Utilizing Geophysics As A Delineation Tool for Groundwater Flow Paths And Contaminants Along A Graben

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Abstract Seepage from industrial operations into an underlying graben structure resulted in a lowered groundwater quality. A geophysical investigation was conducted across this graben to determine its influence on the pollution distribution and to improve the geohydrological understanding. Geophysical modelling indicated zones of elevated conductivity associated with fault planes, tailings dams, discard dumps and quarries. Additionally, groundwater chemistry obtained at high conductivity zones suggested seepage into both the shallow weathered aquifer and the deeper fractured aquifer underlying the study area. This study demonstrated that applied geophysics in combination with geohydrological data is a useful tool for detecting contaminant groundwater flow paths.

Key words Electrical resistivity tomography, electromagnetics, graben, groundwater contamination

Introduction

Mining and industrial sites with abundant infrastructure and complex operations pose a geohydrological challenge when delineating and managing groundwater contaminants along geological structures. Long term groundwater monitoring revealed an increased salinity within a quarry as well as the shallow weathered and lower fractured aquifer in the vicinity of tailings dams, discard dumps and a variety of industrial operations. In addition, streams within the research area exceeded the electrical conductivity limits granted for a water use license.

The study site was located in the north-eastern section of the Karoo Basin, South Africa, resembling a retro-arc foreland basin. According to Johnson et al. (2006), the area is dominated by lithologies of the Permian Vryheid Formation of the Ecca Group, consisting of upward-coarsening cycles of siltstone, mudstone, immature sandstone and carbonaceous shale. Locally, several faults were identified which together form part of a larger graben structure with a displacement of approximately 22 m (Vermeulen and Dennis 2009). Two aquifer types were classified by Grobbelaar (2001) within the study area: An upper weathered Ecca aquifer with an average yield of 0.6 l/s (King 2003) and a deeper fractured Ecca aquifer with an average yield of 0.2 l/s (King 2003). Although these aquifers are relatively low yielding, bedding planes and secondary structures such as fractures and fissures could contribute to the dispersion of contaminants from mining and industrial activities located on the fault system.

Research was based on a study conducted by Vermeulen and Usher (2009) describing the effects of contaminant migration along a graben structure. Results showed that seepage leaked into the groundwater from an adjacent discard dump and that the graben functioned as a highly conductive zone. In addition, a northward decreasing salinity in the direction of a bordering stream suggested that the fault zone could act as a barrier for groundwater flow or that dilution took place over a distance. Overall, surface water was identified as the main factor spreading pollutants across the study site. A drainage system was constructed to prevent seepage from the discard dump. However, this did not improve the water quality of the stream and quarry after a decade of existence. Therefore it was recommended to extend the area of investigation to determine the groundwater flow direction along the fault zones as well as to determine the salt load contribution into the system by individual industrial activities.

This study aimed to identify flow paths of possible seepage from industrial operations into a quarry and graben by combining electrical resistivity tomography, electromagnetic methods and hydrochemical data. Furthermore, this research could contribute to a more comprehensive understanding of whether the underlying graben may aid in the distribution of contaminants along fault planes and into adjacent streams.

Methodology

Electrical resistivity tomography (ERT)

The ERT method was employed to detect groundwater occurrences and changes in lithology by measuring the apparent resistivity. The apparent resistivity is obtained as the product of a measured resistance from the ground and a geometric factor for a given electrode array (Reynolds, 2011). This method is based on the fact that different geological units are more or less resistive to an induced electrical current applied. A detailed description on ERT methods is available in Telford et al. (1990).

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 broad and refined grid with a total of 35 traverses was surveyed across a 12 km section of the fault system using a unit electrode spacing of 5 m and 2.5 m respectively (Fig. 1). The electrode spacing 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. However, a decrease in electrode spacing does not only increase the special resolution but reduces the maximum depth of investigation that can be obtained (Fourie and Vermeulen 2008). The measured data was inverted with the computer program RES2DINV to generate pseudosections of the transects.

