A preliminary study of the relative contributions of diffuse and point sources of pollution arising from gold mining activity in a Witwatersrand goldfield

Ntsume Gabriel.M.[1] , McCarthy T.S [2]

[1]Council for Geoscience. [2]University of Witswatersrand
E-mail: gabriel@geoscience.org.za

ABSTRACT

Gold mining on the Witwatersrand, South Africa, has generated considerable wealth for the country, but has also resulted in several environmental problems, notably pollution of surface and underground water sources. The ores contain pyrite, minor heavy metal sulphides and uranium minerals, and oxidation of these minerals has led to contamination of groundwater beneath tailings dumps (diffuse sources) and water pumped from the mines (point sources). A study of a reach of the Blesbok stream where both diffuse and point pollution sources occur has revealed that these two sources contribute similar amounts to the total pollution load. However, the diffuse source water has not been treated, and appears to contribute the bulk of the heavy metals.

INTRODUCTION

Gold mining on the Witwatersrand began over a century ago in 1886. The gold mining industry has contributed enormously to the economic development of South Africa. The originally small mining communities rapidly gradually grew into towns and the mines and towns expanded together, leading to the formation of the extensive Witwatersrand conurbation with a population in the region of 10 million people today (Beavon, 2004). Although contributing considerable wealth to the country, these industries have left a legacy of environmental problems in the form of surface and ground water pollution and the sterilization of land.

Before the adoption of the ‘all sliming’ cyanidation process for gold extraction in the early 1900s, all tailings from the mines had been deposited dry in the form of so-called sand dumps. The sand from these dumps proved to be particularly wind erodible and all attempts to alleviate the problem at that time met with little success, with possible exception of establishing surface vegetation involving the application of sludge of black wetland soil to the sides of the dumps, a method used for some years.

A more insidious problem, however, arose from the mineral constituents in the dumps. Pyrite is present in all Witwatersrand ores, making up about 3 wt. %. Also present in minor amounts are sulphides of Cu, Ni, Pb and Co, as well as arsenides and uranium-bearing minerals (Feather and Koen, 1972). These minerals are not removed during gold recovery and report to the tailings dumps. Oxygenated rain water entering the dumps leads to oxidation of the pyrite and other sulphides in the material, in the outer layers of the dumps. The sand dumps, are more seriously affected by this oxidation and oxidation fronts has reached more than 2 m into many of the dumps (Marsden, 1986). This oxidation acidifies water passing through the dumps, which leads to the contamination of ground water beneath the dumps and the formation of a plume of contaminated groundwater that flows outwards from beneath the dumps. This acidic water is entering the streams along the Witwatersrand (Jones et al., 1988, Naiker et al, 2003), and constitutes a diffuse and widespread pollution source in the region.

In recent years, another source of mining polluted water has come to the fore. The majority of mines along the Witwatersrand have closed, and the vast void left by mining has gradually started filling with water. Because of the underground connections between the mines, subsurface water is able to flow across much of the region from one mine to the next. In order to continue operations, the few remaining mines are obliged to pump not only water which ingresses on their own properties, but also water originating from neighboring mines. This water may have had a considerable residence time underground, and has become acidified by reaction with ore minerals present in pillars in the old workings. This pumped, contaminated water constitutes a point source of pollution, as opposed to the more diffuse sources arising from dump material. Because the water is pumped, it is possible to treat it prior to discharge into the surface drainage system. Treatment generally involves the addition of lime to neutralize the acidity, followed by aeration to oxidize the iron. The iron is then allowed to settle (iron precipitation at slightly alkaline pH removes much of the heavy metal load as well), and the water is discharged. The main contaminant in this water is calcium sulphate (Van der Merwe and Lea, 2003).

The current study examines a stream that is being affected by both diffuse pollution sources arising from active and abandoned tailings dumps, and a point source arising from mine pumping. In addition, there is also some input of industrial water from a paper mill in the area. All of these sources contribute water to a wetland that has been declared a nature reserve, and is a registered Ramsar Site (Marievale Bird Sanctury). The study was carried out in order to assess the relative contributions of the various mining-related pollution sources to the total load entering the reserve.

THE STUDY AREA

The study area is situated in the eastern portion of the Witwatersrand, near the municipality of Springs (fig. 1). The river system studied is Blesbokspruit and one of its tributaries. The stream is perennial over all the sampling points and is also susceptible to severe flooding during summer rains. During the dry season, discharge into the stream is sustained by ground water emerging through the bed of the stream and by seepage through the banks. Other sources of water arise from discharge of treated sewage water, discharge of treated water from a paper mill, and water pumped from a producing gold mine.

