# CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

## 7.1 CONCLUSIONS

In conclusion it can be stated that this study has shown that both the sandy colluvial soils and the clayey alluvial soils occurring in the study area have been polluted by gold mine tailings derived from poorly stabilised tailings dams occurring up-slope from the study area. The main findings of the study are summarised below:

### GOLD MINE TAILINGS AS A SOURCE OF TRACE ELEMENT POLLUTION AND ACIDITY

- Gold ore mined at Machavie is sulphide rich (Barton & Hallbauer 1996) and an amalgamated sample obtained from a number of sulphide bearing rocks from the rock discard dump at the site showed the sulphide mineral to be pyrite. Trace element analyses of the pyrite, as well as literature data on the composition of pyrite of the Black Reef Formation (Barton & Hallbauer 1996) showed the mineral to be rich in trace elements such as As, Ba, Co, Cr, Cu, Ni and Zn.

- The climate of the area is such that evaporation exceeds precipitation. Acidic leachate produced in the near-surface tailings will therefore tend to move towards the surface due to evaporation. The acidic leachate is rich in trace elements originating from the decomposition of sulphides and other minerals present in the tailings. Secondary minerals such as jarosite ($3KFe(OH)_6(SO_4)_2$) present in the tailings, show that sulphate-rich leachate from the decomposition of sulphide minerals is present in the tailings. The acidic leachate evaporates and a salt residue crystallizes which is composed of iron sulphates, sodium potassium iron sulphates, aluminum iron sulphates, magnesium sulphates, aluminum sulphates and sodium sulphates. These salts have high water soluble concentrations of As, Cd, Co, Cr, Cu, Ni, Pb and Zn. Tailings present as sheetwash or aeolian deposited residue, and tailings within the tailings dams are therefore a potential source of trace element contamination.

- The tailings covering the soils in the study area has an average pH of 3,43, indicating that this material produces acidic leachate from the oxidation of sulphide minerals in the presence of oxygen and water. These acidic solutions have affected the underlying soils as the pH of the topsoils underlying the tailings are all significantly lower than what would be expected under the natural pedological conditions of the area. It can therefore be concluded that the tailings has affected the quality of the underlying soils due to an increase in the acidity of the soils.

**CHARACTERIZATION OF THE DEGREE OF TRACE ELEMENT SOIL POLLUTION**

- Two techniques were employed to characterise the trace element pollution status of the soils underlying the gold mine tailings. Trace element concentrations which, according to the Dutch-B concentration guidelines warrant further investigation, were identified (Chapter 5) and the $NH_4NO_3$ extractable concentrations of these elements were determined (Chapter 6). The results of the two methods are compared in Table 7.1.

  In Table 7.1 the trace elements are ranked according to the percentage of samples in which a particular trace element exceeds the applicable guideline value. From Table 7.1 it is clear that the Dutch-B concentration screening value system fails to identify the pollutants of concern as identified by the $NH_4NO_3$ extractable concentration screening values. Nickel and chromium are the only elements that are identified by both screening systems to be contaminants of concern. The Dutch - B value system however, failed to identify Co which, according to the $NH_4NO_3$ system is a priority pollutant in soil units CU and CF. In the same manner, Zn contamination of unit AU was also not predicted by the Dutch-B value system.

According to literature (e.g. Schloemann, 1994; Davies, 1983) soil leaching systems are more suited for determining the trace element pollution status of soils than for comparing the total element concentrations of soils with screening values. The results of this study confirm this statement.

Table 7.1 Comparison between the results of the Dutch-B concentrations screening and the $NH_4NO_3$ extractable concentrations screening for the investigated area.

| Soil unit | Trace elements of concern according to Dutch-B value screening | Trace elements of concern according to $NH_4NO_3$ extractable concentrations screening |
|---|---|---|
| TC & TA | As >> Cr >> Ni | Ni > Co >> Cr > Cu > Zn > Pb |
| CU | Cr >> As > Ni | Ni >> Co >> Cr > Cu > Pb > Zn |
| CF | Cr >> Cu = Ni | Ni >> Co >> Cr > Cu > Pb |
| AU | As > Co > Ni | Ni >> Zn >> Cu > Cr > Co |
| AL | - | Ni ≈ Zn ≈ Co |

- The inability of the 1M $NH_4NO_3$ leaching technique to liberate As from the soil and tailings matrix is thought to be a result of the chemical form of As in the soil. Arsenic is usually present as an anion (e.g. $AsO_4^{3-}$) in the soil. The $NH_4NO_3$ leaching technique preferentially desorbs easily exchangeable cationic and anionic species from the soil and tailings matrix. Arsenic is not present in significant easily exchangeable fractions and the $NH_4NO_3$ leaching method therefore obtained extractable As concentrations which are mostly below the detection limit of the analytical technique.

## TRACE ELEMENT MOBILITY AS A FUNCTION OF SOIL PROPERTIES

- The mobility of Co, Cr, Cu, Ni, Pb and Zn were investigated by determining the percentage of the total element concentration which is extractable by the 1M $NH_4NO_3$

leaching technique. It was determined that both soil properties (clay content, cation exchange capacity, electrical conductivity and pH) and the pedological properties of the investigated transect determine trace element mobility.

