The pollution and destruction threat of gold mining waste on the Witwatersrand - A West Rand case study

S.H.H. OELOFSE, P.J. HOBBS, J. RASCHER and J.E. COBBING
CSIR, Natural Resources and the Environment, PO Box 395, Pretoria, South Africa, 0001

Waste from gold mines constitutes the largest single source of waste and pollution in South Africa and there is wide acceptance that Acid Mine Drainage (AMD) is responsible for the most costly environmental and socio-economic impacts. While South Africa has made significant progress in shifting policy frameworks to address mine closure and mine water management, and the mining industry has changed their practices to conform to new regulations, vulnerabilities in the current system still remain. The pollution reality of gold mining waste is illustrated by a case study in the West Rand area, where decant from gold mines started in 2002. Potential receptors of the pollution in the case study area include neighbouring property owners, a game reserve and, further afield, the Cradle of Humankind World Heritage Site. The case study illustrates many of the technical, socio-economic and governance challenges faced by industry and regulators in managing the negative impacts derived from mine waste.

Keywords: Acid Mine Drainage; Gold mining waste; Mine residue; pollution impacts

1. Introduction

As at 1997, South Africa produced an estimated 468 million tons of mineral waste per annum (DWAF, 2001). Gold mining waste was estimated to account for 221 million tons or 47 % of all mineral waste produced in South Africa, making it the largest, single source of waste and pollution (DWAF, 2001).

There are more than 270 tailings dams in the Witwatersrand Basin, covering approximately 400 km^2 in surface area (AngloGold Ashanti, 2004). These dams are mostly unlined and many are not vegetated, providing a source of extensive dust, as well as soil and water (surface and groundwater) pollution (AngloGold Ashanti, 2004).

Historically impoundment on land was the preferred option for tailings disposal on the Witwatersrand (Figure 1). The environmental implications of this disposal option include contamination of streams by acid mine drainage (AMD), contamination of streams due to surface run-off from the impoundment area, air and water contamination due to wind erosion of dried-out tailings, possible risk of catastrophic dam failure and release of slimes, physical and aesthetic modification to the environment and difficulty of establishing vegetative cover to permanently stabilize the tailings, due to unfavourable soil conditions in the presence of pyritic tailings.

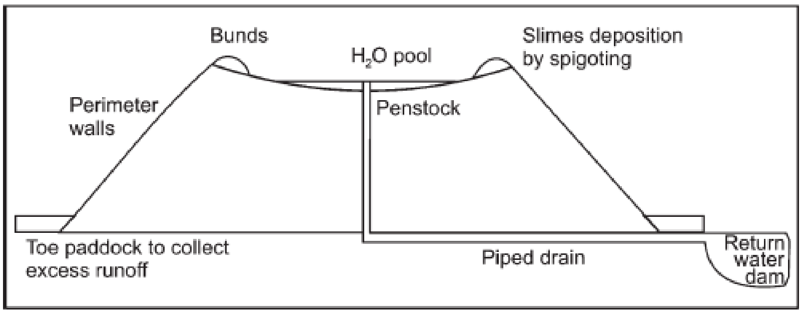

Figure 1. Diagrammatic representation of a typical gold-tailings dam (not to scale) (from Van Niekerk and Viljoen, 2005)

Many of the tailings dams in the Johannesburg area remained undisturbed for nearly a century during which time they have been exposed to oxygenated rainwater. This has resulted in oxidation of the pyrite and other sulphides in the material, particularly an outer layer of the dumps several meters thick (Naicker *et al.*, 2003). The sand dumps are generally more permeable, older and more seriously affected by the oxidation. According to Marsden (1986), the oxidation has typically reached a depth of about 5 m in the sand dumps and about 2 m in the slimes dumps.