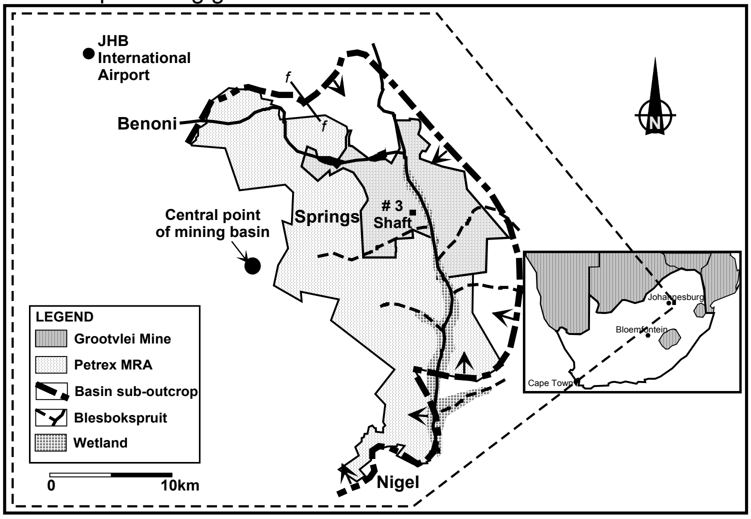

Figure 1 Study area of Blesbokspruit

In addition to surface water analysis, a study was conducted on two tailings dumps located astride a section of the stream and associated wetland. This involved collecting data on the water table within the dumps, as well as examining the chemistry of this ground water. The dumps in question are still in use: Dump 2 is receiving tailings from the continuing mining activities in the area, while Dump 1 is being used as a disposal site for iron oxides precipitated from pumped mine water (figure 2).

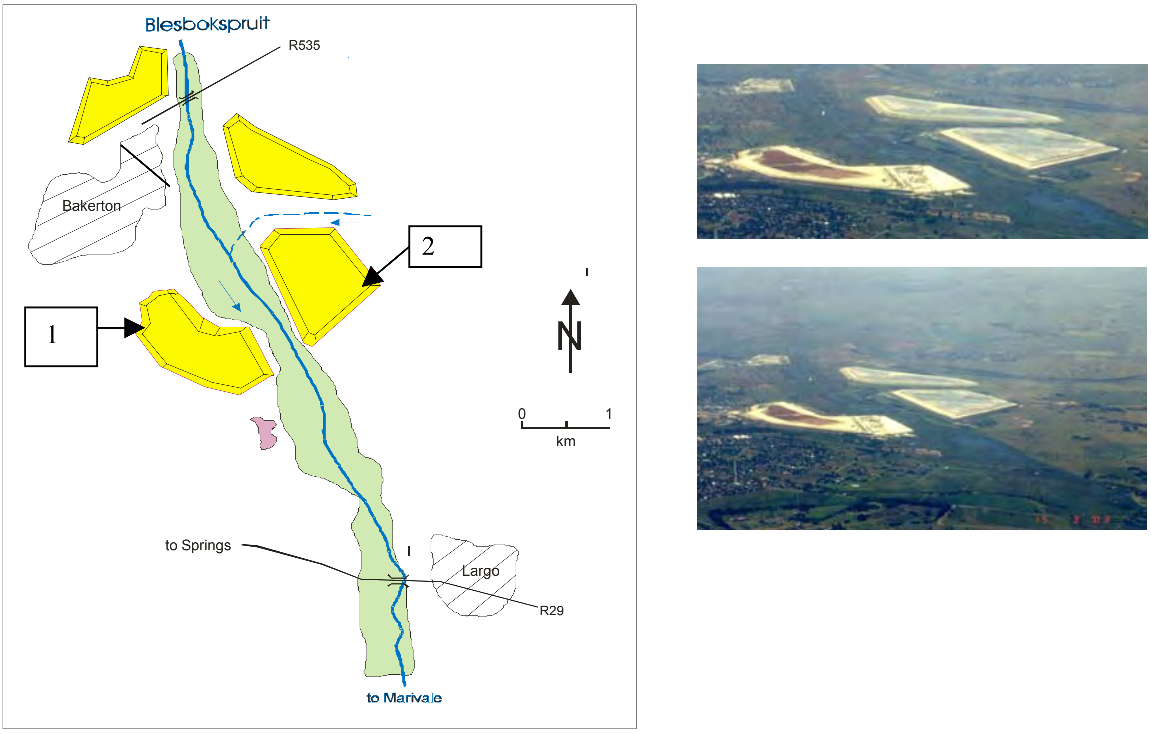

Figure 2 Map and photograph showing the location of dumps investigated an their relation to the Blesbokspruit wetland

Annual rainfall in the area is about 750 mm (Tyson and Wilcocks, 1971), and is strongly seasonal. Most rain falls during the summer, between October and March. Thunderstorms of short duration account for most of the rainfall. Daytime temperature varies between 18˚ C to 28˚ C during summer months and between 11˚ C to 18˚ C during winter.

