Metal pollution sources and transport in mined watershed: an insight from Ermelo Coalfield, South Africa

N. O. Novhe[1], R. Netshitungulwana[2], B. Yibas[3], T. Motlakeng[4], E. Sakala[5]

Council for Geoscience, 280 Pretoria Rd, Silverton, 0184, South Africa,
[1]onovhe@geoscience.org.za,[2]robertn@geoscience.org.za;
[3]byibas@geoscience.org.za;[4]tmotlakeng@geoscience.org.za; [5]esakala@geoscience.org.za

Abstract Metal pollution of water resources is a widespread environmental problem facing a supply of drinking water in South Africa. An investigation has been conducted in respect of a mined watershed in the Ermelo coalfield to identify metal pollution sources and associated pathways. Pollution is derived primarily from both abandoned and operational coal mines, in a form of acid mine drainage characterised by low pH and high concentration of Fe, Al, Mn and SO_4^{2-}. Streams are the major pollutants pathways. Ground geophysical surveys also revealed potential shallow pollution plume. The work conducted has enabled proper prioritization of the identified pollution hotspots and selection of appropriate cost-effective pollution management plan at point sources.

Keywords Coal mines, acid mine drainage, metal pollution, Ermelo Coal Field,

Introduction

Most of the coal mines in South Africa are affected by acid mine drainage, and over years this has led to a deterioration in the water quality in many surface streams (Geldenhuis and Bell 1998). The environmental impacts of AMD have been reported in the coal mine sites (Bell *et al.* 2001, McCarthy and Pretorius 2009, McCarthy 2011). Acid mine drainage, owing to its high content of dissolved solids, suspended solids and iron, low pH value and its possible toxicity, can render the water in the receiving water bodies unfit for many applications, unless costly treatment is applied. Concerns have been raised relating to pollution of domestic water supplies. More spectacular metal pollution incidents have occurred recently, such as the pollution of the Boesmanspruit dam in the Ermelo coalfield situated south of Carolina in the Mpumalanga Province (Fig.1). The dam is an abstraction point that feeds the municipal water treatment works for domestic water supply, and its contamination with elevated metal contaminants has resulted in failure to meet the required water quality standard for domestic use and disruption of water supply to the surrounding communities. This work focus on the investigations conducted in the area around the Boesmanspruit dam, to identify and characterise pollution sources, pathways/transport and to propose suitable management measures.

The area falls within the quaternary drainage region 11XB, which forms part of the Komati West sub-catchment in the Inkomati Water Management Area. The X11B sub-catchments form a watershed between two larger catchments feeding two non-perennial tributaries of the Boesmanspruit. Geologically, the area forms part of the Ermelo Coalfield, situated south of Carolina. The northern and eastern boundaries are defined by the sub-outcrop of the coal-bearing strata against pre-Karoo rocks. All of the coal Seams occur within the Vryheid Formation of the Ecca Group, Karoo Supergroup. Sandstones with subordinate shales represent the bulk of the Vryheid formation (Bell and Jermy 2002). Currently, the area is comprised of both abandoned and operational coal mines, most of which are situated up-

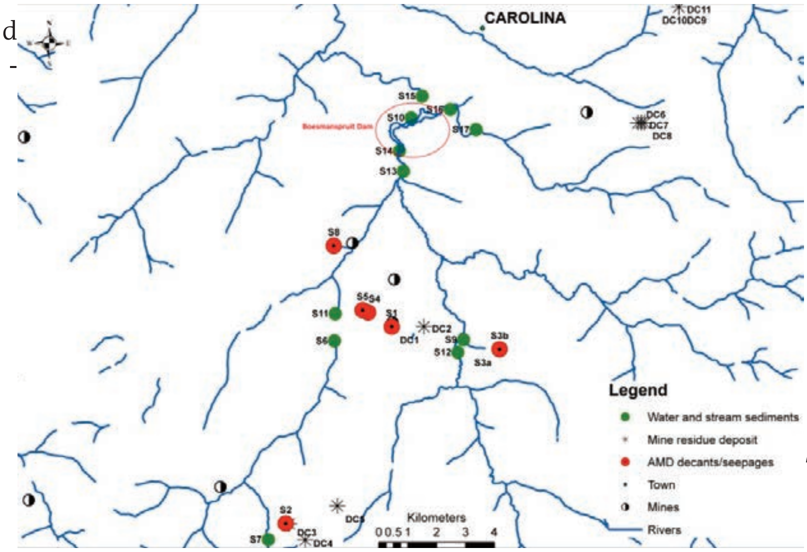

Fig. 1 *Location of Boesmanspruit dam and associated tributaries*

stream of the Boesmanspruit dam (on the southern portion of the area). Of the total saleable production of 222.551 Mt in 2001, the Ermelo Coalfield contributed about 7.2 Mt (Jeffrey 2005).

