced in 1985 and will be completed in 2005. The maximum dam wall height of the current active dam is over 60 m and 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 portion, is approximately 1400 ha. No vegetation occurs on the reclaimed site (southern portion) due to the ongoing reclamation operation. A portion of the active slope wall was grassed in order to prevent wind erosion (Figure E.7).

4.9.3 Geology

The tailings dam is mainly underlain by andesitic lava of the Ventersdorp Supergroup, quartzite of the Black Reef Formation, dolomitic rocks of the Oaktree and Monte Christo Formations, sandstone and mudstone of the Dwyka and Vryheid Formations and post-Karoo dolerite intrusions. However, doleritic and dolomitic rocks cover the largest portion of the area.

4.9.4 Field work

The tailings dam is surrounded by monitoring boreholes, which are sampled on a quarterly basis in order to determine the groundwater quality (total dissolved solids, 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. This 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 tests have been conducted to assess the hydrogeological properties of the aquifer underneath the site. As a result, detailed geological and hydrogeological information was available and incorporated into a numerical groundwater model.

4.9.5 Soils

The following soil types occurred on the active dam site and were identified during the geotechnical feasibility study.

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

Table 4.13 summarises geotechnical soil parameters for study site I, obtained from geotechnical reports of the mining company:

TABLE 4.13 - Summary of soil parameters for study site I.

	Field test results							
	Geotechnical Parameters				**Derived from geotechnical Parameters**			**Soil pH**
Soil units	Clay content %	Plasticity index PI	Dry density kg/m^3	Specific gravity	Void ratio	Saturated permeability m/s	U.S.C.S. soil group	
Alluvium	15-69 (45.2)	12-44 (31)	-	-	-	0.2-3.1 x 10^{-5}	CH, CL, SC, GC	3.7-5.7
Colluvium	19-68 (44.5)	7-50 (21)	-	-	-	0.2-3.1 x 10^{-5}	CL, CH	-
Residual dolerite	5-64 (33.3)	2-35 (20)	-	-	-	10^{-5}-10^{-7}	GC, CH, CL	-
Residual dolomite	9-62 (44.6)	4-52 (27)	-	-	-	10^{-5}-10^{-7}	CH, CL	-

Note: U.S.C.S. symbols are explained in Table 3.11. Values in brackets are averaged values.

The surficial colluvial, alluvial and residual soils have hydraulic conductivities in the range of between 0.2 and 3.1 x 10^{-5} m/s. The deeper residual soils and weathered bedrock showed varying hydraulic conductivities of between 10^{-5}-10^{-7} m/s. Unweathered to slightly weathered bedrock indicate a permeability in 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.

4.9.6 Aquifer properties

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 dolerite rocks, showing a lower permeability than dolomite, and clayey and silty weathered formations, is present. These areas are generally wet due to seepage.

Farther 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 per cent.

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 (compared to shallow boreholes farther way) and thus indicating that seepage originated from the tailings dam.

4.9.7 Assessment of contamination

4.9.7.1 Chemical properties in soils and groundwater

Geochemical analyses of soil samples collected at various depths on the reclaimed portion of the site yielded low pH values ranging between 3.7-5.7, indicating the effect of acid mine drainage, despite relatively low SO_4^{2-} concentrations varying between 370-760 mg/kg. Relatively low SO_4^{2-} concentrations suggest leaching of the subsoil. Trace element concentrations and pH values in soils are shown in Table 4.14:

TABLE 4.14 - Metal and pH ranges in soils of the reclaimed (southern) portion of site I.

Site I	**pH**	**Cu** mg/kg	**Fe** mg/kg	**Mn** mg/kg	**Zn** mg/kg
	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 indication that the soil is becoming brackish. Groundwater quality data for the shallow and deeper boreholes are listed in Table 4.15a/b:

TABLE 4.15a - Range of groundwater quality in shallow boreholes of site I.

Shallow groundwater	**pH**	**EC** mS/m	**TDS** mg/l	**Ca** mg/l	**Mg** mg/l	**Cl** mg/l	**SO_4** mg/l	**CN** mg/l	**Fe** mg/l	**Mn** mg/l
Apr. 1995										
MIN	6.2	109	1098	45	6	30	356	< 0.5	n. a.	< 0.1
MAX	7.8	707	7560	539	780	958	3735	5.0	n. a.	4.3
AVG	7.1	301	3585	321	173	247	1557	1.6	n. a.	1.0
Aug. 1995										
MIN	6.1	83	540	74	58	40	264	n. a.	0.3	< 0.1
MAX	7.7	1220	8892	651	1025	2245	5057	n. a.	66.0	23
AVG	7.0	357	2350	389	268	309	1690	n. a.	14.8	5.0
Nov. 1995										
MIN	6.3	107	612	1	4	48	383	n. a.	< 0.1	< 0.1
MAX	8.1	427	4410	526	744	1783	4153	n. a.	3.9	21.0
AVG	6.6	266	2404	309	290	310	1928	n. a.	0.6	2.6

Table 4.15a continued.

Apr. 1996										
MIN	6.3	107	612	20	121	57	302	n. a.	< 0.1	< 0.1
MAX	8.1	1038	8932	436	776	1801	4295	n. a.	2.6	24.7
AVG	6.6	306	2822	222	283	288	1783	n. a.	0.3	4.0

Note: n. a. means not available. Cyanide (CN) concentrations refer to free CN.

TABLE 4.15b - Range of groundwater quality in deeper boreholes of site I.

Deeper groundwater	**pH**	**EC** mS/m	**TDS** mg/l	**Ca** mg/l	**Mg** mg/l	**Cl** mg/l	**SO$_4$** mg/l	**CN** mg/l	**Fe** mg/l	**Mn** mg/l
Apr. 1995										
MIN	6.8	31	270	22	4	8	31	< 0.5	n. a.	< 0.1
MAX	8.4	785	6510	601	863	1108	3751	4.2	n. a.	29.3
AVG	7.3	269	2402	291	119	217	1418	0.7	n. a.	4.4
Aug. 1995										
MIN	6.2	35	256	73	19	8	35	n. a.	n. d.	< 0.1
MAX	7.9	951	7008	757	796	1516	4015	n. a.	73.0	28.0
AVG	7.0	310	2278	381	216	244	1456	n. a.	14.0	5.0
Nov. 1995										
MIN	6.6	27	188	27	26	12	43	n. a.	< 0.1	< 0.1
MAX	8.5	749	7414	1448	750	1166	3254	n. a.	10.7	21.0
AVG	6.0	262	2555	329	219	180	1123	n. a.	1.1	2.6
Apr. 1996										
MIN	6.6	27	188	27	26	12	43	n. a.	< 0.1	< 0.1
MAX	7.9	622	4874	426	444	1026	2919	n. a.	65.0	4.5
AVG	6.8	236	2058	193	220	190	1230	n. a.	5.8	1.2

Note: n. a. means not available and n. d. means below detection limit. Cyanide (CN) refers to free CN.

The high concentrations of total dissolved solids (TDS) in shallow and deeper groundwater are a result of seepage from the pond, containing high loads of SO_4^{2-} and Cl^-. Considerable concentrations of Ca^{2+} and Mg^{2+} are caused by the dissolution of dolomitic aquifer material, leading to fairly neutral pH conditions. There is no distinctive trend indicating a polluted shallow aquifer and a less polluted groundwater deeper system.

4.9.7.2 Radioactive contamination in surface and groundwater

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 within recommended concentrations of DWAF for domestic use (1996a) and agricultural use (1996d).

4.9.7.3 Short-term impact

Generally, samples from the shallow boreholes show higher total dissolved solid, SO_4^{2-}, Na^+ and Cl^- concentrations than those obtained from the deeper monitoring boreholes. As a result, most of the groundwater samples obtained during the monitoring survey show a predominant Ca-Mg-SO_4 signature, which is typical of water affected by acid mine drainage.

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

The shallow and deep boreholes in close proximity to the tailings dam exceed the crisis limits for SO_4^{2-} of 1200 mg/l, whilst those further away show concentrations which fall between maximum permissible of 600 mg/l and the crisis limit of 1200 mg/kg (South African Bureau of Standards, 1984). Heavy metal analyses were conducted on a random 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 (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 acid mine drainage.

4.9.7.4 Long-term impact

A numerical groundwater model was applied to estimate the degree of future contamination. 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 using 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 per cent of the total salt load of the nearby river. It is estimated that salts in seepage would contribute less than 2.5 per cent to the total salt load after 50 years.

In conclusion, 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.

4.9.8 Discussions and conclusions

The development of a groundwater mound underneath the active dam is of major concern as contaminants can migrate from the pond directly into the dolomitic aquifer without or insufficient attenuation. The Ca-Mg-SO_4 signature of groundwater underneath and in close proximity to the active tailings dam clearly indicates such migration. High hydraulic conductivities along rock fractures and fissures would allow rapid dispersing of contaminants, and thus causing risks in the long-term.

However, a detailed site investigation was conducted and a water quality monitoring program is ongoing. New monitoring data should be implemented into the present groundwater model (as part of the risk management), which allows verifying and refining predicted scenarios. It is anticipated that after decommissioning of the slurry disposal (in the year 2005) on the active dam site, the surface will be covered with an impermeable soil layer to prevent wind erosion (which is currently significant) and to minimise rainfall infiltration.

It must be noted that portions of the slope wall are already covered with soil (Fig. E.7, Appendix E) and the mining company is currently assessing various cover options. It is recommended to investigate the reclaimed portion of the site in more detail, as the presence of phytotoxic elements is most likely, complicating efforts to establish a self-sustaining vegetation cover on this portion of the site. Soil management measures are required to improve growth conditions and to enhance the attenuation capacity of the soil.

4.10 CASES STUDY J

4.10.1 Site location and drainage

Site J is located south of Brakpan (Figure 1.1), in the immediate vicinity of a wetland system on its western border and covers an area of approximately 117 ha. A large township is located approximately 2 km from the eastern border of the site. The wetland extends from the western border of site J along a non-perennial stream, and terminates at the confluence with another perennial stream, which eventually drains into the Vaal dam. Drainage direction is south-westerly towards the wetland system.

4.10.2 Reclamation and rehabilitation status

The site is currently in the process of reclamation and a small quantity of tailings remains on surface. Vegetation, comprising some trees is poorly developed.

4.10.3 Geology

The tailings dam area is underlain by sedimentary rocks of the Dwyka Formation (diamictite and shale).

4.10.4 Field work

A geochemical pollution study was conducted in the wetland system next to the tailings dam, indicating acid mine drainage escape from this study site. Soil samples were taken at five different sampling points down-gradient of the site. Twenty one vibracore holes were drilled up to a maximum depth of 2 m 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 operating mining company 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 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 up-gradient of the site.

4.10.5 Soils

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 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 down-gradient of the site consist of a mixture of soil and yellow oxidised tailings underlain by a red to dark brown clayey soil (due to ferric oxides) with abundant ferruginous concretions. The clay consists predominantly of kaolinite at shallow depths and montmorillonite at greater depths.

Owing to a lack of geotechnical data, no hydrogeological characterisation of the unsaturated zone was possible.

4.10.6 Aquifer conditions

No water table was encountered up to a maximum drilling depth of 40 m. In addition, no aquifer information was available for the borehole approximately 300 m up-gradient 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 below ground surface 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.

4.10.7 Assessment of contamination

4.10.7.1 Chemistry of surface water

The average concentrations of surface water samples from Rand Water, collected approximately 1.5 km downstream of site J are shown in Table 4.16.

Table 4.16 - Average values for selected water quality parameters 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
	6.4	220	1907	559	124	242	42	1797

It is evident that the high SO_4^{2-} content suggests the release of acid mine drainage and associated contaminants (e.g. Fe, Mn and Ni) from study site J. Table 4.17 presents a selection of average metal concentrations at the same sampling point. Cobalt, Mn and Ni exceed the crisis limit value significantly and indicate the high mobility of these elements under nearly neutral pH conditions. Soil and sediment samples downstream of the tailings dam contain significant concentrations of metals.

Table 4.17 - Average metal 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 limit according to Aucamp & Vivier (1987).

Parameter	**As** mg/l	**Co** mg/l	**Cr** mg/l	**Cu** mg/l	**Fe** mg/l	**Mn** mg/l	**Ni** mg/l
Sampling	0.0008	2.8	0.003	0.13	0.01	14	13.4
Crisis limit	0.6	1	0.4	2	2	2	1

Table 4.18 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.

TABLE 4.18 - Surface water quality with increasing distances downstream of tailings dam site J. All concentrations in mg/l.

Distance Downstream	**pH**	**Eh** mV	**EC** mS/m	**SO_4**	**HCO_3**	**Ca**	**Co**	**Fe**	**Mn**	**Zn**
2 km (a)	5.8	94.4	320	1517	18.9	564	4	< 1	21	16
2.5 km (b)	5.4	118.7	310	1428	15.7	561	4	< 1	22	13
5.0 km (c) before confluence	6.6	48.7	210	759	91.1	289	< 1	< 1	6	< 5
7.0 km (d) after confluence	7.4	5.8	200	893	116.3	273	< 1	< 1	< 1	< 5

The table above indicates the improvement in water quality as the distance to the tailings dam from the study site increases. Although the pH becomes fairly neutral at sampling point (d), SO_4^{2-} concentrations still exceed the maximum allowable concentration of 600 mg/l (South African Bureau of Standards, 1984). Thus, water treatment needs to be considered before using the water for domestic or agricultural purposes. High Ca^{2+} concentrations might be caused by lime treatment of slime, which causes a rise of pH. Metal concentrations of Mn and Zn decrease significantly farther downstream as a result of dilution effects. Redox conditions (Eh values) indicate a slight oxidising milieu. Rivers and streams show generally Eh values in the order of 400 mV.

4.10.7.2 Radioactive contamination

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. Total α-activity was about 2 Bq/l downstream of tailings dam site J, (corresponding to sample (a) in Table 4-18) and 0.4 Bq/l approximately 5 km downstream (similar to sampling point (c) in Table 4-18), thus indicating a significant decrease of concentration caused by dilution and adsorption on organic material such as peat.

4.10.7.3 Short-term impact

Peat samples downstream of the tailings dam at site J contain very high concentrations of trace elements as a result of adsorption. Results for some trace elements are shown in Table 4.19:

TABLE 4.19 - Trace element concentrations in a peat sample near site J.

Element	**Cd** mg/kg	**Co** mg/kg	**Cu** mg/kg	**Pb** mg/kg	**Zn** mg/kg	**Th** mg/kg	**U** mg/kg
	25	946	438	261	931	110	195

It is apparent from Table 4.20 that all considered trace elements occur in anomalous concentrations in soil samples affected by seepage from tailings dam site J.

TABLE 4.20 - Trace element concentrations of 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	2040	6117	1071	713	17844	247	10516
AVG	455	582	274	340	1882	69	1095
Standard deviation	523	1096	290	194	2948	55	1744
Factor above average background	21	42	7.9	2.6	41.8	4.6	10.6

Affected soils, sediments, peat and the wetland systems act as a metal pool downstream of the tailings dam, accumulating considerable amounts of metals, because heavy metals seem to be immobilised under prevailing pH (fairly neutral) conditions and the presence of organic material. Sulphate-reducing bacteria in the peat may also lead to precipitation of chalcophile elements from solution as sulphides.

4.10.8 Discussions and conclusions

The extremely high metal concentrations in soils and sediments down-gradient of the study site J pose a long-term environmental risk. Phytotoxic elements such as Co and Ni in soils and sediments would complicate efforts to establish a self-sustaining vegetation cover, even if only a minor portion of the total element concentration is mobile.

A detailed risk-based site investigation is recommended, which should extend to the affected soils and sediments down-gradient of the site. In addition, vadose zone monitoring is advised, as the future contamination potential (worst-case scenario) of affected soils and sediments is considerably high.

4.11 CASE STUDY K

4.11.1 Site location and drainage

Site K is situated north of Springs in immediate vicinity of a large tailings dam (Figure 1.1). The tailings dam covers an area of approximately 111 ha and 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.

4.11.2 Reclamation and rehabilitation status

The tailings dam was used for the disposal of slurry during the period 1969 to 1994. Since 1994 the tailings dam has been in the process of reclamation. The current reclamation status is estimated with 15 per cent of the total volume having been reclaimed. No vegetation occurs on site K.

4.11.3 Geology

The northern part of the tailings dam is underlain by dolomite, whilst the southern part is underlain by Karoo sedimentary rocks (the formation is not known). 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 dolerite sill with 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.

4.11.4 Field work

A number of boreholes have been drilled in order to monitor the groundwater quality (on a quarterly basis) affected by acid mine drainage released from the tailings dam as well as to abstract contaminated groundwater down-gradient of the site.

4.11.5 Soils

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 to depths between 2-5 m. Clayey sands dominate the unsaturated zone to a depth of a few metres.

4.11.6 Aquifer conditions

A perched aquifer was encountered at a general depth of 3 m. A permeability test on a sample taken from a depth of 1.8 m above the perched aquifer indicated a very low hydraulic conductivity in the order of 10^{-10} m/s.

Furthermore, three different aquifers have been identified in the course of a detailed groundwater study:

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

4.11.7 Assessment of contamination

4.11.7.1 Short-term impact

The impact and extent of soil contamination underneath the study site is unknown since only a minor portion has been reclaimed. However, only limited groundwater quality data were available.

High SO_4^{2-} concentrations (range of 1000-2800 mg/l) in abstraction and monitoring boreholes around and on the site indicate the impact of acid mine drainage released from the tailings dam. The pH values are neutral to slightly alkaline with an average value of 7.9 in groundwater samples collected beneath the tailings dam, indicating the presence of buffer minerals and the effect of recharge. Cobalt, Cu, Fe, Ni, Mn, Zn concentrations measured from groundwater samples and sampled from piezometers in the dolomitic aquifer are below the recommended maximum limit (South African Bureau of Standards, 1984) for domestic use. Sulphate concentrations range 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 study site show significantly higher concentrations with respect to Co, Cu, Fe, Ni and Mn than those sampled in the dolomitic aquifer. The pH is extremely low (around 2) resulting in the dissolution of metals. Total dissolved solids concentrations are extremely high in these samples and reach a mean of 14600 mg/l reflecting high salt loads. Hence, the fairly neutral pH in the groundwater is caused by the high buffer capacity of the dolomitic groundwater in the area. Metal mobility is relatively low under these pH conditions, despite high salt concentrations.

4.11.7.2 Long-term impact

A numerical groundwater model was used to assess the future contamination 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 remobilization of contaminants or the seepage from residual paddocks, have not been included in the model. The impact of remobilization of contaminants is considered to be likely to be short-term only, based on the results of the model. Additionally, the effect of paddocks on groundwater quality is not likely to result in a considerable redistribution of contaminants.

4.11.8 Discussions and conclusions

Vadose zone monitoring on the reclaimed portion and groundwater monitoring up- and down-gradient of the study site is advised as the future contamination is likely to be high. This is already indicated by contaminated groundwater underneath the site.

The removal of the remaining tailings might improve water quality in the long-term, but a risk-based site investigation is recommended once the reclamation is completed. New monitoring data should be integrated into the present groundwater model to verify and to refine predicted scenarios.