MATERIALS AND METHODS

Procedures

Water samples were collected for analysis along the Blesbok stream (Blesbokspruit) and from the eastern tributary that flows between mine dumps (figure 2). Elevations of a set of piezometers on the two dumps astride the wetland and depth to the water table in each were obtained in order to examine the piezometric surface in and around the dumps. Ground water samples were collected from piezometer tubes on and around the dumps for analysis(figures 2 and 3). Water samples were also collected from piezometer tubes placed in the wetland in order to determine the composition of ground water underneath the wetland.

Water samples were collected during August 2004, towards the end of the dry season. All samples were acidified with 2ml of nitric acid and stored in clean plastic bottles. Samples were filtered within twenty four hours on the return to the laboratory and stored in a refrigerator at 4˚C.

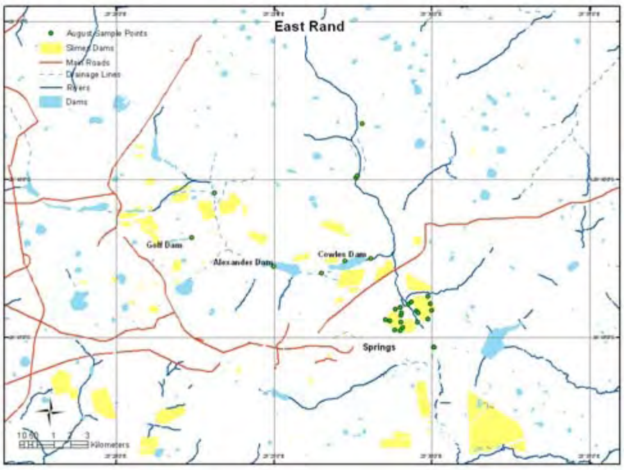

Figure 3 Map showing the distribution of surface and ground water samples of the study area

Field Measurements

The pH, redox potential, total dissolved solids and conductivity were measured on each water sample immediately after collection using Milwaukee waterproof testers.

Analytical methods

Samples were analysed in the geochemical laboratory of the Council for Geoscience.

Samples are diluted between 20 and 50 times to minimize total dissolved solids. The samples are made up in 2 % HNO_3 to keep solute elements in solution. Analytical grade HNO_3 and ultra pure water (18.2 mega Ohm) was used in all preparations.

ICP-MS was used for the analysis of cations. The instrument used was a Perkin Elmer Elan 6000. A multi-element standard solution (Merck VI) was used to calibrate the instrument, and a single point calibration was used for each element (Total Quant Method). Standard isotopic interference corrections as well as common polyatomic interference corrections were applied. All isotopes of a specific element were used to calculate concentration. Anions were determined using a Dionex QIC ion chromatograph, and standardization was carried out using commercial standards.

Results

The piezometer elevation data are listed in Table 1 and the analytical results in Tables 2 and 3. Figure 2 shows a simplified, schematic map of the sampled river system, and also illustrates the various water sources contributing to the river system.

Site number	Elevation (m)	Depth to water table (m)
P4L2	1605.129	9.9
P4L1	1604.052	13.99
P3L1	1603.420	16.2
PE1	1609.964	15.595
PE2	1614.029	12.315
PE3	1627.187	18.295
PJ5	1626.037	11.605
PJ4	1626.157	15.11
PJ3	1626.057	17.95
PJ2	1615.317	10.46
PJ1	1607.778	5.84

Table 1: Elevation of water table in dumps (Frazer Alexander)