Material and methods

Fieldwork observation and sampling have been conducted to identify and characterise pollution sources in the area. Both water (discharges from flooded underground mines, leachate from mine residues and stream water) and solid (mine residue deposits and stream sediments) samples have been collected and analysed. Water samples were analysed by means of ICP-MS and IC analytical techniques and the elements concentrations were compared to the South African domestic water quality standard. Solid samples were analysed by means of XRF, XRD and ICP-MS analytical techniques for metal loadings and mineralogical compositions. Acid base accounting (ABA) was also conducted on the mine residues samples to determine the potential of acid generation. Two geophysical methods namely Frequency Domain Electromagnetic (FDEM) profiling and electrical resistivity tomography (ERT) were applied in order to identify depth and lateral extent of any possible pollution plume. The 20 m horizontal coil separation of EM34 FDEM unit used has depth of investigation of about 15 m while IRIS Syscal Pro ERT system can probe up to around 40 m depth.

Results and discussions

The pollution manifest itself in a form of acid mine drainage seepages as well as run-off from mine residue deposits, such as discard coal dumps and slimes; decants from flooded abandoned underground coal mines; and seepages of acid mine drainage from abandoned backfilled open cast mines. Most of the identified pollution sources are situated upstream of the Boesmanspruit dam, and in some areas there is direct discharges/seepages into the tributaries of the Boesmanspruit (Fig. 1). Onsite and laboratory analyses of the water parameters, such pH, Electrical conductivity (Ec), and metal composition have been conducted in respect of the identified pollution sources and the adjacent streams.

All the sampling points are indicated in Fig. 1 and the results are summarised under Table 1 and 2. The analytical data is compared with the limit for human consumption, as per the Department of Water Affairs (DWAF) guideline. These problem areas are generally characterised by low pH, with elevated concentration as much as two and even three orders of mag-

Sample ID	pH	Ec mS/m	Fe (mg/L)	Al (mg/L)	Mn (mg/L)	SO_4^{2-} (mg/L)	As(mg/L)
	6-9*	**N/A**	**0-0.1***	**0 - 0.15***	**0-0.05***	**0-200***	**0-0.01***
S1	2.4	1,017	3,307.23	820	264.62	21,492.52	0.98
S2	3	710	2,091	261.35	14.4	4,404.09	0.05
S3a	3.1	235	308	37.24	23.7	2,067	0.06
S3b	3.2	280	128	26	32	1,889	0.05
S4	3	170	2.67	3.31	42.32	1,243	0.05
S5	3	157.2	4.9	1.16	20.52	952	0.05
S8	6.9	11.64	4.0	0.3	1.16	10	0.04

*Department of Water Affairs limit for Human consumption

Table 1 Analytical data for acid mine drainage sources in the study area

Sample ID	pH	Ec mS/m	Fe (mg/L)	Al (mg/L)	Mn (mg/L)	SO_4^{2-} (mg/L)	As(mg/L)
	6-9*	**N/A**	**0-0.1***	**0 - 0.15***	**0-0.05***	**0-200***	**0-0.01***
S6	3.8	145	<0.1	6.77	36.04	929	0.04
S7	4.6	16.07	0.28	275	0.04	31	0.05
S9	7.4	9.02	< 0.1	0.3	0.24	7	0.04
S10	4.3	65.5	<0.1	2.41	10.43	361	0.04
S11	7.3	8.84	<0.1	0.28	0.08	7	0.04
S12	7.2	111	<0.1	0.27	1.45	622	0.04
S13	6.8	9.63	< 0.1	0.34	0.05	4	0.04
S14	7	32	< 0.1	0.31	0.15	69	0.04
S15	7	56.7	< 0.1	0.4	0.28	265	0.04

*Department of Water Affairs limit for Human consumption

Table 2 Water quality data for the Boesmanspruit dam and associated tributaries

nitude of Fe, Al, Mn and Sulphate most and slightly elevated As than the acceptable limit. The analytical data is summarised in Table 1.