5 ENVIRONMENTAL IMPACT ASSESSMENT

5.1 INTRODUCTION

The unsaturated zone is considered to be both a barrier (geochemical and physical) and a pathway between the primary contamination source (i.e. tailings dam) and the receiving aquifer. Consequently, the properties of the unsaturated zone define the degree of aquifer vulnerability. Water movement and contaminant attenuation conditions have the potential to mitigate the contamination of the groundwater system. However, once this barrier has become contaminated, it can also act as a source for ongoing groundwater contamination. Figure 5.1 illustrates the various contaminant pathways of tailings impoundments.

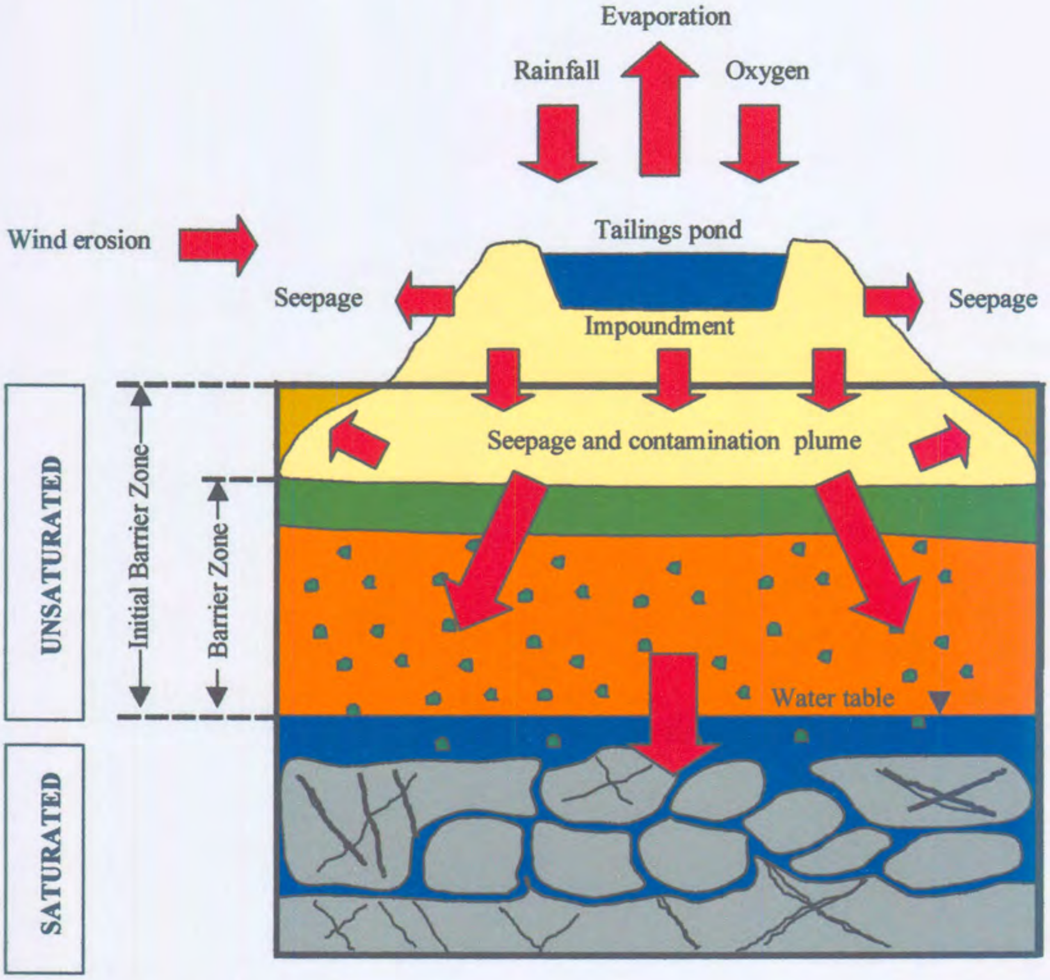


FIG. 5.1 - Conceptual model of a cross-section of a tailings impoundment depicting various contaminant pathways (modified after Parsons & Jolly, 1994).

In most mining operations it is common practice to discharge all contaminated effluents from the ore processing facility to the tailings impoundment. Therefore, minimising the quantity of ponded water escaping from the impoundment will be necessary to avoid pollution, and forms an integral part of best practice environmental management.

5.2 CHARACTERISATION OF THE PRIMARY CONTAMINATION SOURCE

The major and trace element chemistry of five different tailings dams, situated in the East Rand area south-east of Johannesburg is shown in Tables 2.6a and 2.6b. Samples were collected at different gold mine tailings dams from the oxidised zone up to a maximum depth of approximately one metre. It was found that gold mine tailings contain significant concentrations of trace elements. In addition, the mobility of various trace elements in 13 tailings samples was investigated. The extractable concentrations and the relevant threshold value for soils are presented in Table 5.1.

TABLE 5.1 - Extractable elements in gold mine tailings (1 M NH_4NO_3 soil extraction method). Samples were obtained from five different tailings dams in the East Rand area (n=13). Extraction test data for tailings are summarised in Table B-4. Threshold values for soils after Prüeß et al. (1991).

Element mg/l	**25th percentile value**	**75th percentile value**	**Threshold for soils**
As	n. d.	n. d.	0.1
Ca	860	1770	n.a.
Co	1	17.5	0.5
Cr	n. d.	2.25	0.1
Cu	2.5	12.52	2
Fe	2.5	55	n.a.
Mg	72.5	802.5	n.a.
Mn	2.5	27.5	n.a.
Ni	2.5	57.5	1
Pb	n. d.	0.5	2
S	1257.5	4837.5	n.a.
U	n. d.	n. d.	0.04
Zn	1.5	27.5	10

Note: n.d. means not detectable and n.a. information not available.

The extractable portions of Co, Cr, Cu, Ni, Pb and Zn in the bulk of the tailings samples exceed the threshold value for soils. High concentrations of S (maximum > 10000 mg/l) in the leachate indicate the oxidation of sulphide minerals such as pyrite resulting in acid mine drainage. It can be summarised that all investigated reclaimed sites have shown soils with elevated concentrations of contaminants, which are typically contained in tailings material. This clearly indicates the escape of acid mine drainage and associated contaminants from the impoundment into the unsaturated and 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 phytotoxic effects.

It is interesting to note that no correlation was found between total element concentrations and sampling depth within the oxidised zone of the investigated tailings dams in the East Rand area (Rösner et al., 1998). Steffen, Robertson & Kirsten (1988) reported similar findings.

5.3 SHORT-TERM IMPACT ON THE SUBSURFACE

5.3.1 Unsaturated zone (vadose zone)

The soil underneath reclaimed tailings dams has been contaminated with various trace elements and salts. Table 5.2 summarises the trace element and Fe concentrations in soils underneath the reclaimed study sites. Average background values for the relevant geological units (Vryheid Formation and Malmani Subgroup) are listed in Table 3.10.

TABLE 5.2 - Trace element concentrations in soils underneath the study sites (n=81). Underlined values indicate more than a two-fold excess of the relevant average background value.

Element		Study sites (75th percentile values)						
		A	B	C	D	E	F	G
As	mg/kg	53.5	19.8	26.3	24.5	22.8	28.8	40.0
Co	mg/kg	15.0	33.0	40.5	52.5	33.3	26.3	21.3
Cr	mg/kg	346.0	351.0	252.8	192.8	303.0	208.3	129.8
Cu	mg/kg	81.5	131.3	51.0	93.8	53.5	64.3	42.25
Fe	%	10.6	13.0	10.5	9.6	7.6	8.53	4.5
Ni	mg/kg	72.5	158.0	76.3	111.8	85.5	144.0	73.0
Pb	mg/kg	23.25	13.5	18.0	21.0	21.0	10.8	4.8
Zn	mg/kg	75.0	93.8	38.8	53.3	57.8	84.5	44.0
Th	mg/kg	14.8	18.3	18.8	18.0	17.0	20.0	19.3
U	mg/kg	10.8	n. d.	8.0	n. d.	n. d.	818.0	n. d.

The 75th percentile values (Table 5.2) for some elements significantly exceed the average background value for the relevant lithological unit (Table 3.10). However, the total element concentration is a poor reflection of trace element bio-availability. Therefore, Table 5.3 summarises the results of the soil extraction compared with a given threshold concentration after Prüeß et al. (1991):

TABLE 5.3 - Threshold excess ratio of trace elements in soil samples of study site F (n = 16). Extraction test data for soils are summarised in Table B.5 (Appendix B).

	As	Co	Cr	Cu	Ni	Pb	U	Zn
MAX	0	40.0	12.5	3.8	77.5	0.5	1500.0	6.3
AVG	0	8.1	0	0.35	14.8	0	105.1	1.3
Number of samples with ratio > 1	0	10	1	5	11	2	3	10

Extractable concentrations of Co, Ni and Zn exceed their threshold values for soils in more than 50 per cent 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 excess with depth as a result of a reduced vertical migration (attenuation).

Furthermore, Cr, Pb and U exceed the threshold in at least one soil sample. Uranium exceeds the threshold to the greatest extent, being 1500 times above the threshold concentration in one sample at study site F. The high U concentrations emanate from radioactive waste material from an former uranium extraction 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 detection limit of the analytical technique and as such did not exceed the threshold value of 0.1 mg/l. Detection limits for XRF and ICP-MS techniques are presented in Table 3.3a, 3.3b and 3.4, respectively.

The mobility of various elements in soil samples of study site F is shown in Table 5.4. Extractable trace element concentrations are expressed as a percentage of the total element concentration.

TABLE 5.4 - Mobility (in percentage of the total concentration) of elements in soil samples from study site F (n=16). Average values were only calculated if more than two samples showed a value larger than 0 per cent. The MIN values were in all instances below 0.1 per cent mobility. All data are summarised in Table B.6.

	As %	**Co** %	**Cr** %	**Cu** %	**Fe** %	**Ni** %	**Pb** %	**U** %	**Zn** %
MAX	-	66.7	0.5	8.3	19.3	50.7	12.5	6.4	39.1
AVG	-	14.9	-	0.9	1.8	8.6	-	-	11.4

Cobalt, Ni and Zn are the most mobile trace elements and the mobility decreases for each element with increasing soil 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 portions.

Figure 5.2 below shows the relation between soil depth and pH on a site-specific base, where the soil pH increases with increasing depth (best-fit curve). This can be a result of buffering reactions by minerals such as carbonates or alternatively, by a fluctuating shallow groundwater table, which causes mixing and dilution effects with dolomitic groundwater. It is evident that some sites show a more distinct trend (e.g. sites B, E and G) than others.

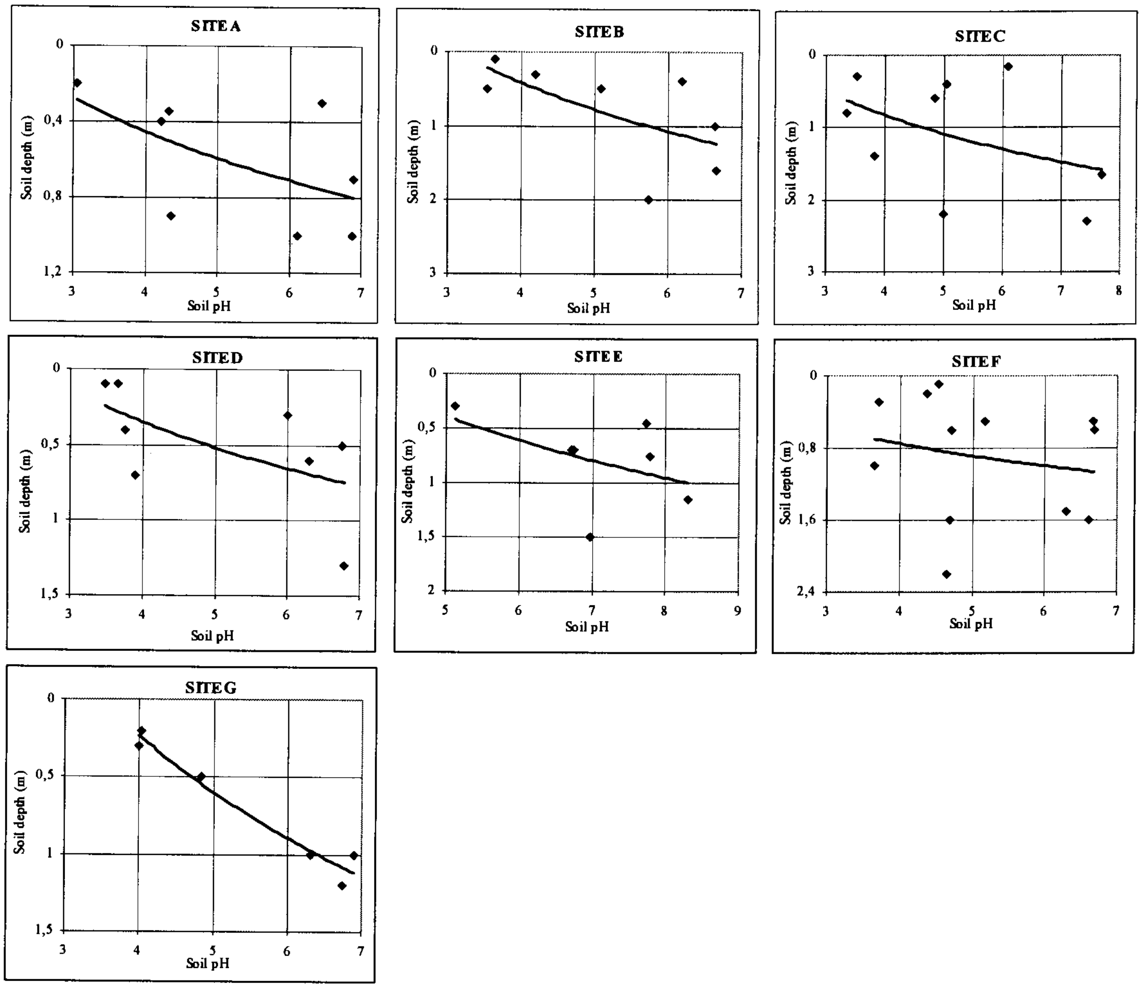


FIG. 5.2 - Relation between soil depth and soil pH on a site-specific base (all sites n=58).

Trace elements can be distinguished by their geochemical behaviour with respect to the ease of solubility and mobility. One of the master variables for dissolution reactions is the soil pH, another one the redox conditions (not determined in this study). Generally, most of the metals dissolve in the acid range (pH below 7) and precipitate under neutral to alkaline conditions (pH above 7) in soils, the exception being the amphoteric metals like Al, As, Cr, Pb, V and Zn.

Figures 5.3a to 5.3h illustrate the element mobility of Co, Cu, Ni, U, Zn, Cr, Pb and Fe as a function of the soil pH. It is evident that considerable dissolution of these elements only takes place at a pH < 4.5, predominantly occurring in the topsoil. Cobalt, 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 trend compared to Co, Ni and Zn. 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.

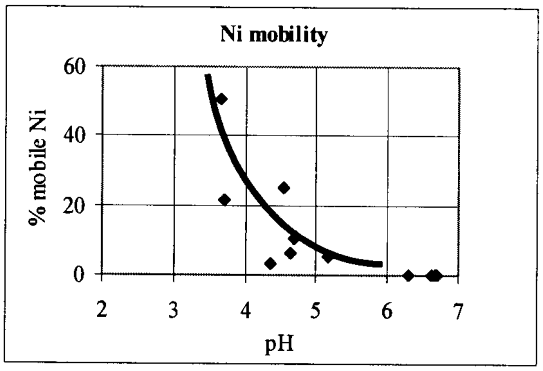


FIG. 5.3a - Ni mobility in soils

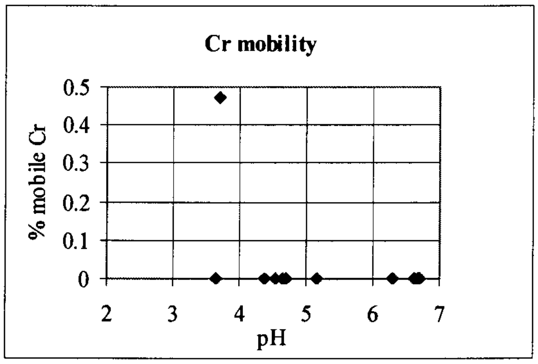


FIG. 5.3b - Cr mobility in soils

Alloway (1995) reported similar findings for Cr (Figure 5.3b), which is contained in the majority of soils and where the relatively insoluble and less mobile Cr^{3+} form predominates and generally occurs as insoluble hydroxides and oxides or even chromite ($FeCr_2O_4$). In addition, the acid character of acid mine drainage-affected soils suggests a rapid reduction from Cr^{6+} to Cr^{3+}, which can substitute Al^{3+} in clay minerals. However, soils of the study area tend to be dominated by kaolinite, which is characterised by a low cation exchange capacity. In addition, Alloway (1995) reports that above a soil pH of 5.5 complete precipitation of Cr^{3+} is likely. Brooks (1987) compared the solubility of Cr and Ni and found that Ni is clearly more mobile than Cr, corresponding to the findings of this study.

The mobility of Ni increases as the pH (Figure 5.3a) and cation exchange capacity decrease (Alloway 1995). Kabata-Pendias (1994) reported that over 60 per cent of Ni in soils may be associated with the residual fraction, approximately 20 per cent with the Fe-Mn oxide fraction and organic matter while the remainder is bound up with the carbonate fraction (Alloway 1995). However, the presence of ferruginous soils caused due to intense weathering and free drainage (Brink, 1985) in the study area suggests that a large portion of Ni is likely to be bound on Fe-hydoxides, whereas organic material is probably absent. In addition, it is well established that the Ni uptake by plants increases as the exchangeable fraction in soils increases due to the acidification caused by acid mine drainage. Hence, 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 (Hutchinson 1981).

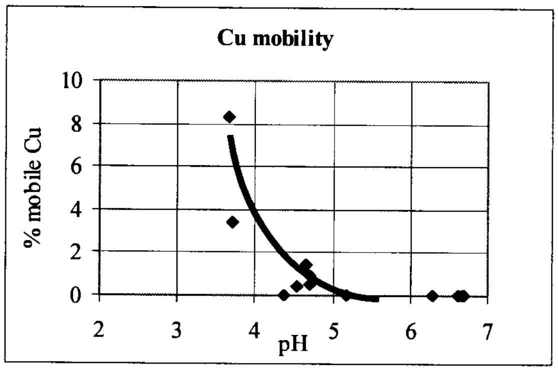


FIG. 5.3c - Cu mobility in soils

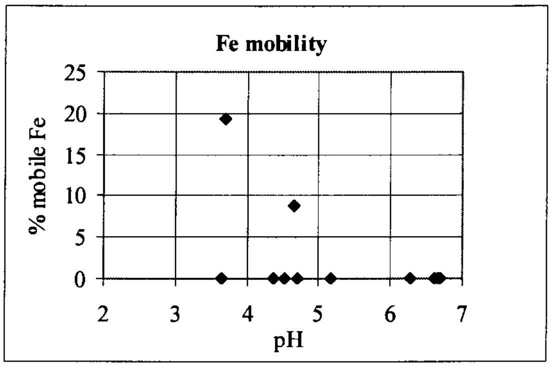


FIG. 5.3d - Fe mobility in soils

Although Cu (Figure 5.3c) is less mobile than Co, Ni and Zn it is important to note that Cu concentration levels of 1.5 to 4.5 mg/kg damage or kill roots of growing plants (Alloway, 1995).