- There are weak indications that higher mobilities of the majority of trace elements in the soils and tailings occur at low clay contents and at low cation exchange capacities (CEC). High cation exchange capacities are associated with high clay contents. This means that at a high clay content a high colloidal surface area is available and trace elements in solution are easily adsorbed. At a low clay content (and associated low CEC) less colloid surface areas are available for cation adsorption. As the soil water usually contains more major cation species (e.g. $Ca^{2+}$ and $Mg^{2+}$ in natural soils and $NH_4^+$ in the 1M $NH_4NO_3$ leaching technique) than trace elements, these trace elements will be easily replaced by the major species when adsorption sites are limited. This causes the trace elements to be mobile when adsorption sites are limited.

  In the alluvial soil, higher trace element mobilities occur in the upper soil unit AU than in the underlying unit AL. This is the result of an increase in the clay content (and therefore the CEC) of the alluvial soils with increased soil depth, causing trace elements to be adsorbed to a higher degree. In addition the low hydraulic conductivity of the alluvial soils means that trace element rich leachate has a slow vertical migration rate, increasing the contact time with colloidal surfaces, which promotes adsorption.

- No statistical correlations were obtained between the electrical conductivity of both the tailings and the investigated soils and trace element mobility. In the tailings and alluvial soils however, there is a tendency for higher trace element mobilities to occur at low electrical conductivities. In the colluvial soils there are indications that higher mobilities occur at higher electrical conductivities.

- The pH of both the tailings and the investigated soils was shown to be a main variable in controlling the mobilities of the investigated trace elements. In the tailings, the mobilities of Co, Cr, Cu, Ni, Pb and Zn increase sharply below a pH of 3,5. In the alluvial and colluvial soils a sharp increase in trace element mobilities occurs below a pH of 5 to 4,5.

- Lateral soil moisture seepage and evaporation are the two main pedological processes which are thought to control some of the main vertical and lateral trace element mobility trends observed in the investigated transect. Lateral movement of soil moisture in the colluvial soils is impeded when the clayey alluvial soils are reached. Flow lines are forced to the surface resulting in the deposition of trace elements through evaporation at the so-called seepage line. This process is thought to cause the localised high extractable concentrations and mobilities of certain trace elements in the tailings and soils in the region of test pit MT15.

  Soil moisture in the G-horizon of the alluvial soils is drawn upwards thorough capillary forces. Trace elements dissolved in the upward moving soil moisture precipitate as soluble salts in the upper soil unit AU and in the tailings cover (unit TA) due to evaporation. This enrichment process contributes to the higher extractable concentrations and mobilities of trace elements in unit AU compared with the underlying unit AL.

## 7.2 RECOMMENDATIONS

Based on the findings of this study, the following recommendations for further action and further studies are made:

- This study has shown that redistribution of the gold mine tailings from the existing tailings dams is degrading and polluting the receiving soil environment. It is therefore important that tailings dams be stabilised by establishing a grass cover on the surface of the dams. This will inhibit wind and water erosion of the tailings dams.

- It has been shown that low extractable trace element concentrations and low trace element mobilities occur in the alluvial soils between test pit MT4 and MT1, on the bank of the Kromdraai Spruit. This portion is approximately 90 m long. There is however high extractable trace element concentrations and trace element mobilities in the tailings cover overlying the soils. As these soils have not yet been degraded it is important that the tailings cover overlaying these soils be removed. It is proposed that the tailings cover be removed (with a bulldozer) and stockpiled in a berm approximately 100 meters away from the Kromdraai Spruit. A grass cover should be established on the berm as well as in the exposed alluvial soils to inhibit erosion. This should decrease the movement of tailings polluted sheetwash towards the river which will cause degradation of the unpolluted soils.

- The study has determined that the pH of the tailings and the soils plays an important role in determining the mobilities of the investigated trace elements, with all the elements (except Pb) being most mobile under low pH conditions. This suggests that liming of the tailings and soils could be an effective rehabilitation measure to minimize trace element mobility. It is however known that certain trace elements (e.g. As) are more mobile under high pH conditions and liming could therefore be detrimental as certain trace elements may be mobilized while others will become less mobile. Batch experiments could be conducted on the affected soils and tailings by determining the trace element concentration of leachate obtained from the affected soils under various soil pH values. Such a study will determine the effectiveness of liming as a rehabilitation option.

- Total arsenic concentrations in the tailings and soils suggest that As is a priority pollutant. Extractable As concentrations were however mostly below the detection limit of the analytical technique (i.e. the easily exchangeable arsenic fraction in the samples are very small). The risk that As poses on the receiving environment could therefore not be investigated. It is proposed that the chemical nature of the As in the soils and tailings be further investigated to establish if As is indeed a pollutant of concern. Total chromium concentrations in the tailings and soils was also high, but the element has a low mobility. Chromium should also be further investigated to determine the risk posed by the element. The influence of the high sulphate concentrations in the soil solution on trace element mobility should also be considered in any further studies.

- The current landuse of the study area is grazing land for cattle. The ability of the existing grass cover of the polluted tailings and soils to bio-accumulate trace elements which are hazardous to animal life should be investigated. Certain plants can bio-accumulate certain trace elements (e.g. Cd) to levels which are detrimental to the health of grazing animals and subsequent individuals higher up in the food chain.

- Groundwater in the study area are used for both agricultural and domestic purposes. The study area is underlain by a dolomitic aquifer which is usually highly sensitive to pollution due to groundwater compartmentilation. A detailed groundwater study of the area should be conducted to establish the extent to which the regional groundwater quality of the area has been affected. This will determine if human and livestock health is being negatively affected.