Mine residue deposits

Mine residue deposits (MRDs), such as discard coal and slimes, are denoted as DC1 to DC11. Based on acid base accounting results, Ermelo coalfield MRDs are classified as potential acid generating. Fig. 2 shows subdivision according to the ration of AP and NP (NPR). Majority of the samples plot at NPR>1. The acid potential of all the samples exceeds the neutralization potential. The acid potential (AP) ranges from 11 kg $CaCO_3$/ton to 250 kg $CaCO_3$/ton, whereas neutralization potential (NP) ranges from - 11 kg/ton $CaCO_3$ to 24 kg $CaCO_3$/ton. The sulphur percentage ranges from 0.9 to 8 %, averaging at 2 %. Based on XRD results, pyrite is the important acid producing mineral, whereas kalionite, mica and plagioclase are the potential acid consuming minerals. XRF results identified Al, Mn and Fe as potential pollutants that may affect the quality of water, provided the physico-chemical conditions prevailing at the MRDs site allow leaching of these metals in significant amounts. In addition, As, Ni, Co are intermediate in concentration. Analyses in respect of seepages from mine residues samples (DC1 and DC2) also revealed low pH and high concentration of Fe, Al, Mn and SO_4^{2-} (ranges from 2,091–3,307; 261–820; 14-264 and 4,404–21,492 in mg/L respectively). It was also observed during the time of investigation that in

Samples ID	Fe (57)	Al (27)	Mn (55)	V (51)	Cr (52)	As (75)
S6	25,985.5	35,696.6	302.6	47.2	78.0	4.9
S8	7,626.1	12,937.9	61.2	18.1	25.9	<2
S7	63,541.0	43,193.5	1,780.3	153.6	304.6	11.4
S10	6,003.8	9,484.7	69.1	11.2	25.3	<2
S11	126,209.0	66,954.8	1,151.6	107.2	126.3	19.3
S12	49,967.4	46,057.5	762.5	88.3	217.6	6.6
S13	14,897.0	19,160.1	166.9	21.4	34.5	<2
S14	12,357.0	19,266.2	129.9	25.1	75.3	<2
S15	7,272.1	12,725.8	99.3	14.7	38.2	<2
S16	16,215.0	13,655.4	120.4	31.6	118.6	2.1
S17	18,141.2	22,977.3	218.0	40.4	56.7	2.5

***Table 3** stream sediments geochemistry of the study area (as ppm)*

some areas the river, dam and ponds were filled with coal fines, especially in the central tributary. As indicated by ABA results, the coal fines also have a potential to contribute to the generation of AMD, and the possible sources are the adjacent mining activities through runoff associated with poor storm water management measures or poorly designed mine dump residues.

Geophysical surveys were done across two streams to investigate the lateral and depth extents of a possible contaminant plume from coal mine tailings. FDEM and ERT surveys were carried out a south-north line (Fig. 3). FDEM method identified high conductivity zone with readings of the order of 250 mS/m at depth of 15m. ERT survey identified a sub-vertical low resistivity zone which extends to depth at station 50 m. The bedrock is deepest within this zone. An abrupt break in the bedrock topography at station 200 m could be due to a saturated dipping fault zone as evidenced by very low resistivity values of about 20 Ωm. Visible traces of mine residue (AMD) in water were noted on surface at this point corresponding to water sample number S7. The interpreted fault zone extends to depths greater than 40 m could be a potential plume or pathway to groundwater resources.

Underground flooded and Backfilled open cast mines

Decants from abandoned underground mines have been identified in the area, denoted as S3 and S8. Field tests, in respect of decant point S3 revealed that the water quality is very poor (pH = 3.1, EC = 235 mS/m) with elevated concentration of Al, Mn, Fe and sulphate (37.24, 308.0, 23.70 and 2067 in mg/L respectively). The flow/discharge rate was determined using the bucket and stop watch method, and was found to be 50.3 m^3/day). The analyses conducted in respect of decant S8 show that the water quality is not as poor as S3. The pH is near neutral (pH = 6.9) but with elevated Fe, Al, Mn than the acceptable limit (4.0, 0.3 and 1.16 in mg/L respectively). Several subsidence areas and sinkholes have been identified in areas around the

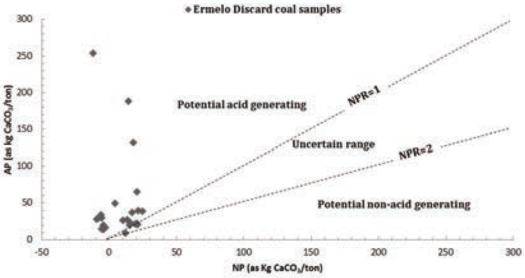

***Fig. 2** Acid Potential vs. Neutralisation potential graph indicating areas of likely acid generation and unlikely acid generation*