Iron mobility (Figure 5.3d) is very low and significant mobility was only found in two soil samples at a pH < 5. The results correspond to the general immobile character of Fe, where a carrier such as colloids is required to allow migration in soil water/groundwater. It is important to note that Fe-precipitates such as Fe-oxides provide additional adsorption surfaces for other metals within the soil system. Total Fe (measured as Fe_2O_3) concentrations found in soil samples of the study area range from 3-24 weight-per cent and are often associated with the occurrence of ferricretes.

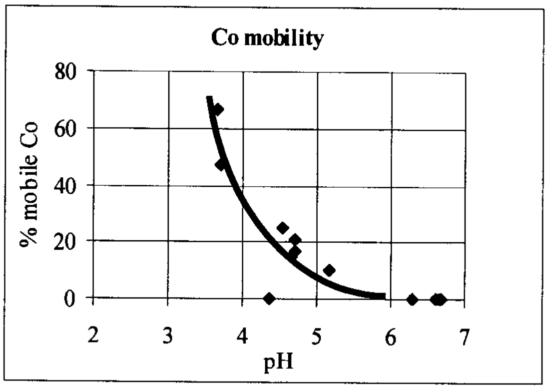


FIG. 5.3e - Co mobility in soils

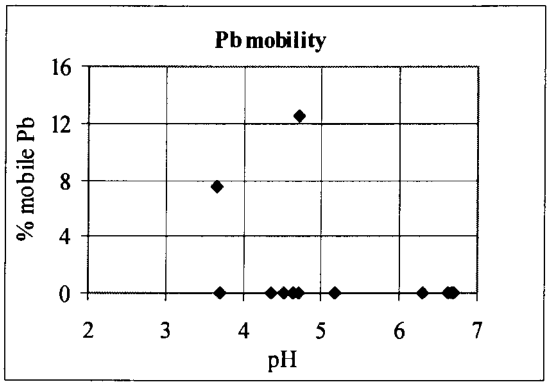


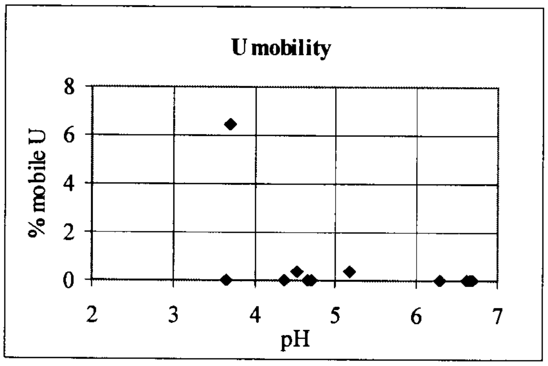
FIG. 5.3f - Pb mobility in soils

Cobalt (Figure 5.3e) shows a very high mobility (pH < 5) up to 67 per cent compared to the solid phase. This would result in a higher plant uptake and is as also reported by

Alloway (1995). Furthermore, Co is often found adsorbed onto Mn minerals such as MnO_2. A positive correlation coefficient of $r = 0.63$ ($n = 81$) was calculated for MnO versus Co, which corresponds with the above observation.

Lead (Figure 5.3f) has a very low mobility in soils, and thus accumulates within the topsoil. Similar observations were made in Finland, Canada and in the United Kingdom by Alloway (1995) who found that soils affected by mining operations show higher accumulations of Pb in topsoils than in unaffected soils, suggesting a low mobility even under acid soil conditions.

The mobility of U (Figure 5.3g) is very low, but three samples showed an elevated mobility occurring only in the topsoil. Uranium mobility is very low and occurs only under strongly acid soil conditions ($pH < 5$). In case of elevated mobility, the threshold excess value of U ranged from 62 to 1500. However, the correlation coefficient between U/As gave a positive coefficient of $r = 0.74$ ($n = 81$), which is also reflected by the immobility of As. The formation of the uranyl cation UO_2^{2+} is the most likely reason for the solubility (e.g. $(UO_2)SO_4$ is soluble) of U over a wide pH range. However, the low mobility of U found in the soil underneath reclaimed tailings deposits could be caused due to a co-precipitation (secondary mineral) with arsenate in the soil (Bowie and Plant, 1983) after U was released from the primary mineral during the operation of the tailings dam.



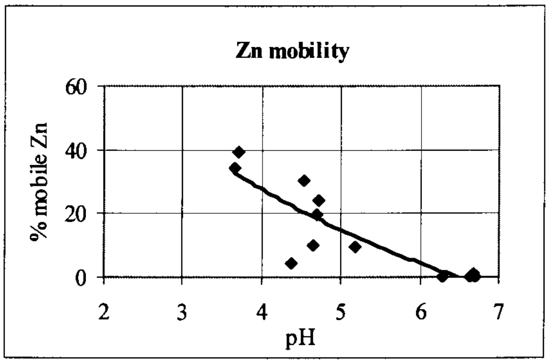


FIG. 5.3g - U mobility in soils

FIG. 5.3h - Zn mobility in soils

Zinc (Figure 5.3h) has a high mobility, where the solubility increases with decreasing soil pH, corresponding with the findings of Kabata-Pendias (1994) for acid soils. Figures 5.4a to 5.4h show element concentrations versus soil depth at the study sites A-G (the dotted reference line indicates the highest average background value).

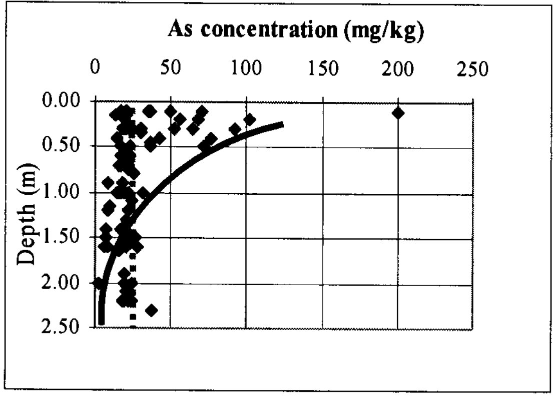


FIG. 5.4a - Total As contents in soils (n=81)

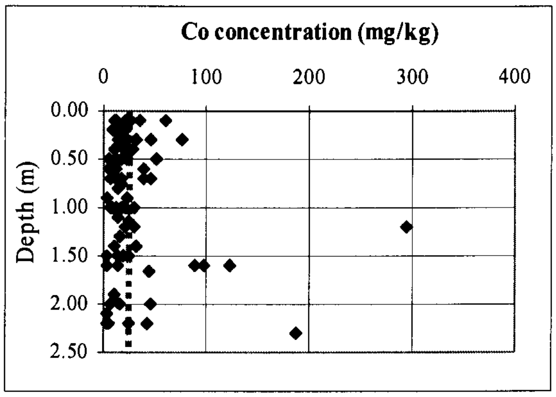


FIG. 5.4b - Total Co contents in soils (n=81)

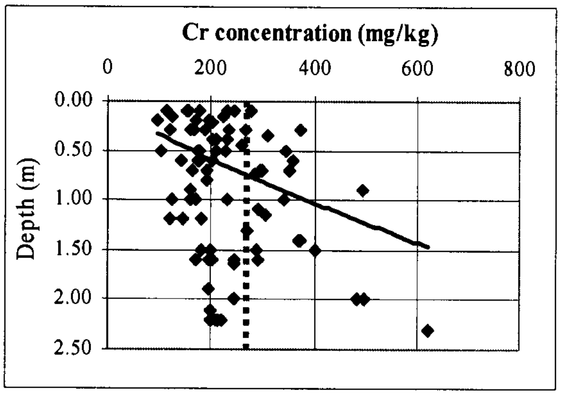


FIG. 5.4c - Total Cr contents in soils (n=81)

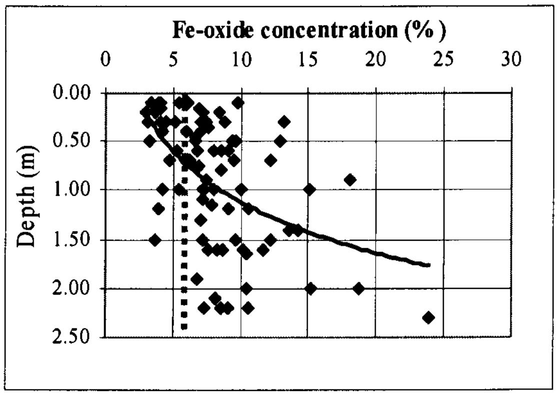


FIG. 5.4d - Total Fe contents in soils (n=81)

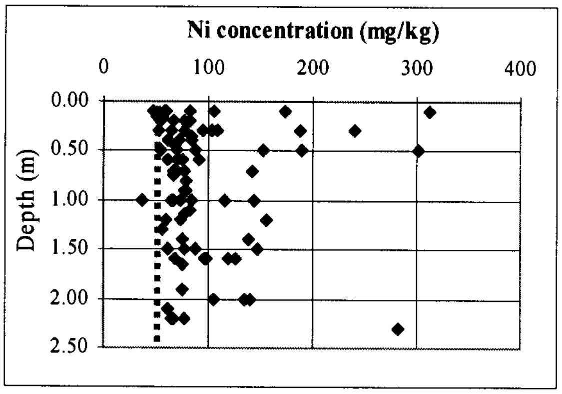


FIG. 5.4e - Total Ni contents in soils (n=81)

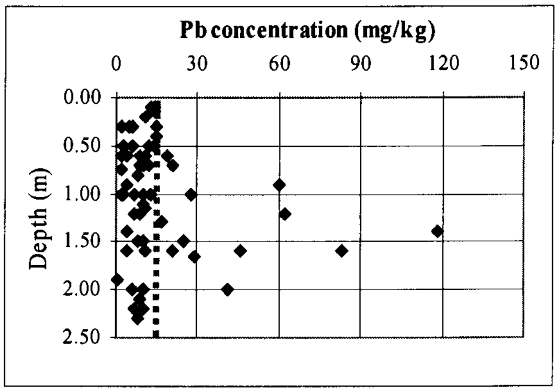


FIG. 5.4f - Total Pb contents in soils (n=81)

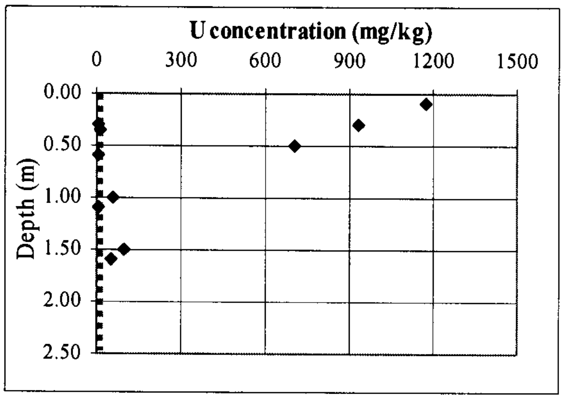


FIG. 5.4g - Total U contents in soils (n=10)

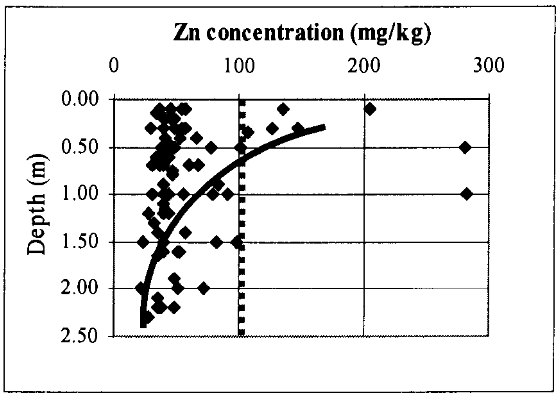


FIG. 5.4h -Total Zn contents in soils (n=81)

Chromium and Fe show a weak linear trend (using best-fit curves) by increasing concentrations with increasing soil depth. However, the trend of As and Zn suggests an exponential decrease in concentration with depth. Furthermore, Co, Ni and Pb show no trend with soil depth, although Co and Ni showed a high mobility using extraction tests. Uranium concentrations are the highest only in the upper soil units. It can be summarised that there is no clear geochemical pattern regarding a correlation between soil depth and total element concentrations as a result of heterogeneous site and soil conditions.

However, highest concentrations seem to occur generally in the upper soil units and depth related element accumulations were found, if single test pits were considered. Although, generally clay minerals have a much higher adsorption capacity for trace elements compared to coarser grain size fractions, no correlation was found between the clay content in soils and total element concentrations indicating the presence of preferential flow paths that bypass matrix flow. It is anticipated that the flow rate under such conditions is high, resulting in a contact time between seepage and solid phase, which is insufficient to allow significant sorption effects for contaminants. Trace element concentrations versus the relevant clay content in soils is shown in the following Figures 5.5a to 5.5d.

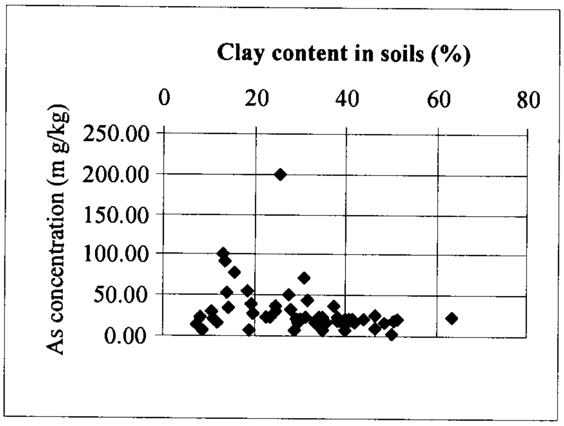


FIG. 5.5a - As content versus clay amount

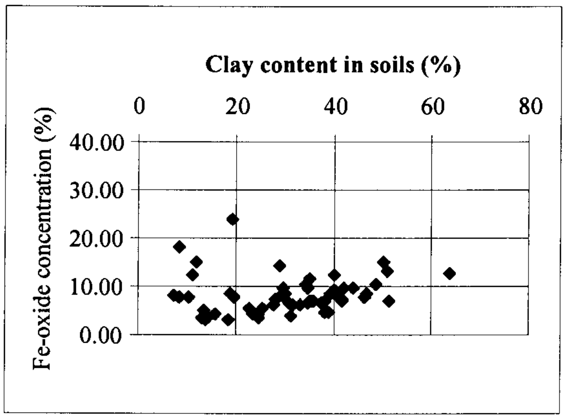


FIG. 5.5b – Fe content versus clay amount

These observations correspond to the findings of Merrington & Alloway (1993) which investigated the properties of heavy metals in soils affected by old iron mines in England.

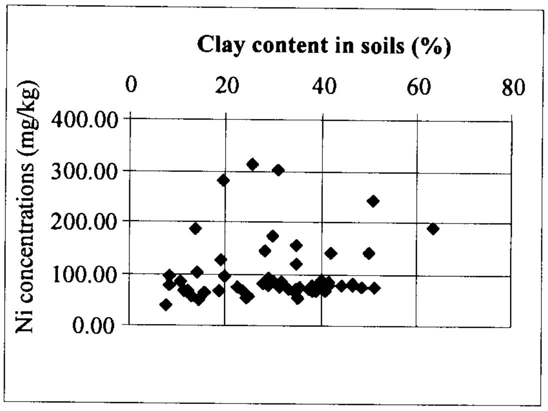


FIG. 5.5c - Ni content versus clay amount

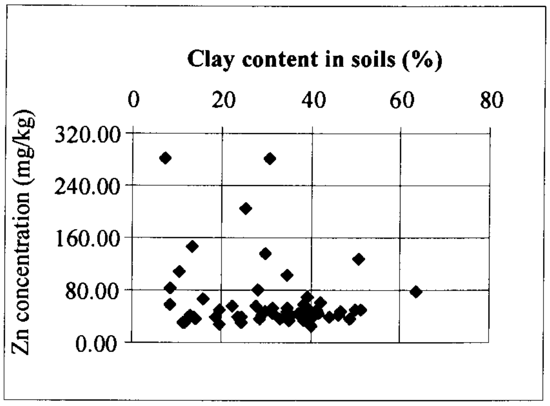


FIG. 5.5d - Zn content versus clay amount

In conclusion, trace element values exceeding threshold concentrations (i.e. 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 pyrite oxidation and the associated generation of acid mine drainage. All of the investigated trace elements are most mobile when pH < 4.5 and least mobile when a soil pH > 6 prevails. Cobalt, Ni and Zn are the most mobile trace elements and phytotoxic, corresponding to 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 (i.e. bound to silicates). Arsenic concentrations were below the lower detection limit in all soil 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 extraction tests were only conducted at one site and further tests would be necessary to confirm and support these findings.

Furthermore, hydraulic conductivities derived from geotechnical properties (estimated from techniques of Mathewson, 1981 and Tavenas et al., 1983) and *in situ* test data indicate a low to very low vertical hydraulic 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, because of their retardation. Soil conditions indicating preferential flow (bypass of the soil matrix) were observed in nearly all test pits, but attempts to identify dominating contaminant migration pathways and mechanisms would be premature and further investigations are necessary.

Extraction tests on gold mining tailings (Table 5.1) have shown high S concentrations contained in the leachate. Hence, incomplete reclamation of tailings would result in an additional reservoir for acid generating processes and contaminant release.

The mitigation of acid mine drainage at greater soil depths may have various reasons such as the presence of acid neutralising minerals (e.g. carbonates) or a seasonal fluctuating groundwater table, which causes dilution (mixing with dolomitic groundwater) effects.

Finally, many countries such as the Netherlands (Ministry of Housing, Physical Planning and Environment, 1997) provide guidelines for soil quality to assess the degree of soil contamination. However, these guidelines were established in Europe and North America, where humid climate conditions, which determine different soil conditions, predominate. No soil protection guidelines are available for climatic conditions such as those experienced in the study area.

5.3.2 Saturated zone (groundwater system)

5.3.2.1 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 total dissolved solid 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). Scott (1995) 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 total dissolved solid concentrations indicates discharge areas (Palmer, 1992), but in the case of the study area, it is more likely to indicate acid mine drainage-related pollution. Although the relative proportions of cations in this groundwater remain similar to those of unaffected groundwater, the anion signature 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 study 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 occasionally contain 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 would cause a SO_4-dominated water type in dolomitic aquifers.

5.3.2.2 Groundwater quality in the study area

Groundwater quality beneath and in close vicinity of 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 general, groundwater quality seems to improve further down-gradient of the tailings dams and reclaimed sites as a result of dilution effects and the high acid neutralisation capacity of the dolomitic aquifer. However, groundwater quality in close proximity to the sites is characterised by elevated metal (e.g. As, Cd, Co, Fe, Mn and Ni) and total CN concentrations, occasionally exceeding drinking water standards in boreholes. Sulphate concentrations are often very high in the immediate vicinity to the tailings dam (generally > 2000 mg/l, but up to 4000 mg/l).

Water in perched or shallow aquifers is of very poor quality. Table 5.5 shows the seepage water quality of the case study sites C and G and in an old open mine shaft next to a tailings dam, which is situated about 1.7 km south-east of Duduza (Figure E.9). For comparison, these data are supplemented with pond water qualities from gold tailings operations in Arizona, USA.

