Tracer Test in Mine Water of the Abandoned Edendale Lead Mine, South Africa

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Abstract Tracer tests are deployed to determine the hydraulic connectivity of flow paths or connections from surface and underground mines. This paper describes a mine water tracer test in a flooded, South African underground lead mine. Sodium chloride was injected as a tracer into one shaft and the electrical conductivity was measured continuously. The EC curve showed multiple peaks and tracer recovery was 17 %. The mine aquifer appears to be fractured and there is poor hydraulic connectivity. It appears that the main hydraulic processes within the flooded mine is subject to advection flow. There was no contamination in the receiving water course as the metal concentrations are within regulated standards; the likelihood of water quality degradation is therefore moderate.

Key words abandoned mine, tracer test, fractured aquifer, mass recovery, Edendale, South Africa

Introduction

In many parts of the world, mining is known as one of the main cause of environmental concerns. Economic and environmental reasons have caused closure of many mines without rehabilitation and has led to alteration of the hydrogeological environment (Banks et al. 1997; Razowska 2001). In South Africa, legislation and guidelines have been adopted to address mine closure and post-mining water management even so abandoned mines remain a liability (Kgari et al. 2016). Silver mining in South Africa started around 1880 when the “Pretoria Silver Belt” was prospected in Pretoria, Gauteng Province. Consequently, the development of mineral mining grew country wide and as a result, many of the smaller mines were abandoned (Kgari et al. 2016; Reeks 2012). When mines are abandoned, the rebound of the water table can lead to contaminated groundwater to flow into underlying aquifers causing degradation to the quality of receiving surface water and groundwater, eventually making it unsuitable for further use (Cidu et al. 2007; Wolkersdorfer 2005; Younger et al. 2005). Environmental problems associated with abandoned mines are controlled by the type of mining employed (underground or surface mining). Approximation of mine water quality draining from surface mines is well developed but such is more or less absent in abandoned flooded underground mines. The flooding of underground mines might cause the supporting structures to collapse and subside causing inaccessibility to the shafts or adits of the mine. This further increases the permeability and porosity and alters the groundwater flow as the underlying aquifer becomes fractured (Booth et al. 1998; Mhlongo and Amponsah-Dacosta 2016; Younger 2000). Hydrodynamics governing the movement and transport of mine water in flooded underground mines is not commonly acknowledged in South Africa. The general focus of most investigations in South Africa has been on contamination treatment and inhibition of water discharge (Kgari et al. 2016). However, planning remediation strategies and the calculation of reactive transport within the mine depend on the understanding of the volume of flooded mines and hydraulic properties (Wolkersdorfer 2005).

Tracer tests have been employed to trace the hydrodynamic conditions of flooded underground mines and interconnections of groundwater flow. The publications of tracer tests results in abandoned underground mines are not commonly known. Therefore, there is less experience in mine water tracing. Tracers are used depending on site conditions and aims (Wolkersdorfer et al. 2002). Although, in the past, tracer techniques focused on groundwater flow in karstic aquifers, there has been development in previous decades for the use of tracers as a hydrologic investigating tool. Tracers are inferred to as any constituent which by design is introduced into the aquifer to determine flow paths, groundwater velocities, mass flow and contamination transport (Divine and McDonnell 2005). Understanding the hydraulic connection between mine workings, surface and ground water is needed for source determination of water and pollutants at the discharge point as so to support remediation measures (Kgari et al. 2016).

The main objective of the present study was to conduct a tracer test in the mine water of the abandoned Edendale Lead Mine (Tshwane East) with the aim of identifying potential mine water pollution and to characterize the mine water quality, to eventually understand the hydrodynamic processes around the mine. This is important as there are a primary and high school nearby and the mine is located adjacent to the Edendalespruit, where numerous farms and some private residential areas rely on borehole water.

