Borehole-Mediated Remediation of Contaminated Groundwater within the Vicinity of a Mining Operation in South Africa

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ABSTRACT: Mining of ores involves the excavation of large quantities of waste rock from which the desired mineral ore is extracted. The waste rock forms the major source of most of the pollutions caused by mining. The contaminants, most often, are easily leached out and these have the potential to contaminate the surrounding environment including surface and groundwater. In this project, boreholes were sunk across the pollution plume as remediation measure to reverse the movement of the plume. Direct current (dc) resistivity equipment was used to precisely locate the migration of the plume and the borehole positions cited. The water quality parameters investigated included pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Si, F^-, T/alk, Cl^- SO_4^{2-}, NO_3^- and NH_4^+. Samples were taken after every three months for a period of three years. Base flux assessment was also conducted. Piper hydro-chemical plots were constructed in order to determine whether any significant change in the hydro-chemical composition had occurred at a specific sampling locality. Reduction of levels of water quality parameters was achieved over a period of a year after remediation boreholes were strategically sunk along the pollution plume. The following reduction were achieved, 48% SO_4^{2-}, 35.6% Mg^{2+}, 71% Cl^- and 95% NO_3^-. The base flux assessment indicated that positive (groundwater gradient from the aquifer towards a nearby river) and negative (groundwater gradient from the river towards the aquifer) gradients occurred along three and two lines respectively. From the Piper plots, all borehole water samples were characterized by $Ca/MgCl_2$ and $Ca/MgSO_4$ groundwater. The results obtained in this study demonstrated that positioning of boreholes strategically along the pollution plume and pumping out contaminated groundwater reversed the plume movement. Consequently, significant reduction in the levels of water quality parameters was achieved. This resulted in the contaminated groundwater meeting the set drinking water quality standards.

Keywords: Bore-Mediated, Remediation, Groundwater, Contamination, Mine.

INTRODUCTION

Mining of ores involves the excavation of large quantities of waste rock from which the desired mineral ore is extracted. The ore is then crushed into finely ground tailings for processing with various chemicals and separating processes to extract the final product. After the extraction, waste rock and tailings which often contain acid-generating sulphides, heavy metals, and other contaminants, are usually stored above ground in large free-draining piles. This waste rock and the exposed bedrock walls form the major source of most of the pollutions caused by mining (Bick, 1975). During precipitation, heavy metals, among other contaminants, are easily leached out and these have the potential to contaminate the surrounding environment.

Of all the wastes generated through various mining activities, Acid Mine Drainage (AMD) appears to be one of the major problems facing the mining industry globally. AMD occurs when sulphide bearing minerals in rock are exposed to air and water, changing the sulphide to sulphuric acid. AMD generated from these mining activities most often, contain high concentrations of dissolved minerals (Kleinmann and Hedin 1989). Furthermore, unlike industrial pollution, acid mine drainage can continue indefinitely, even after mining activities had stopped (Chadwick, 2004). It has been reported that about 180,000 acres of reservoirs and lakes and 12,000 miles of streams and rivers have been polluted by acid mine drainage in the US (Kim, *et al.*, 2001).

The relationship between mining and the environment in South Africa has improved tremendously over the years as a result of introduction of various legislations in the early 1990s. However, there are still some

abandoned mines that are yet to be commissioned for closure in order to meet the South African Minerals and Petroleum Resource Development Act of 2006.

A mine situated near Steelpoort in Mpumalanga, South Africa operated open pit mining and its mining activity involved the excavation of vanadium bearing titaniferous magnetic ore body. Every process in the extraction of the desired mineral from the ore at the mine had some pollution problems. In the past, water management of tailing dams in this area were carried out in such a way that could not account for the proper monitoring of groundwater particularly, boreholes within the vicinity of the mine. Available information indicate that boreholes in the area contain very high levels of sodium (Na^+), magnesium (Mg^{2+}), sulphate (SO_4^{2-}), nitrate (NO_3^-), ammonia (NH_3) and vanadium (V), resulting in Total Dissolved Solids (TDS) concentration of 150 000 mg/L. Also, between 1995 and 2003, the contaminant concentrations which emanated from the mine activities steadily rose in the underlying groundwater aquifer such that an inorganic plume developed towards a nearby river. Furthermore, the presence of a dyke across the pollution plume seemed to have contributed to the movement of contaminants towards the river, thus widening the plume.

In order to monitor and manage the pollution plume movement and seepages, information on water quality of the boreholes is very important. Such information is needed for a better water management within the chosen area of study. In this project, boreholes were sunk across the pollution plume and the contaminated groundwater pumped into a line dam as remediation measure to reverse the movement of the plume towards the river.

METHODS AND MATERIALS

Study Area

The mine is located in Mpumalanga Province, South Africa as shown in Figure 1. The operation is located in the Steelpoort River valley and the site is elevated ~800 m above sea level, at a Latitude of S24° 49′ 07.9″ and Longitude of E30° 07′ 08.4″, whereas the surrounding valley (to the southwest and northwest) is ~1080 to 1400 m respectively above sea level. The long term average temperature is 16.1°C, while the average rainfall is in the range of 6 mm to 130 mm per annum. The study area falls within a summer rainfall region, with over 70% of annual rainfall occurring during the October to February period.
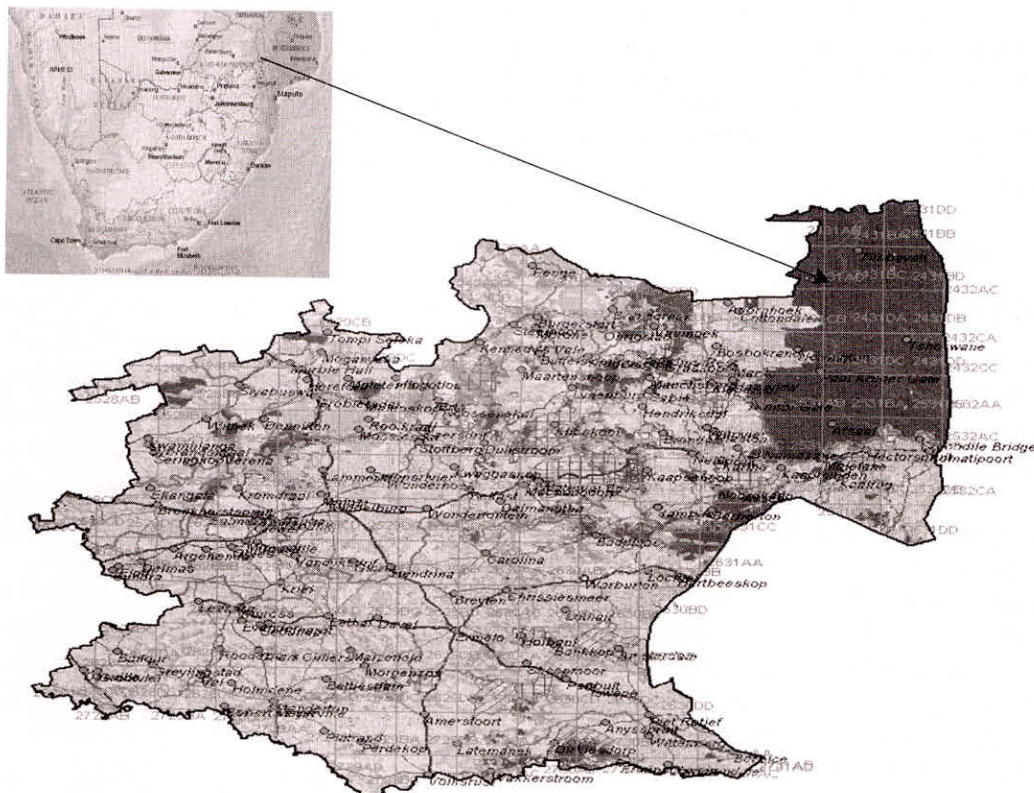