No.	Ph	Ec	TDS	Eh	**Na**	**Mg**	**Ca**	**Fe**	**Mn**	**Co**	**Ni**	**Zn**	**As**	**Cl**	**SO_4**
Units		Ms/cm	ppm	mV	ppm										
G1	6.8	256	1750	110	212	149	272	0	15	0	1	0	0	183	1457
G2	6.8	351	2390	23	155	407	333	0	1	0	53	0	0	697	1711
G3	6.2	577	3930	-13	472	244	511	314	111	1	3	2	0	760	3478
G4	6.4	503	3440	138	507	359	511	0	41	0	0	0	0	808	2679
G5	6	425	2930	139	388	290	454	0	107	0	0	0	0	475	2642
G6	5.5	525	3580	106	568	219	544	108	150	1	1	0	0	964	3249
G7	5.4	453	3090	160	385	125	550	18	317	0	0	0	0	546	2683
G8	6.1	524	3590	137	465	295	597	0	136	0	0	0	0	706	2627
G9	7	3	3860	30	112	278	434	0	0	0	0	0	0	1703	701
G10	5.9	467	3190	225	549	255	466	0	58	1	2	0	0	655	2680
G12	6.6	566	3870	2	358	533	627	15	0	0	0	0	1	564	4014
G13	6.5	383	2620	3	319	351	536	71	2	0	1	0	7	506	1952
G15	7	415	2840	24	354	4	679	0	0	0	0	0	1	641	2041
G16	7.3	125	850	3	181	40	62	0	3	0	0	0	0	142	115
G17	6	568	3880	148	704	234	558	0	67	0	0	0	0	898	2776
G18	3.5	559	3830	387	524	192	479	267	8	1	6	4	0	334	3548
G19	5.7	479	3270	22	45	331	468	994	33	10	44	7	6	64	4475
G20	6.5	605	4130	-98	785	117	606	24	1	0	0	0	1	1067	2138
G23	7.8	53	360	1	25	235	448	0	0	0	0	0	0	58	21
G24	7.5	27	180	66	204	128	225	0	0	0	0	0	0	4	4
G21	6.5	7	130	-76	252	259	718	309	70	1	0	0	0	3952	10108
G22	7.1	525	3590	-80	773	297	640	0	7	0	0	0	0	515	1849

Table 2: Analytical results of ground water (G) in ppm

No.	Ph	Ec	TDS	Eh	**Na**	**Mg**	**Ca**	**Fe**	**Mn**	**Co**	**Ni**	**Cu**	**Zn**	**Cl**	**SO_4**
Units		Ms/cm	ppm	mV	ppm										
S1	5.9	50	340	251	50	6	28	1	0	0	0	0	0	179	100
S2	7.8	173	1180	42	315	16	52	0	0	0	0	0	0	524	300
S3	7.7	64	430	116	60	11	37	0	0	0	0	0	0	181	220
S4	8	167	1130	126	341	14	38	0	0	0	0	0	0	529	290
S5	8.2	66	440	131	74	11	30	0	0	0	0	0	0	91	110
S6	7.7	75	500	136	81	12	34	0	0	0	0	0	0	135	330
S7	2.9	320	2190	540	65	112	238	35	21	2	5	1	11	41	3090
S8	6.3	80	530	220	66	14	26	0	0	0	0	0	0	87	20
S9	8.3	169	1120	228	181	11	45	0	0	0	0	0	0	132	93
S10	5.5	595	4040	106	734	289	480	109	136	1	1	0	0	132	92.9
S11	7.4	145	990	-66	211	572	681	0	1	0	0	0	0	174	421
S12	7.8	156	1060	-20	2350	392	101	0	1	0	0	0	0	209	272
S13	7.4	182	1240	-12	208	731	154	1	0	0	0	0	0	180	634

Table 3: Analytical results of surface water (S) in ppm

DISCUSSION

Dump water – surface water interactions

The water table is elevated beneath the dumps relative to the surrounding area, and rises as much as 35m above the surface water level in the wetland that is developed between the two dumps (figure 3). Ground water is seeping from the edges of the dumps. The head thus created is likely to result in discharge of ground water into the bed of the wetland and stream located between the dumps.