Location and mining history

The abandoned Edendale Lead Mine is a former underground lead and silver mine located in Pretoria East, Silverton on farm Nooitgedagt 333 JR South Africa (Fig. 1). It is situated in the Silverton Formation of the Pretoria Group that forms part of the Transvaal Supergroup. This formation comprises of carbonate mudrocks which are interbedded with sandstones, chert and dolomite. Geologically the host rocks around shafts E12 and E13 comprises of quartzite of the Magaliesberg formation imbedded with limestone and shales (Eriksson et al. 2012). Detailed historic mine plans are not available, but Edendale mine No. 1 is on the north of the R513 and Edendale mine No. 2 is on south of the road. The remaining shafts were numbered by the Council of Geoscience and not according to the historic mine plans. Only three mine shafts remain: shaft 1 at mine 1 and shafts 12 and 13 at mine 2. For the purpose of this study the shafts are referred to as Edendale mineshaft 1, 12 and 13 (E01, E12, E13). Mining operation lasted from 1890 to 1974, producing 6333 t of ore: 4762 t of lead, 1127 t of silver and 105 t of antimony (Glass 2006). When mining began 120 years ago, galena, zinc, sphalerite, chalcopyrite, and cerussite were the main minerals mined. In 1904 mine 1 and mine 2 had shafts which were 41 and 61 m in depth respectively. During this period 11000 t of ore was mined of which 80 % was galena. Furthermore, a shaft in mine 2 was sunk to 212 m in 1905 and 1120 t of lead ore was produced (Reeks 2012). A new shaft was opened in 1921 and in a depth of 17 m connected to the adjacent shaft. This new shaft was sunk 36 m beneath the cerussite vein, which was 46 cm wide and produced first grade galena. Westward of the new shaft, a connecting shaft was also opened and had initially

54 m in depth and later was sunk to 214 m. Annually, the mined vein produced 40 t of ore (Reeks 2012). This increase in depth caused water inflows which required massive pumping allowing the mine to sell million litres of water to other mines monthly. The Edendale Point of Discharge (EPD) discharges water into the Edendalespruit as so a conduits to the Roodeplaat catchment dam. Currently the measured water level is 1.9 m at E12 which is 6.49 m deep and 2 m at E13 which is 3.45 m deep(Fig. 2). Water volume in the two shaft was calculated using mineshaft breathe and width of 1 m and 1.5m respectively. At present the total volume estimated at E12 is 6.89 m^3 and 0.99 m^3 at E13 with a flow rate of 0.5 L/min at EPD.

Methods

Water samples were collected at the shafts using a dropper rope, at the point of discharge and upstream as well as downstream of the mining area in the Edendalespruit. Water samples were collected 3 times from various sample localities (Fig.1) in both wet and dry seasons from 2015-03-09 to 2016-10-29. On-site parameters (pH, redox, temperature, electrical conductivity and dissolved oxygen) were measured using Hach instruments at point of sampling. Bicarbonate alkalinity was determined on-site using a Hach digital titrator and mathematically from the difference in the ion balance. Major and minor anion concentrations were determined on non-acidified and acidified water samples by ICP-MS an a discrete analyser at Waterlab Pty (Ltd) as well as major and minor trace element concentrations which were analysed by ICP-MS and ICP-OES. 21 kg of food quality NaCl were dissolved into 75 L of tap water in the lab before the start of the tracer test and the solute was injected into shaft E12 on 2016-09-11. The concentration of sodium chloride was measured by van Essen Diver electrical conductivity probes which were placed at the discharge point and shaft E13. Monitoring measurements were conducted for a period of 4 months at 20 min intervals. Recovery rate was calculated using electrical conductivity measured at EPD equation (1-4) where, t: time; C: concentration; Q: flow; C_m: Mean concentration; Δsalt: difference salt mass; : total mass, F: Factor (0.5295); RR: Recovery Rate

1. $C = EC \times F$

2. $\Delta salt = Cm \times t \times Q$

3. $\sum mass = \frac{\Delta salt}{1000}$

4. $RR = \frac{\sum mass}{Injected\ mass}$ %

Results and Discussion

Mine Water

The mine water discharging from the mine and in the mine shafts shows a circumneutral pH of 6.1–7.4, with a redox potential between 90 and 470 mV and oxygen saturation below