Fig. 1: Map of South Africa (top left) and Mpumalanga Province (bottom) showing the location of mine

MATERIALS

Glassware

All glassware used was of Pyrex brand. They were all soaked in dilute HNO_3 overnight, thoroughly washed, rinsed properly with tap water, deionised water and finally with acetone. They were then dried in an oven at 45°C for 24 h before use. 500 mL and 250 mL bottles treated with few drops of concentrated nitric acid with screwed caps were used for the collection of water samples and they underwent the same washing procedure as indicated above.

Reagents

For water quality determination, analytical reagent standard solutions, Na_2SO_4 $10H_2O$ (Meck Germany), $NaNO_2$ and KNO_3, (Riedel-deHaen, Germany) with concentration of 1000 mg/L were used as the stock solutions to establish the calibration curves. Working standards were prepared by appropriate dilution of each standard stock solution. The chromogenic reagent (RI), for the Griess-Losvay reaction, was prepared by dissolving 10 g $C_6H_8N_2O_2S$ (Switzerland) and 1 g $C_{12}H_{14}N_22HCl$ (Sigma, Germany) in 100 mL of phosphoric acid (Merck, Germany) and 800 mL of water. The reagents were stored in a brown glass in a refrigerator.

A Carrier Solution (CI) was prepared by dissolving 0.4 g $C_{10}H_{14}N_2Na_2O_8.2H_2O$ (Merck, Germany) in 1 L of water. The pH of this solution was adjusted to 9.0–9.5 with a few drops of NH_3 solution (Riedel-deHaen, Germany). Copperier cadmium column was prepared by adding 5 g Cd particles (Merck, Germany) diameter between 0.5 and 1 mm to 50 mL $CuSO_4$ (Merck, Germany) and stirring for 2 min. The resulting copperised cadmium was washed with 2 mL HCl (Riedel deHaen, Germany), two times with 50 mL, and NH_4Cl (Merck, Germany) solution. The resulting particles were packed into Teflon tube with 7cm of length and 1.5 mm of inner diameter.

For sulphate determination, a buffer solution was prepared by dissolving 0.4 g of EDTA $2H_2O$ and 70 g of ammonium chloride in 1 L of water (same solution used as carrier in nitrate and nitrite determination). A barium chloride reagent solution (R4) containing a potassium hydrogen phthalate-hydrochloric acid buffer at pH 2.5 was prepared by adding 388 mL of 0.1 M HCl (Riedel-deHaen, Germany) to 500 mL of 0.1 M $C_8H_5KO_4$ (Riedel- deHaen, Germany), 10 g of $BaCl_2$, $2H_2O$ (Merck, Germany), 1 g of thymol (V.P. Portugal) and 0.62 g of gelatine (VP., Portugal) were dissolved in this buffer and the solution diluted to 1 L with water. The reagent was filtered through a Millipore membrane (type HA) (45 μm).

Instrumentation

For the determination of metals, SHIMADZU AA-6300 atomic absorption spectrometer, GFA-EX7i graphite furnace atomiser linked to ASC-6100 Auto sampler with a Sony gigabyte PC and Sony monitor were used. TDS, pH and EC were determined using a HANNA Combo pH and EC meter (model HI 98130). The anions, NO_2^-, NO_3^-, PO_4^{3-}, Cl^-, and F^- were determined using ion selective electrodes (ISE). SO_4^{2-} was determined by titrimetric method using standard barium chloride solution. Total Alkalinity (T/alk), (Mg^{2+} and Ca^{2+}) was determined using standard EDTA solution and Eriochrome Black T as indicator.

Equipment

Direct current (dc) resistivity equipment was used to precisely locate the migration of the plume. The equipment used is shown in Figure 2. It is based on the flow of electrical current in water. Borehole positions were cited using the equipment shown in Figure 2.
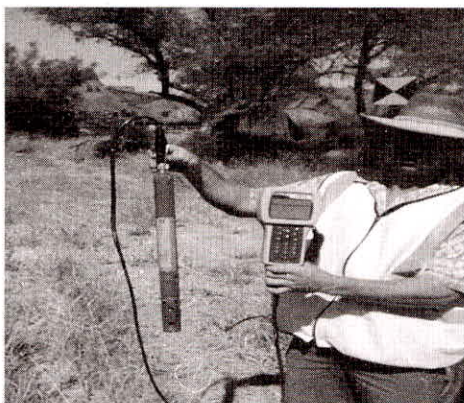

Fig. 2: Direct Current (DC) resistivity sensor (left) for boreholes citing and sludge testing (right)

METHODS

Resistivity Measurement

The Magnetic Resonance Sensor (MRS) was used to determine groundwater occurrence from 1–00 m. The resisitivity equipment showed the water bearing formation from 1 m to the bottom on the investigated depth. This works on the signal to noise ratio and the signal phase changes smoothly as the pulse moment increases. The resistivity method is very sensitive to the water Electrical Conductivity (EC) which influences the aquifer resistivity. The magnetic resonance sensor transmissivity was calculated from,

$$T = K\Delta z \qquad \qquad \qquad \text{... (1)}$$

Where, T = transmissivity (m^2/s), K = the MRS permeability (m/s) and z = the aquifer thickness (m).