Electromagnetic Method (EM)

A frequency-domain, small-loop system, Geonics EM34-3, was applied to detect pollution plumes and groundwater flow paths within the subsurface. As described by Telford et al. (1990), a transmitter coil generates a transient electromagnetic field in and over the earth's surface and a receiver coil measures the response of the ground to the propagation of the incident alternating electromagnetic waves created. The distance between the transmitter and receiver coil was kept constant at a 40 m inter-coil spacing. A 40 m inter-coil spacing was

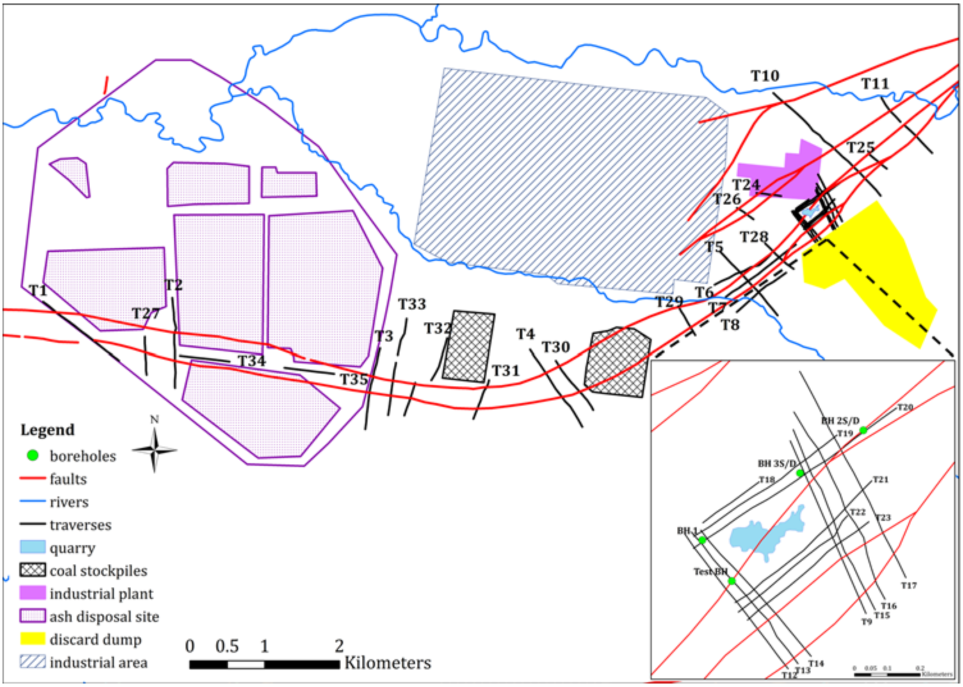

Figure 1 *Schematic map of the study area indicating the outlines of the geophysical survey grids.*

utilised to allow measurements up to an approximate depth of 60 m. The coils were moved along each transect at regular intervals of 5 m whereby the measured apparent conductivity was recorded (in mS/m). Coordinates of measuring stations were noted in 50 m intervals. Both, the vertical and horizontal dipole modes were employed to detect electromagnetic anomalies at depth and near-surface, respectively (Reynolds, 2011). Only 11 traverses were surveyed with the EM method due to disturbances of surrounding industrial operations and excessive infrastructure. In order to enhance the geohydrological interpretation, the EM profiles were compared to the ERT pseudosections, borehole logs and groundwater chemistry of monitoring wells in close proximity of the surveyed transects.

Results and Discussion

A geophysical investigation conducted across the graben displayed low apparent resistivity values in close proximity to ash tailings dams, discard dumps and mine water dams, insinuating that seepage may drain from these facilities. For example, Fig. 2 showed a broad, low apparent resistivity zone between the fault mapped at station 1100 m and station 1400 m near an ash tailings dam. This could imply that seepage from the ash tailings dam percolates into the shallow weathered aquifer and deeper fractured aquifer. In addition, the pseudosection of Profile T1 pointed out that a lithology comprising lower apparent resistivity may exist within the graben between the two fault planes at stations 550 m and 1100 m as previously observed by Vermeulen and Usher (2009).