Table 5.5 - Seepage water quality of study sites C and G, an open mine shaft and for comparative reasons of gold tailings operations in Arizona, USA from Lampkin & Sommerfeld (1981).

Parameter		**Average contents at sites C and G**	**Open mine shaft**	**Pond from gold tailings in Arizona, USA**
pH		5.5	2.0	n. a.
Total Alkalinity		178	n. a.	n. a.
Total Hardness		1760.5	1695	n. a.
TDS	mg/l	4508	4386	n. a.
EC	mS/m	489.5	516.0	n. a.
SO_4	mg/l	2883	2975	n. a.
Cl	mg/l	271.5	223	n. a.
NO_3	mg/l	< 0.1	<0.1	n. a.
F	mg/l	0.4	0.6	n. a.
Al	mg/l	1.5	86.3	n. a.
As	mg/l	0.12	< 0.10	n. a.
Ca	mg/l	372	453	176.4
CN	mg/l	< 0.2	2.2	n. a.
Cu	mg/l	0.1	1.2	21.0
Fe	mg/l	217.1	98.1	109.1
K	mg/l	79.7	43.6	1.5
Mg	mg/l	202	137	53.1
Mn	mg/l	179.9	29.2	16.1
Na	mg/l	244.5	279.0	13.4

Table 5.5 continued.

Ni	mg/l	2.3	16.9	n. a.
Pb	mg/l	0.03	0.02	n. a.
Zn	mg/l	0.2	3.3	115.6

Note: n. a. means information not available. Accuracy of the analysis, which is outlined in paragraph 3.3, for open mine shaft: Δ -18.3 per cent (high inaccuracy).

It is apparent that SO_4^{2-} as well as some metals (e.g. As, Fe, Mn, Ni, Pb and Zn) and CN exceed the recommended target water quality standards. The pH in the seepage of the old open mine shaft is extremely low and enhances metal leaching. As a result some metal concentrations such as Fe and Mn are substantially lower due to precipitation as hydroxides. Even if the topsoil would be treated with lime and fertilisers (e.g. superphosphate) in order to achieve suitable soil conditions for plant growth, it may take a long time until groundwater quality will gradually improve. Finally, 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.

5.3.2.3 Estimation of seepage and sulphate loads

A load estimation was undertaken in order to assess the annual discharge of seepage and SO_4^{2-} from the reclaimed sites in South Africa into the groundwater system. Rösner et al. (1998) have shown that the total area of land affected by reclaimed gold mine tailings amounts to approximately 13 km^2. All these sites are situated within the Vaal Barrage catchment system, which plays a major role for water supply of the Johannesburg region. Vegter (1984) estimated a net recharge value of 12.5 per cent of the annual rainfall for the Gauteng Province, which equals 80-100 mm recharge per year (Vegter, 1984).

Thus, the load estimation can be expressed as:

1. Conversion of recharge/year (i.e. 80 mm/year) into an area size. Method after Hölting (1996).

$$\textit{80 mm recharge/year equals } 2.536\ l/(s \cdot km^2) \qquad [5.1]$$

2. Conversion of recharge value from seconds per km^2 to year per km^2

$$2.536 \frac{l}{s \cdot km^2} = 79.97 \cdot 10^6 \frac{l}{year \cdot km^2} \qquad [5.2]$$

3. Multiplication of recharge value with the relevant area size (i.e. 13 km^2)

$$79.97 \cdot 10^6 \frac{l}{s \cdot km^2} \cdot 13 km^2 = 1.0397 \cdot 10^3 \frac{Ml}{year} \qquad [5.3]$$

The estimation above has shown that the accumulated volumes of seepage amount annually to approximately 1000 Ml. For the SO_4^{2-} load estimation two scenarios with concentrations of 1006 mg/l and 4760 mg/l, respectively were considered. These values were obtained from seepage analyses conducted at study sites C and G (Table 4.4a and 4.10a), respectively and also correspond to measurements at other sites (study sites H and I). The results for the two scenarios are as follows:

1. Scenario: 1046 t SO_4^{2-}/yr for all reclaimed sites (13 km^2) equals 804 kg/ha · yr
2. Scenario: 4949 t SO_4^{2-}/yr for all reclaimed sites (13 km^2) equals 3.81 tons/ha · yr

It should be noted that the process of pyrite oxidation is kinetically controlled and long-term predictions can be only made by using relevant geochemical models. Furthermore, without any site rehabilitation, a load decrease of SO_4^{2-} and associated contaminants will only occur once the source of oxidation (i.e. pyrite) has depleted. In addition, changes in land use might enhance pyrite oxidation, thus resulting in even higher contaminant loads.

It is of great concern that sites, which were reclaimed a long time ago (e.g. study site C, more than 10 years ago) still show very high SO_4^{2-} concentrations in the seepage. However, it is premature to quantify accurately the amount of seepage and subsequently the load of contaminants for all gold mine tailings dam sites in the country. Various attempts have been made in the past (Steffen, Robertson & Kirsten, 1988), but the lack of appropriate long-term water quality data around such tailings dam sites as well as lacking technical information about the sites themselves (e.g. the presence of pollution control measures) result in many unknown parameters.

5.4 LONG-TERM IMPACT ON THE SUBSURFACE

5.4.1 Unsaturated zone

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 risk assessment would be required if land development such as housing is envisaged.

The concentrations of Fe_2O_3 (total), MnO and various trace elements (i.e. 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 according to Müller (1979). Based on the results of this comparison, a table listing contaminants of concern for each site was produced (Table 5.6). This methodology allows the assessment of potential future trace element loads in the investigated soil profiles. Significant contamination is reflected by contamination classes III-VI, where the average background value is considerably exceeded.

TABLE 5.6 - Hazard rating of the study sites by using the geochemical load index system (after Müller (1979).

Hazard rating of the study sites						
Study site	**Class I** None–moderately contaminated	**Class II** Moderately contaminated	**Class III** Moderately–highly contaminated	**Class IV** Highly contaminated	**Class V** High–excessively contaminated	**Class VI** Excessively contaminated
A	Ni, Zn	As, Cr, Cu, Fe, Pb, V	Sn, U	-	-	-
B	As, Cr, Fe, Mo, Th, V, Zn	Cu, Ni	Co	Pb	-	-
C	As, Cr	Cu, Fe, Ni, Mn, Pb, V	-	Co	-	-
D	Cu, Mn, Th	As, Cr, Fe	Ni, Pb	Co, U, V	-	-
E	As, Cr, Cu, Ni, Th, Zn	Co, Fe	Pb, V	-	-	-
F	Fe, Cr, Cu, Mo, V, Zn	Co, Mn , Th	As, Ni	-	-	U
G	As, Ni, Sn	Co	-	-	-	-

Table 5.6 can be summarised as follows:

- Moderately to highly contaminated sites (class III): five sites with respect to the following trace elements: As, Co, Ni, Pb, Sn, V and U. Cobalt and Ni are phytotoxic and, therefore have negative effects on plant growth (Alloway, 1995). High As concentration was only found in one case. However, As is less mobile than other metals and thus, effects are negligible.
- Highly contaminated sites (class IV): three sites with respect to Co, Pb, U and V. Vanadium is not a typical mine tailings contaminant, and enrichment caused by natural processes in association with ferricrete in soils (Figure E.11) is most likely (Németh, Molnár, Csillag, Butjás, Lukács, Pártay, Féher & Van Genuchten, 1993 and Alloway, 1995). High U concentrations were found only at one site.
- One site has been classified as an excessively contaminated site (class VI) as a result of U (measured as U_3O_8) concentrations more than 100-fold above the natural background. It is unlikely that the high U concentrations in the soil emanate from the gold mine tailings, the U concentrations are rather caused by the deposition of radioactive material deposited prior to the construction of the tailings dam.

It can be concluded that the long-term impact of typical mine tailings on soils and groundwater will mainly depend on the availability of minerals with a sufficient acid neutralisation capacity in soils. The ongoing production of SO_4^{2-} and acids are a result of sulphide mineral oxidation by residual tailings material on the surface. When the topsoil becomes highly acidic (pH around 4.5), the acidity starts to migrate into the subsoil. Once the subsoil becomes acidic, only the most acid-tolerant plants can be grown (Fenton, 1997). Acidification of the subsoil is a form of permanent soil degradation and therefore, the primary contamination source should be completely removed from the reclaimed sites in order to minimise further acid and salt generation.

5.4.2 Saturated zone

Only a limited number of tailings dams in South Africa have been investigated in detail with respect to the hydrogeological conditions, including contaminant analysis. One South African mining company applied numerical groundwater models for two tailings dam sites, situated within the study area. The model applications 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 (closure) of tailings operations.

Acid and salt generation in tailings dams and the subsequent impact on the groundwater system can only be mitigated by preventing the moisture and oxygen flux into the impoundment or soil, which can be only achieved by cover systems. Such a cover would also prevent wind erosion and the subsequent dispersion of contaminants in the near surrounding of the deposit or footprint. The models have also shown that deterioration of groundwater quality occurs only in the immediate vicinity of the impoundment. Groundwater quality improves with increasing distance down-gradient of the tailings dam mainly due to dilution and sorption effects. Seepage emanating from tailings dams is, however, likely to affect water quality negatively in nearby surface water systems due to discharge from affected groundwater or surface run-off, which would have an adverse impact on water users in that particular area.

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 reduction of mining operations resulted in a rapid groundwater table recovery in the dolomitic aquifers in the East Rand area. This might affect water courses such as the Blesbokspruit to effluent rather than influent streams in future, characterised by recharge from the aquifers (Scott, 1995). The effect of groundwater recovery cannot be regarded in isolation from the release of acid mine drainage from tailings dams.

6 RISK ASSESSMENT AND REHABILITATION MANAGEMENT

6.1 INTRODUCTION

Rehabilitation is defined as the restoration of a disturbed land area to a landform and productivity which conforms with the landform and productivity of the locality before disturbance took place.

Section 38 of the Minerals Act (50/1991) in South Africa 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;
- 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 of the Department of Minerals and Energy.

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 remediation of the subsurface (soil and groundwater) is of major importance for the mitigation of adverse effects on the aquifer and in order to enable land development. As a result, waste remediation efforts are heavily influenced by statutory and regulatory compliance and in some countries, such as the USA, waste remediation is often dictated 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. However, in case of contaminated sites or footprints, 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).

6.2 RISK ASSESSMENT

6.2.1 Principles and definition

With introduction of the second edition of the *Minimum Requirements for Water Monitoring at Waste Management Facilities,* DWAF (1998) has endorsed a risk-based framework within which contamination at waste facilities can be identified, assessed and environmentally soundly managed.

In this context, the term *risk* has a multitude of uses and is not to be confused with *hazard.* In the context of contaminated land or soils, the term risk is generally defined with the likelihood of human health problems occurring if no clean-up measures were taken at the site (EPA, 1997a). In terms of contaminated sites or land, risks to human health and the environment can be regarded as being comprised of three components (Young, Pollard & Crowcroft, 1998):

- Source, reflecting a toxic substance or group of toxic substances with the potential to cause harm;
- Pathway, reflecting a route by which a receptor could be exposed to, or affected by, the toxic substance(s);
- Receptor, reflecting a particular entity which is being harmed or adversely affected by the toxic substance(s).

The probability of a hazard being realised (i.e. the risk), depends on the conditions of a linkage between these components, including site-specific factors such as the contaminant concentration in the exposure medium, the bio-availability, the ease of access to the exposure pathway and the duration of exposure.

The term of *risk assessment* can be basically defined as an evaluation of the probability of harm and, in context with contaminated sites, is concerned with gathering and interpreting information on the characteristics of sources, pathways and receptors at a specific site and to understand the uncertainties inherent to the ensuing assessment of risk.

The requirements of the risk assessment define the scope of a site investigation and, thus potential remediation measures. In practice, this involves the geochemical characterisation of the contaminant(s), relevant soil properties and groundwater conditions encountered and the site factors that influence contaminant fate and migration.

Because the unsaturated zone is often a physical and geochemical barrier zone between the source of contamination and the receptor (i.e. groundwater), the understanding of the contaminant transfer between these components is an essential prerequisite to the site investigation, risk assessment and the subsequent development of rehabilitation strategy.

6.2.2 Methodology

Four key phases have to be generally assessed as part of a risk assessment according to EPA (1997b). These phases including their practical implementation are described below:

6.2.2.1 Hazard assessment

The hazard assessment is the qualitative evaluation of the adverse health effects of a toxic substance(s) in animals or humans.

Practical implementation: Collection and analysis of samples from different media (i.e. soil, air and/or water, sediments, fish, plants, animals) from and around the site of concern. Development of a *Conceptual Site Model* (method according to the EPA, 1997b) that reflects the site conditions including contaminant sources (current and future land use), release mechanisms (i.e. bio-availability), exposure pathways, migration routes, and potential human and ecological (e.g. groundwater) receptors.

6.2.2.2 Exposure assessment

The exposure assessment is the evaluation of the components, magnitude, time, and duration of actual and anticipated exposures and of doses, when known; and when appropriate, the amount of people who are likely to be exposed.

Practical implementation: Assessment of exposure pathways for contaminants from the source to the receptor via the pathway, whereas contaminants of concern have to be identified in Phase 1. As a result, a *Reasonable Maximum Exposure* (EPA, 1997a) scenario is calculated which reflects the highest level of human exposure that could reasonably be expected to occur from the contaminant identified in Phase 1. This scenario also assesses the duration of exposure time that could occur if no clean-up measures at the site take place. Such an exposure assessment ensures that the selected clean-up or remediation measure protects all people potentially affected by the contaminated site, with a focus on the most vulnerable or sensitive populations (e.g. children). These populations are also termed *critical group*.

6.2.2.3 Dose-response assessment

The dose-response assessment is the process of estimating the relation between the dose of a substance(s) and the incidence of an adverse health effect situation.

Practical implementation: Determination of the toxicity, or harmfulness, of each contaminant identified in Phase 1. It is obvious that the type and intensity of potential health problems depend on the contaminant itself and the duration of exposure. For example, a likely dose could be derived from the consumption of contaminants as a result of drinking polluted water every day for 30 years. The EPA uses two methods to evaluate effects on human health arising from exposure of toxic substances from contaminated sites. One approach calculates the probability of cancer incidents occurring as a result of exposure (e.g. 1 in 10 000 probability). The second method evaluates non-cancer health effects of contaminants from the site (EPA, 1997a).

6.2.2.4 Site risk characterisation

The site risk characterisation is the process of estimating the probable incidence of an adverse health effect to humans under various conditions of exposure, including an assessment of the uncertainties involved (usually a sensitivity analysis).

Practical implementation: Determination of the most critical risks and whether these risks are significant enough to cause negative or adverse effects on health for people living near the site. The results of the three previous Phases 1, 2 and 3 are combined, evaluated and summarised. Figure 6.1 illustrates an example for a risk-based investigation for contaminated sites.

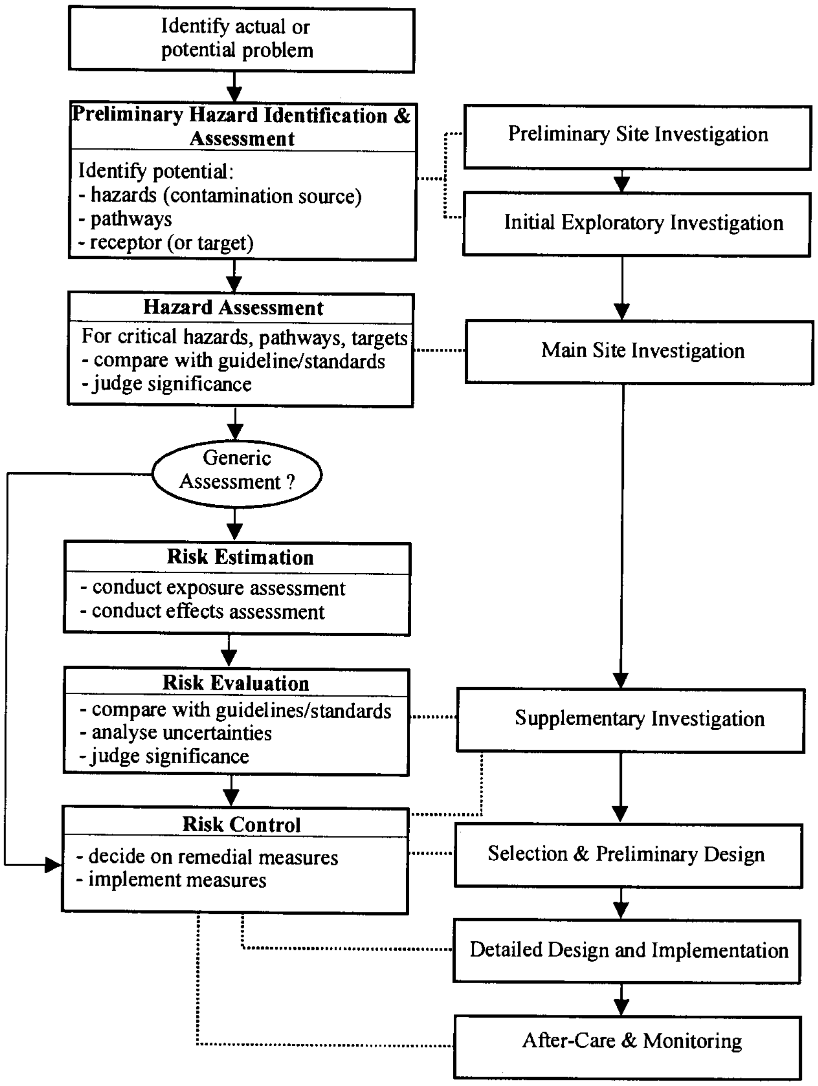


FIG. 6.1- Scheme for a risk-based site assessment
(after Griffiths & Smiths, 1998)

Subsequently, a total site risk is calculated, whereby uncertainties have to be taken into account in order to prioritise decisions on the most efficient clean-up or rehabilitation measures aiming at risk reduction to acceptable levels. The latter is achieved by the application of *Hazard Ranking Systems* and a *Site Ranking Methodology*, which were introduced by the EPA (1997a). A detailed discussion of the application of risk assessment for contaminated sites is given in EPA (1997b) and Skivington (1997).

6.3 REMEDIATION APPROACHES 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:

- 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 to an acceptable level. The TCLP (toxic characteristic leaching procedure) is a protocol used by the 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*). 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 paragraphs will provide a brief introduction of both rehabilitation strategies and their application potential for this type of contamination.

6.3.1 Treatment technologies

Soil 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 aqueous solution, adsorption and remobilization characteristics, size, density, shape of contaminated particles, bio-degradability 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, because metals and metal compounds cannot be destroyed, with the exception of volatile elements such as As and Hg (Rulkens, Grotenhuis & Tichy, 1995). 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 remobilization);
- 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 material, which have been reclaimed. If only the top 30 cm (i.e. topsoil) 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 topsoil would not be sufficient - some contaminants have already reached the groundwater system, indicating that contamination of the subsoil or deeper parts of the unsaturated zone has been occurred.

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 such large quantities of material necessary to address the problem. Therefore, present-day treatment technologies are confined to rehabilitation scenarios where only small volumes of soil are involved.

