# An integrated approach to evaluate the hydrogeological setting around a water-filled quarry in a mining environment

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**Abstract**

An integrated approach was employed using electrical resistivity tomography, aquifer tests, hydrochemistry and isotopes data to evaluate the geohydrological setting and pollution distribution around a water-filled quarry. A discard dump upstream from the quarry was identified as the main source of pollutants. Pollutants were transported along a fault system and a hydraulic zone at 20 m depth and concentrated in the quarry. Overflow from the quarry led to a rapid distribution of pollutants along the surface. This study indicated that the combination of analytical tools was efficient in identifying pollution sources and flow paths into and subsequently from the quarry.

**Keywords:** Hydraulic zone, fault system, discard dump, hydrochemistry

## Introduction

Mining and industrial activities alter the Earth's sub-surface leading to changes in the natural surface- and groundwater flow paths and hydraulic conductivities of disturbed ground. In addition, mine water seepage from discard dumps often affect the water quality of the surrounding environment (Morin and Hutt 2001). Poor water quality was detected in a water-filled quarry at an industrial and mining complex in the north-eastern section of the Karoo Basin, Mpumalanga, South Africa. Locally, the area is dominated by the Permian Vryheid Formation of the Ecca Group, containing upward-coarsening cycles of siltstone, mudstone, immature sandstone and carbonaceous shale (Johnson et al. 2006). Several faults were mapped in the area, which form part of a larger graben structure with a displacement of approximately 22 m (pers. com. Vermeulen 2015). Two aquifer types control the geohydrological setting and were classified as the upper weathered and a deeper fractured Ecca aquifer (Grobbelaar 2001), with an average yield of 0.6 L/s and 0.2 L/s, respectively (King 2003). Although these aquifers are relatively low yielding, bedding planes and secondary structures such as fractures and faults could form preferential flow and transport paths for contaminants from mining activities into the quarry.

A continuous hydrocensus at the study site indicated that the quarry had high sulfate concentrations resulting in an elevated electrical conductivity (EC), exceeding the water use license requirements of 90 mS/m and a TDS of 585 mg/L of the industrial complex. The quarry was mined for dolerite in the production of gravel during the construction of a railway line. It is underlain by a fault system and located in a graben north of an active discard dump for coal fines. Previous research in the area highlighted that seepage from the discard dump in the south had leaked into the groundwater and that the graben functioned as a highly conductive zone contributing to the spreading of contaminants towards the quarry (pers. com. Vermeulen 2015). As a mitigating measure, a cut-off trench was constructed around the discard dump which improved the groundwater quality immediately surrounding the trenched area. However, the water chemistry of the quarry did not improve over time. Therefore, it was recommended to re-evaluate the hydrogeological setting around the quarry to identify the sulfate source leading to elevated EC and TDS values.

This study aimed to identify the groundwater flow direction within the graben and potential flow paths for contaminants into and from the water-filled quarry. An integrated approach was utilized by applying electrical resistivity tomography, groundwater levels, aquifer tests, water chemistry and isotope analyses. The objectives were to determine the source of high EC and sulfate concentration found in the quarry and surroundings, and to evaluate the distribution of mine water seepage along the mapped fault system.

## Methods

### *Electrical resistivity tomography (ERT)*

Electrical resistivity tomography measures the apparent resistivity of geological units by inducing an electrical current into the sub-surface via electrodes. The apparent resistivity is then obtained as the product of a measured resistance from the ground and a geometric factor for a given electrode array (Reynolds 2011). Since different lithologies are more or less resistive to an induced electrical current, changes in the geology and groundwater occurrences can be detected. A Terrameter ABEM SAS 1000 with a Lund Imaging System and a Wenner array was utilized to measure the apparent resistivity of the subsurface. A grid with 13 traverses was surveyed around the quarry to identify low resistivity areas indicative of possible groundwater flow paths (Fig. 1). A unit electrode spacing of 2.5 m was chosen based on a) the need to record data with a high spatial resolution and b) the physical limitations on the lengths of the electrode arrays posed by the surface infrastructure, quarries and wetlands. The measured data was modelled with the software RES2DINV (Loke and Barker 1996) and interpolated with the Krigging method to generate a horizontal visualization of the ERT model.