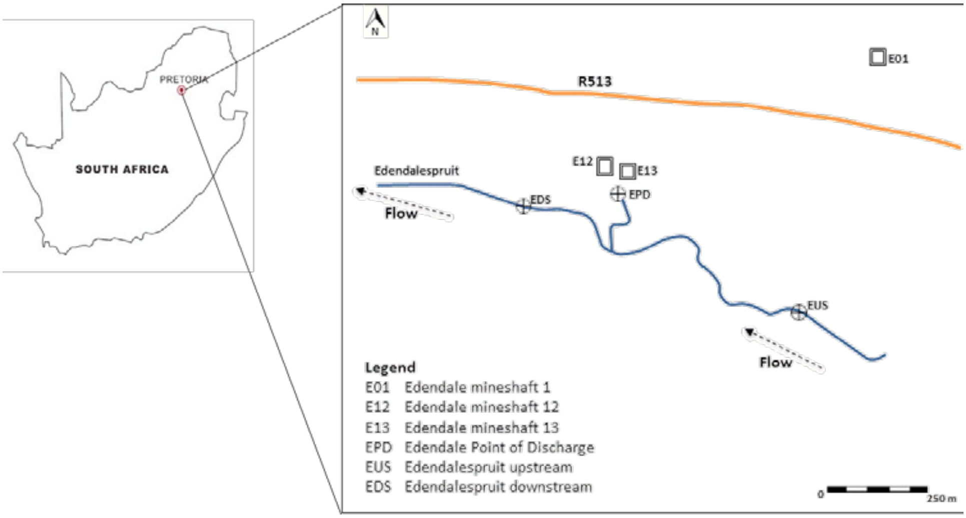

***Figure 1** Location of the abandoned Edendale Lead Mine*

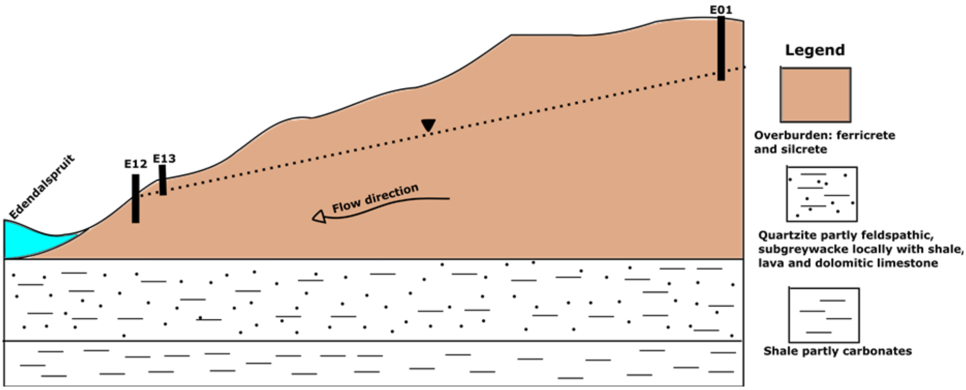

***Figure 2** Conceptual model of hydrogeology of the abandoned Edendale Lead Mine*

60%, with substantially lower values in she shafts and the point of discharge (Tab. 1). These low oxygen concentrations are a result of bacterial activity and plants in the Edendalespruit stream which consume oxygen. Pb, Ag and Sb were below the detection limits. Moderate silicon concentrations were detected at all sites but slightly higher at shaft E12. Na was found to be slightly higher downstream the mine site, possibly as a result of chemicals formerly used in the ore processing plant. An indication for that could be the higher electrical conductivity downstream this location. SO_4^{2-}-concentration is 239 mg/L downstream and 136 mg/L upstream, with low concentrations within the shafts and the point of discharge. Ca and Mg were slightly high at the discharge point (68 mg/L and 41 mg/L, respectively) but according to EPA (2009), there is no health effect at concentrations below 100 mg/L. Mn concentrations were 1.3 mg/L at EPD and 2.8 mg/L at E13, which is above the secondary contamination limit of 0.05 mg/L primary drinking water standard (EPA 2009). In a Piper diagram, it can be seen that the mine water of the Edendale Lead Mine is alkaline (Fig. 1). Mine water characterized at EPD are in the HCO_3 type while E12, E13, EUS and EDS are dominated by the Mg–Ca type, so as in E13 and EUS, the SO_4 type is introduced and Cl type is also introduced at E13. The samples show relatively more alkaline earth metals then alkali metals. The main rock type found in the study area is limestone and dolomite, which explains the concentrations of Mg, Ca and bicarbonate in most of the samples.