6.3.2 On-site management

The isolation approach 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 soils affected by acid mine drainage:

- Altering soil pH;
- Increase sorption capacity;
- Precipitation of trace elements as some insoluble phase.

The influence of soil pH, cation exchange capacity, 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 remediation 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 remediation (common situation), changing the soil pH may reduce the mobility of some elements whilst mobilising others such as Mo (Pierzynski et al., 1994). Fenton (1997) reported that the following quantities of lime are required in order to achieve a pH increase of 0.5:

- 2.5 tons/ha for a clay;
- 1.7 tons/ha for a silty clay loam;
- 1.5 tons/ha for a sandy clay loam;
- 1.0 tons/ha for a sandy loam.

In the study area, the majority of samples from the upper soil units had a strongly acid character (pH 3-4), whereas samples from deeper depths showed generally higher pH-values (pH 5-7). Thus, approximately 10 tons/ha lime would be required to neutralise a silty clay loam from pH 4 to pH 7. Additionally, more lime is required to maintain a certain level of soil quality. Quantities depend on climatic conditions and range from 75-1000 kg/ha/year (Fenton, 1997). However, these lime quantities are only estimations since the quantities for a specific site have to be determined on the base of the dominating clay mineralogy in the soil, and more importantly the reactivity of the liming material itself. An extensive discussion on this topic is also found in Logan (1992) and Whitney & Lamond (1999).

Bio-availability of some trace elements to plants is mainly influenced by the soil pH and cation exchange capacity, with availability decreasing at neutral to alkaline pH values and as the exchange capacity increases. It should be noted that the soil pH does not predict the amount of lime necessary to neutralise acid soil. That requires the determination of the soil reserve acidity, which is a function of the soil pH as well as the cation exchange capacity. To measure reserve acidity, the soils cations such as Ca must be extracted using a buffer solution, where the adsorbed cations exchange with cations in the buffer solution. Subsequently, the cations are filtered and the quantity of cations, which can neutralise acids (mainly Ca and to some extent Mg) determines the amount of lime required to neutralise acidity. Thus, a soil with a high cation exchange capacity will require more lime than one with a low exchange capacity.

An increase in soil cation exchange capacity in order to improve the soil retention capacity for contaminants, can be achieved for instance by:

- Adding clays with a high cation exchange capacity (e.g. montmorillonite);
- 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 or phosphate-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) discuss 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.

Certain elements might exert a lower risk to humans because of phytotoxic reactions to plants and were discussed in paragraph 2.7. However, some elements, such as Cd, Mn, Mo and Zn, are not affected by this phenomenon, as a result of insolubility or strong retention of the element in the soil that prevent plant uptake (Pierzynski et al., 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 poses a direct risk to human health.

6.3.2.1 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 entering the subsurface.

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 acid mine drainage and a lack of buffer minerals) which prevents the establishment of vegetation as a result of leached nutrients. In addition, incomplete reclamation often results in tailings material remaining on the surface. This residual tailings material provides an additional reservoir for acid mine drainage generation and associated contaminants and complicates rehabilitation efforts even more.

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 an appropriate vegetation cover for an extended period of time (also as a result of highly soil compaction), if exposed to weathering.

Treatment options were discussed in the previous paragraphs and amelioration could be achieved by addition of soil amendments such as lime or 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. 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).

A further option is to cover remaining tailings with soil. Such a cover or cap would prevent leachate migration and reduce the need for other cost intensive techniques such as soil clean-up or groundwater treatment. A detailed discussion is given in Daniel (1983), Hutchison & Ellison (1992) and Johnson, Cooke & Stevenson (1998).

6.4 REMEDIATION OF GROUNDWATER CONTAMINATED BY ACID MINE DRAINAGE

Most of the remediation techniques used in practice 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 USA became available (EPA, 1989 and 1996a; Mackay & Cherry, 1989; Travis & Doty, 1990 and Kavanaugh, 1996). The most common groundwater remediation strategy in the USA 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 USA 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 U.S. National Research Council in 1994. A number of 77 remediated sites were investigated in the U.S. with regard to their 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 & Cherry, 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 control of the pollution source (e.g. vegetation cover, drainage systems) and, if contamination in the subsurface occurs, on limiting the bio-availability of contaminants within the unsaturated zone. Various clean-up technologies have been reviewed by the EPA (1987a). The long-term management of the contaminated subsurface will be discussed in the following paragraphs.

6.5 LONG-TERM ENVIRONMENTAL MANAGEMENT FOR LARGE CONTAMINATED AREAS

Areas such as those 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 groundwater quality.

The parameters, which control the balance between retention and mobility of contaminants in soils and sediments are also termed *master variables* (i.e. pH, but also redox conditions and the presence of complexing agents such as dissolved organic matter and inorganic anions) according to 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 contamination 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 6.2 illustrates the relationship between the master variables, the major element cycles and contaminants.

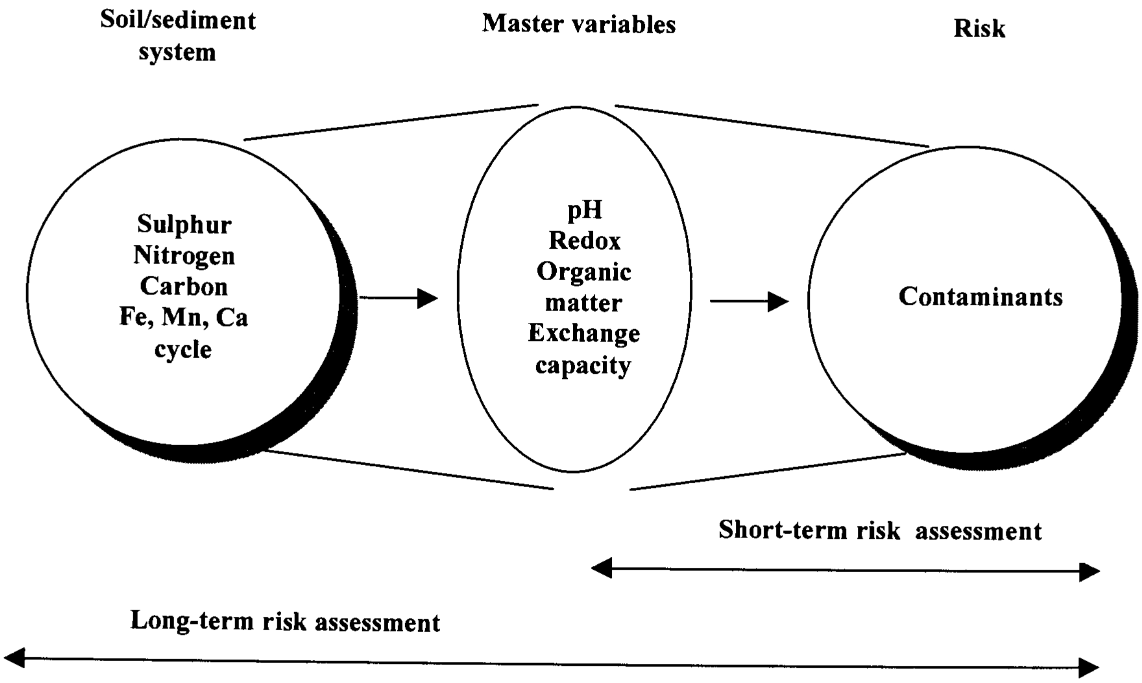


FIG. 6.2 - Association between the master variables, the major element cycles and contaminants (modified after Salomons & Stigliani, 1995).

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. 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 those affected by mining operations.

6.6 ENVIRONMENTAL MONITORING AND AFTER-CARE MANAGEMENT

How effectively contamination can be mitigated and how sustainable the rehabilitation effort is under long-term conditions determine the success of rehabilitation (Van der Nest & Van Deventer, 1996). Consequently, the only available tool to measure the success of rehabilitation at a specific site is the monitoring approach. Only monitoring reveals if improvement occurs as a direct result of the rehabilitation measure. Monitoring would also justify the use of a specific remediation method for further applications under similar conditions. Therefore, monitoring serves as a quality control tool for rehabilitation management and thus, forms an integral part of a risk assessment and after-care measures for previously contaminated and subsequently rehabilitated sites.

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 could for example consist of the establishment of boreholes suitable for groundwater sampling up and down-gradient of the site. Groundwater monitoring approaches are discussed in detail in textbooks such as Palmer (1992), Daniel (1993), and by Mulvey (1998), whereas vadose zone monitoring techniques are described in Everett, Wilson & Hoylman (1984).

In addition, *The Minimum Requirements for Water Monitoring at Waste Management Facilities* (DWAF, 1998) give guidance on this issue. In this context, it should be emphasised that this guideline states:

> *"It is a minimum requirement that a risk assessment, to determine the risk of water becoming polluted, be performed at all waste sites before the installation of a monitoring system. The risk assessment ensures that the design of the monitoring system is adequate…"*

Finally, the use of remote sensing techniques (e.g. using satellite images) could provide an important tool for the monitoring of reclamation activities of mining companies as well as of the nearby environment (rapid developing residential areas such as townships and illegal land use) of tailings dams.

6.7 FINANCIAL IMPLICATIONS OF REMEDIAL MEASURES

Acid mine drainage is recognised as a global pollution problem. At the 1998 Environmental Workshop of the Minerals Council in Australia 17 international companies, representing about 40 per cent of the world's mining activity, have agreed to join forces to control acid mine drainage. It is assumed that rehabilitation of acid mine drainage-related environmental damages will cost an estimated US $ 550 million in Australia and US $ 35 billion in North America (Dorfling, 1998). The cost figures for South Africa to rehabilitate existing mining facilities and to mitigate such damages are currently unknown. Table 6.1 provides a selection of cost ranges for some rehabilitation approaches.

TABLE 6.1 - Summary of selected rehabilitation measures and associated costs (after Wood, 1998).

Rehabilitation measure	**Estimated cost range**
Surface amendment	US $ 15-65/ton
Vertical slurry wall: shallow	US $ 45-95/m^2
Vertical slurry wall: deep	US $ 95-190/m^2
Excavation and disposal off-site	US $ 10-80/ton
Cover system	US $ 32-50/m^2
Containment	US $ 16-80/ton
Soil washing	US $ 80-400/ton
Physico-chemical washing	US $ 80-275/ton
Ex-situ stabilisation/solidification: inorganic	US $ 32-56/ton
Solidification: lime based	US $ 32-65/ton

Clean-up costs for contaminated soils (i.e. soil washing) range between US $ 80–400/ton (Wood, 1998). This study has shown that at least 5.5 million tons of material would have to be treated in South Africa, if only the contaminated topsoil (< 30 cm) underneath the reclaimed sites would have to be considered. Consequently, only the topsoil clean-up would cost at least US $ 440 million, assuming the lowest treatment cost scenario of US $ 80/ton. In addition, the following costs can be expected and would add 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 (i.e. subsoil) and/or at higher soil clean-up costs (> 80 US $/ton)
- Groundwater remediation;
- Removal and treatment of contaminated sediments in waterways;

- Remediation of existing gold mine tailings dams (e.g. cover systems) to prevent wind erosion and, thus mitigate the generation of acid mine drainage;
- Revegetation of reclaimed sites.

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. 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.

6.8 ENVIRONMENTAL MANAGEMENT MEASURES REQUIRED FOR THE INVESTIGATED SITES

One of the findings of this research study is the recommendation of site-specific environmental measures for the study sites A-K (field testing only at sites A-G). It must be noted that this study serves as a hazard assessment or Phase 1 of a risk assessment and, thus recommendations are of preliminary nature. Table 6.2 summarises the environmental management measures, which are suggested for the investigated sites.

It was found that paddock systems are inappropriate in pollution prevention and should be removed from the reclaimed sites. In addition, residual tailings, which remain in excessive volumes on site, should be covered with an impermeable layer (assuming that the cover option is associated with lower costs compared to the removal), in order to reduce wind-erosion and infiltration of rainwater into the tailings dam.

TABLE 6.2 - Summary of environmental management measures recommended for the study sites A-K.

Site	Monitoring		Soil management	Site Summary
	Vadose Zone	Groundwater		
A	O	No	R	Topsoil pH 3-4, metal contents above background, site is not entirely reclaimed.
B	R	R	R	Topsoil pH about 3-4, metal contents such as Co and Ni above background, site is partially situated on dolomite.
C	R	O	O	Topsoil pH about 3-4, acidity tends to migrate into the subsoil, metal contents of above background. The site has a vegetation cover.
D	R	O	O	Topsoil pH 3-4, metal contents such as Co above background. The site has a vegetation cover.
E	O	O	No	Topsoil pH is fairly neutral, metal contents of Ni and Co above background, but with low mobility, remove residual tailings material; site is partially situated on dolomite.
F	R	R	R	Topsoil pH 3-5, metal contents such as Co and Ni above background, very high U content, removal of residual tailings is ongoing.
G	No	No	No	Topsoil pH varies from 4 to neutral, metal contents such as Co above background, remove paddocks.
H	O	R	O	Rehabilitation plan is currently developed; cover residual tailings; site is partially situated on dolomite
I	R	R	R	Groundwater risk assessment including monitoring is ongoing; site is partially situated on dolomite; this site is the largest gold mining tailings dam in South Africa
J	R	No	O	Remove residual tailings material
K	R	R	O	Groundwater investigations are ongoing; site is partially situated on dolomite; geochemical soil data lacking

Note: Soil management comprises liming of those portions of the topsoil identified as acid soils and the addition of fertilisers and organic material. In cases of excessively polluted soils excavation should be considered. R means "required", O means "optional" or future requirement, No means "no measures necessary". Grey shaded are those sites, where no field and laboratory tests during this study were conducted.

It is apparent that most of the sites require monitoring of the vadose or unsaturated zone, as this zone represents the physical and geochemical barrier zone between the source (i.e.

contaminated site) and the receptor (i.e. groundwater system) and, thus is of major significance for the assessment of contamination. Additionally, sites with a perched water table or dolomitic aquifer should be monitored with respect to groundwater quality. A risk assessment is only recommended if significant contamination of soil and/or groundwater is indicated. It should be mentioned that for some of the investigated sites, environmental management measures such as removal of residual tailings, soil analyses, liming of acid soils, groundwater monitoring and numerical groundwater modelling were already undertaken by the operating mining company, although such measures were previously not mandatory.

The EPA (1997b), other EPA sources and Skivington (1997) provide additional information on risk assessment and their practical implementation.

7 DISCUSSION AND CONCLUSIONS

7.1 DISCUSSION

Acid mine drainage is recognised as a global pollution problem and is related to the generation of large volumes of mine waste such as the tailings produced as a result of intensive mining activities for gold, coal and other mineral resources in South Africa. To date, more than 270 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). Up to 1998 a total of 70 tailings dams were reclaimed throughout the Johannesburg region in order to extract the gold, still present in economically viable concentrations (currently approximately 0.40 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 below an area, also known as the footprint.

It is known that gold mine tailings, originating from sulphide-bearing ore, are prone to the generation of acid mine drainage. It is estimated that the remediation of environmental damages related to acid mine drainage will cost about US $ 500 million in Australia and US $ 35 billion in the United States (regulated under the *Superfund* program, see footnote 1) 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 $ 80-400/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 (< 30 cm) underneath the reclaimed sites would have to be considered. Hence, only the topsoil treatment would cost at least US $ 440 million, assuming the lowest treatment cost scenario of US $ 80/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 cost 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 characterised by a risk assessment as high risk areas. 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.

Ten selected reclaimed gold mine tailings dam sites, situated in the Gauteng Province and one in the North-West Province of South Africa, were investigated in this study. All reclaimed sites were analysed in terms of their short-term impact and conservative predictions were also attempted to assess the long-term impact (worst-case scenario). In addition, the contamination 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. The database was supplemented by further soil and groundwater data of the investigated sites, 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.

7.2 CONCLUSIONS

In conclusion, this study has shown that contamination occurs in the subsurface below the footprints of former gold-mine tailings deposits. However, based on the findings of this study, it is premature to quantify this impact as the results have to be incorporated into a risk assessment approach for some of the sites. This investigation therefore provides a first step towards a risk assessment and serves as a hazard assessment/identification.

It is important to recognise that slight changes in the pH or Eh conditions (e.g. by changes in land use, climate, hydrology) of soils, affected by acid mine drainage 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 an in-depth understanding of the long-term dynamic aspects of these contaminant processes, which pose a serious threat to the vulnerable dolomitic groundwater resources 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 are summarised as follows:

1. 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^-) and are often associated with elevated trace element (e.g. As, Fe, Mn, Ni, Pb and Zn) concentrations, exceeding target water quality standards in some boreholes.
2. The low pH (range between 3-4) in the topsoil enhances leaching of soil nutrients, essential for plant growth and only acid tolerant plant species can survive under such conditions. The acid conditions are a result of acid mine drainage released from the tailings and a $CaCO_3$ deficiency in the soil. When the pH drops around 4.5 in the topsoil, the acidity starts to migrate into the subsoil and indicates a permanent soil degradation.
3. An estimation of seepage quantities and SO_4^{2-} loads for all reclaimed sites (total area of 13 km^2) has shown that an accumulated amount of approximately 1000 Ml seepage is annually discharged into the groundwater system, containing a SO_4^{2-} load between 1000–5000 tons based on conservative recharge and concentration figures.
4. Elevated trace element concentrations in the soils affected by acid mine drainage and the high mobility of phytotoxic elements such as Co and Ni could hinder the establishment of a vegetation cover.
5. Generally, the trace elements are most mobile when the soil pH < 4.5 (prevailing in the upper soil units), and least mobile when a soil pH > 6 (prevailing in the deeper soil units). Cobalt, Ni and Zn are the most mobile trace elements for the selected reclaimed site and exceed soil threshold values. Chromium, Cu, Fe, Pb and U are less mobile compared to the above elements, indicating that a significant portion of those is likely to be contained in the residual fraction (i. e. bound to silicates) of the solid phase.
6. The application of the geochemical load index for the assessment of the long-term impact at seven sites classified three sites as moderately to highly contaminated, three sites as highly contaminated and one site as excessively contaminated.
7. Soil conditions indicating preferential flow (bypass of the soil matrix) were observed in nearly all soil profiles and even sites with relatively impermeable soils showed contamination in the underlying groundwater system.

8. The extractable concentrations of Co, 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 contamination for soils and groundwater.
9. Leaching tests and a load calculation have shown that even reclaimed sites (i.e. footprint) continue to release significant salt contents contained in seepage for an extended time period (> 10 years). Incomplete reclamation of tailings would result in tailings material remaining on the surface. Such material provides an additional reservoir for acid generating processes and ongoing contaminant release.
10. The clean-up costs of environmental damages, caused by acid mine drainage from mine waste disposal sites are expected to be excessively high. The most common rehabilitation measure applied in South Africa is liming of acid soils and additional lime is also needed to maintain a certain level of soil quality after the initial treatment. Fertilisers are required to improve growth conditions for plants. However, it can be expected that even after site rehabilitation has occurred, the subsoil and groundwater might remain polluted for an extended period of time.

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APPENDIX A

Soil parameters and test pit logs

Table A.1 - Summary of soil parameters of study sites A-G.