## Aquifer tests

Slug tests were employed to estimate an initial yield of the borehole to assess its viability for a pumping test. In addition, a slug test provides a first indication of the aquifer transmissivity, considering 90% recovery of the static water level (van Tonder and Vermeulen 2005). All slug tests were interpreted with the FC program for Aquifer Test Analysis (van Tonder et al. 2013). To evaluate the slug test data, the harmonic mean was calculated to alleviate the impact of large outliers.

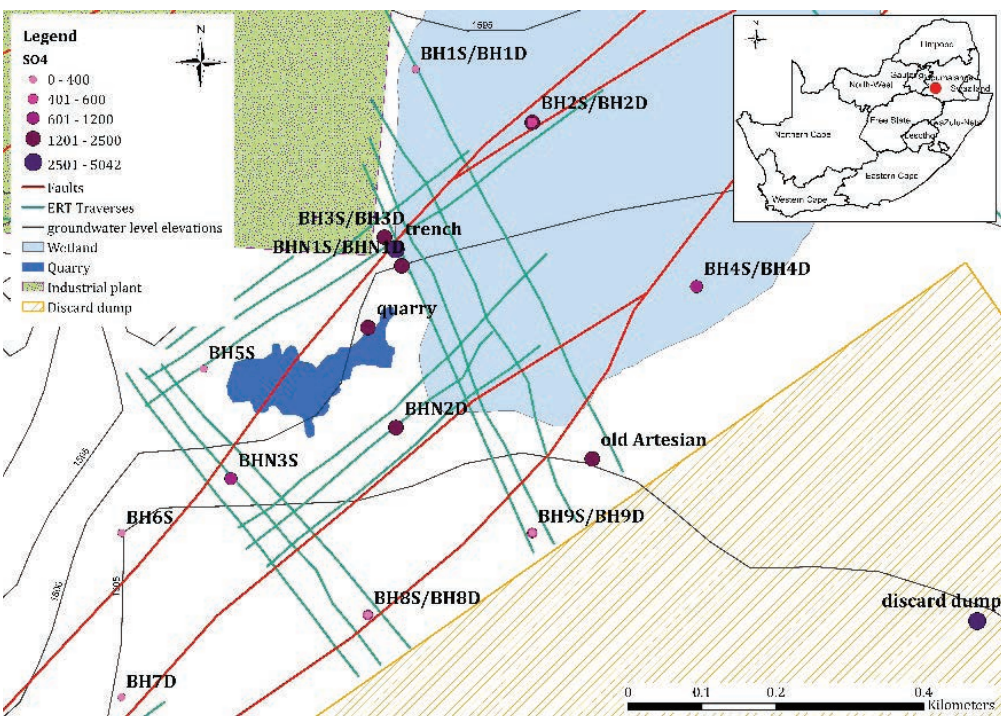


*Figure 1 Schematic map of the study site indicating geophysical survey traverses and sample locations with proportional sulfate concentrations.*

Constant rate pumping tests were conducted over a minimum time of eight hours to determine the aquifer parameters. Prior to each pumping test, a calibration test was performed by pumping the borehole at three different rates of the pump capacity and evaluating the recovery of the static water level to more than 90%, to obtain an appropriate pumping rate (van Tonder *et al.* 2001a). Each pumping test was executed according to the procedure described in the pumping manual for fractured rock aquifers by van Tonder et al. (2001a) and interpreted based on the basic flow characteristic (FC) method. This method applies derivative fitting of drawdowns and includes boundary information as well as the Gaussian error propagation analysis to estimate the sustainable yield of a borehole (van Tonder *et al.* 2001b).