The MRS permeability is estimated from,

$$K = C_p n^a (T_2^*)^b \qquad \qquad \text{... (2)}$$

where, C_p = an empirical factor; n = the water content estimated from MRS measurement (%) and T_2^* = the transverse relaxation time (ms).

Borehole Drilling

The boreholes were cited at strategic sites in the area of concern as determined by the resistivity measurement. The location of the boreholes was at the nip zone of the plume in order to pull back the concentration towards the source as well as to reduce high concentration from the source flowing through. The actual borehole drilling basically involved the use of a hydraulic diamond-head drilling machine fitted onto the truck and mechanically operated. Four abstraction and remediation boreholes were sunk across the plume and were used to pump back and reduce the concentration of the pollutant from the plume. Most of the boreholes drilled were of the depth range of 30 m to 33 m, 9–10 m below the water table in the area. Monitoring holes to determine ground-water level response as a result of pumping from the remediation system abstraction boreholes were also established. Boreholes where drilled across the plume.

Water Sample Collection

For water quality determination, water samples were collected from the following boreholes and surface sampling points located along the pollution plume: ABS-B1, ABS-B2, ABS-B3 and ABS-B4 as shown in Figure 3:

* three pollution source boreholes (VNTP)
* two surface sampling points (downstream and upstream) in the Steelpoort River (STP-S1 and STP-S3)
* three control boreholes.

Water samples were taken directly below the water surface with a bailer. The sample taken were poured into the pre-marked sample bottles (500 and 250 mL preserved with HNO_3 to reduce volatility). The bottles were filled to the brim, squeezed slightly while the lid was screwed tightly in order to expel all the air from the bottles. The cap was sealed with insulation tape. In order to avoid cross contamination, the bucket/jug was rinsed with distilled water after each sample. Thereafter, the sample bottles were properly labelled and placed in a cooler bag. Sampling and analysis were conducted on a five monthly frequency.The water samples collected were analysed for the following variable quality parameters namely Ca^{2+} Mg^{2+}, Na^+, K^+, Si, F^-, total alkalinity, Cl^-, SO_4^{2-}, NO_3^- and NH_4^+ to compare with the baseline sampling results from 1994 to 2004. The comparison was done in order to check if pumping from the plume caused any significant change to the salt load as anticipated.
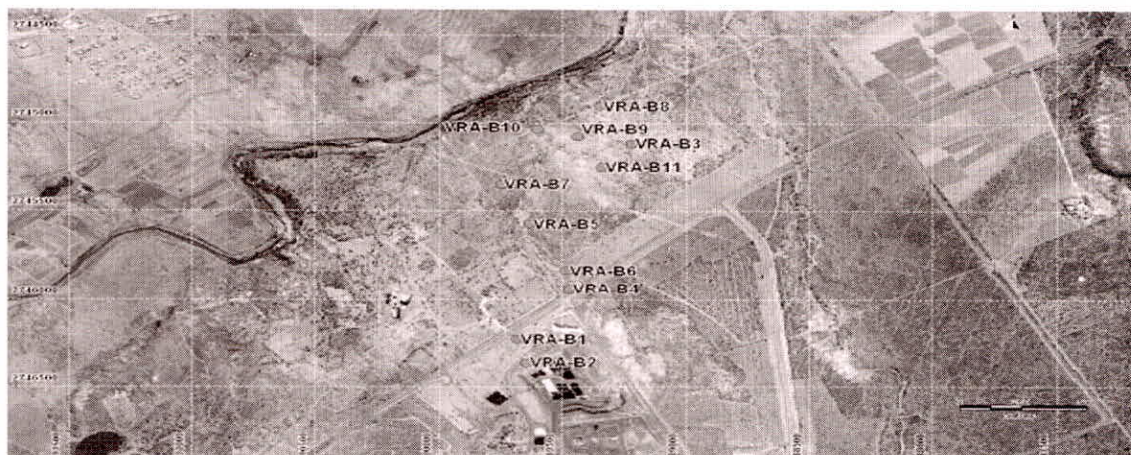

Fig. 3: Localities of boreholes around the plume

Water samples from Steelpoort River were collected directly below the water surface with rinsed sampling bucket/jug. The samples collected were poured into pre-marked sample bottles (500 mL and 250 mL) and the bottles were filled to the brim, squeezed slightly while the lid was screwed on tightly in order to expel all the air from the bottles. The cap was sealed with insulation tape to avoid any leakages during transportation to the laboratory.

Recovery Test Control

Samples were spiked with known amounts of standards of the ions to be measured and thereafter analysed using FAAS.

Determination of Water Quality Parameters from Steelpoort River

The anions, NO_2^-, NO_3^-, PO_4^{3-}, Cl^- and F^- were determined using standard ion selective electrodes; while SO_4^{2-} was determined as discussed earlier. pH, TDS, and EC were measured using conductometric method with a pH meter. The following metal ions, Ca^{2+}, Fe^{2+}, Cu^{2+}, Na^+ and K^+ were determined using Flame atomic absorption spectrophotometer (FAAS); whilst Mg^{2+} and Si were determined using Graphite flame atomic absorption spectrophotometer (GFAAS). Standards and samples for each metal where aspirated into the FAA and GFAAS after acid digestion of the samples, to get the respective absorbance of the cations and from the calibration curves, the respective concentrations were calculated.

Quality Assurance

All reagents were prepared from analytical grade materials according to specific procedures using appropriate solvents, de-ionized and distilled water depending on the protocol. Blanks for each analysis were prepared by mixing all the reagents and solvents in appropriate proportions leaving out the analyte which was either the sample or the standard in each case. Most standards were freshly prepared except in cases where the protocols indicated otherwise. Recovery tests were carried out by spiking the samples with known amounts of standards of NO_2^-, NO_3^-, PO_4^{3-}, Cl^-, F^- and NH_4^+. Blind samples were spiked into the standards and samples respectively to further test the reliability of the Ion Selective Electrodes (ISE). A similar quality assurance procedure was used for the species which were determined by FAAS. One-way analysis of variance (ANOVA-1) was used to test whether there was significant variation of the species determined between sampling periods. Mean concentrations of the samples were calculated from the data obtained from various months using Microsoft Excel and Statistical Package for Social Scientists (SPSS).