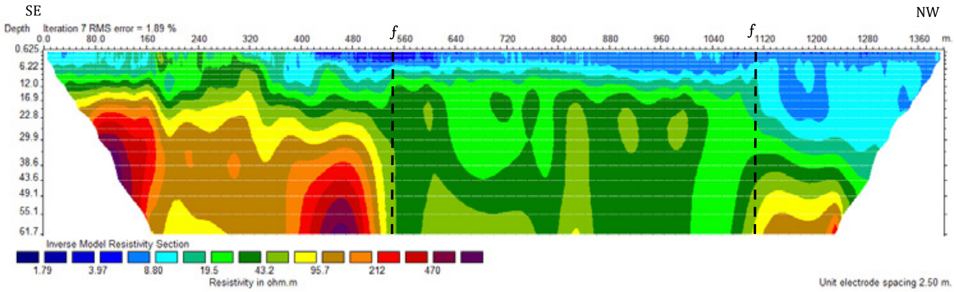

***Figure 2** Inverted resistivity model along Profile T1.*

A pseudosection of Profile T20 (Fig. 3) was conducted north of the water-filled quarry containing a high salinity. It had raised concerns that seepage from the quarry could contribute to groundwater and surface water pollution in the area and along the underlying fault. Profile T20 showed a shallow zone of elevated apparent conductivity that increased in depth from station 90 m to 700 m. This could imply seepage from the quarry into the shallow weathered and fractured aquifer. High apparent conductivity values below 1.79 Ωm near the surface between stations 320 m to 700 m could indicate that wetlands are affected by drainage from the adjacent quarry. Furthermore, the elevated apparent conductivity between station 90 m and 280 m could represent a potential flow path into the quarry based on the elevation profile of the area. A dolerite sill north of the quarry could form potential flow paths along the contact zone with the country rock.

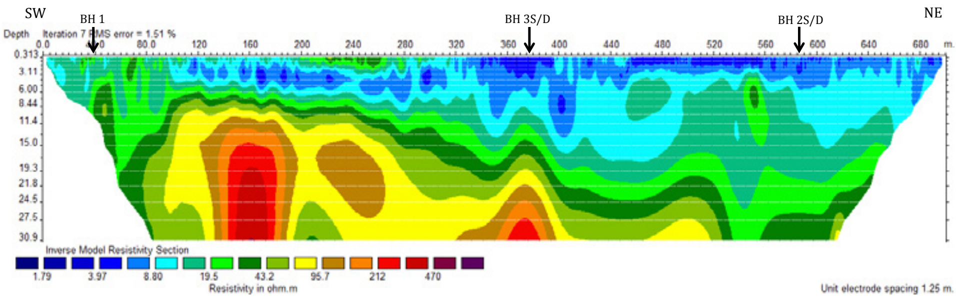

***Figure 3** Inverted resistivity model along Profile T20.*

Based on the groundwater chemistry of the monitoring boreholes presented in Fig. 1, the shallow and deeper boreholes BH 3S/D located downstream of the water-filled quarry seemed to be influenced by seepage from the quarry. Both, the monitoring boreholes and the quarry contained the same Ca/Mg/SO_4/Cl water type (Fig. 4). This suggests a possible groundwater flow connection between the quarry and the underlying aquifers, and is also supported by the ERT pseudosection. In addition, groundwater samples of the deeper borehole BH 3D and the quarry showed the same electrical conductivity (EC) trend. Shallow borehole BH 2S was drilled into a fault plane and indicated a shift in groundwater type from Ca/Mg/HCO_3 to Ca/Mg/SO_4/Cl during one decade of monitoring. Furthermore, both the quarry and borehole BH 2S showed the same EC trend over time. This could point to a possible link between the quarry and the shallow aquifer by means of the highly conductive fault plane underlying the quarry. In comparison, the groundwater chemistry of the underlying deeper fractured aquifer obtained from borehole BH 2D did not seem to be affected by seepage from the quarry as the water type remained constant as Ca/Mg/HCO_3 water. The groundwater chemistry of borehole BH 1, located west of the quarry, did not correlate with the hydrochemistry of the quarry and could therefore represent a different aquifer system.