### *Water sampling for chemical and isotope analysis*

Water samples were collected with a metal flow-through bailer and stored in pre-rinsed plastic bottles for chemical analyses and in glass bottles for isotope analyses. An Inductive Coupled Plasma/Optical Emission Spectrometry was used to determine the elemental concentrations of the samples by the Institute for Groundwater Studies (IGS) laboratory. A Los Gatos Research (LGR) Liquid Water Isotope Analyser was employed by the iThemba laboratory to determine the stable isotope composition of δD and δ18O. These delta values were expressed as per mil deviation relative to a known standard, standard mean ocean water (SMOW).

## Geophysical investigation

Three general resistivity zones were identified in the ERT model around the water-filled quarry: A zone of low resistivity below 13 Ωm, an intermediate resistivity zone ranging from 16 to 142 Ωm and a zone of high resistivity above 212 Ωm. A high resistivity zone (>470 Ωm) north of the quarry suggested the presence of a dolerite sill (Fig. 2B, C and D) and was confirmed by geological logs obtained during previous construction in the area. A wetland north-east of the quarry correlates with low resistivity values due to saturated material (Fig. 2B). This saturated zone extends partially to a depth of approximately 20 mbgl (Fig. D). Another low resistivity zone was identified at the contact between the dolerite sill and the country rock north of the quarry and along the northern fault extending to the saturated zone of the wetland (Fig. 2B). These low resistivity zones could either indicate the presence of clay-rich material or saturated material. This together with the fractured zone and the fault could represent groundwater flow paths from the quarry into the shallow weathered aquifer feeding into the wetland. South-west of the quarry, an additional zone of low resistivity was modelled, which is intersected by the northern fault. Drilling of an analytical borehole, BHN3S (Fig. 1), into this zone showed that the area was backfilled with coarse ash, dolerite and other building material with a groundwater level at 4.22 mbgl.

In the south-east of the model section, the geology showed high resistivity values eluding to the presence of a dolerite sill, confirmed by subsequent drilling (BH8D, Fig. 1). Similar results were found at a depth of approximately 12 mbgl, except for an additional low resistivity zone that was visible along the middle fault, south-east of the quarry (Fig 2C). At an approximate depth of 19.7 mbgl, the low resistivity zone along the middle fault was more pronounced and extended to the south-east of the southern fault (Fig. 2D). This zone borders the active section of the discard dump and could indicate that mine water seeps into the underlying strata along these faults. The low resistivity zones together with the groundwater level elevations support the presence of flow paths from the discard dump to the quarry and from the quarry into the wetland along the northern fault and dolerite contact zone.

## Aquifer testing

A slug test investigation provided an initial estimate of the fracture ($T_{early}$) and matrix transmissivity ($T_{late}$) as well as the hydraulic conductivity (K) of the fracture. The average $T_{early}$ and $T_{late}$ in the graben was 2 $m^2$/d and 0.17 $m^2$/d, respectively. In the fault zone, the average $T_{early}$ was one order of magnitude higher and the average $T_{late}$ two orders of magnitude higher compared to the graben. The average hydraulic conductivity of the fracture was estimated at 12.04 m/d. Borehole