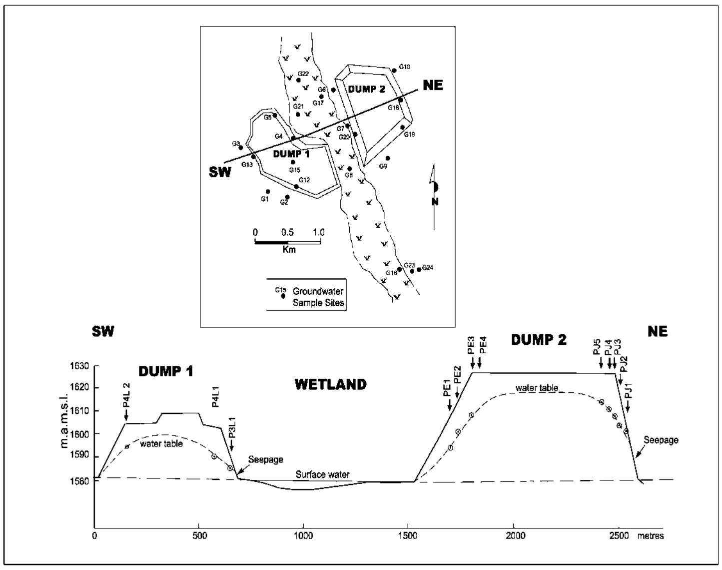

Figure 4: Cross section of dump1 and dump 2 and Blesbokspruit wetland showing the elevation of water table. Piezometer with P (Frazer Alexander) and with G are water sampling points.

The distribution of ground water sampling points on and around the two dumps is shown in figure 3 and the water compositions are listed in Table 2. The ground water within the dumps has a high conductivity (383 to 605 mS/cm) and is dominated by Ca, Mg and Na sulphates. Heavy metal concentrations are generally low (<1ppm). The pH is generally between 5 and 6, although one sample had a pH of 3.5 (G18).

The ground water samples collected in the area around the dumps also have a high conductivity (350 to 570 mS/cm) and are sulphate dominated with low heavy metal concentrations. This indicates that plumes are emerging from beneath the dumps. Ground water samples collected beneath the wetland (G8, G17 G22) generally have high conductivity and are similar in composition to dump water. In contrast, ground water samples collected some distance away from the dumps (G23 and G24) have low conductivity (27 and 53 mS/cm). Thus it appears that contaminated ground water is flowing from beneath the dumps into the wetland via sub-surface flow. The water has similar characteristics to that described by Naiker et al (2002) entering a streambed some distance to the west of the present study area from ground water seepage, although the water in the latter study had considerably lower pH and elevated heavy metal concentrations.

Surface water along the Blesbok stream and tributary

The sulphate and chloride concentrations and electrical conductivity provide useful indicators of water sources and quality changes along the Blesbok stream, and accordingly will be used in this preliminary analysis of pollution sources in the stream. Figure 4 illustrates schematically the sample distribution and the chemical parameters used in this analysis.

Water flowing from Golf dam (S7) has high conductivity and high concentration of sulphate and low chloride reflecting its proximity to tailings dumps in the vicinity. The stream water is comparable in composition to ground water in the dumps, suggesting that essentially all of the discharge in this reach arises from contaminated plumes from dumps. Water in the Mannamore canal (S6) has lower conductivity, but sulphate still exceeds chloride. Some water from mine sources is probably present. The water quality seems to improve in Alexander dam (S5) and conductivity is lower than both S6 and S7. Wetlands and lakes seem to improve water quality in the region (unpublished data) although the reasons for this are not fully understood. Sulphate rises slightly downstream of Alexander dam (S3), again possibly due to input of contaminated ground water.

Water discharged from the paper mill (S4) into Cowles dam has a relatively high salinity, but is dominated by chloride rather than sulphate. Outflow from the dam still reflects this high chloride (S2) and is similar to mill discharge in composition, indicating that discharge from this plant dominates inflow to the dam.

Water flowing from the north in the upper reaches of the Blesbok stream has relatively low concentrations of heavy metals and a low conductivity (S1, S8). This water is sourced from groundwater entering the bed of the stream as well as discharge of treated water from a sewerage plant (Etwatwa).