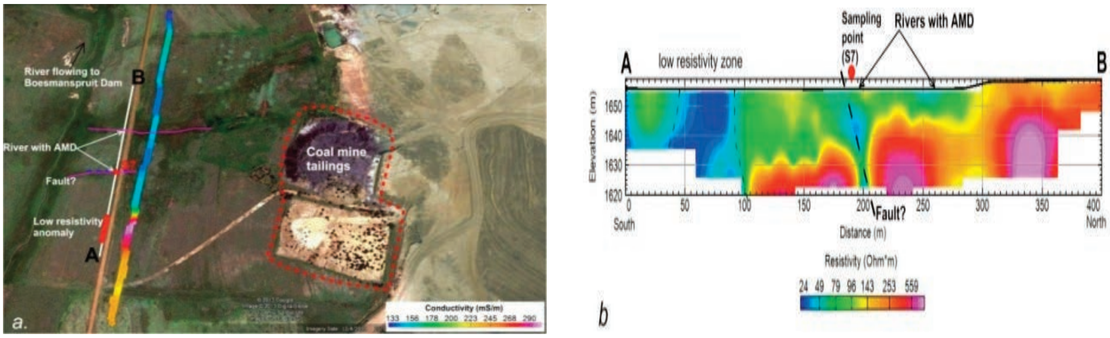

Fig. 3 *Geophysical survey results showing (a) elevated earth conductivity values above 250 mS/m and (b) interpreted fault zone where AMD flows on surface at one coal mine south of Boesmanspruit dam*

decant points, indicating failures in respect of the remaining mine workings (such pillars). Investigation done by Vermeulen and Usher (2006) concerning recharge in South African underground collieries, revealed subsidence areas and sinkholes as potential water ingress points. AMD also emanates from old opencast workings which have been backfilled (S4 and S5).

Pollutants pathway and metal fate

Streams are considered as major pollutants pathways/transport. The analytical data for the water quality and stream sediments geochemistry are summarised in Table 2 and 3. For the water quality, comparison was made with the targeted limit for human consumption as per DWAF guideline showed that the quality of water is generally poor, especially in the vicinity of pollution sources. Water sample number S7 and S6 generally show extremely poor water quality, comparing to other points that are situated downstream of the Boesmanspruit tributaries. Stream sample S6 is situated in close proximity of the old backfilled open cast mine area (hot spots number S4 and S5) which seeps AMD into the central tributary. Sample S7 is situated in immediate proximity of an old mine residues dump (DC2, DC3 and DC4), which also discharge acid leachate into the central tributary. However, the water quality improves downstream or away from the AMD sources. The general downstream improvement in water quality could be attributed to natural attenuation associated with the existence of extensive wetlands in the area. The wetlands serve as a sink for pollution where polluting metals are trapped in sediments and peatlands (Tutu *et al.* 2008). The dam (S10) was acidic during the time of investigation, with a pH of 4 and is comprised of high levels of Al, Mn, and sulphate and As (2.4, 10.43, 361 and 0.04 mg/L respectively). The high concentration of the metals in the dam as compared to the stream tributaries could be attributed to the low pH.

The stream sediments results also show that the major contaminants in the area include Fe, Al, Mn, whereas minor contaminants include As, V and Cr. The metal fate in the stream follow similar pattern as the water samples, in that the concentration decreases away from the pollution sources. Sample number S6, S7, S11 and S12 that are situated upstream, in close proximity of the pollution sources, are comprised of high concentration of the major contaminants Fe, Al and Mn (in a range of 25,985–126,209; 35,696–66,954 and 302–17,80 in mg/kg respectively). The downstream samples also show decreased concentration of Fe, Al and Mn (in a range of 7,272–18,141; 12,725–22,977 and 99–218 in mg/kg respectively). The dam (S10) also shows decreased concentration of the major contaminants Fe, Al and Mn (7,626; 9,484 and 69 in mg/kg respectively).

Conclusions and Recommendations

The metal pollution of the Boesmanspruit dam is associated with the coal mining activities (both active and abandoned), and might continue for a long period unless proper management measures are developed and implemented. However, the extent in which individual mines contribute towards the problem is not yet known due to the lack of long-term flow data in the catchment.

Major pollutants in the surrounding surface water include Al, Mn, Fe and sulphate which are the major environmental signatures of the Ermelo Coalfield and are associated with acid mine drainage. Major pollution sources relate to decant of acid mine drainage from flooded underground coal mines and seepages associated with backfilled open cast mines and mine residue deposits. Streams are the major pollutants pathways/transport into the domestic water supply dam. The concentration of contaminants decreased downstream and away from the pollution sources. Ground geophysical surveys revealed elevated electrical conductivity readings above 250 mS/m at 15 m depth and an interpreted fault zone could be a possible conduit of pollution from the old coal mine dump.

It is recommended that the identified pollution sources such as decants and seepages from the back filled opencast mines be treated at point source. Suitable passive treatment can be implemented based on the quality of the water to be treated and the required water quality standard. Measures to reduce ingress of water into the backfilled open cast area and the abandoned underground must also be investigated.

Proper storm water management measures must be put in place in respect of the mine residue deposits sites, to contain the seepages and prevent further runoff. An extensive mapping of the areas contaminated with coal fines/carbonaceous sediments and development of appropriate cleaning measures must be conducted.

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