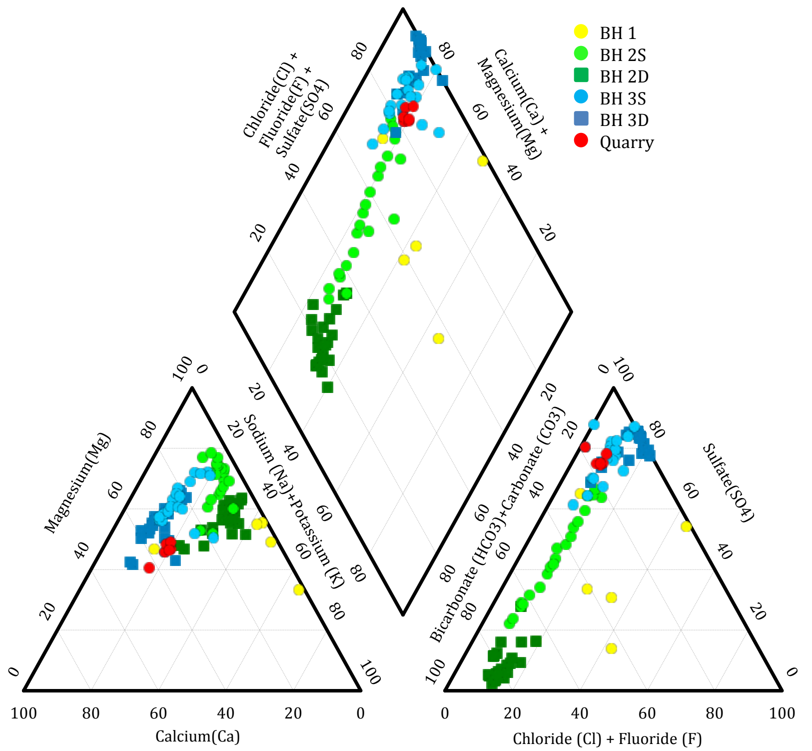

Figure 4 *Piper diagram indicating the groundwater chemistry of boreholes along transect T20.*

Resistivity Profile T13 was constructed west of the water-filled quarry extending southeast to northwest as indicated in Fig. 5. In the south-eastern section, a more resistive zone was visible near the surface which could constitute a partly weathered dolerite sill based on high apparent resistivity values. A shallow low resistivity zone from station 180 m to 250 m

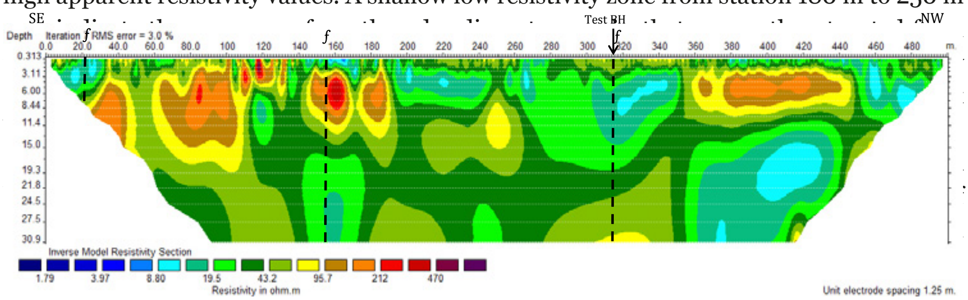

***Figure 5** Inverted resistivity model along Profile T13.*

An additional pseudosection, Profile T9, was generated east of the water-filled quarry from south-southeast to north-northwest (Fig. 6). A zone of increased apparent resistivity was modelled near the surface to an approximate depth of 20 m from station 0 m to 150 m, possibly indicating the presence of a dolerite sill. A decrease in apparent resistivity below a depth of 20 m could be explained by a change in lithology to less resistive sedimentary rocks of the Karoo Supergroup. Parallel to the quarry between station 240 m and 400 m, a shallow zone of low apparent resistivity was modelled, correlating with a wetland. From station 400 m to 480, the zone of low apparent resistivity increased in depth and corresponds with a mapped fault at station 425 m. This fault plane could have formed a zone of elevated conductivity and might provide groundwater flow paths linked to the quarry. In the northern section of Profile T9, from station 500 m to 560 m, a zone of increased apparent resistivity near the surface could indicate a change in lithology and might represent a dolerite sill.