SAMPLE DESCRIPTION			PARTICLE SIZE				ATTERBERG LIMITS					IN-SITU PROPERTIES				PERMEABILITY
TEST PIT and Sample No.	**DEPTH (m)**	**UNIFIED SOIL CLASSIFICATION SYSTEM (U.S.C.S.)**	**% Clay**	**% Silt**	**% Sand**	**% Gravel**	**LL**	**LS**	**PI**	**PI ws**	**Exp**	**pH**	**Bulk density (kg/m³)**	**SG**	**e %**	**K (cm/s)**
Study Site A																
A/1/1	0.20	SC-SM	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	1×10^{-7}
A/1/2	0.40	SC	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	1×10^{-7}
A/1/3	1.00	SC-SM	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	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	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	1×10^{-7}
A/3/2	0.30	SC	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	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	12.10	31.40	45.80	10.70	25.24	5.49	8.99	5.65	low	6.87	-	-	-	-
Study Site B																
B/1/1	0.10	CL	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	1×10^{-8}
B/1/2	0.50	CL	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	1×10^{-8}
B/2/1	0.30	ML	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	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	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	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	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	19.02	21.68	50.30	9.00	34.84	8.36	15.61	8.21	low	6.66	-	-	-	-
Study Site C																
C/1/2	0.80	CL	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	8×10^{-8}
C/1/3	1.40	CL	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	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	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	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	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	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	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	1×10^{-8}
C/3/3	1.65	CH	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	1×10^{-9}
Study Site D																
D/1/1	0.10	CL	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	9×10^{-7}
D/1/2	0.30	CL	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	9×10^{-7}
D/1/4	1.30	SC	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	7×10^{-7}
D/2/1	0.40	CL	31.33	24.67	44.00	0.00	34.09	9.88	16.48	14.55	low	3.76	-	-	-	-

Table A.1 continued.

SAMPLE DESCRIPTION			GRADING ANALYSES				ATTERBERG LIMITS					IN-SITU PROPERTIES				PERMEABILITY
TEST PIT and Sample No.	**DEPTH (m)**	**UNIFIED SOIL CLASSIFICATION SYSTEM U.S.C.S.**	**% Clay**	**% Silt**	**% Sand**	**% Gravel**	**LL**	**LS**	**PI**	**PI ws**	**Exp**	**pH**	**Bulk density (kg/m^3)**	**SG**	**e %**	**K (cm/s)**
Study Site D																
D/2/2	0.70	CL	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	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	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	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	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 x 10-8
Study Site E																
E/1/2	0.70	CL	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 x 10^{-8}
E/1/3	1.50	CL	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 x 10-7
E/2/1	0.45	CH	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 x 10^{-7}
E/2/2	0.75	CH	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	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 x 10^{-8}
E/3/1	0.30	CH	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	39.19	29.61	31.00	0.00	48.69	7.30	28.31	26.88	high	6.75	-	-	-	-
Study Site F																
F/1/1	0.60	CL	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 x 10^{-8}
F/1/2	1.00	CL	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 x 10^{-7}
F/1/3	1.60	CL	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	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	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	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	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	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 x 10^{-7}
F/3/4	1.60	CL	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	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	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	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 x 10^{-8}
Study Site G																
G/1/1	0.30	SC	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 x 10^{-7}
G/1/3	1.00	SC	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	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 x 10^{-7}
G/3/1	0.20	SC	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	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	31.45	21.15	34.60	12.80	30.85	8.60	11.54	8.23	low	6.74	-	-	-	-

Note: 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. U.S. soil symbols are explained in Table 3.11.

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Test Pit Log

Test pit number: A/1

			Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
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 0,05	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	3,6	0,02	102	188	10	197	43	3	55	0	0	0	0	62	41
0,30 0,55 0,60	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
1	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
1,30 1,50	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.																							
2	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 ferrugenised residual sandstone of the Vryheid Formation.																							
	As above but very dense																							
3	**Notes** 1. Gradual refusal at 1,50 m on hardpan ferricrete. 2. No water table encountered.																							

Date: 04.06.98 **Locality: Case Study Site A** **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

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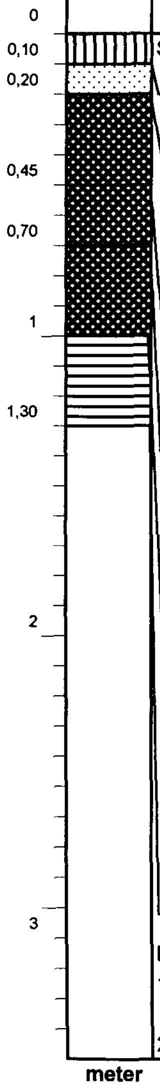
Test Pit Log

Test pit number: A/2



Profile description	Sample number	Geotechnical description						Geochemical description (elements in mg/kg)															
		% 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 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. 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 coarse-, 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: 04.06.98 **Locality:** **Case Study Site A** **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

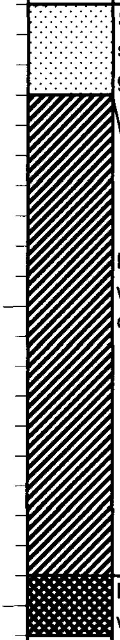
Test pit number: A/3

				Geotechnical description						Geochemical description (elements in mg/kg)															
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 0,03 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 1	▓	Abundant coarse-, 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 A/3/4	11,31 12,1	5 6	- -	- -	- -	- -	6,63 6,66	12,2 15,1	0,04 0,07	20 16	204 302	7 22	351 341	57 70	17 12	67 65	9 28	0 0	17 12	0 0	279 332	31 31
1,40 2	▓	Abundant coarse-, 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 coarse-, 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.																							

Date: 04.06.98 **Locality: Case Study Site A** **Elevation:** 1630 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: B/1



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 0,30	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^{-8}	3,64	9,8	0,06	17	281	27	232	87	19	173	13	0	16	0	156	135
		B/1/2	34,68	12	1619,22	2,45	0,51	1×10^{-8}	3,53	9,6	0,06	17	259	18	226	89	20	153	14	0	17	0	158	102
1	Moist, red brown, firm, intact, sandy clay with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/1/3	-	-	-	-	-	-		10,1	0,06	17	231	8	230	79	20	115	13	0	18	0	165	91
1,90 2 2,10	Moist, red brown, firm, intact, sandy clay with numerous coarse-, medium- and fine-grained subrounded ferricrete gravel; Ferrugenised colluvium.	B/1/4	-	-	-	-	-	-		10,4	0,07	19	236	7	246	87	21	106	10	0	19	0	172	72
3																								

Geotechnical parameters: % Clay, PI ws, Dry density, SG, e, K cm/s. Geochemical parameters (elements in mg/kg): pH to Zn.

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

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																								
0,15	Slightly moist, pale yellow brown, very soft, layered sandy silt, Tailings.	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
0,40	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.	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
0,90																								
1	Moist, red brown, firm, intact, sandy silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	B/2/3	-	-	-	-	-	-	-	13,6	0,06	17	293	10	374	130	14	139	4	0	16	0	197	57
1,80	Moist, dark red brown, firm, intact, silt with occasional fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.																							
2		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
2,20	Moist, dark red brown, firm, intact, silt with occasional coarse-, medium- and. fine-grained subrounded ferricrete gravel; Ferrugenised colluvium																							
3																								

Geotechnical parameters: % Clay, PI ws, Dry density, SG, e, K cm/s. Geochemical parameters (elements in mg/kg): pH, Fe %, Mn %, As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Sn, Th, U, V, Zn.

Notes

1. No refusal.
2. No water table encountered.

Date: 21/4/1998 **Locality:**Case Study Site B **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: B/3

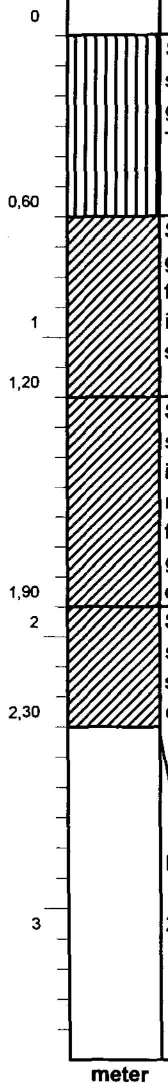
Depth (meter)		Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
				% Clay	PI ws	Dry density	SG	e	K cm/s	pH	Fe %	Mn %	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0	▥	Slightly moist, light grey banded yellow brown, very soft, layered sandy silt, Tailings.																							
0,30	▨	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
0,50	▨		B/3/2	-	-	-	-	-	-		6,2	0,03	22	204	13	163	46	20	78	9	0	21	0	96	40
0,90 1	▨	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	41,8	14	-	-	-	-	6,63	7,2	0,04	19	197	9	230	51	19	85	13	0	23	0	113	44
1,40	▩	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
2 2,10	▩	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.																							
3		**Notes** 1. No refusal. 2. No water table encountered.																							

meter

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 parameters						Geochemical parameters (elements in mg/kg)															
		% 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, 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
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 x 10^{-8}	3,92	8,5	0,04	25	212	14	191	50	18	79	8	0	21	0	126	47
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 x 10^{-8}	3,82	14,2	0,06	7	526	33	369	67	0	76	118	0	0	0	254	36
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

Notes

1. No refusal.
2. No water table encountered.

Date: 04.06.98 **Locality:** Case Study Site C **Elevation:** 1605 m **Profiled by:** P Aucamp & T Rösner

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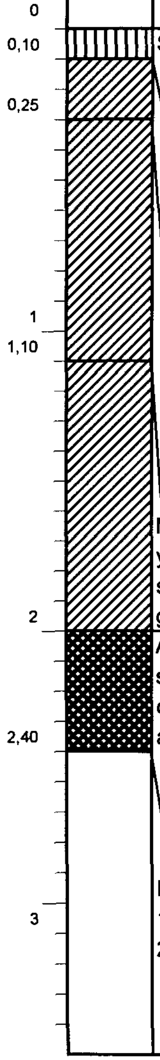
Test Pit Log

Test pit number: C/2



	Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)																
			% 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
0,10 0,25	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
		C/2/2	35,75	24	-	-	-	-	5,05	7,1	0,07	15	383	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 coarse-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	**Notes** 1. No refusal. 2. Perched water table at 2,00 m.																							

Date: 04.06.98 **Locality:** Case Study Site C **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

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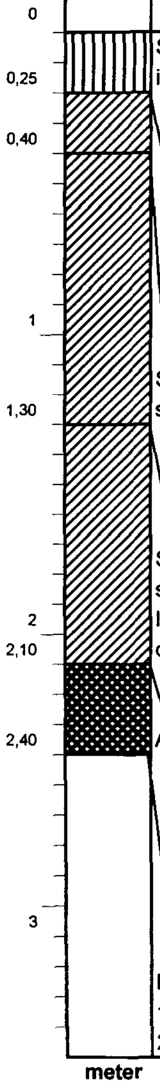
Test Pit Log

Test pit number: C/3



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 parameters						Geochemical parameters (elements in mg/kg)															
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.																							
	C/3/4	-	-	-	-	-	-	-	7,3	0,10	24	292	42	213	42	14	65	7	0	18	0	178	36
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.																							

Notes

1. No refusal.
2. No water table encountered.

Date: 04.06.98 **Locality: Case Study Site C** **Elevation:** 1608 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: D/1

Depth (meter)		Profile description	Sample number
0 – 0,03 – 0,20	▥	Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.	D/1/1 D/1/2
0,20 – 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/1/3
0,60 – 1,10	▨	Moist, yellow brown, firm, open structured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	
1,10 – 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
		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.

Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
	% 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
D/1/1	27,77	12	1684,51	2,61	0,55	9×10^{-7}	3,65	6,15	0,04	50	207	21	155	51	14	82	0	0	8	0	100	54
D/1/2	41,64	13	1566,60	2,64	0,69	9×10^{-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
D/1/4	20,93	9	1644,29	2,69	0,64	7×10^{-7}	6,78	10,2	0,37	9	1252	90	195	78	10	99	46	0	8	0	199	38

Depth scale: 0, 0,03, 0,20, 0,60, 1, 1,10, 1,60, 2, 3 meter

Date: 21/4/1998 **Locality:** Case Study Site D **Elevation:** 1605 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: D/2

Depth (meter)	Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)																
			% 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 0,25	Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.																								
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/2/1	-	-	-	-	-	-	-	8,9	0,06	64	342	23	189	93	6	109	0	0	1	0	150	55
1 1,10	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
2 2,40	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	1696	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
3	**Notes** 1. No refusal. 2. No water table encountered.																								

Date: 21/4/1998 **Locality: Case Study Site D** **Elevation:** 1604 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: D/3

Depth (meter)	Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
			% 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 0,05	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
0,40 0,80	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
1 1,40	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
2	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 x 10^{-8}	-	6,8	0,03	20	228	10	196	50	17	75	1	0	19	0	85	49
2,30	Moist, light grey mottled and stained yellow brown and black, stiff, slickensided clay; Residual mudrock of the Vryheid Formation.																							
3	**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: E/1

				Geotechnical parameters						Geochemical parameters (elements in mg/kg)																	
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	▥	Slightly moist, pale yellow brown mottled black and orange brown, very soft, layered sandy silt, Tailings																							
0,30	▨	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
0,50	▨		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	▨	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.																							
1,30	▨	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 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																							

Date: 04.08.98 **Locality:** Case Study Site E **Elevation:** 1585 m **Profiled by:** P Aucamp & T Rösner

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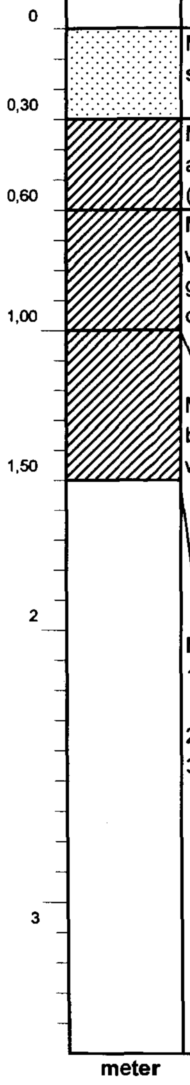
Test Pit Log

Test pit number: E/2



Profile description	Sample number
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
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
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

Notes

1. Refusal at 1,50 m on alluvial boulders (quartzite and chert)
2. No water table encountered
3. Stable sidewalls

Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
	% 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
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
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
E/2/3	46,55	34	1535,06	2,68	0,75	8×10^{-8}	8,31	7,8	0,10	10	266	25	305	58	14	78	11	0	15	0	161	41

Date: 04.08.98 **Locality:** Case Study Site E **Elevation:** 1580 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: E/3

	Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
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
1,10	Moist, black, firm, slickensided 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	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.	E/3/3	-	-	-	-	-	-	-	3,6	0,02	23	109	14	287	27	19	61	10	0	17	0	118	83

1
2
3
meter

Notes

1. Refusal at 1,30 m on alluvial boulders (quartzite and chert)
2. No water table encountered
3. Stable sidewalls

Date: 04.08.98 **Locality:** Case Study Site E **Elevation:** 1606 m **Profiled by:** P Aucamp & T Rösner

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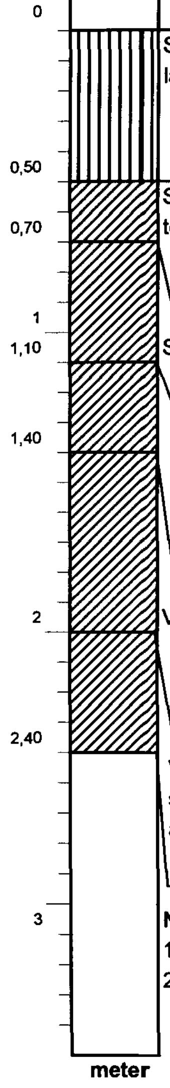
Test Pit Log

Test pit number: F/1



Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
		% 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																							
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	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
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	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
Moist, dark red brown, stiff, intact sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.	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
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	-	-	-	-	-	-	-	8,2	0,09	21	178	3	200	43	24	62	9	0	21	0	133	36
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

Date: 21/4/1998 **Locality: Case Study Site F** **Elevation:** 1583 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: F/2

Depth	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, 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
0,30	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
1,00	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
2																								
2,20		F/2/4	-	-	-	-	-	-	-	9,0	0,11	18	186	4	209	54	23	66	7	0	20	0	144	37
2,40	Very moist, dark red brown, stiff, intact sandy clay with abundant coarse-, medium- and fine-grained subangular ferricrete gravel; Ferrugenised colluvium.																							
3	**Notes** 1. No refusal 2. No water table encountered																							
meter																								

Geotechnical parameters; Geochemical parameters (elements in mg/kg)

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

Depth (meter)		Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)																
				% Clay	PI	Dry density	SG	e	K	pH	Fe %	Mn %	As	Ba	Co	Cr	Cu	Mo	Ni	Pb	Sn	Th	U	V	Zn
0 0,05 0,30	▥ ▨	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
1,00	▨	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 x 10^{-7}	5,17	6,6	0,04	72	183	51	178	56	36	301	3	0	13	704	131	281
1,40	▩	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
1,70 2	▩	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
3		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

meter

Date: 21/4/1998 **Locality: Case Study Site F** **Elevation:** 1585 m **Profiled by:** P Aucamp & T Rösner

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Test Pit Log

Test pit number: F/4

Depth (meter)		Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
				% 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 grey, very soft, layered sandy silt, Tailings.																							
0,20	▨	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
	▨	Moist, red brown, firm, open textured sandy clay with abundant fine-grained gypsum crystals (up to 5 mm in diameter); Colluvium.																							
2 2,10	▨	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 x 10^{-7}	4,65	8,5	0,06	19	191	5	199	53	21	78	7	0	19	0	138	49
2,40																									
3																									

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

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Test Pit Log

Test pit number: G/1

Depth (meter)		Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
				% 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 – 0,25	▥	Slightly moist, pale yellow, very soft, layered sandy silt, Tailings.																							
0,25 – 0,60	░	Moist, dark grey stained black, medium dense, intact clayey sand; Colluvium.	G/1/1	14,10	6	1786,21	2,64	0,48	1 x 10^{-7}	3,99	3,1	0,02	52	176	47	122	41	19	103	0	0	9	0	47	39
0,60 – 1,30	░	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
1,30		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.																							

Depth scale: 0, 0,25, 0,60, 0,80, 1, 1,30, 2, 3 meter

Notes

1. Gradual refusal at 1,30 m on hardpan ferricrete.
2. No water table encountered.

Date: 04.06.98 **Locality: Case Study Site G** **Elevation:** 1610 m **Profiled by:** P Aucamp & T Rösner

Test Pit Log

Test pit number: G/2

		Profile description	Sample number	Geotechnical parameters						Geochemical parameters (elements in mg/kg)															
				% 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 banded and mottled yellow brown and orange, very soft layered sandy silt, Tailings.																							
0,45	░	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
0,80 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 x 10^{-7}	6,31	5,4	0,05	22	192	18	159	47	24	73	3	0	19	0	74	56
		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.																							
2																									
3																									

Notes

1. Gradual refusal at 1,10 m on hardpan ferricrete.
2. Perched water table at 0,95 m.

meter

Date: 04.06.98 **Locality:** Case Study Site G **Elevation:** 1607 m **Profiled by:** P Aucamp & T Rösner

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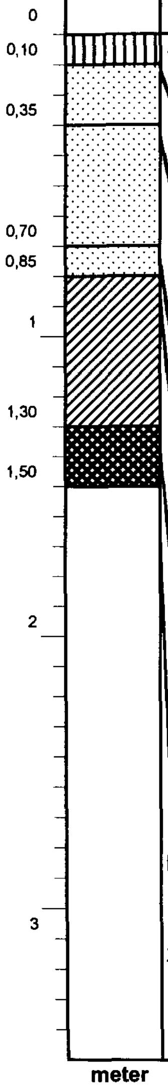
Test Pit Log

Test pit number: G/3



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, 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.																							

