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

EXECUTIVE SUMMARY

1. INTRODUCTION

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

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

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

2. OBJECTIVES OF THE STUDY

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

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

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

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

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

3. METHODOLOGY

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

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

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

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

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

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

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

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

4.1 IMPACT ON THE UNSATURATED ZONE

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

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

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

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

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

4.2 IMPACT ON THE SATURATED ZONE

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

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

5. DISCUSSION AND CONCLUSIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6. RECOMMENDATIONS

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

Investigate gold-mine tailings dams:

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

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

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

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

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

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

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

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

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

General recommendation:

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

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