2. Acid Mine Drainage

The types of mine waste problems are numerous, but the most difficult one to address is the acid mine drainage (AMD) that emanates from both surface and underground workings, waste and development rock, and tailings piles and ponds (Durkin and Herrmann, 1994). Surface impacts are mostly from tailings and rock dumps and adversely affect both groundwater and surface water quality. Underground impacts are generally characterized by the inflow of water into the underground workings and the subsequent dewatering of the aquifer (Banister *et al.*, 2002). Elaborate pumping systems employed in the beginning of the 20th century to increase profits resulted in the modification of the water table, appearance of sinkholes, and elevated levels of water, air, and soil pollution (Adler and Rascher, 2007; Adler *et al.*, 2007; IIED, 2002). The rebound of water levels after mine closure can lead to contaminated groundwater being discharged (Johnson and Hallberg, 2005). The primary management issues for underground gold mine closure therefore include long term decant risk, acid mine drainage, water pumping and treatment and allocation of responsibility especially in light of the interconnectedness of the mines (Pulles *et al.*, 2005).

Acid mine drainage probably presents the single most important factor in dealing with tailings and waste rock and their impact on the environment (Ritcey, 2005). Due to the more disaggregated (and more concentrated, in the case of tailings) nature of the acid-generating minerals in the waste materials, AMD that flows from them may be more aggressive than that which discharges from the mine itself. Another consideration here is the potential long-term pollution problem, as production of AMD may continue for many years after mines are closed and tailings dams decommissioned (Johnson and Hallberg, 2005).

Acid mine drainage is produced when sulfide-bearing material is exposed to oxygen and water. The production of AMD usually, but not exclusively – occurs in iron sulfide-aggregated rocks. Although this process occurs naturally, mining promotes AMD formation simply by increasing the quantity of sulphides exposed (Akcil and Koldas, 2006).

Releases of AMD have low pH, high electrical conductivity, elevated concentrations of iron, aluminium and manganese and raised concentrations of toxic heavy metals. The acid produced dissolves salts and mobilizes heavy metals from mine workings. Dark, reddish-brown water and pH values as low as 2.5 persist at the site (Akcil and Koldas, 2006). AMD is not only associated with surface and groundwater pollution, but is also responsible for the degradation of soil quality, for harming aquatic sediments and fauna, and for allowing heavy metals to seep into the environment (Adler and Rascher, 2007).

AMD follows the same flow pathways as water; therefore AMD can best be controlled by controlling water entry into the site of acid formation by diversion of surface water away from the residue storage areas, prevention of groundwater infiltration into the mine workings, prevention of hydrological seepage into the affected areas and controlled placement of acid-generating waste (Akcil and Koldas, 2006). Diversions most commonly consist of ditches, which are difficult to maintain for long periods of time. Groundwater discharge areas should be avoided as isolation and interception of contaminated groundwater is very difficult to achieve. Under-drains can be installed in locations of the dumps, and the infiltration by meteoric water can be further retarded through the use of sealing layers (Akcil and Koldas, 2006).

3. The West Rand case study

In April 2005 the media drew attention to the West Rand basin with news headlines such as "*A rising acid tide*" and "*Acid river rocks Cradle of Humankind*". The reports went on to state that "*South Africa's renowned Cradle of Humankind in Gauteng, home to one of the world's richest hominid fossil sites, is under threat from highly acidic water pollution...*" (Independent online, 14 April 2005) and "*It is also threatening to drown the Sterkfontein caves.*" (Mail and Guardian, 12 April 2005). The Mail and Guardian continues to accuse scientists, mining companies and government of reluctance to discuss the mine water decant and its impact publicly "*…….. and yet it is the start of a problem of such magnitude that it will affect our environment and health for decades to come*" (Mail and Guardian, 12 April 2005). Whilst undeniably sensationalist, these reports highlight important issues that inform the government-society-science trialogue (Turton *et al.*, 2007).

A slimes dam complex located north of Randfontein on the West Rand, Gauteng Province, South Africa occupies a footprint of some 300 ha, is about 50 m high and situated on the continental water divide. The dam is predominantly bare of vegetation, and dust suppression by means of water spraying is an ongoing management activity. Dust suppression has the additional benefit of facilitating the disposal of considerable volumes of AMD presently decanting from a nearby shaft.