Geotechnical parameters: % Clay, PI ws, Dry density, SG, e, K cm/s. Geochemical parameters (elements in mg/kg): pH, Fe %, Mn %, As, Ba, Co, Cr, Cu, Mo, Ni, Pb, Sn, Th, U, V, Zn.

Notes
1. Gradual refusal at 1,50 m on hardpan ferricrete.
2. No water table encountered.

Date: 04.06.98 **Locality: Case Study Site G** **Elevation:** 1612 m **Profiled by:** P Aucamp & T Rösner

APPENDIX B

Geochemical results

Table B.1 - Summary of geochemical soil analyses (technique: XRF, all trace elements in mg/kg).

Site	Sample-No.	TiO_2 %	MnO %	Fe_2O_3 %	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 B.1 continued.

Site	Sample-No.	TiO_2 %	MnO %	Fe_2O_3 %	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 B.1 continued.

Site	Sample-No.	TiO_2 %	MnO %	Fe_2O_3 %	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

Table B.2 - Main statistical parameters from Table B.1.

	TiO_2 %	MnO %	Fe_2O_3 %	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	5.8	117.5	96.6	41.0	54.1	28.1	46.1	27.1	17.0	12.4	12.4	82.9	4.6	7.2	1.2	11.9	239.5	1.6	18.7	7.2	181.9
AVG	1.06	0.09	8.17	20.2	151.7	237.5	29.5	96.6	60.1	59.5	28.6	80.0	29.1	27.0	420.6	21.6	16.4	0.2	2.1	299.6	6.4	12.3	14.7	37.7

Table B.3 - Background values for the Vryheid Formation (all trace elements in mg/kg, n=21).

Sample-No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**AVG**	**STDEV**
TiO_2 %	1.06	1.08	1.01	0.96	0.95	0.92	0.99	0.95	0.96	1.01	0.91	0.89	0.95	0.97	1	0.91	1	0.84	0.91	0.89	0.99	0.96	0.06
MnO %	0.14	0.05	0.1	0.04	0.11	0.08	0.06	0.08	0.1	0.12	0.13	0.08	0.07	0.07	0.06	0.05	0.08	0.06	0.08	0.06	0.09	0.08	0.03
Fe_2O_3 %	6.44	3.3	4.99	4.48	4.6	2.58	2.63	4.31	5.05	4.59	5.85	4.8	4.37	4.44	4.87	3.77	4.96	3.13	5.62	2.51	5.1	4.40	1.07
As	26	18	25	24	17	18	14	19	22	15	20	22	27	25	20	28	24	23	31	21	26	22.14	4.41
Ba	246	266	270	257	267	183	177	196	277	279	341	192	161	169	171	153	174	145	251	85	214	213.05	60.72
Co	18	12	18	10	18	12	10	15	15	18	21	13	13	14	13	12	15	10	15	11	15	14.19	3.08
Cr	157	93	123	130	117	83	107	115	139	145	175	132	134	132	149	136	130	96	223	80	131	129.86	31.89
Cu	43	28	46	24	33	26	24	33	46	34	37	41	36	37	37	35	39	29	39	21	38	34.57	7.09
Mo	20	30	18	19	19	25	28	25	21	22	22	17	28	24	23	20	23	27	21	39	22	23.48	4.99
Nb	21	24	20	21	18	20	21	20	18	20	18	17	21	21	21	19	21	20	19	20	20	20.00	1.52
Ni	61	33	51	38	42	29	26	44	53	41	46	50	50	51	55	48	56	38	59	32	54	45.57	9.99
Pb	12	5	15	5	33	17	14	20	25	15	16	30	10	8	10	20	14	3	11	4	17	14.48	8.04
Rb	89	84	89	97	78	72	73	76	72	80	70	83	79	81	83	68	79	69	82	50	80	77.81	9.63
Sb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0.76	3.49
Sc	18	12	13	13	12	8	10	12	15	12	15	14	13	14	13	12	15	10	16	9	14	12.86	2.37
Sn	0	2	0	0	0	0	2	0	7	1	0	0	0	1	2	1	0	6	0	0	0	1.05	1.96
Sr	36	33	37	45	25	36	32	29	102	29	27	29	27	26	25	26	23	24	35	22	34	33.43	16.72
Th	15	18	12	18	8	12	14	12	12	12	10	8	15	16	15	12	14	15	14	15	13	13.33	2.69
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00
V	99	41	69	55	68	36	34	61	75	67	97	67	66	67	73	59	79	44	106	37	74	65.43	20.11
W	8	8	8	6	6	10	9	6	7	8	8	7	8	9	7	7	7	8	7	8	14	7.90	1.73
Y	31	29	29	31	22	23	23	26	28	27	26	25	28	28	27	24	25	24	22	21	30	26.14	3.02
Zn	68	48	125	41	136	205	230	142	199	80	74	145	93	87	79	60	67	49	78	56	108	103.33	54.74
Zr	492	623	494	443	553	609	656	616	591	579	579	502	603	555	542	520	528	560	532	793	549	567.57	72.56

Table B.4 - Extraction test results of the gold mine tailings (all element concedntrations in mg/l).

Sample-No.	1	2	3	4	5	6	7	8	9	10	11	12	13
As	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1574.50	660.00	202.50	860.00	1082.50	500.00	1362.50	1770.00	1342.50	2185.00	2182.50	1750.00	3020.00
Co	0.50	1.00	0.00	0.00	10.00	17.50	25.00	30.00	2.50	15.00	15.00	10.00	25.00
Cr	0.00	0.00	0.00	0.00	1.75	1.25	1.75	2.25	1.00	0.50	5.00	2.50	5.00
Cu	2.50	2.50	0.00	0.25	12.52	17.50	22.50	22.50	1.50	2.50	7.50	5.00	10.00
Fe	0.75	2.50	0.50	0.00	50.00	87.50	105.00	60.00	25.00	7.50	55.00	37.50	5.00
Mg	7.50	72.50	17.50	10.00	460.00	687.50	802.50	927.50	290.00	312.50	955.00	650.00	1487.50
Mn	1.25	2.50	0.50	0.50	15.00	22.50	25.00	27.50	10.00	42.50	35.00	25.00	45.00
Ni	1.25	2.50	0.00	0.00	32.50	57.50	77.50	105.00	10.00	45.00	47.50	35.00	80.00
Pb	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.75	0.25	0.50	0.50	0.50	0.75
S	1257.50	697.50	60.00	650.00	3090.00	3712.50	5097.00	6132.50	2510.00	4837.50	4820.00	4827.50	11262.50
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.25	1.50	0.25	0.00	7.50	10.00	12.50	15.00	10.00	80.00	40.00	27.50	60.00

Note: 0 means below detection limit.

Table B.5 - Threshold excess ratios for the extractable trace element concentrations in soils of study site F.

Sample-No.	F/1/1	F/1/2	F/1/3	F/1/4	F/2/1	F/2/2	F/2/3	F/2/4	F/3/1	F/3/2	F/3/3	F/3/4	F/4/1	F/4/2	F/4/3	F/4/4
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Co	-	40	-	-	-	-	-	1.5	30	10	4	5	30	5	2	1.5
Cr	-	-	-	-	-	-	-	-	-	-	-	-	12.5	-	-	-
Cu	-	3.75	-	-	-	-	-	-	0.13	-	-	0.25	1.25	0.13	-	0.38
Ni	-	72.5	-	-	2.5	-	-	0.25	77.5	15	2.5	10	40	10	2	5
Pb	-	0.38	-	-	-	-	-	-	-	-	-	0.25	0.5	-	-	-
U	-	-	-	-	-	-	-	-	118.75	62.5	-	-	1500	-	-	-
Zn	-	2.75	-	-	0.2	0.05	-	0.15	6.25	2.75	0.2	1	5.75	1	-	0.5

Note: - indicates where no excess occurred.

Table B.6 - Trace element mobility in soil. Extractable trace element concentrations are expressed as a percentage of the total concentration.

Sample	**F/1/1**	**F/1/2**	**F/1/3**	**F/1/4**	**F/2/1**	**F/2/2**	**F/2/3**	**F/2/4**	**F/3/1**	**F/3/2**	**F/3/3**	**F/3/4**	**F/4/1**	**F/4/2**	**F/4/3**	**F/4/4**
Soil pH	6.69	3.66	6.62	-	4.37	6.67	6.29	-	4.53	5.17	-	4.7	3.7	4.71	-	4.65
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Co	-	66.67	-	-	-	-	-	18.75	25	9.8	14.29	16.67	46.88	20.83	4	15
Cr	-	-	-	-	-	-	-	-	-	-	-	-	0.47	-	-	-
Cu	-	8.33	-	-	-	-	-	-	0.45	-	-	0.96	3.38	0.47	-	1.42
Fe	-	-	-	-	-	-	-	-	-	-	-	-	19.34	-	-	8.81
Ni	-	50.7	-	-	3.01	-	-	0.38	24.84	4.98	3.01	10.42	21.39	10.87	1.36	6.41
Pb	-	7.5	-	-	-	-	-	-	-	-	<0.01	12.5	-	-	-	-
U	-	-	-	-	-	-	-	-	0.4	0.36	-	-	6.44	-	-	-
Zn	-	34.38	-	-	4.35	1.09	-	4.05	30.49	9.79	5	19.61	39.12	24.39	-	10.2

Table B-7: Correlation matrix (Pearson coefficient) for selected major and trace elements in solid tailings samples from five different tailings dams situated in the East Rand area (source data from 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 B-8: Correlation matrix (Pearson coefficient) for selected trace elements in soils of the sites A-G (n = 81).

Element	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

Table B-9: Correlation (Pearson coefficient) of selected trace elements with the clay content in the soil (n=59).

	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

r = 1	maximum positive correlation between two variables;
r = 0	no correlation between two variables;
r = -1	maximum negative correlation between two variables.

APPENDIX C

Geochemical properties of selected elements and compounds

Table C.1 - Main geochemical properties of elements of concern.

Element	**Occurrence in the gold-bearing conglomerates**	**Geochemical properties In soil and waters**	**Environmental and health effects**	**Permissible contents in water and soil**
Sulphate (SO_4)	Predominantly from the oxidation of sulphide-bearing minerals such as pyrite [FeS_2].	Readily soluble in water, excess Ca^{2+} e.g. in dolomitic aquifers results in the precipitation of $CaSO_4$.	Contents of 200-400 mg/l cause a salt and bitter taste in drinking water. Higher contents (> 600 mg/l) can cause diarrhoea (DWAF, 1996a).	Target water quality ranges from 0-200 mg/l in waters for domestic use (DWAF, 1996a).
Arsenic (As)	Arsenopyrite [FeSAs]. Further sources are realgar [As_2S_2] and orpiment [As_2S_3].	Arsenic is rarely encountered in natural waters (Lide, 1999). However, As dissolves under acid conditions such as in the presence of AMD.	A toxic, non-essential element that causes chronic (cancer) and acute poisoning (nerve damage). As (III) shows phytotoxic effects at contents between 1-4 mg/kg in plant leaves (Alloway, 1995). Long-term exposure of 200-300 µg/l can cause skin cancer, contents above 1000 µg/l are considered to be lethal to man (DWAF, 1996a).	Target water quality for domestic use is ≤ 10 µg/l and < 200 µg/l (only for short-term exposure) for potable water (DWAF, 1996a). For comparison, the limit of the European Union for drinking water is given as 50 µg/l (EU 98/83/EG). The target soil quality is given as < 29 mg/kg and intervention value with > 55 mg/kg dry weight (Dutch List, 1997).
Cobalt (Co)	Cobaltite [CoAsS] and other sulphide minerals such as pyrite. In pyrite, Co can be camouflaged by Fe.	Properties are similar to Fe and Ni, where the pH is the main parameter for the solubility. During the weathering process, Co may dissolve more readily than Ni. Co is usually found in soils in Co (II) species. At low pH it is oxidised to Co (III) and often found associated with Fe (Lide, 1999).	Only a few plant species accumulate Co under acidic soil conditions above 100 mg/kg which causes severe phytotoxicity. Contents of 0.1-5 mg/l when added to nutrients have been found to be toxic in a variety of food crops. However, the occurrence of Co is not common under field conditions (DWAF, 1996d).	No target water quality for domestic use is available, but a concentration of ≤ 50 µg/kg is recommended in soils (DWAF, 1996d). The target soil quality is given as < 20 mg/kg and the intervention value with > 240 mg/kg dry weight (Dutch List, 1997).

Table C.1 continued.

Chromium (Cr)	Cr is widely distributed in soils and rocks where it occurs in minerals such as chromite [(Fe, Mg) (Cr, $Al)_2O_4$].	Occurs as Cr (III) and Cr (VI) in waters, where Cr (III) is most stable. Cr is transported primarily in the solid phase in streams, and therefore is not bio-available (Moore & Ramamoorthy, 1984).	Although Cr is present in all soils and plants, it is considered agriculturally as a deleterious element, where Cr (VI) is more phytotoxic than the Cr (III). Phytotoxic effects occur between 5-30 mg/kg in plant leaves (Alloway, 1995). However, Cr is essential to animals and man and is often found in high contents in combination with nucleic acids. The normal human adult body contains about 6 mg (Crounse et al., 1983).	Target quality in waters for domestic use is 50 µg/l (BGA, 1993). Drinking water generally contains the same Cr levels as surface and groundwaters. The target soil quality is given as < 100 mg/kg and the intervention value with > 380 mg/kg dry weight (Dutch List, 1997).
Copper (Cu)	Widely distributed in sulphides, arsenites, chlorides, and carbonates.	At neutral to alkaline pH, the content in surface waters is usually low, whereas in acidic waters, Cu readily dissolves and significantly higher contents might occur (Lide, 1999).	Cu is an essential element for almost all living organisms and the normal average human adult contains about 100-150 mg (Crounse et al., 1983). Contents above 30 mg/l can cause acute poisoning for man with nausea and vomiting (DWAF, 1996a).	Target water quality for domestic use water is < 1 mg/l and for potable water should not exceed 30 mg/l (1996a). The target soil quality is given as < 36 mg/kg and the intervention value with > 190 mg/kg dry weight (Dutch List, 1997).
Iron (Fe)	Magnetite [Fe_3O_4], pyrite [FeS_2] and weathering products such as goethite [FeO(OH)].	Important factor controlling the migration of Fe is the contents of other metals such as Mn (DWAF, 1996a). AMD can cause a very low pH in waters resulting in dissolved contents of Fe to the order of several hundred mg/l (DWAF, 1996a).	Is an essential element for all living organisms and an average human adult contains about 4-5 g (Crounse et al., 1983). Poisoning is rare, since very high contents of dissolved Fe in natural waters hardly ever occur. Chronic poisoning can be expected at 10-20 mg/l (Lide, 1999).	Target water quality for domestic use is ≤ 0.1 mg/l. No target soil quality is given since Fe is a major constituent of soils.
Nickel (Ni)	Pyrrothite [$Fe_{1-x}S$], which can contain up to 5 % Ni and pentlandite [$(Fe, Ni)_9S_8$]. Further mineral sources are chalcopyrite [$CuFeS_2$] and gersdorffite [NiAsS]. In addition, Ni can be camouflaged by Fe in pyrite.	Is strongly retained by soils, preferably in the fine particle size fraction (Moore & Ramamoorthy, 1984). During weathering Ni is readily remobilized, whereas precipitation occurs mainly in the presence of Fe and Mn oxides (Alloway, 1995) or possibly as As oxides. Ni, Fe and Co arsenates are insoluble, except at low pH.	Ni is is phytotoxic under acid soil conditions (Németh, Molnár, Csillag, Butjás, Lukács, Pártay, Féher & Van Genuchten, 1993) and toxic to man, causing liver and heart damage, cancer and dermatitis at high concentrations.	Target water quality for domestic use is not available. The limit for agricultural use such as irrigation is given as ≤ 0.2 mg/l (DWAF, 1996d). The target soil quality is given as < 35 mg/kg and the intervention value with > 210 mg/kg dry weight (Dutch List, 1997).

Table C.1 continued.

Manganese (Mn)	Spahlerite [(Zn, Fe)S], which often contains some Mn.	Similar to Fe, where both elements tend to dissolve under aerobic conditions and co-precipitate under anaerobic conditions. Once Mn is dissolved, it is difficult to remove from solution except at high pH, where it precipitates as the hydroxide (DWAF, 1996a).	Mn is essential to a wide variety of animals (Crounse et al., 1983). Although it is less toxic than other metals, chronic effects occur at contents above 20 mg/l (DWAF, 1996a).	Target water quality for domestic use is given as ≤ 0.05 mg/l (DWAF, 1996a). No target soil quality is given since Mn is a major constituent of soils.
Lead (Pb)	Galena [PbS].	Contents of Pb in soil solution reach a minimum below a pH of 5-6 and increase below pH 4 - 5 and above 6-7, because metal-organic complexes are formed in this pH range (Lide, 1999). Chemical properties are similar to those of Cd, Co, Ni and Zn (DWAF, 1996d). In connection with AMD, Pb forms insoluble $PbCO_3$ (cerussite), $PbSO_4$ (anglesite) compounds or Fe-hydroxides. Much of the Pb transported in streams is in the form of suspended matter, and thus not bio-available (Lide, 1999).	Pb is non-essential and above normal blood and tissue levels toxic to humans and animals. Pb is neither as toxic as many other heavy metals nor as bio-available, however, it is generally more ubiquitous in the environment and is a cumulative toxin in the mammalian body, thus toxic concentrations can accumulate in the bone narrow (Alloway & Ayres, 1996). Significant health effects such as limitation of neurological functions can be expected from contents above 50 µg/l. Very high levels of Pb are lethal to man (Lide, 1999).	Target water quality for domestic use is given as ≤ 10 µg/l (DWAF, 1996a). The target soil quality is given as < 85 mg/kg and the intervention value with > 230 mg/kg (Dutch List, 1997).
Zinc (Zn)	Sphalerite [ZnS], which is often associated with galena.	Zn is dissolved under acidic conditions, whereas at pH > 8 it precipitates as the relatively stable hydroxide $Zn(OH)_2$ (Moore & Ramamoorthy, 1984). Zn strongly interacts with Cd, which shows similar geochemical properties (Lide, 1999).	Zn is an essential element is a variety of animals (Olson, 1983). Zn is phytotoxic and less toxic to man than other heavy metals (Alloway & Ayres, 1996); acute toxic effects can be expected at contents above 700 mg/l (DWAF, 1996a). Zn is mainly a cause of	Target water quality for domestic use is given as ≤ 3 mg/l. The target soil quality is given as < 140 mg/kg and the intervention value with > 720 mg/kg dry weight (Dutch List, 1997).

Table C-1 continued.