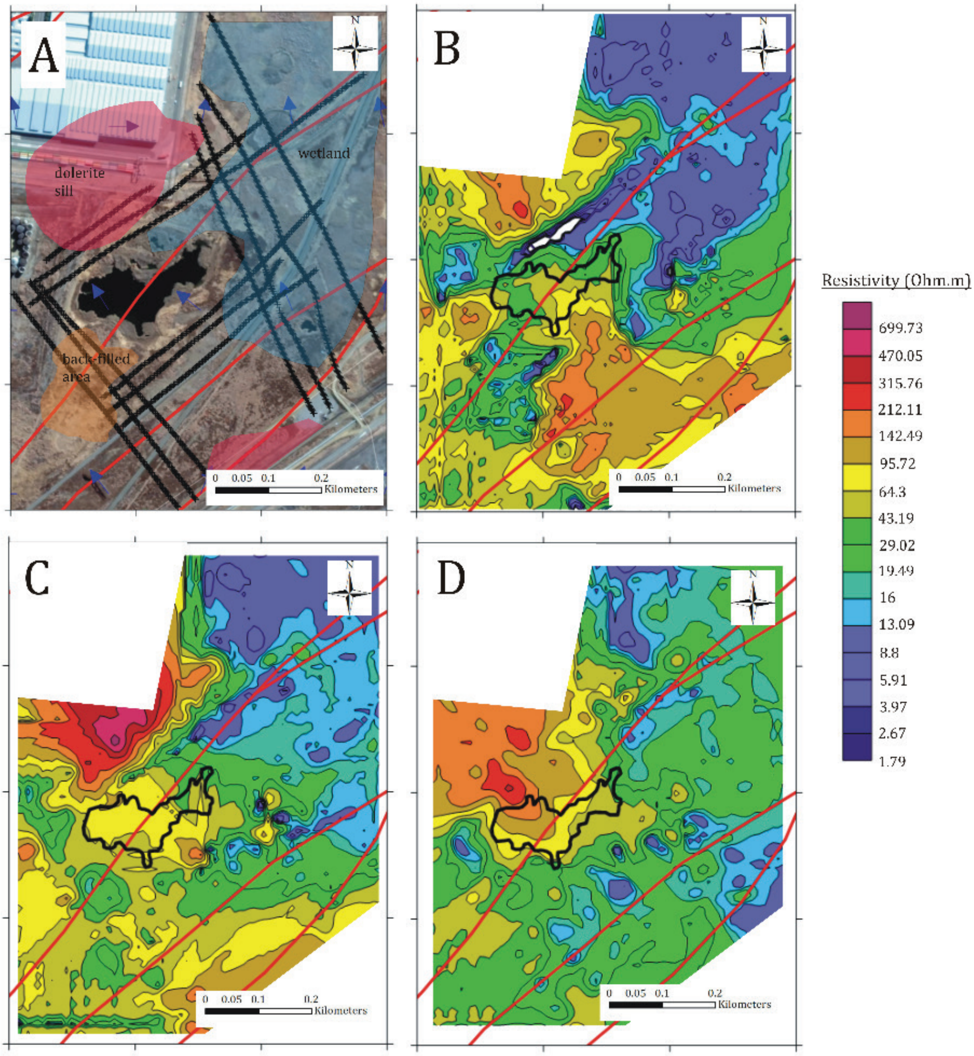


***Figure 2*** *Resistivity interpretation: A) satellite image with resistivity profiles and groundwater flow direction (Google Earth pro 2018); B) resistivity distribution at a depth of 6.22 m; C) 12 m; and D) 19.7 m below surface; mapped faults are indicated in red.*

BHN3S was drilled into the back-filled area and had an elevated $T_{early}$ of 1760.07 m$^2$/d, $T_{late}$ of 6.23 m$^2$/d and an estimated K-value of 8800.37 m/d of the fracture. This was also the only borehole deemed viable to conduct a pumping test. Based on the basic FC method, borehole BHN3S had a $T_{early}$ and $T_{late}$ of 29.28 m$^2$/d and 27.9 m$^2$/d, respectively which relates to the unconsolidated material of the back-filled area.