The slimes dam, together with others in the wider area, is the legacy of many decades of underground gold mining and, more recently, opencast mining in the region. The hydrogeological cross-section (Figure 2) reveals the receiving subsurface environment underlying and downgradient of the facility. The positioning on top of a karst aquifer reflects the weighting afforded economic as opposed to environmental factors that historically governed the placement of mine residue sites (Wilson *et al.*, 1998). Groundwater drainage from the dolomitic strata is dominated by a spring discharging in a westerly direction at an estimated 25 L/s in March 2007 (Hobbs and Cobbing, 2007). The spring rises some 380 m to the north-northwest of the toe of the slimes dam. A subordinate groundwater flow vector is manifested toward the north, mainly as a result of abstraction from a borehole located about 590 m from the toe of the facility on a neighbouring property.

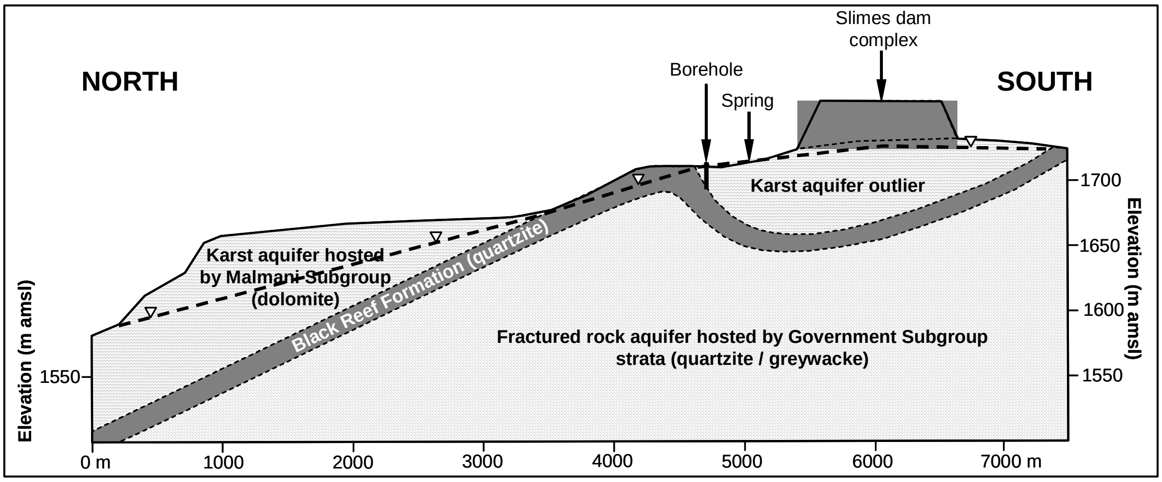

Figure 2. Hydrogeological cross-section showing potentiometric surface (dotted line)

The water quality analyses presented in Table 1 reflect the hydrochemistry of the spring and borehole water, and compare these to that of natural dolomitic groundwater in the wider region. The SANS 241 (SABS, 2005) recommended operational limits for a Class I drinking water provide a further basis for comparison.

Table 1. Groundwater chemistry in the vicinity of the slimes dam

Parameter	Spring water		Borehole water		Natural groundwater	SANS 241 Class I
pH	3.9	✗	6.1	✓	7.2	5.0 – 9.5
Electrical conductivity (mS/m)	265	✗	111	✓	17	< 150
Calcium (mg/L Ca)	262	✗	101	✓	16	< 150
Magnesium (mg/L Mg)	133	✗	57	✓	10	< 70
Sodium (mg/L Na)	111	✓	60	✓	4	< 200
Potassium (mg/L K)	7.8	✓	3.6	✓	0.5	< 50
Chloride (mg/L Cl)	98	✓	70	✓	2.5	< 200
Sulphate (mg/L SO_4	1516	✗	447	✗	22	< 400
Total Alkalinity (mg/L $CaCO_3$)	2.5	✓	16	✓	56	unspecified
Nitrate (mg/L N)	4.1	✓	6.5	✓	1.6	< 10
Fluoride (mg/L F)	0.1	✓	0.1	✓	0.1	< 1.0
Iron (mg/L Fe)	0.103	✓	0.012	✓	0.031	< 0.2
Manganese (mg/L Mn)	100	✗	0.035	✓	0.012	< 0.1
Zinc (mg/L)	0.433	✓	0.012	✓	0.012	< 5.0