Table 1 *On-site parameters and mine water composition (mg/L) from the abandoned Edendale Lead Mine. Pb, As, Ag and Sb were below the detection limit; n: chemical analysis / on-site parameter; ± is standard deviation of sample population. Average of the pH calculated using the {H+}, b.d: below detection limit.*

	EUS	E12	E13	EPD	EDS
pH	6.9 ± 0.4	6.7 ± 0.1	6.7 ± 0.2	6.7 ± 0.4	6.6 ± 0.7
Redox, mV	328 ± 123	319 ± 42	306 ± 86	224 ± 65	227 ± 65
EC, µS/cm	437 ± 134	603 ± 15	466 ±118	615 ± 18	670 ± 84
Temp, °C	21.5 ± 2.5	22.9 ± 1.3	23.8 ± 2.0	21.8 ± 2.1	22.0 ± 1.5
HCO_3^-	371 ± 260	406 ± 16	336 ± 179	421 ± 13	399 ± 165
SO_4^{2-}	55 ± 70	0.6 ± 1.2	27 ± 24	5 ± 4	102 ± 121
Cl	5 ± 1	5 ± 1	4 ± 2	5 ± 1	4 ± 2
B	0.009 ± 0.007	0.010 ± 0.007	0.012 ± 0.008	0.019 ± 0.010	0.011 ± 0.009
Ba	0.050 ± 0.350	0.131 ± 0.009	0.110 ± 0.012	0.086 ± 0.061	0.079 ± 0.020
Ca	39 ± 19	59 ± 1	42 ±16	63 ± 4	61 ± 5
Fe	0.028 ± 2.025	0.129 ± 0.164	0.029 ± 0.04	0.058 ± 0.041	0.027 ± 0.04
K	3.5 ± 0.7	3.7 ±0.4	3 ± 1	4.5 ± 0.6	1.5 ± 1.7
Mg	32 ± 16	37 ± 1	26 ± 9	40 ± 2	52 ± 2
Mn	0.12 ± 0.15	0.73 ± 0.04	1.74 ± 0.80	1.25 ± 0.36	0.11 ± 0.11
Na	7 ± 4	9 ± 0.4	6 ± 3	10 ± 0.6	17 ± 2
P	0.01 ± 0.01	0.04 ± 0.04	b.d.	0.01 ± 0.1	0.02 ± 0.01
Si	12 ± 6	19 ± 0.2	13 ± 3	17 ± 0.1	17 ± 2
Sr	0.127 ± 0.070	0.174 ± 0.270	0.127 ± 0.030	0.179 ± 0.020	0.193 ± 0.030
Ti	0.078 ± 0.030	0.119 ± 0.011	0.077 ± 0.020	0.119 ± 0.014	0.120 ± 0.023
Zn	0.09 ± 0.08	0.06 ± 0.04	0.39 ± 0.20	0.02 ± 0.02	0.23 ± 0.27
n	3 / 3	3 / 9	3 / 9	3 / 10	3 / 3

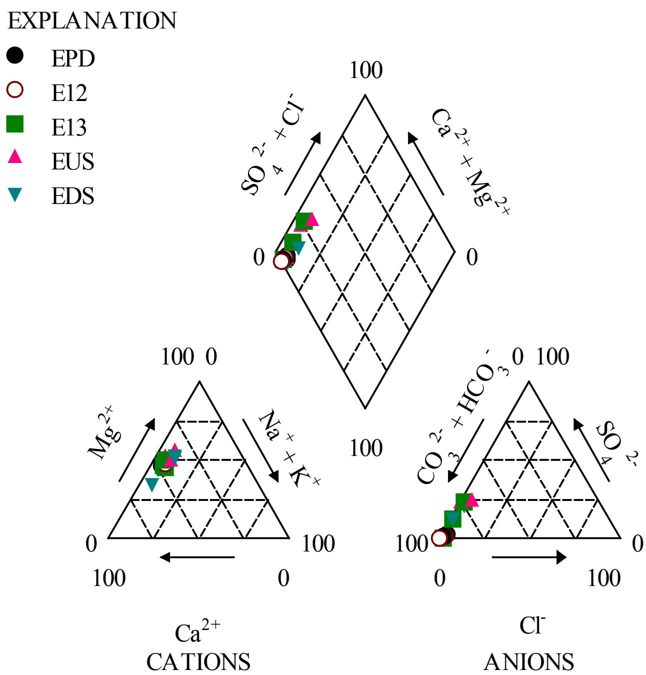

***Figure 3**: Piper diagram for samples collected at the abandoned Edendale Lead Mine; n = 15, averages of three sampling campaigns.*