## Hydrochemistry and isotope study

A water type distribution in form of stiff diagrams and EC values indicated an area with high EC (>370 mS/m) values from the discard dump to north of the quarry (Fig. 3). The slurry pond of the discard dump contained mine water characterized by $SO_4$, Na and K. Groundwater samples north of the discard dump to north of the quarry and water from the quarry itself contained predominantly

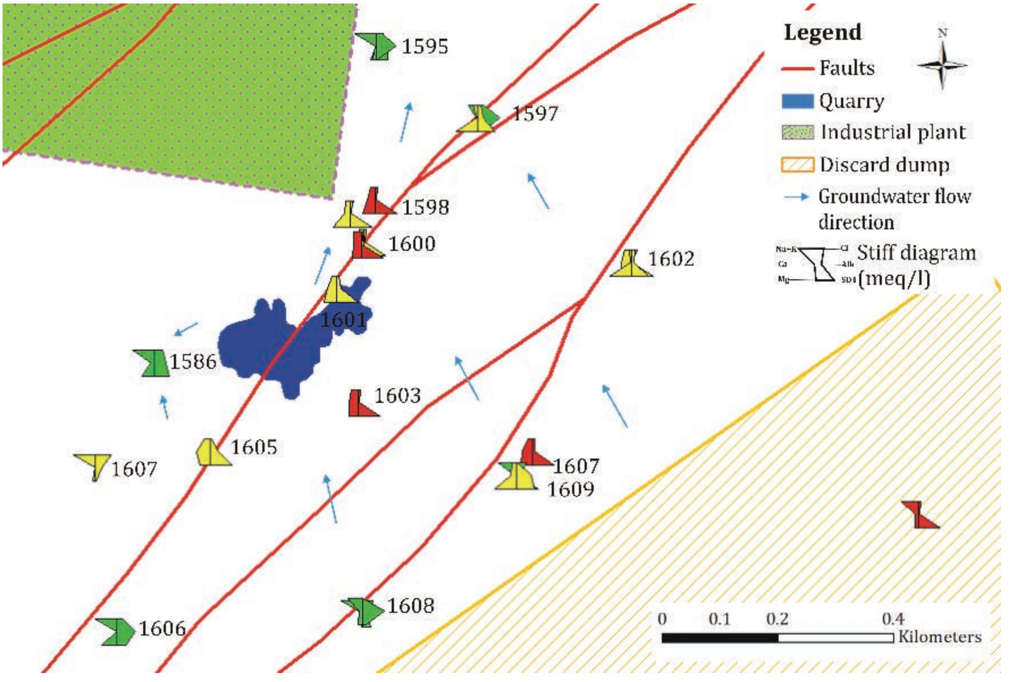


***Figure 3*** *Water type distribution with means of Stiff diagrams, water level elevations (m) and colour coded EC values according to SA drinking water standards (mS/m): green < 150, yellow <370 and red > 370.*

$SO_4$ and Mg. This area with high EC values and same groundwater chemistry correlates with the low resistivity zone identified during the ERT survey and supports the presence of flow zones from and into the quarry (Fig 2). In addition, the groundwater flow direction points towards the north with elevated hydraulic heads in the boreholes adjacent to the discard dump.

West of the quarry, the groundwater was dominated by Mg, Na and K. Further north, boreholes were unpolluted and more alkaline in nature, characterized by Mg, $HCO_3$, Na and K. Analytical borehole BHN3S contained elevated Ca, Mg and $SO_4$ concentrations which were likely to have originated from the back-filled material. Based on the local groundwater flow direction and pumping test results, a connection exists between the back-filled area with a high transmissivity and the quarry.

A surface- and groundwater isotope analysis around the quarry demonstrated that most groundwater samples plotted along the global meteoric water line (GMWL) defined by Craig (1961) (Fig. 4). This indicates that the groundwater is mainly of meteoric origin. In comparison, boreholes BHN1D, BHN1S, BHN2D, BH3D, BH3S and BH4S deviated from the GMWL and local meteoric water line (LMWL) as they were more isotopically enriched than the other groundwater samples. An enrichment was caused by secondary evaporation during rainfall, seasonal variations in precipitation and mixing of surface- and groundwater (Clark and Fritz 1997) such as seepage from the isotopically more enriched quarry. The surface water samples form a different group being isotopically enriched due to an extended evaporation period. Furthermore, the same grouping supports the conjecture that the quarry and trench receive seepage from the discard dump upstream, taking the groundwater chemistry, flow directions and conductive zones, identified in the ERT, into consideration.