RESULTS AND DISCUSSION

Recovery Test Control

Samples were spiked with known amounts of standards of the ions measured. The recoveries obtained were between 95–102%. The high percentage recovery validated the methods used for the analyses of the cations and anions.

ABS-B1–B4 (Existing boreholes before the remediation scheme)

Water samples were abstracted from existing boreholes, pumped into a lined dam over a period of time and monitored. The results of the analyses of water samples from the boreholes (ABS-B1-ABS-B4) are shown in Tables 1–4. As can be seen from the

Table 1: Levels of Water Quality Parameters Determined in Water Samples from Borehole ABS-B1

Site	Date	Variable Parameter (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F^-	T/alk	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+
ABS-B1	04/2004	7.7	3220‡	29600	449‡	389‡	7610‡	34	44	0.31	526	197	18400‡	133‡	191‡
ABS-B1	110/2004	6.7	2170‡	28100	461‡	270‡	5570‡	44	43	0.31	552	294	12600‡	126‡	376‡
ABS-B1	05/2005	7.7	1880‡	17210	421‡	263‡	3700‡	14.5	9.2	0.42	343	193	11800‡	94.6‡	460‡
ABS-B1	110/2005	7.8	1480‡	13800	364‡	152‡	3330‡	13	7.8	0.30	523	153	8490‡	97.5‡	292‡
ABS-B1	06/2006	7.7	1340‡	13200	430‡	179‡	3610‡	12.7	30.5	0.75	523	165	7830‡	69.7‡	243‡
ABS-B1	08/2006	7.9	1300‡	12300	374‡	162‡	2830‡	15.1	30.9	0.68	534	218	7380‡	142‡	145‡
ABS-B1	09/2006	7.7	1400‡	12310	447‡	186‡	2830‡	18.1	33.9	0.75	453	222	6920‡	179‡	212‡
ABS-B1	110/2006	7.7	1350‡	11800	384‡	168‡	1950‡	13.2	29.8	0.39	279	226	6410‡	140‡	206‡
ABS-B1	11/2006	7.7	1120‡	9560	352‡	137‡	2290‡	13.3	62.7	0.64	506	211	5850‡	81.7‡	205‡
ABS-B1	12/2006	7.7	1070‡	9260	337‡	126‡	2380‡	11.2	30.4	0.67	509	186	5260‡	85.6‡	179‡

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeded recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 2: Levels of Water Quality Parameters Determined in Water Samples from Borehole ABS-B2

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F^-	T/alk	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+
ABSB2	04/2004	7.3	2580‡	25200	433‡	554‡	6390‡	34	44	0.33	530	197	15900‡	134‡	193‡
ABS-B2	10/2004	6.8	1850‡	18700	433‡	573‡	4630‡	36	46	0.3	532	197	10100‡	136‡	194‡
ABS-B2	05/2005	7.4	1770‡	15200	422‡	385‡	3590‡	14.5	29.2	0.42	488	195	8880‡	96.6‡	215‡
ABS-B2	10/2005	7.7	1530‡	14700	347‡	235‡	3680‡	12.5	29.6	0.68	496	196	9000‡	96.7‡	191‡
ABS-B2	08/2006	7.8	1270‡	11800	363‡	156‡	2740‡	14.8	30.7	0.59	505	176	7160‡	102‡	115‡
ABS-B2	09/2006	7.5	1130‡	9980	418‡	206‡	2250‡	15.1	35.5	0.42	430	217	5670‡	157‡	77.6‡
ABS-B2	10/2006	7.8	1360‡	10300	588‡	180‡	1950‡	14.2	29.1	0.34	510	206	6370‡	8.22‡	187‡

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 3: Levels of Water Quality Parameters Determined in Water Samples from Borehole ABS-B3

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F^-	T/alk	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+
ABS-B3	Apr-04	6.7	1001	10592	577	583	1551	12.7	46	0.33	420	190	6291	165	0.2
ABS-B4	Oct-04	7.0	1100	12292	662	688	1845	12.9	48	0.42	440	194	6214	155	0.2
ABS-B5	Apr-05	7.4	1153	10486	587	580	1720	8.4	48	0.31	442	160	5911	119	3.86
ABS-B6	Oct-05	7.5	850	6722	386	356	1260	6.86	35.3	0.16	513	128	3940	1.97	0.21
ABS-B7	Apr-06	7.5	651	5386	262	261	996	4.65	39.6	0.07	456	78.4	3293	122	0.01
ABS-B8	Oct-06	7.7	713	5746	376	70	824	5.4	33.9	0.14	490	56.4	1970	10.4	0.01

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 4: Levels of Water Quality Parameters Determined in Water Samples from Borehole ABS-B4

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F^-	T/alk	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+
ABS-B4	04/2004	7	2721‡	28600	577‡	115‡	5990‡	34	41	0.34	527	199	18800‡	213‡	363‡
ABS-B4	10/2004	6.6	2300‡	22900	449‡	627‡	5230‡	46	51	<0.2	568	235	12900‡	217‡	412‡
ABS-B4	05/2005	7.5	1800‡	16000	386‡	336‡	3590‡	11.5	38.6	0.42	486	187	9000‡	196‡	77.9‡
ABS-B4	10/2005	7.7	715‡	5590	189‡	99‡	1290‡	11.1	39.9	0.16	497	71.1	3340‡	<0.01	44‡
ABS-B4	06/2006	7.4	637‡	4580	165‡	117‡	995‡	6.33	36.9	0.07	356	70.7	2740‡	158‡	42.4‡
ABS-B4	08/2006	8.5	646‡	5490	154‡	103‡	1310‡	7.9	37.6	0.14	312	65	2810‡	104‡	0.56‡
ABS-B4	9/2006	7.7	876‡	7350	342‡	212‡	1680‡	10.8	36.4	0.25	434	57.5	4410‡	59.5‡	2.71‡
ABS-B4	10/2006	7.7	763‡	5570	182‡	147‡	1370‡	9.02	39.4	0.2	519	84.7	2730‡	109‡	2.71
ABS-B4	11/2006	7.3	738‡	5970	177‡	149‡	1330‡	6.35	35.1	0.15	412	79.5	3060‡	157‡	40.1
ABS-B4	12/2006	7.8	716‡	5930	165‡	136‡	1490‡	7.43	73.4	0.13	329	76.1	3230‡	106‡	50.9