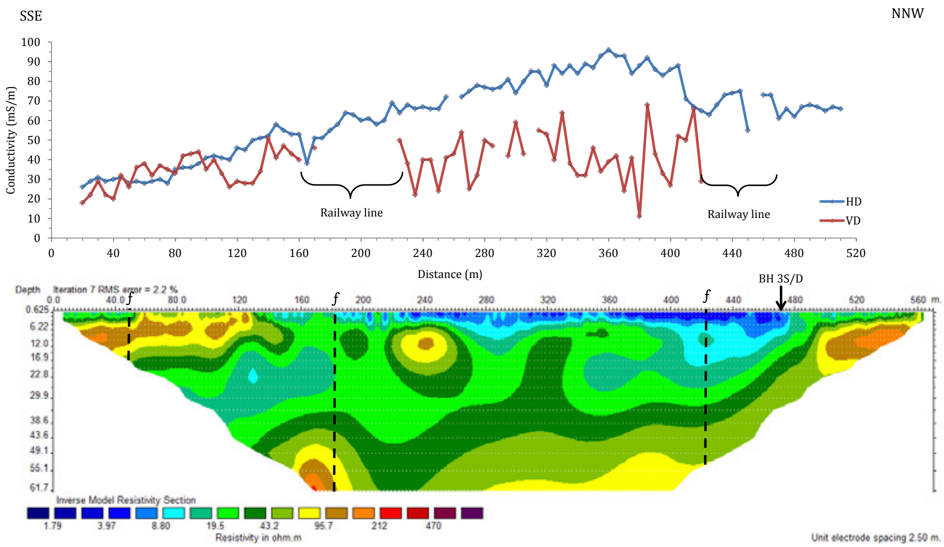

***Figure 6** EM profile and inverted resistivity model along Profile T9.*

In comparison, the horizontal dipole EM profile along the transverse T9 confirmed an increase in conductivity from station 80 m to station 360 m, most probably resulting from an underlying thicker zone of saturated weathered material. A sudden decrease in conductivity at station 170 m and between station 410 m and 420 m could point to a sudden change in lithology caused by a fault, previously mapped, or could relate to interference generated from the railway line. A general increase in conductivity between station 170 m and 480 m could represent the graben comprising more conductive, less consolidated sedimentary rocks. The vertical dipole EM profile showed a general decrease in conductivity at elevated depth which corresponds with the increased apparent resistivity modelled. However, no specific magnetic anomalies were detected.

Conclusions

A geophysical survey confirmed the presence of previously mapped faults within the graben system. Both ERT and EM methods showed that apparent conductivity values were often elevated near ash tailings dams, water-filled quarries and discard dumps. These zones of elevated conductivity proposed possible seepage of mine water into the underlying aquifers.

Furthermore, ERT pseudosections of a refined grid around a water-filled quarry with high salinity indicated zones of elevated apparent conductivity along the northern fault zone as well as along a backfilled area. High apparent conductivity values were also modelled north of the quarry at the contact zone of a dolerite sill. These findings elucidated that possible flow paths exist west of the quarry via the backfilled zone with a possible elevated transmissivity as well as north and north-east of the quarry along the contact zone with the dolerite sill and the fault zone, respectively. An increase in apparent conductivity from south to north, measured with the horizontal dipole of the EM, could not only indicate a change in lithology near the surface but could also relate to the elevated salinity in the shallow weathered aquifer caused by contaminants. Groundwater monitoring data confirmed an increase in salinity from the quarry downstream towards the boreholes in the northeast.

This study highlighted the complexity in identifying contaminant sources from industrial operations along a graben which may contribute to the elevated salinity in the underlying aquifer systems. Whether the graben provides groundwater flow paths between different pollution sources needs yet to be confirmed with additional measures including drilling of boreholes, aquifer testing and isotope studies. Nevertheless, the geophysical survey was found to be a useful tool in determining high conductivity areas across a large scale structure and will assist the client in managing the water use license enforced by legislations.

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