✗ denotes non-compliance with SANS 241:2005 Class I recommended operational limit

The spring water reflects a clearly compromised drinking water quality in regard to six (marked × in Table 1) of the listed parameters, most notably pH, sulphate and manganese. Viewed in isolation, the borehole water only reveals marginal non-compliance with the SANS 241 (SABS, 2005) standard in regard to one parameter (sulphate). A comparison with the natural ambient dolomitic groundwater, however, reveals the measure of overall water quality degradation manifested in both the borehole and the spring water. The similarities (and differences) in water quality are more clearly revealed in Figure 3.

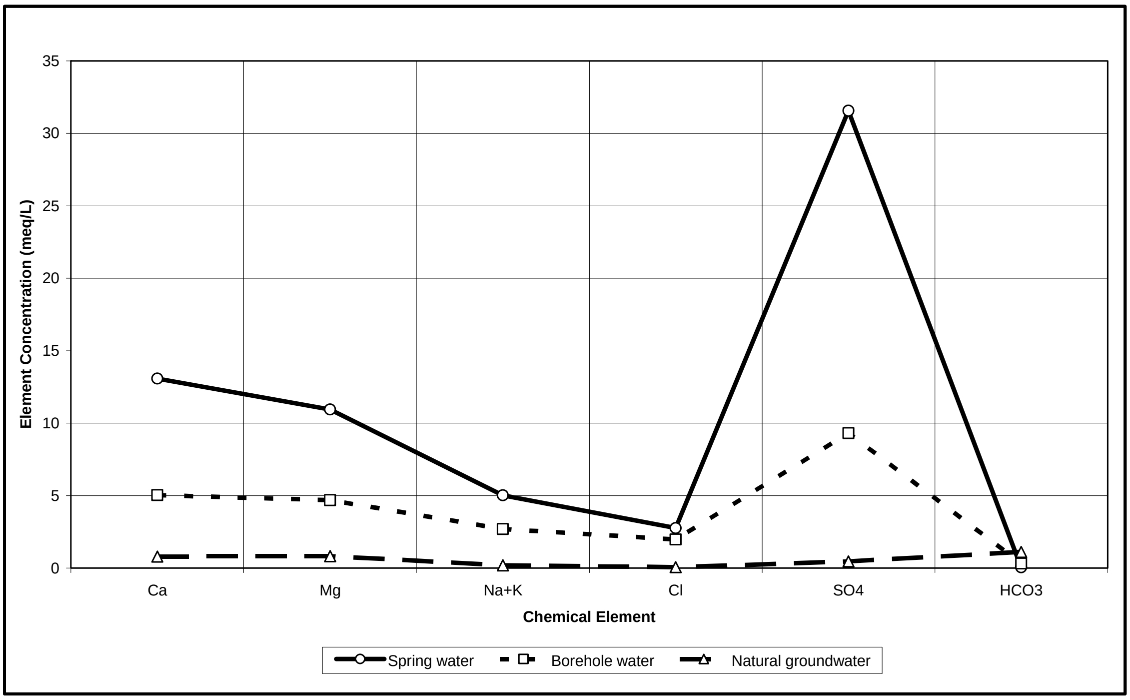

Figure 3. **Graphical comparison of groundwater chemistry**

Under circumstances where the spring water drains via a shallow open ditch across private property toward the west, concern must exist for the exposure of humans and animals along the flow path to the contaminated water. The ditch passes through at least one small farm dam that is used for recreational purposes. An ICP scan revealed elevated levels of numerous trace metals such as aluminium, cadmium, cobalt and nickel in the spring water (Hobbs and Cobbing, 2007). The water eventually reports to a surface water drainage, where its impact is subsumed under the effluent discharge from a municipal waste water treatment works located upstream of the confluence. Although more work needs to be done in order to establish beyond doubt whether the slimes dam is responsible for the groundwater pollution, at the very least the results suggest that, following the precautionary principle, further investigations need to be conducted with some urgency. If the slimes dam is indeed responsible, it will need to be established whether the pollution arises from the rainwater percolating through the slimes dam, or from the water that is used in dust suppression, or a combination of both.

To the northeast of the slimes dam complex, acid mine drainage from defunct and flooded underground mine workings first reported to surface via a borehole in August 2002. Decant has subsequently been manifested at various mine shafts and diffuse surface seeps in the area. Up until the completion in early-2005 of storage and pumping facilities to contain and manage some 15 ML/d of decant on average, the

AMD reported to an adjoining natural water course and flowed northward through a game reserve, further downstream of which lies the Cradle of Humankind World Heritage Site. Aquatic biomonitoring programmes carried out in 2000 and in 2004, i.e. before and after decant commenced, revealed a drastic drop in macro-invertebrates in the water course (Du Toit, 2006). The impact of AMD on the drinking water supply of game in the game reserve has also been blamed for various phenomena such as a significant decrease in the populations of Blesbuck, Springbuck and Lion, and diseases amongst game such as liver necrosis and testicular degeneration (Du Toit, 2006).