Chemistry Standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

tables, the pH ranged from 6.6–8.5. This range is nearly within the neutral region and this may suggest that a natural buffering may have occurred from the structures. All the boreholes showed elevated levels of other water quality parameters, Electrical Conductivity, Total Dissolved Solids, cations (Ca^{2+}, Mg^{2+} and Na^+) and anions (SO_4^{2-}, NO_3^- and NH_4^+), except in Table 3. The levels of these parameters actually exceeded the World Health Organization drinking water guidelines (WHO, 1996) and South African domestic water use standards (DWAF, 1996a). The levels of the metals were much higher than the concentrations reported for

groundwater near iron Duke pyrite mine in Zimbabwe (Ravengai *et al.*, 2005). However, the levels of these parameters significantly ($p < 0.05$) decreased over a period of time as a result of the water pumping exercise. This indicated that the presence of the boreholes may have reversed the flow of the pollutants within the plume. The high sulphate (SO_4^{2-}) level may have been due to the conversion of sulphide-bearing minerals into sulphate.

The following sulphate (SO_4^{2-}) contour maps (Figure 4) provide a good indication of how the overall situation at the mine has changed over the past number

of years. A significant decrease in sulphate (SO_4^{2-}) can be seen in Figure 4. The visual information in the (SO_4^{2-}) contour maps suggests that the pollution plume as defined by the 2000 mg/L SO_4^{2-} concentration contour line is shrinking. The seepage of good quality water from the old open pit mine which is currently used as an off-channel storage dam for supplying water to the new operation may have also contributed to the decrease in sulphate (SO_4^{2-}) observed. In time, the maps (Figure 4) will also provide definitive answers in terms of the effectiveness of the abstraction scheme as well as the decommissioning activities in reducing the pollution load on the aquifer.

VNTP (Remediation boreholes to reverse plume movement to the river)

The results of the analyses of source water from three boreholes are shown in Tables 5–7. As observed earlier in Tables 1–4, the source waters contain highly saline inorganic pollutants dominated by Mg^{2+}, Na^+, F^-, Cl^-, SO_4^{2-}, NO_3^- and NH_4^+. The pH was within the neutral region. The levels of the parameter observed in Tables 5–7 do not comply with the SANS 241:2005 Drinking Water Standard (DWAF 1996a). The general decrease in the levels of the parameters measured as exhibited in Tables 1–4 was not repeated in Tables 5–7.

Groundwater level assessment was performed in order to determine changes in storage of water in the mine shallow weathered zone aquifer. Changes in storage within the mine aquifer results from both natural mechanisms such as recharge from rainfall and outflow from the aquifer in the form of groundwater base flow into the Steelpoort River, as well as from external induced stresses such as the abstraction of groundwater from the remedial abstraction boreholes tapping the aquifer.

In order to standardise this assessment, an arbitrary aquifer lateral delineation was performed. Five flow lines from Figure 5 were selected to calculate groundwater gradients for base flux assessments. Positive gradients (groundwater gradient from the aquifer towards the Steelpoort River) existed along three of the lines and negative gradients (groundwater gradient from the Steelpoort River towards the aquifer) along two of the lines (Table 8). It follows therefore, that along two of the chosen flux lines, the aquifer was actually being fed by water from the river.
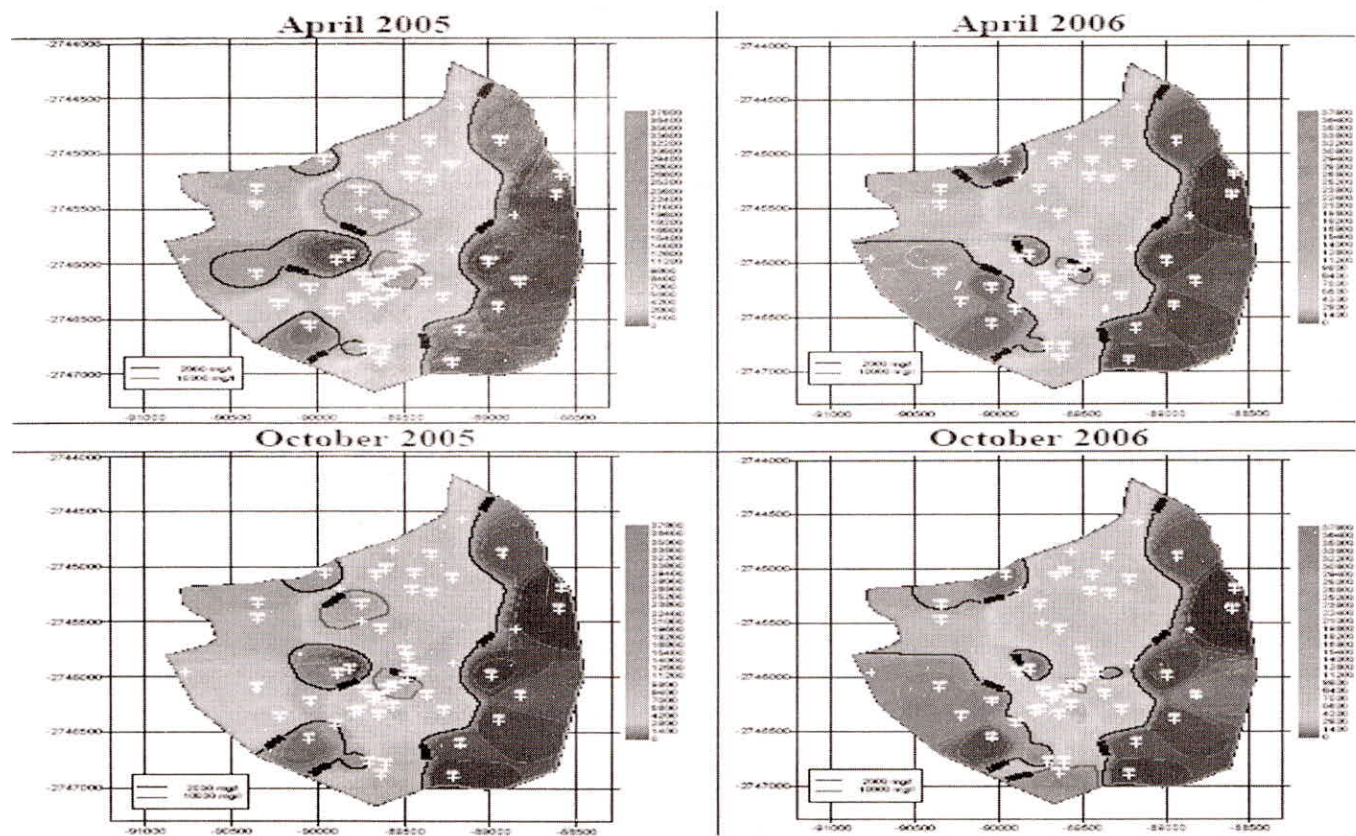