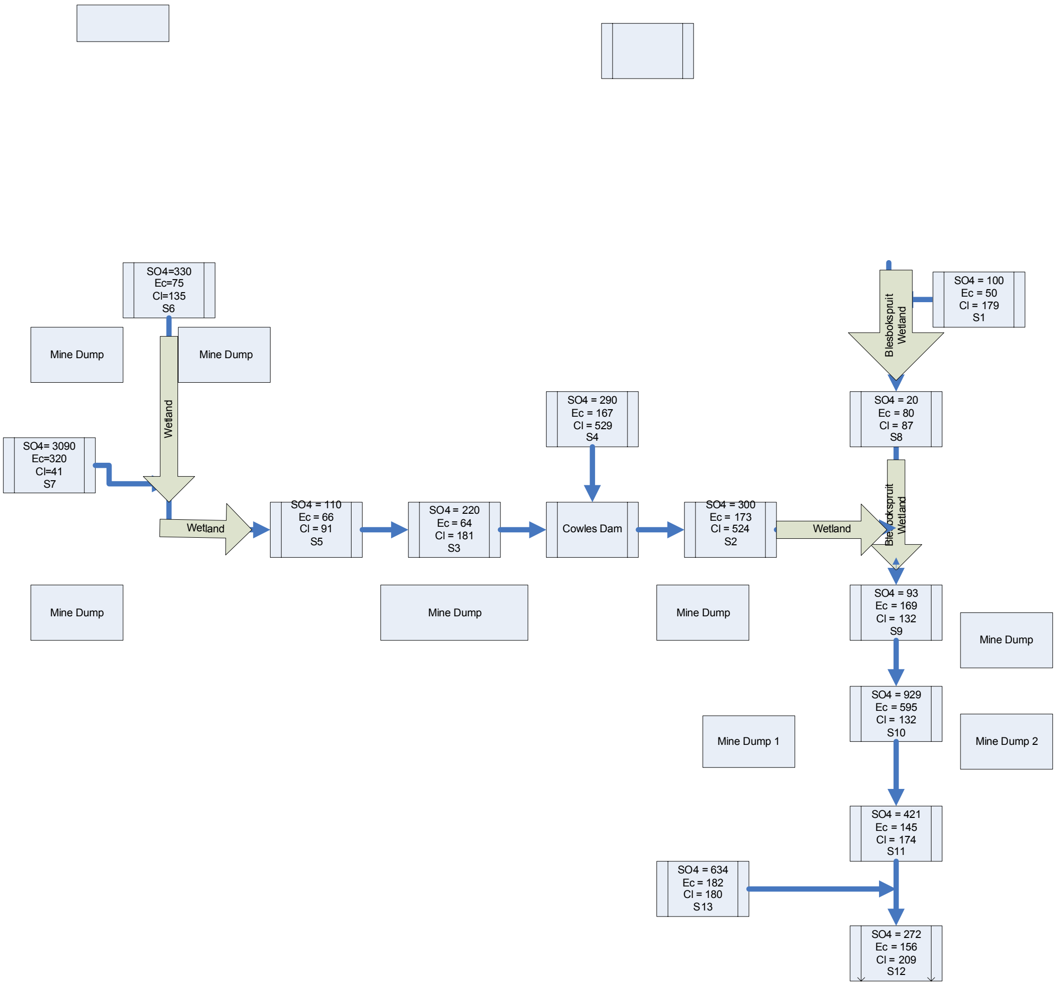

Figure 5: Flowing diagram showing the surface water (S).

The combined discharge from the northern source and Cowles dam outflow (S11) has a conductivity intermediate between these two sources with sulphate equal to chloride. After passing through the wetland between the dumps described in the previous section, electrical conductivity has increased (S12) and sulphate is substantially higher than chloride, indicating significant inflow of sulphate-rich ground water.

Downstream of this wetland, treated pumped mine water is discharged into the stream. This treated water has a conductivity somewhat higher than the water in the stream upstream of the discharge point, and a high sulphate concentration relative to chloride. The mixed water in the stream downstream of the discharge point has an intermediate conductivity and sulphate comparable to the mine discharge.

Of significance is the comparison between stream water immediately above the discharge point and the discharge water. The former has sulphate concentration of around 400 ppm, compared to that of treated mine water of about 640 ppm. Uncontaminated local ground water has sulphate concentrations of around 20 ppm (G23, Table 2), while treated sewage has sulphate of the order of 100 ppm. These data indicate that the contribution of dispersed mine-related pollution sources to stream water quality in system studies is substantial.

It is significant that treated mine water has a lower dissolved solid load than polluted water emanating from the dumps (200 vs 300 to 500 mS/cm).

CONCLUSIONS

This preliminary study of the effects of mine-related pollution has shown that the water table within active mine dumps are substantially elevated relative to that in the the surrounding areas, and the resulting hydraulic head drives plumes of polluted water from beneath the dumps. Such contaminated water will discharge into streams if present in the area. The water has near neutral pH and is low in heavy metals, but is high in sulphate. Pollution of this type is very diffuse, and is probably widespread in the Witwatersrand goldfields. It is significant that water from such sources has a higher dissolved solid load than discharged mine water.

This study has also shown that the contribution of diffusely sourced polluted water to stream discharge is substantial. Given the fact that there are relatively few points of discharge of pumped mine water, whereas diffuse pollution sources are widespread through the region, it must be concluded that these diffuse sources contribute the bulk of the pollution load.

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