Uranium (U)	Uraninite [UO_2], which alters to limonite and hematite. Further sources are zircon and monazite (Meyer, Saager & Kölpel, 1986). Note, that the Wits ore is low in Th (CNS, 1997).	U has a complex decay chain resulting in emissions of different radiations and the generation of different radioactive daughter products. U can accumulate in waters and migrate over long distances even at $pH > 7.5$, because of its ability to form complexes such as with carbonates in dolomitic waters (Bowie & Plant, 1983).	U and its compounds are highly toxic, both under chemical and radiological aspects. However, U contents in human bodies vary due to geographic differences of U in the environment averaging 0.02 mg per 70 kg (Lide, 1999).	A U content of 0.07 mg/l should not be exceeded in water for domestic use. Contents above 0.284 mg/l indicate a cancer risk < 1 : 200 000 and above 1.42 mg/l an increased cancer risk for humans in the long-term or renal damage in the short-time (DWAF, 1996a). Target water quality for irrigation waters is given as > 0.1 mg/l only over the short-term and on a site-specific base (DWAF, 1996).
Cyanide (CN)	CN is typically not contained in the Wits ore, but added [NaCN] during the gold recovery process.	Most of the aqueous cyanide is in the hydrocyanic form and is largely undissociated at pH values < 8 (DWAF, 1996f). In addition, the cyanide ion (CN^-) decomposes in aqueous solutions to cyanate (OCN^-), which is not stabile and further decomposes to CO_2 and NH_3 (Mortimer, 1987).	Toxicity depends on various factors such as pH, temperature, dissolved oxygen content, salinity and the presence of other ions in solution. Chronic effects are expected at concentrations of about 4 μg/l and acute effects at concentrations > 11 μg/l free cyanide (DWAF, 1996 f). The lethal dose for humans is 1-3 mg/kg body weight (Lide, 1999).	The target water quality for free cyanide in aquatic ecosystems is given as ≤ 1 μg/l (DWAF, 1996 f). For comparison, the limit of the European Union for drinking water is given as 50 μg/l for total CN (EU 98/83/EG). The target soil quality is given as < 5 mg/kg (pH < 5) and the intervention value with > 50 mg/kg dry weight (pH < 5) would require remedial actions (Dutch List, 1997).

Note: Abbreviations DWAF = Department of Water Affairs and Forestry. BGA = Bundesgesundheitsamt, Germany. Dutch List, 1997 refers to the Netherlands Ministry of Housing, Physical Planning and Environment, 1997

APPENDIX D

Study site maps

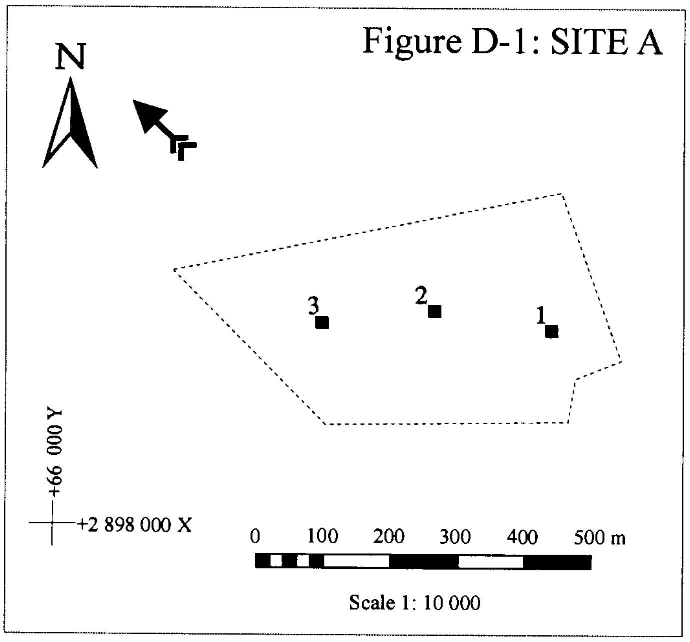


Figure D-1: SITE A

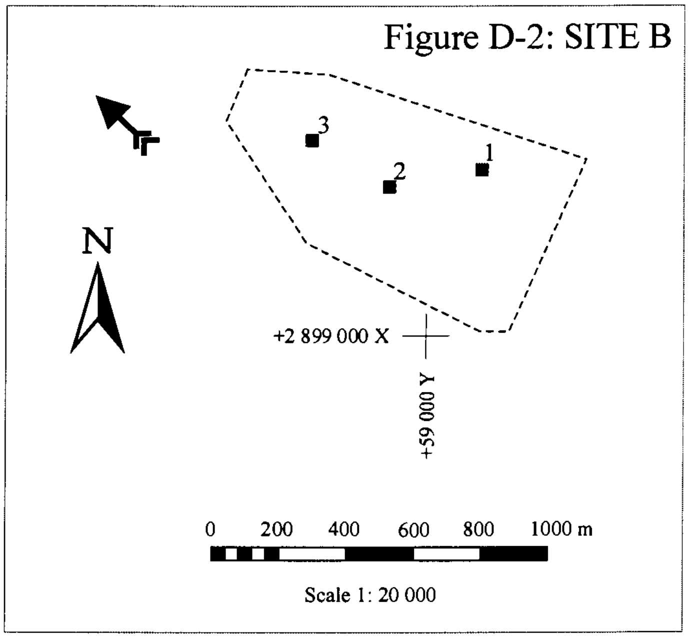


Figure D-2: SITE B

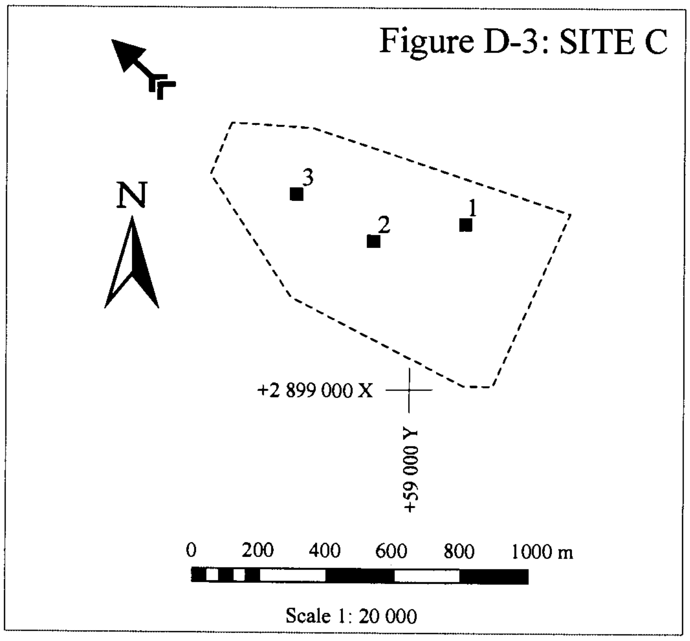


Figure D-3: SITE C

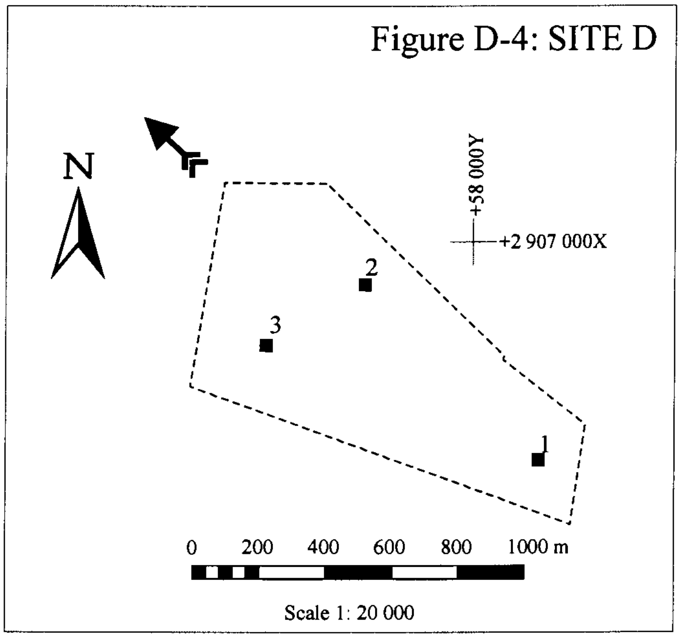


Figure D-4: SITE D

LEGEND

■ Test pit (TP)
↖ Prevailing wind direction
⬚ Site boundary

Figure D-5: SITE E

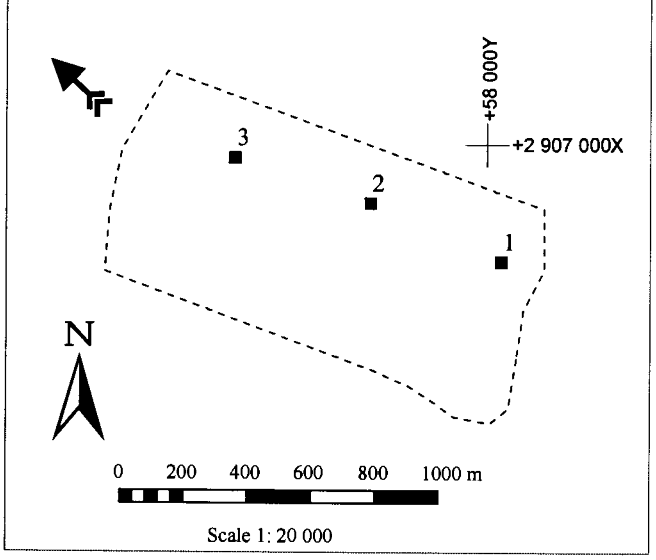


Figure D-6: SITE F

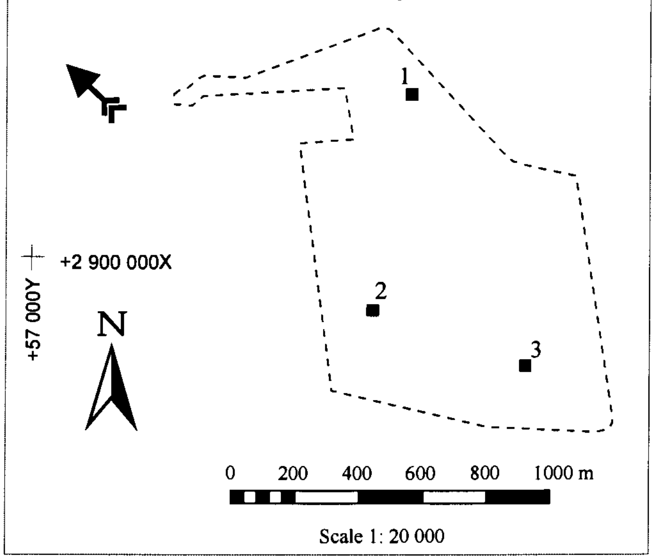


Figure D-7: SITE G

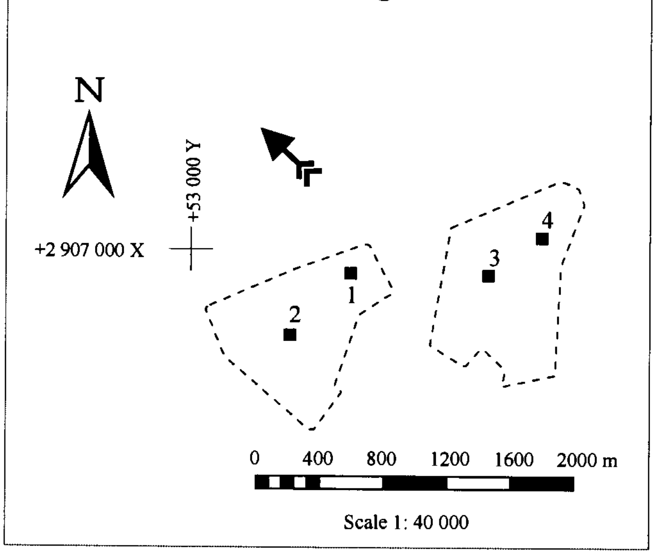
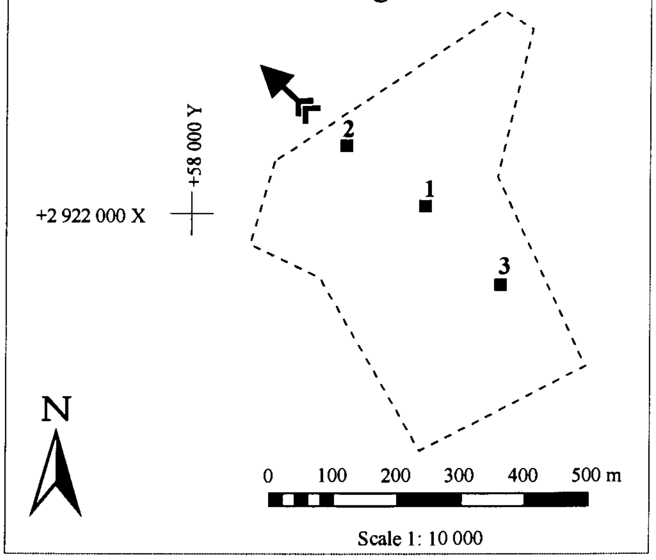


Figure D-8: SITE H



LEGEND

■ Test pit (TP)

↖ Prevailing wind direction

⬚ Site boundary

APPENDIX E

Photographs

Fig. E.1 - Study site A. Partially reclaimed. Dam height approximately 15-20 metres.

FIG. E.2 - Study site B. Some portions of tailings remaining on the surface. Paddocks were established to prevent storm water run-off.

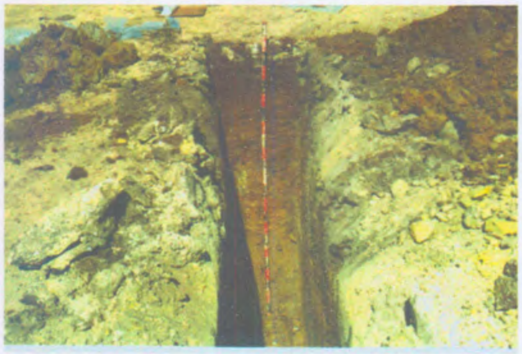


FIG. E.3 - Study site B. One of the test pits, maximum depth 2.40 m.

FIG. E.4 - Study site D. Some portions of tailings remaining on the surface. Grass cover is poorly developed.

FIG. E.5 - Study site E. Some portions of tailings remaining on the surface. Paddocks were established to prevent storm water run-off.

FIG. E.6 - Study site F. Some portions of tailings remaining on the surface. Grass cover is poorly developed

FIG. E.7 - Study site I. Rehabilitation of the slope wall to prevent wind erosion and dust generation.

FIG. E.8 - Track-mounted backactor on a Mercedes Unimog in action at one of the investigated sites.

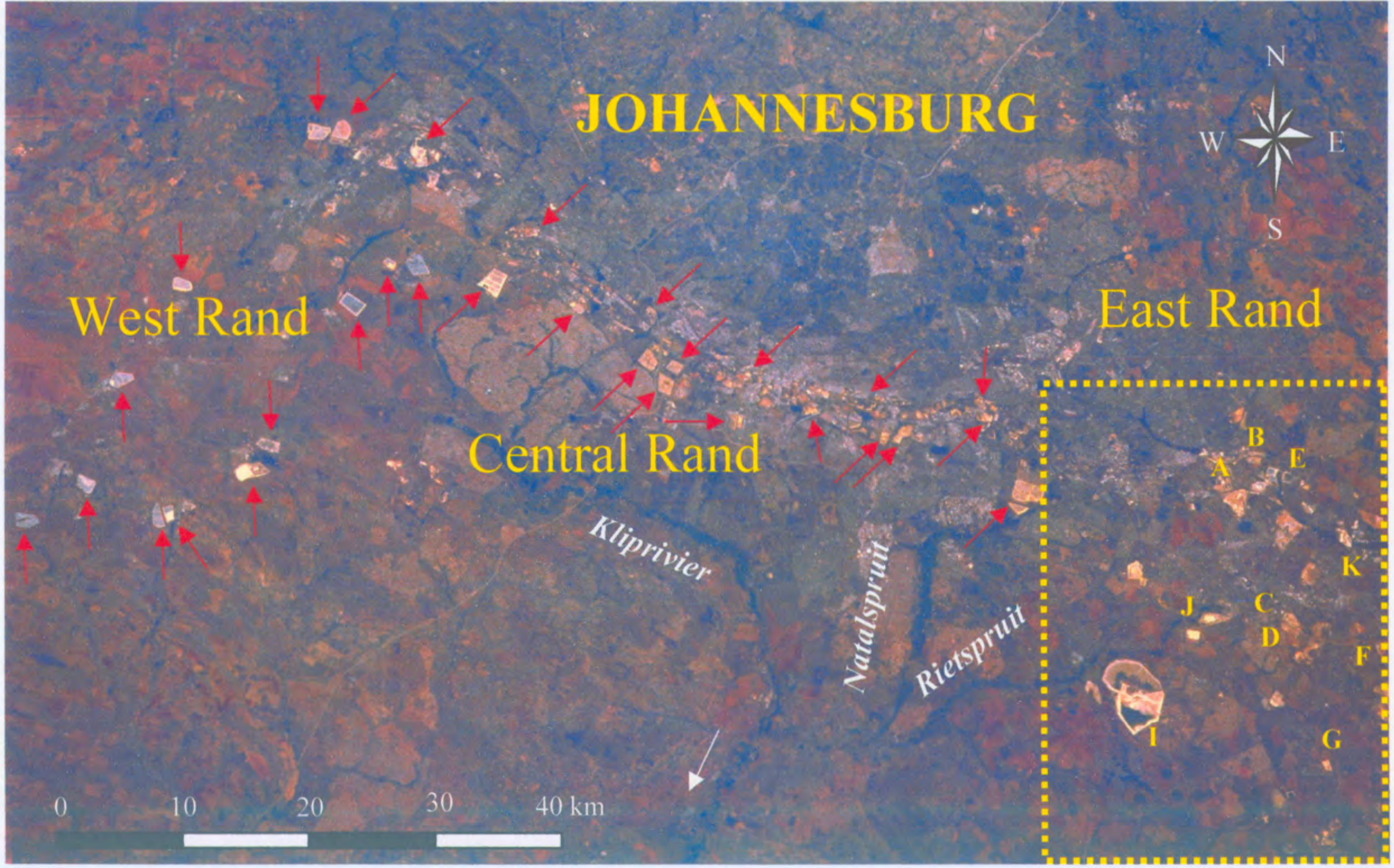
FIG. E.9 - Seepage sampling next to an operating tailings dam site near Duduza. The water is highly acidic.

FIG. E.10 - Seepage in test pit C/2. A sample was taken for chemical analysis.

FIG. E.11 - Ferricrete block consisting of iron concretions.

FIG. E.12 - Precipitation of secondary minerals such as gypsum. Photograph taken at study site G.

Fig. E.13 - Satellite image of the Johannesburg area, depicting the location of tailings dams, drainage systems and the study area



→ Location of tailings dams

NASA: STO53-080-032/1 (1994)

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I declare that this thesis which I am submitting to the University of Pretoria for the Ph.D. degree, represents my own work and has never been submitted by me to any other tertiary institution for any degree.

Thorsten Rösner
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Thorsten Rösner