Fig. 4: Contour maps on SO_4^{2-} concentration changes

Table 5: Levels of Water Quality Parameters Determined in Water Samples from Borehole VNTP-B1

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F	T/alk	Cl⁻	SO_4^{2-}	NO_3^-	NH_4^+
VNTP-B1	04/2004	6.0	15400‡	345000	866‡	972‡	82000‡	104	39	0.34	587	199	214000‡	366‡	662‡
VNTP-B1	10/2004	7.4	4780‡	37600	799‡	810‡	13600‡	106	97	4.3	1530	631	32000‡	382‡	840‡
VNTP-B1	05/2005	7.3	2000‡	38700	395‡	334‡	9630‡	111	14.6	0.41	477	798	23100‡	447‡	89‡
VNTP-B1	10/2005	6.6	1356‡	251000	666‡	391‡	51500‡	203	15.8	17.6	421	4962	143000‡	4200	46.0‡
VNTP-B1	06/2006	7.4	9330‡	118000	449‡	477‡	37300‡	276	27.3	3.73	532	2160	66600‡	596‡	55.8‡
VNTP-B1	08/2006	7.3	9560‡	147000	416‡	349‡	44200‡	243	17.5	3.1	424	898	68800‡	609‡	73.9‡
VNTP-B1	10/2006	6.7	7210‡	76300	571‡	351‡	2300‡	104	54.6	1.97	225	58.6	51600‡	904‡	39.7‡

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 6: Levels of Water Quality Parameters Determined in Water Samples from Borehole VNTP-B2

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F	T/Alk	Cl⁻	SO_4^{2-}	NO_3^-	NH_4^+
VNTP-B2	04/2004	6.3	1420‡	124000	152‡	61‡	33400‡	51	67	5	213	279	8200‡	213‡	428‡
VNTP-B2	10/2004	6.8	9700‡	150000	724‡	2350‡	40600‡	325	145	8.4	155	186	9180‡	278‡	420‡
VNTP-B2	05/2005	7.1	1603‡	34900	1381‡	966‡	8230‡	49	38	0.4	240	119	2270‡	127‡	305‡
VNTP-B2	10/2005	8.2	3190‡	36800	504‡	1320‡	7990‡	39.6	42	2.54	745	678	2050‡	514‡	155‡
VNTP-B2	06/2006	6.9	4830‡	55100	390‡	205‡	17100‡	97.9	10.8	1.65	257	571	1280‡	603‡	160‡
VNTP-B2	08/2006	6.4	6070‡	80700	502‡	304‡	18900‡	142	24.2	2.06	178	673	1090‡	337‡	291‡
VNTP-B2	10/2006	6.9	7720‡	87500	293‡	272‡	29500‡	121	19.2	2.58	219	61.8	970‡	8.97‡	336‡

Chemistry Standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 7: Levels of Water Quality Parameters Determined in Water Samples from Borehole VNTP-B3

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F	T/alk	Cl⁻	SO_4^{2-}	NO_3^-	NH_4^+
VNTP-B3	04/2004	7.7	12600‡	199000	802‡	535‡	49300‡	266	10.6	1056	1360	199	134000‡	2730‡	8400‡
VNTP-B3	10/2004	7.7	11900‡	182000	783‡	508‡	51500‡	396	9.1	865	1550	235	114000‡	792‡	7810‡
VNTP-B3	05/2005	7.6	>2000‡	133000	825‡	535‡	31000‡	115	15.2	200	1200	187	99900‡	134‡	6049‡
VNTP-B3	10/2005	7.5	11400‡	155000	714‡	523‡	32000‡	190	4.27	771	218	71.1	48800‡	403‡	9960‡
VNTP-B3	06/2006	7.8	6500‡	87800	384‡	259‡	25200‡	145	7.4	517	857	70.7	105000‡	362‡	4080‡
VNTP-B3	08/2006	7.8	11100‡	170000	375‡	350‡	44200‡	278	6.16	36.5	642	65	89700‡	186‡	8030‡
VNTP-B3	09/2006	7.9	10600‡	150000	419‡	344‡	49400‡	305	12	963	31.5	57.5	69500‡	134‡	31‡

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 8: Base Flux Assessment (mine aquifer into Steelpoort River)

Flux Tube	Permeability (m/day)	Tube Width (m)	Saturated Thickness October 2006 (m)	GW Gradient October 2006	GW Flux October 2006 (m^3/month)
1	0.055	290	12.7	+0.0147	89.47
2	0.055	675	13.5	−0.0169	254.5
3	0.055	400	11.4	−0.0282	211.3
4	0.055	600	9.23	+0.0144	131.6
5	0.055	360	23.2	+0.0472	649.9

Positive gradient = flow from the Aquifer into the Steelpoort River; Negative gradient = flow from the Steelpoort River into the aquifer and k value of 0.055 m/day represents the optimized permeability for the aquifer host matrix.

Fig. 5: Arbitrary aquifer delineation for water storage, salt load and base flux assessments

The information contained in Table 8, indicated that the aquifer discharged some 871 m^3/month of contaminated base flow into the Steelpoort River in October 2006, while it received some 466 m^3/month of river quality water from the Steelpoort River. It is important to note, however, that the water received from the Steelpoort River will be contained in aquifer sections close to the river and that due to groundwater gradients in the aquifer further to the south; this water will not penetrate the aquifer to distances further from the river.