4. Socio-economic impacts of AMD

Access to clean water is universally accepted to be a precondition for economic and social development (Molden and Merrey, 2002; Gilbert *et al*., 1997). It is also an essential resource for drinking, household use and food production. Pressure from a growing AMD pollution load in the West Rand area of South Africa, is putting this invaluable resource under threat and it is therefore unsurprising that the decanting of AMD near Krugersdorp is accompanied by several socio-economic consequences, of which human and animal health risk is of the greatest concern.

Residents in the decant area that rely on borehole water, raised concerns about the orange colour of the water which is a result of sulphur compounds present in AMD. Long-term exposure to AMD polluted drinking water may lead to increased rates of cancer, decreased cognitive function and appearance of skin lesions (Adler and Rascher, 2007; Ashan, 2004; Bellinger *et al*., 1992). Studies on the exposure of pregnant woman to relatively low concentrations of heavy metals and other industrial chemicals in drinking water revealed that the neural development of the fetus could be compromised which can result in mental retardation (Grandjean and Murata, 2007; Grandjean and Landrigan, 2006; Bellinger *et al*., 1987). Recent studies conducted by the South African Council for Geosciences (CGS), concluded that AMD in some of the areas contains high levels of radioactivity (Coetzee *et al*., 2005, 2006) which may increase the risk for cancer.

Soil pollution may, apart from contaminating food produced in the area, also affect the health of specific cultural groups through the phenomenon of geophagy (the practice of eating earth) that is common in sub-Saharan Africa. It is believed that the mineral content in clays contain high levels of calcium, iron, copper and magnesium that are essential minerals for the human diet, but even more critical during pregnancy (Wiley and Katz, 1998).

As a result of polluted mine water spilling out into the environment and the strong sentiments about the relationship between the mining industry and government, AMD has become a very visible and highly political issue in South Africa (Adler and Rascher, 2007). Mine closure and the associated increase in AMD also has serious consequences for communities previously supported by the mining sector (Adler and Rascher, 2007; Warhurst and Norhona, 2000; Claassen, 2006). Mine closure results in loss of job opportunities and increased unemployment. In addition, informal settlements with associated social pathologies are on the increase. Subsistence farming is often the last resort for such communities, but AMD may render the available water resources unfit for agricultural use (Warhurst and Noronha, 2000).