Tracer Test

During the tracer test, the electrical conductivity increased in the wet months (Fig. 4), which can clearly be attributed to the sodium chloride tracer (Wolkersdorfer et al. 2002) being transported by the rain water infiltrating into the subsurface. Only 17.1% of the injected tracer was recovered (Fig. 5). Considering the geological and hydrodynamic setting, the low recovery rate might be caused by a poor hydraulic connectivity between the point of injection and point of discharge or a density driven settlement of the concentrated tracer. The first EC peak occurred in October 2015, second, third and fourth peaks were detected in November, December and January respectively. When there are multiple peaks in the EC measurement it shows that the tracer might be transported via various flow paths so as the dispersion and velocity are not the same (Leibundgut et al. 2011) or the rain events cause the tracer to be flushed out of the mine. No peaks were observed in E13 (Fig. 4). Therefore, it can be assumed that the tracer does not flow into shaft E13. This result shows that the tracer is transported from shaft E12 directly to the point of discharge but not to the adjacent shaft E13.

Conclusions

As has been shown, the mine water at the abandoned Edendale lead mine has a circum-neutral pH. Due to the low concentrations of potentially toxic elements, no negative effects on the population's health will be expected. In the Piper diagram, it can be seen that the mine

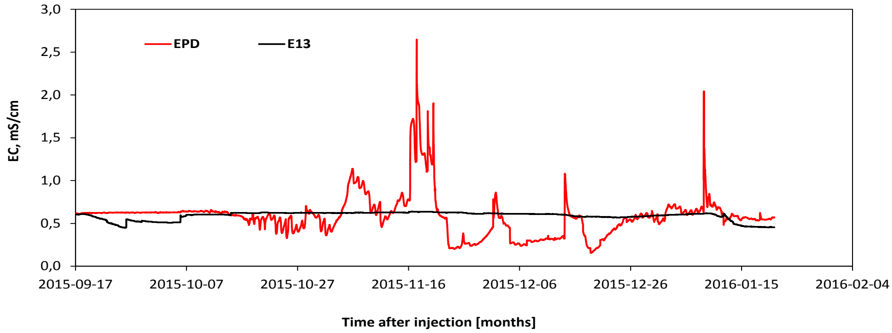

Figure 4 *EC measurement in shaft E13 and the discharge point of the abandoned Edendale Lead Mine during the tracer test*

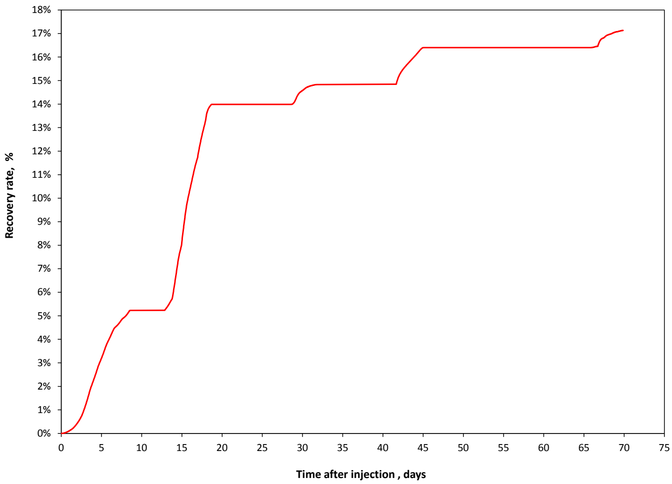

Figure 5 *Recovery rate of the Edendale tracer test.*

water is of the HCO_3-Ca-Mg type. The tracer injected into shaft E12 was only detected at EPD which is an indicator that there is no transport to shaft E13. Furthermore, the tracer test proved that the flow is advection based and there is no active hydraulic connection between the two shafts. Because 17% of the injected NaCl was recovered after 4 months of the tracer test, either an obstruction because of an adit collapse, a denser mine water-brine pocket is still in the shaft or there is diffuse flow into the adjacent mine workings or the host rock. Both the EC measurements and the low tracer mass recovery are indicative for this assumption. Overall, the results obtained so far show that there will be no deteriorating contamination of the receiving water courses.

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