Piper plots were compiled for the mine pathway groundwater boreholes for the period 2004–2006 and the plots are shown in Figures 6–7. The purpose of this exercise was to determine whether a significant change in hydro chemical composition had occurred at a specific sampling locality. A visual assessment of the composition plots for the monitoring period 2004–2006 show that the constituents of the boreholes were typical of mine water in this area. As can be seen from the diagrams, all the boreholes had similar water qualities. All boreholes selected can be classified as having stagnant groundwater conditions, characterised by Ca/MgCl$_2$ and Ca/MgSO$_4$ groundwater. These are influenced by external sources and caused by dominant recharge characteristics. Calcium (Ca^{2+}), magnesium (Mg^{2+}) and Sulphate (SO$_4^{2-}$) were the dominant cations and anion respectively. These can be attributed to the natural geological formation where dolomites are present.
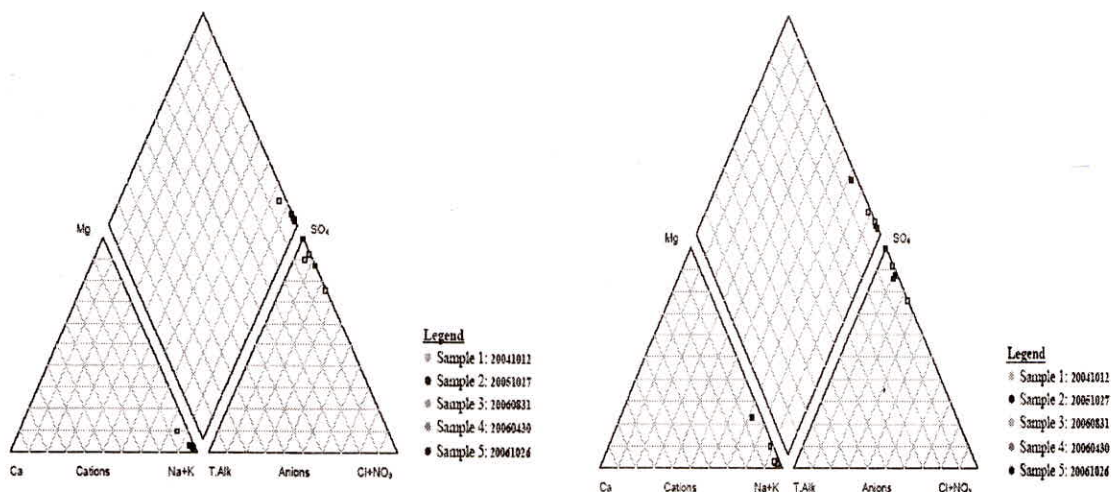

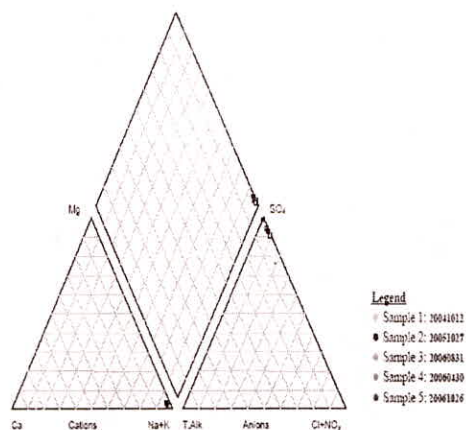**Fig. 6:** Piper diagram for VNTP-B1 (left) and VNTP-B2 (right)

Fig. 7: Piper diagram for VNTP-B3

River (Downstream and upstream river samples)

SPT-S1 (Downstream Sampling Point)

The levels of physical and chemical parameters determined in downstream Steelpoort River samples

are shown in Table 9. As can be seen from the Table, the pH ranged from 6.1–8.7 which is within the neutral pH region. The values of the other parameters varied from 0.01 mg/L for ammonium nitrogen (NH_4^+) to 670 mg/L for Total Dissolved Solid (TDS).

STP-S2 (Upstream sampling sites)

A general decrease in water quality parameters was observed from 2004 to 2006 (Table 10). This could be ascribed to the reduction of polluted plume reaching the water course. The abstraction could have reduced the volume of groundwater seeping into the river hence, the observed reduction in pollutant parameters level. Significant reduction was observed for SO_4^{2-}, Na^+, NO_3^- and EC which are major salt formers. Similar studies were carried out by Sibiliski and Okonkwo (2007). Most of the boreholes contaminated by slime dam waste seepage had high water quality parameter levels as found in this study before remediation programme.

Table 9: STP-S1 Levels of Physical and Chemical Parameters of Downstream Steelpoort River Water Samples

Site	Date	Variable Parameters (mg/L)												
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F	T/alk	Cl	SO_4^{2-}	NO_3^-	$NH4^+$
STP-S1	04/2004	8.1	43.1‡	260	29‡	18‡	31‡	1.6	15.6	<0.2	296	124	120‡	3.0	<0.2‡
STP-S1	10/2004	8.3	109‡	670	48‡	55‡	109‡	3.2	16.4	<0.2	308	109	26‡	3.2	1.4‡
STP-S1	05/2005	6.1	57‡	280	32‡	20‡	34‡	1.5	14.6	0.4	204	63	111‡	2.8	<0,2‡
STP-S1	10/2005	6.4	82‡	514	48‡	41‡	75‡	0.8	14.0	0.24	264	103	26.8‡	3.02	1.4‡
STP-S1	06/2006	6.5	92.8‡	530	45‡	41‡	82‡	0.3	15.4	0.12	333	97.4	68‡	3.0	0.05‡
STP-S1	08/2006	8.7	127‡	620	50‡	64‡	145‡	1.5	16.8	<0.2	95.4	40	224‡	4.64	0.03‡
STP-S1	09/2006	8.1	24.3‡	152	18‡	13‡	13‡	1.0	10.0	0.6	123	15.1	14.9‡	0.7	<0.01‡
STP-S1	10/2006	8.2	35.1‡	224	24‡	18‡	24‡	0.8	9.89	0.2	121	26.2	22.2‡	1.36	0.01‡

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); TDS = Total dissolved solids.