5. Governance

A review of local literature and legislation by Godfrey *et al.* (2007) has shown that currently much confusion exists in South Africa with regards to the roles and responsibilities of the Department of Minerals and Energy (DME) and the Department of Environmental Affairs and Tourism (DEAT), with respect to the management of mining waste. Both departments have placed certain requirements on mines before a closure certificate is granted, the main requirement being an environmental management plan (EMP) which is compulsory for any mine and for which DME is the lead agent (Pulles *et al.* 2005). Co-operative governance is, however, not very effective in protecting the environment against the negative impacts of mining waste.

Closure planning as embodied in EMP reports of gold mines in South Africa is currently inadequate to protect the water resources impacted by mining activities. The status at the end of 2001 of approximately forty gold mine closure plans, as described in their EMP reports, are summarized by Banister *et al.* (2002). The pertinent misconceptions and shortcomings described by Banister *et al.* (2002) include that most mines recognize that tailings dams generate AMD, but it is generally and incorrectly assumed that the impact will decrease to acceptable levels when the mining operations cease. It appears to be quite widely assumed that the larger particle size of waste rock dumps makes them a lesser pollution risk. This view is erroneous, as the waste rock dumps have very large inventories of fine material and are much more permeable to oxygen than tailings dams (Bannister *et al.*, 2002). It is also not clear if the extent of contamination plumes is known.

6. Conclusions

If indeed the extent of "*… problems related to mining waste may be rated as second only to global warming and stratospheric ozone depletion in terms of ecological risk*" (EEB, 2000), then the Witwatersrand gold mining area of South Africa is at serious risk. Being the economic heartland of South Africa, few natural ecosystems remain and, as indicated by the case study, the impacts of mining and other problems related with mine closure and mine water management that cannot easily be addressed over the short term, may have devastating consequences for more than just ecosystems. It will be a sad day if AMD is allowed to impact negatively on archaeological material preserved over millennia, leaving questions of human origin unanswered.

The end of mining in the region is sadly not the end of impacts from mining and the mine waste dumps. Long term closure and post-closure management measures will determine the ultimate fate of an environment which includes sites of international importance such as the Cradle of Humankind.

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8. Biographies

Suzan H.H. Oelofse obtained a Ph.D. in Botany at the Rand Afrikaans University, Johannesburg, South Africa in 1994. She worked in government on pollution and waste management policy and strategy development and regulating environmental impacts of the industry sector on water resources and the marine environment for 10 years. She joined the CSIR in 2006 as scientist conducting research on understanding the opportunities and constraints provided by general and hazardous waste generation in Southern Africa.

Jude Cobbing is a consulting hydrogeologist based in Pretoria, South Africa. He has a BSc in Geology from the University of Cape Town, and a MSc in Hydrogeology from London University. His interests include minewater assessment and remediation, groundwater management strategies, down-hole geophysical logging and water and sanitation issues in rural Africa. Mr Cobbing is also a qualified teacher and retains an interest in groundwater education and communicating groundwater issues to the public.

Phil Hobbs has 28 years of experience covering a wide range of groundwater studies across a broad spectrum of geological and geohydrological environments. The studies include the exploration and development of groundwater resources for water supply purposes at local (domestic) and municipal (bulk) scale, the evaluation and assessment of land use activities such as waste disposal, mining and residential development on the groundwater environment, and the mapping of groundwater resources at regional scale. The spectrum of geological and geohydrological environments include Archaean granite and Bushveld Igneous Complex rocks, much of the Transvaal Supergroup (including the dolomites) and Karoo Supergroup strata, and Tertiary and Quaternary sediments comprising limestones and alluvial sediments. More recent experience is associated with resource directed measures (RDM), and pertains to determinations of the groundwater Reserve at rapid and intermediate level, and the associated classification of groundwater resources and setting of resource quality objectives (RQOs). Experience relating specifically to the mining industry derives from groundwater investigations conducted at various mining operations, currently in the West Rand Basin with its associated acid mine drainage issues.