## Discussion and conclusion

An analysis of the groundwater flow directions, chemistry and isotope study together with the ERT model suggests that seepage from the quarry feeds into a wetland to the north-east. A link between the quarry and saturated zone of the wetland was identified

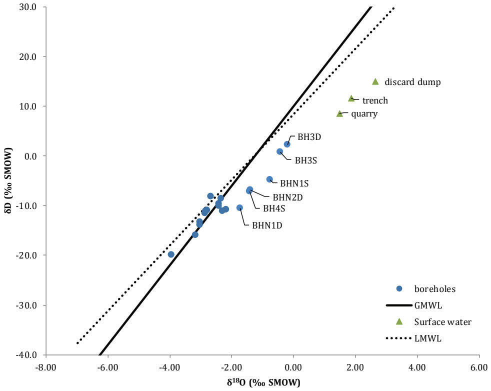


***Figure 4*** *$\delta^2H$ and $\delta^{18}O$ relative to standard mean ocean water (SMOW) of surface- and groundwater samples collected around the quarry compared to the global (GMWL) and local meteoric water line (LMWL).*

along a contact zone between a dolerite sill and country rock in the shallow weathered aquifer as well as through the fault system (Fig. 2). These observations are further supported by the local groundwater flow directions and chemistry $SO_4$ and Mg dominated groundwater compared to unpolluted boreholes characterised by Mg, $HCO_3$, Na and K groundwater in the northern section of the study area. Additionally, continuous surface overflow from the quarry contributes to elevated sulfate concentrations measured in the trench and wetland downstream of the quarry.

Furthermore, this investigation indicated that the quarry and wetland receive mine water from the discard dump via a hydraulic zone along the southern faults at an approximate depth of 20 mbgl. This hydraulic zone was identified by low resistivity values in the ERT model (Fig. 2D) and confirmed with a down-the-hole profile of borehole BH4D, displaying an increase in EC and a drop in pH at an approximate depth of 19 mbgl. Sulfate and Mg dominated groundwater in the hydraulic zone and water sampled from the quarry and trench downstream, support the presence of a conduit between the discard dump, the quarry and the adjacent wetland. Next to the discard dump, borehole BH9D displayed an elevated piezometric head and transmissivity compared to other boreholes, suggesting a connection with the discard dump. A high skin value obtained during the pumping test indicated that a piezometric head was caused by the elevated water table in the adjacent discard dump (pers. com. Vermeulen 2015). In addition, groundwater levels of the monitoring boreholes in the study area showed a flow direction from the discard dump towards the north which forms a topographic low at a bordering river.

A connection between the back-filled area west of the quarry and the quarry itself was confirmed by means of low resistivity values and a pumping test. The pumping test displayed high transmissivity values for both the fracture and matrix and a fast recovery of the static water level of the borehole. Overall, the pumping tests in the area highlighted that the groundwater flow occurs rather along a zone and not along a single fracture based on similar Tearly and Tlate values for fracture and matrix, respectively according to the FC method. This study showed that a combination of analytical methods including ERT, aquifer tests, groundwater flow directions, hydrochemistry and isotope data was sufficient in identifying groundwater flow paths into and from a water-filled quarry and detecting pollution sources.

Although the active section of the discard dump is lined and a cut-off trench was constructed around the facility to prevent mine water seepage from reaching the surface- and groundwater, this study found that these measures were insufficient. It it recommended to construct a numerical flow model to determine the salt load contribution of the discard dump into the system and to evaluate at which depth the present trench would be effective in intercepting the seepage from the dump. Water treatment options for the quarry should be assessed and surface overflow should be prevented by implementing a pumping system.

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