Table 10: STP-S2 Levels of Physical and Chemical Parameters of Downstream Steelpoort River Water Samples

Site	Date	Variable Parameters (mg/L)												
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F	SO_4^{2-}	Ca^{2+}	Cl	NO_3^-	NH_4^+
SPT-S2	Apr-04	8.1	40.0	258	29.0	18.0	30.0	1.30	15.9	0.2	208	124	17.0	1.70	0.20
SPT-S2	Oct-04	8.3	96.4	586	42.0	50.0	96.0	2.90	17.4	0.2	308	99.0	62.0	1.90	0.60
SPT-S2	May-05	8.1	46.0	264	30.2	19.1	32.7	1.30	17.2	0.2	208	97.0	42.4	2.36	0.02
SPT-S2	Oct-05	8.8	94.8	590	33.3	45.4	13.0	1.31	18.1	0.45	324	90.6	65.9	1.58	0.002
SPT-S2	Jun-06	8.4	40.2	258	29.1	22.2	34.1	0.83	10.6	0.43	154	27.7	28.5	2.02	0.051
SPT-S2	Aug-06	8.3	49.3	296	32.1	23.6	41.3	0.86	9.23	0.26	181	43.8	29.7	1.89	0.004
SPT-S2	Sep-06	8.2	47.7	280	34.7	24.9	37.4	1.07	10.7	0.13	176	36.8	20.6	1.66	0.47
SPT-S2	Oct-06	8.2	82.7	480	44.8	38.0	76.0	1.16	13.7	0.17	266	92.9	45.5	1.50	0.01

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m); EC = Electrical conductivity (µS/m).

Control Boreholes

Control boreholes were sunk at a distance of about 2000 m from the pollution source. This distance was assumed to be far from the pollution source such that the pollutants could not have migrated to the control points. Hence the sampling points were assumed to be contaminant free and those parameters determined were due to natural geochemical processes. The mean values of the water quality parameters measured for the boreholes are shown in Table 11. From the quality assessment, it was observed that the quality of water from the control boreholes was safe for human and animal consumption according to DWAF and DEAT, SA standards.

Since the downstream part of a river receives most of the pollution load, it was deemed necessary to compare the values of water quality parameters of the downstream with the standard limits. Figure 8 compares the Electrical Conductivities between 2004 and 2006 against the South African Standard limits. It can be seen from Figure 8, that the STP-S1 (downstream) was within the South African Standard limits 1 and 2 (DWAF, 1996a).

CONCLUSIONS

From this study, sufficient information was generated on the water quality indicator parameters of the plume investigated. The sinking of boreholes and the abstraction of polluted groundwater managed to reduce pollutant levels as indicated by the shrinking of SO_4^{2-} contours within the pollution plume. A reversal of groundwater flow as a result of abstraction was observed. Water flowed from the river towards the pollution plume and thus diluted the polluted groundwater.

Table 11: CNT-B3 Levels of Physical and Chemical Parameters of Downstream Steelpoort River Water Samples

Site	Date	Variable Parameters (mg/L)													
		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Si	F^-	T/alk	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+
CNT-B3	Apr-04	8.1	94.0	524	42.0	88.1	48.5‡	1.81	44.1	0.01	498	71.6	29.5	3.00	0.01
CNT-B3	Oct-04	7.0	94.5	544	40.7	85.3	49.4	1.84	41.3	0.05	430	68.3	8.20	1.51	0.01
CNT-B3	May-05	8.7	94.3	558	42.5	90.4	49.7	1.94	40.3	0.24	443	43.8	19.5	1.59	0.01
CNT-B3	Oct-05	7.9	97.4	580	41.8	85.0	48.2	1.97	39.2	0.19	461	69.8	22.7	1.48	0.001
CNT-B3	Jun-06	7.9	98.8	574	43.8	93.9	48.4	1.78	40.9	0.05	455	65.9	20.1	1.68	0.05
CNT-B3	Aug-06	8.1	95.1	552	33.5	84.7	44.9	1.87	40.4	0.08	448	65.1	22.4	1.51	0.01
CNT-B3	Sep-06	7.7	84.9	452	38.3	81.6	23.2	1.92	41.5	0.01	431	37.6	7.30	1.23	0.01
CNT-B3	Oct-06	7.7	102	349	38.0	83.2	59.2	2.38	39.9	0.03	429	77.0	2.61	1.87	0.01

Chemistry standard: South African Drinking Water Standard (mg/l); ‡ Value exceeds recommended maximum limit; EC = Electrical conductivity (µS/m).
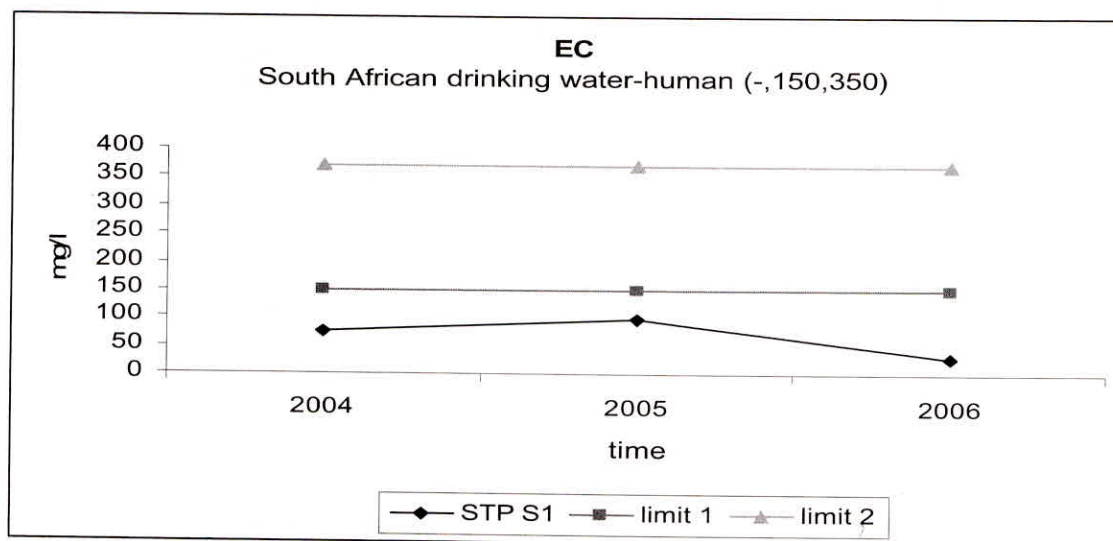
Fig. 8: EC for STP-S1 against the SA drinking water standards

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